Acoustics of Sequential Spaces

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I, Tingting Yang, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Acknowledgements

The legendary night has just begun. However, when I moved the pen at this moment, I was already relieved. You need the heart to play this. It is time to groove.

The process of earning a Ph.D. is not complicated and involves repeatedly meeting with people who were different from me. To start with music or art, I am a simple person who can perceive beauty even in the thunder of rain. Unlike most Ph.D. candidates, I hardly feel alone in spiritual world. However, this could be my endless personality defect during my Ph.D. At first, it grows in the eyes of people and finally cuts into my flesh. However, being out of anger is not enough to survive predicaments.

So, first of all, with a sincere heart, I would like to thank all the editors of the papers published during my Ph.D. and all anonymous reviewers. Your outstanding and sincere corrections have built miracles in my life.

Patrick told SpongeBob, “Knowledge can never replace friendship, I prefer to be an idiot.” I am grateful to my grandparents who passed away while I was studying. If possible, I would accompany them to the end of the universe. Also, I would like to thank the families of Uncle Eric and Aunt Tancy. In our little time together, these joys made me calm. I would like to thank Jin and Ji: you are my grown-up mirror and childhood kite. Sincere thanks to Jarrad and Yanel. In a world full of greedy people, you always waited for me in front of the British Museum. Sincere thanks to Xuerong and Ziyan who sent me protective clothing by transoceanic express delivery and accompanied me for lunch, be it in the morning or at midnight. This is the year 2121. Am I home, am I with you, every second, every minute, every day, and every night?

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This is the end of everything, and yet, the beginning of everything, again.

Abstract

“Sequential spaces” are spatial systems comprising multiple spaces in sequence connected by openings, common in public spaces with crowd transit (e.g., museums, shopping malls, and transportation hubs). Related to sound diffraction and insulation, this thesis aims to achieve a minor breakthrough in architectural acoustics through establishing disciplines, not focusing on a single or performance space, but targeting large-scale buildings with a listener in motion.

The necessity of applying good practice in asymmetric dynamic auditory perception between approaching and receding sound sources, and inconsistent sound attenuation with distance for separating partitions of same construction is demonstrated by subjective and objective outcomes through real and virtual acoustics.

The first stage observes dynamic auditory perception of noise as a stationary primary sound source in a museum. The asymmetry of the loudness and listener envelopment between approaching and receding sources occurs with broadband noise. Perceptual priority increases with a rising level.

The second stage confirms sound attenuation with distance in accordance with the needs of users (connected room volume, individual room volume, source position, and room absorption) in practice. As connected room volume increases, average sound pressure level is remained for rooms originally connected, while reverberation time generally decreases. The level difference between source and first receiving room is magnified to 1.5 times the sequential one.

The third stage explores sound attenuation with distance when parameters of contextual (opening dimension and position, number of rooms), acoustic (absorption coefficient and distribution) and source (directional radiation from the opening and an additional source) factors are efficient in predictions based on finite element method.

The final stage examines dynamic auditory perception of voice and music with or without background noise through a validated reproduction of virtual environment. Three perceptual distinctions emerge between approaching or receding sound sources and are defined as approach, plummet, and convergence effect.

Impact Statement

This thesis is hoped to support good practice in architectural acoustics by offering clarity on when and how dynamic auditory perception and sound attenuation with distance from the source can be designed appropriately and professionally, in order to achieve improved outcomes. The results of the thesis will be especially useful to support early intervention and preventative work where design decisions about architectural acoustic may be less clear than in comfortable and safety situations.

To assist novices and experienced architects, as well as acoustic professionals and researchers, as well as others interested in widening their knowledge in order to better serve clients and society, the purpose of this thesis is to lead the reader into actual acoustic situations, that is, the prominent distinction in acoustics between either a single enclosure or sequential spaces in either a static or a dynamic context. It attempts in some depth to correctly and accurately avoid the pitfalls, and enable the reduction of post-construction work that might arise owing to the bias and inconsistency in either the dynamic auditory perception of a listener in motion, or the objective physical performance of sound attenuation with distance from the source imposed by practical aspects of the space and source.

The detailed guidance for practitioners, and associated materials, presents some new insights into sound diffraction and insulation in large-scale public projects with crowd transit (e.g., museum, shopping malls, and transportation hubs) for subjective and objective aspects, in terms of conducting accepted surveys and measurements under the representative conditions and essential problems in practice, as general references for achieving a successful and cost-effective design.

Content

List of Symbols

ab	Absorption coefficient (-)
A	Average sound pressure level in a room (dB)
d_{op}	Opening/separating wall area ratio (%)
D	Sound pressure level difference (dB)
l	Length of a room (m)
$L_{A\mathrm{eq}}$	Equivalent continuous sound level using *A*-weighting (dB(A))
L_{AX}	Equivalent continuous sound level using *A*-weighting exceeded for *X* % of the measurement period (dB(A))
$L_{C\mathrm{eq}}$	Equivalent continuous sound level using *C*-weighting (dB(C))
N	Number of rooms (-)
p_{op}	Opening/separating wall position ratio (%)
T	Reverberation time (not specific) (s)
T_X	Reverberation time using the decay of *X* dB (s)
T_{m}	Reverberation time middle frequency (s)
w_{op}	Width of the opening (m)
w_{sp}	Width of the separating partition (m)
ΔD	Decrease in sound pressure level difference (dB)
ΔL	Decrease in sound pressure level (dB)

List of Abbreviations

ANOVA	Analysis of variance
EDT	Early decay time
FE	Finite element
FEM	Finite element method
HVAC	Heating, ventilation, and air conditioning
ISO	International Standards Organization
PRISMA	Preferred Reporting Items for System Review and Meta-Analyses
MANOVA	Multivariate analysis of variance
PA	Public address
PML	Perfectly matched layer
RE	Real environment
RT	Reverberation time
SPL	Sound pressure level
SNR	Signal to noise ratio
VA	Voice alarm
VE	Virtual environment
UCL	University College London

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1 Introduction

1.1 BACKGROUND AND NECESSITY

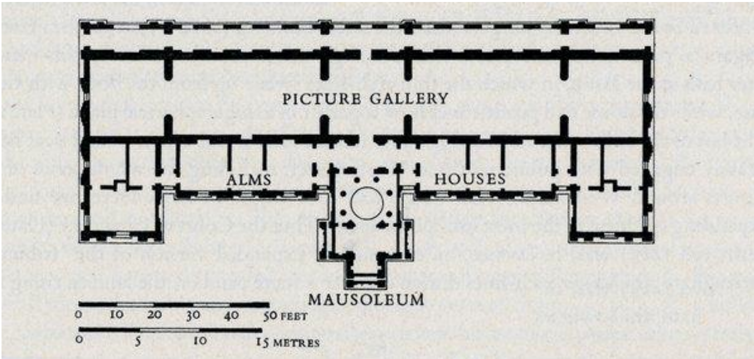
First, spaces used for listening or performing (e.g., concert halls, conference rooms or recording studios) have a necessity for acoustics with the development of sound measures, predictions, and evaluation systems (Beranek, 1996, Barron, 1993). In contrast, less effort is made when designing the acoustics of multiple connected spaces for nonperforming purposes, although we use them on a daily basis, and they are not uncommon, especially in large public buildings (e.g., museums/exhibition spaces, shopping malls, or transportation hubs).

Normally, there are two main types of room in which there can be significant sound attenuation with distance from the source: (1) large rooms (i.e., often with room volumes greater than 200 m^3) with absorbent surfaces and/or large scattering objects and (2) corridors or passageways (Hopkins, 2007). Hence, we are talking about the acoustics of large rooms that are broken up into individual large rooms by separating partitions with openings. As subjects moving across the space conducting human activities, our hearing of sound sources follows the nature of mammals. It is interesting to note that, for example, rattlesnakes increase their rattling rate as potential threats approach, and this abrupt switch to a high-frequency mode makes listeners, including humans, think they are closer than they actually are (Forsthofer et al., 2021).

Issues in such spaces may be similar to but are potentially quite distinct from what we have done with performing spaces. Lower frequencies (compared to the opening dimension) spread out more than higher frequencies, resulting in more diffraction of sound waves. A decrease in SPL with distance from the source across the space with regard to the propagation method, e.g., sound diffraction and insulation, is related to the organization of floor plans. The direct and/or indirect sound transmission of a partition wall should not interfere with the listening in the space. In addition, the relevant studies in the area of coupled rooms, usually two spaces, are also fruitful. Theories, e.g., wave and geometrical approaches, have been developed. Several factors, i.e., opening, room volume, and room absorption, are frequently suggested to be the determinants of SPL distribution, leading to different degrees of coupling effects between the source and receiving room. Predictions in computational simulation using FEM, ray tracing and other methods have progressively improved in consistency and accuracy, validated through *in situ* measurements in multiple connected spaces, such as churches, or laboratory experiments. There are many successful engineering applications in concert halls adopting coupled rooms strategies adjusting reverberation through a changeable room volume to benefit performances. However, practicality of coupled rooms strategies in large-scale public spaces is not demonstrated. Additionally, the primary sound sources in public buildings are broadband sound sources (e.g., human voices, music, or sound emitted by HVAC systems), which can impose either positive or negative effects on the well-being of people. Regarding the perceptual dimension, a listener moves across a space, while an audience is normally assumed to be sitting at a static position having a stationary relationship with the source in a concert hall. Dynamic auditory perception has been frequently discussed in psychoacoustics, but research exploring its associations with indoor building environments, is hard to find for both real and virtual experiences.

To define these issues, the term “multiple connected spaces” is found to be too general because the specifics are more concerned with the sequence rather than the subject itself, not only in the acoustic spatiality but also for a dynamic hearing experience. This is the reason for defining the term “sequential spaces”—a spatial system comprising multiple spaces connected by openings in the in-between separating partition in sequence. When a listener moves from one space to another, the sound in the current space gradually becomes inaudible, whereas the sound in the next space becomes clearer. Among the architectural practices of large-scale public buildings, exhibition spaces, which emphasize the logics of a functional space and traffic flow in their design, can mostly typically represent the spatial composition in the context of a sequence. Gautrand (2014) stated that Sir John Soane first established the architectural form of museums and art galleries through his design of the Dulwich Picture Gallery in 1817, which comprises a series of interconnected spaces with continuous walls to hang exhibits in a way that predominates the spatial relationship in museum design, as shown in **Figure 1.1**.

(a)



(b)

Figure 1.1 Dulwich Picture Gallery. (a) Site photo © Dulwich Picture Gallery. Photo: Joakim Boren; and (b) floor plan.

The necessity of this thesis is not to assert a switch of the research priority of performing spaces (if existing), although acoustics is not understood by the architects or designers who are not fully prepared for a project such as a concert hall or opera house. They are unconsciously or unwillingly naïve under most circumstances, which can be attributed to the fact that hearing cues in our daily lives are never as direct as lighting in this career, although this insensitivity can result in errors that require extensive efforts and costs to refurbish.

Therefore, this thesis was progressively conducted to evaluate some basic issues and attributes that are yet to be explored for spaces precisely termed sequential spaces. By providing supporting facts and principles in both objective and subjective aspects, this thesis aims to provide both designers and acoustic professionals with a better understanding of acoustics.

1.2 OBJECTIVE AND QUESTION

As clarified in **Section 1.1**, it is reasonable to believe that many sound measures, predictions and evaluation systems adopted in a single space for performing are not applicable in sequential spaces because of the distinction in the dynamic auditory perception of a listener in motion, or the sound attenuation with distance from a sound source. The research objectives of this thesis are consequently twofold in the physical and psychological aspects, which values advancement in both real and virtual acoustic tools for sound measurement, prediction and evaluation systems.

The underpinning research questions exploring the effects of several acoustic and perceptual attributes in the subjective and objective aspects are:

1. What are the real-world psychological outcomes?
    - The presence of a stationary primary sound source in sequential spaces may be a mix of multiple sound sources, such as noise (e.g., a crowd). **How is noise as a stationary primary source perceived in sequential spaces?** A listener (in motion) response is to be looked at; and
    - The dynamic auditory distance between a listener in motion and a stationary source is relative to movement direction. **What is the perception symmetry or asymmetry between approaching or receding noise sources in sequential spaces?** An in-depth understanding of the rising and falling level with dynamic loudness leads to more interesting answers.
2. What are the real-world physical outcomes?
    - The same construction measured in a laboratory will obtain the same results in terms of sound insulation performance every time, but there will be variation from room to room and project to project as measured *in situ*. **How do the needs of users** (i.e., connected room volume, individual room volume, source position, and acoustic absorption) **affect the sound attenuation with distance from the source in sequential spaces in practice**? There are some concerns for the calculation to convert from level difference between the rooms that is obtained under a laboratory condition to the *in situ* one.
3. What is a model of a prediction environment?

- Normally, the prediction of a sound field in a single space derives from given information (e.g., the spatial dimension and acoustic absorption). They are believed to be relevant to the prediction in sequential spaces. **How does parametrized information of contextual, acoustic, and source factors** (i.e., opening dimension and position, directional radiation from the opening and an additional source, absorption coefficient and distribution, or number of rooms) **affect sound attenuation with distance in sequential spaces?** While the criteria for a good simulation model in predicting a single space could be used—the more details that can be built up, the more precise the results—it is rather valuable to see how an answer would help us think about any pattern worth understanding better.

4. What is a model for a virtual environment?

- Physically, the entire sound attenuation with distance and the differences in level among rooms are defined once the position of a sound source is settled; however, **what are the individual or common effects of approaching and receding sound sources on the same path in sequential spaces?** None of the paths are sufficiently loud in dB to cause an auditory discomfort that could yield path avoidance behaviour; and
- The issues that are related to the design of PA and VA systems are of great importance in large-scale public buildings, and **what are the individual or common effects of sound source types (i.e., music or human voice) on dynamic auditory perception in sequential spaces?** No results were found from previous studies with a listener in a static condition demonstrating a difference between static and dynamic auditory perception.

1.3 STRUCTURE AND CONTENT

Chapter 2 first addresses sound fields among separating partitions with openings, providing a literature review of the propagation methods of sound diffraction, sound insulation, and the theoretical and applied aspects of coupled rooms studies. Direct and indirect sound transmission in sequential spaces is fundamentally concerned with the coupling between these fields. Second, a systematic review of sound environments in large public buildings with crowd transit is presented to cover current research concerning the use of objective measures, perceptual attributes and methodologies. The layout of this systematic review is intended to present an overview that is specific to the spaces of interest in practice as a handbook.

Chapter 3 looks at main methodologies involving objective techniques (i.e., field measurements relating to sound insulation and computational simulations relating to wave theory and FEM) and subjective disciplines (i.e., questionnaires and soundwalks.) This chapter deals with the underlying theory behind the experiments and the reasons for adopting different experimental methods. For the reader who is relatively new to acoustics in this topic, it should be sufficient to provide a basic background in room acoustics and indoor soundscapes.

Chapter 4 is a case study of the subjective evaluation of noise perception, of which *in situ* perceptual surveys were conducted in two comparable exhibition space sites where a primary noise source was present or absent. The aim of this chapter is to give insight and understanding into dynamic auditory perception in relatively simple constructions with respect to the directional aspect of a listener.

Chapter 5 contains another case study of the objective physical outcomes of sound attenuation with distance from the source in practice, of which *in situ* measurements were carried out at three educational sites. This chapter concerns sound insulation *in situ* where there is both direct and flanking transmission and the conditions are adjusted in accordance with the needs of users.

Chapter 6 looks at a parametric study of computational simulation for prediction models, of which the adjustment of a sound field was modelled in five spaces. This modelling is based on prediction using FEM and validated with a bridge between the *in situ* measurements in Chapter 4. These form a basis from which measurement, prediction, and design decisions can be approached on more complex sound fields.

Chapter 7 is a design-based study of virtual reproduction, of which the VE of case sites was correspondingly built up in accordance with the RE developed from Chapter 4 with a validation of the investigated perceptual attributes, and then used to explore the perception difference effects imposed by directional and source aspects.

Chapter 8 presents the key research findings, design guidance for practitioners, and attempts to help any future researchers further the work.

Figure 1.2 summarizes the structure and content of the key chapters. Each chapter is developed in relation to the research questions listed in **Section 1.2**.

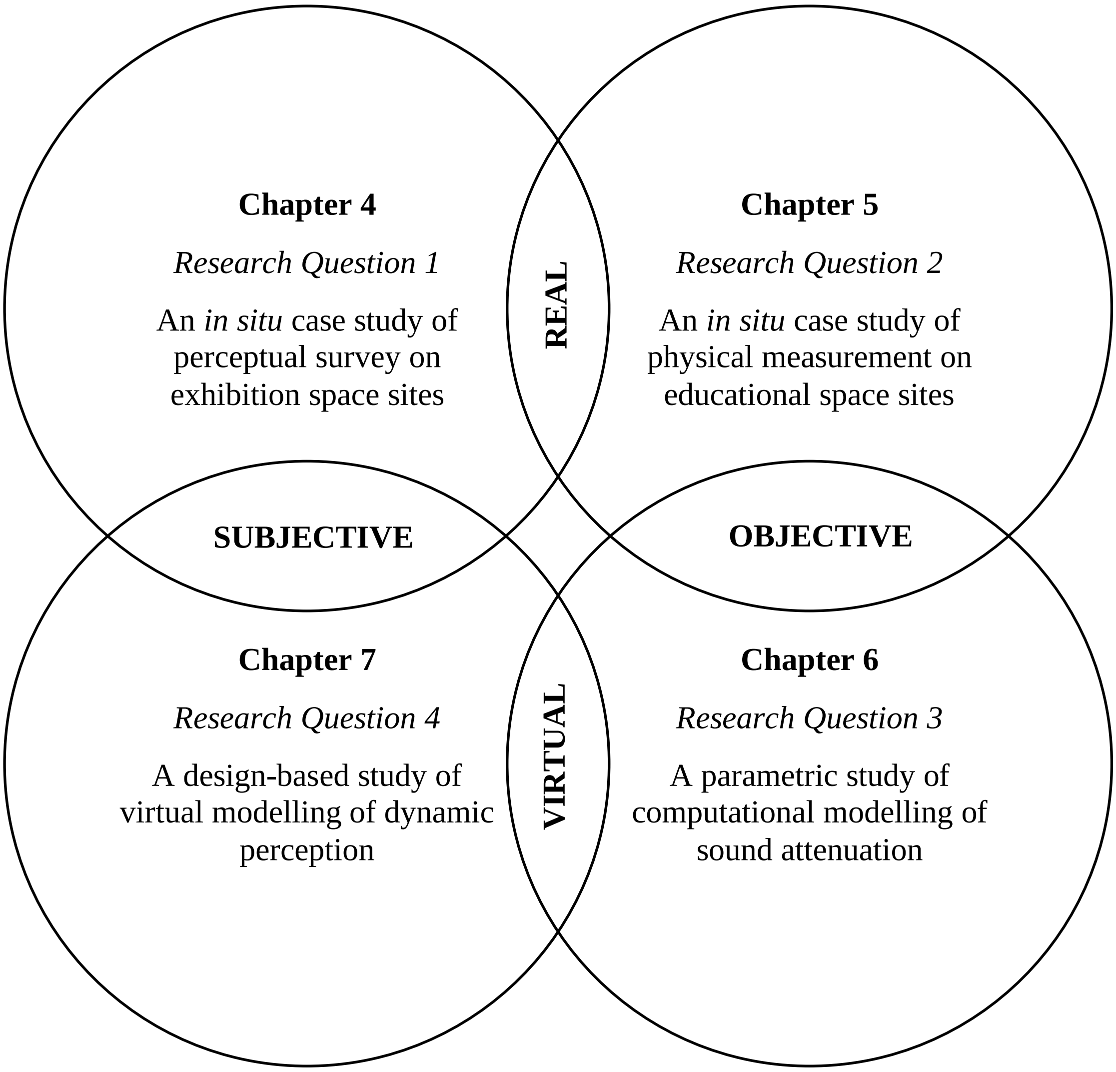


Figure 1.2 The structure and content of the four key chapters of the thesis.

2 Literature Review

This chapter is composed of two parts. First, relevant propagation methods, i.e., sound diffraction and sound insulation, as well as the developments of coupled rooms studies reviewed. Second, a systematic review of sound environments in large public buildings with crowd transit is conducted to categorize current surveys and measurements of relevant practice and summarize the outcomes and shortcomings of existing research.

2.1 SOUND FIELDS AMONG PARTITIONS WITH OPENINGS

2.1.1 Sound Diffraction

Diffraction of sound waves is commonly observed. It occurs when a sound wave encounters an obstruction such as a tree or a rock. Part of the wave hits the tree and reflects, and the other parts of the wave pass by the tree and then begin to fill the medium directly behind the tree. Katy Payne (Payne, 2022) discovered that elephants effectively use low frequencies (i.e., infrasonic waves below 20 Hz) to communicate. As the elephants communicate while migrating in large herds, the low-frequency sound spreads out to fill the medium (i.e., the forest air), diffracting around forest obstacles to make the herd's movements extremely synchronized. This phenomenon help explain two additional mysteries: first, how males locate females for breeding hundreds of kilometres away and second, how elephant families separated by many miles are able to find one another in dense vegetation (Bannon and Kaputa, 2021).

In a building environment, we hear sounds around corners and barriers or notice sound diffracting through door openings, allowing us to hear others who are speaking from adjacent rooms. Diffraction occurs when sound moving through one medium encounters an opening, such as an open window or doorway. A sound wave is a disturbance in the medium. The part of the wave that hits the wall is reflected, absorbed, or both. The wave that passes through the opening is temporarily shortened; then, after it passes through the opening, it expands to fill the medium. Lower frequencies spread out more than higher frequencies because they experience more diffraction. Higher-frequency sound is more channelled, and the higher the frequency is, the less diffraction occurs and vice versa. The fact that sound diffraction is more pronounced for longer wavelengths implies that low frequencies can be heard around corners and obstacles better than high frequencies, as illustrated in **Figure 2.1**.

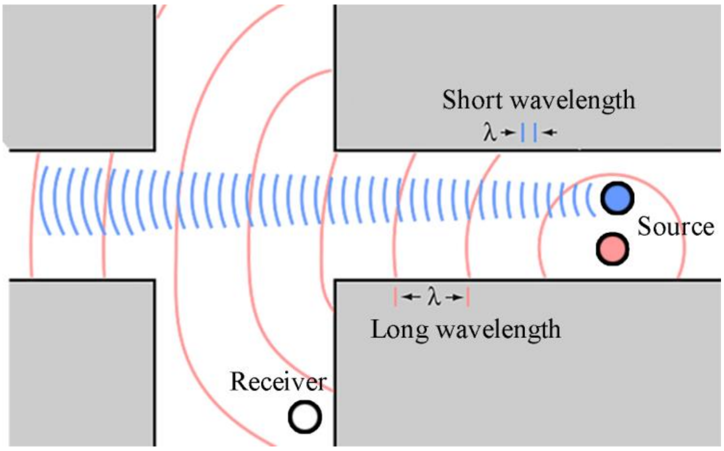


Figure 2.1 Diffraction of sound waves in a building environment (adapted from (HyperPhysics, 2022)).

For the same opening dimension, the sound wave with a longer wavelength will be diffracted more (larger angle of diffraction), and the sound wave with a shorter wavelength will have a lower diffraction capacity (smaller angle of diffraction). When the wavelength of the incident sound wave is kept constant and the opening dimension changes, the wave diffracting off the smaller opening diffracts to a much greater extent than the wave diffracting off the larger opening. The smaller the size of the opening is, the greater the effect of diffraction.

2.1.2 Sound Insulation

Sound insulation is the reduction of sound passing between rooms as the main method of controlling the movement of sound within buildings. Most of the sound is directly transmitted through partitions, such as walls and floors, as either airborne sound or impact sound. Airborne and impact sounds are distinct. The former refers to sound that is transmitted through the air (e.g., people talking in an adjacent room), and the latter refers to sound generated from footsteps on a floor, which can be heard in the room below through sound radiation. To choose the best method of sound insulation, it is necessary to identify the type of sound transfer. In this thesis, we mainly discuss airborne sounds transmitted through walls.

Regarding partition construction, heavyweight parts of a building, such as concrete walls, provide good sound insulation. They cannot pass much sound into the next room because sound waves are vibrations and it is difficult for a heavy wall to vibrate.

However, partitions made of lightweight elements are commonly adopted in open-plan layouts for the convenience of increasing connected room volume, or changing individual room volume. This issue is particularly prevalent in public space design, e.g., exhibition spaces and open-plan offices, rather than dwellings. The term “lightweight” is relative. For example, the sheer weight of the plasterboard on each side of a wall is an important feature of the specification, and the total thickness of plasterboard needs to be 30 mm. The plasterboard is nailed to frames. The two layers of plasterboard are staggered so that they are fixed to alternate studs and the joints do not coincide. A typical value for plasterboard on a timber stud wall is 35.0 dB. In this thesis, we mainly discuss separating partitions in lightweight constructions.

The amount of airborne sound in a space can be reduced by acoustic absorption, which reduces the amount of sound reflecting back into the space from the surfaces enclosing it, which reduces the amount of sound transmitted into the space from an adjacent space through the building fabric (Hopkins, 2007). Increasing the sound absorption in a room has little effect on sound passing between rooms; that is, the absorption provided has a large effect on the sound qualities within the room but generally has little effect on the amount of sound passing in or out of the room (McMullan, 1991). For example, the partition using fibre glass to separate two rooms does not stop much sound from passing between the rooms, but the absorption of sound by the porous fibre glass creates different acoustic qualities for each room and causes them to sound rather “dead”.

Flanking transmission is omnipresent in buildings and its effects are not confined to any particular part of the building acoustic frequency range. Standard BS EN ISO 10848-5:2019 (British Standards, 2019) provides criteria for laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms. In fact, it is not uncommon for the flanking structure to radiate sound power levels similar to or higher than those of the separating wall or floor itself. Flanking walls contain openings in many different positions with a wide range of boundary conditions. In conjunction with the uncertainty in the wall dimensions and material properties, this implies that a statistical approach to plate vibration is more practical than deterministic calculations of the modal response (Hopkins, 2007). In practice, the vibration level of the beams does not decrease with distance from the source because flanking paths to more distant beams become more important with increasing distance. Large floors of approximately 200 m^2 built from individual concrete slabs with a screed finish can also show significant vibration attenuation with distance (Steel et al., 1994).

2.1.3 Coupled Rooms

Coupled rooms refer to connected spaces, usually two, comprising subspaces with an opening in a separating partition. Such spaces can commonly be found in classical opera houses or even residential dwellings. The coupling effect can be categorized into three degrees: strong, moderate, or weak. For the strong coupling effect, coupled rooms can be calculated as a single space. In contrast, for the weak coupling effect, coupled rooms should be considered a composition of several single spaces that each can be separately calculated. For the moderate coupling effect, researchers investigate the effects of various contextual and acoustic factors.

Eyring (1930) pointed out the difference in the RT formula between a single space and coupled spaces and accordingly established an early model. Morse (1944) used the wave approach to analyse the normal mode with a small opening area, assuming a rigid boundary between two spaces. Harris and Feshbach (1950) computed the resonant frequency of two coupled spaces and studied the effect of the opening dimension and position on the resonant frequency. Furthermore, they suggested (1950) that the partition position, opening dimension , and opening position can affect the distribution of the sound field. By analysing the acoustic wave motion in a coupled space, Thompson (1984) found that the nonplanar pressure distribution in the proximity of the coupling area was a result of the incompressible component of fluid motion. Kuttruff (2000) applied statistical methods to explore sound attenuation. Harrison et al. (2001) used geometric acoustics to simulate the conditional room volume, opening dimension, and opening position in auditoriums and demonstrated that the room volume was the most crucial factor affecting the double slope of the decay. Ermann (2005) conducted a statistical analysis and concluded that decay shows the double slope feature only when the opening area is below 1.5% of the entire surface of a shoe box or the absorption coefficient is below 0.07. Meissner (2010) investigated the effects of mode degeneration and localization in coupled rooms based on the assumption that low absorption leads to weak coupling. Another study indicated that the sound energy density and intensity in coupled spaces were substantially affected by mode localization (Meissner, 2012). Poblet-Puig and Rodrıguez-Ferran (2013) formulated a coupling technique based on field eigenfunction representation to analyse sound transmission through openings between cuboid rooms. They found that the opening position and room volume play major roles in the coupling effect.

Coupled rooms strategies is applied mainly in designing concert halls to have adjustable volume and reverberation. For example, the Morton H. Meyerson Symphony Center (Wikipedia, 2021a), as shown in **Figure 2.2,** is large, with a seating capacity of 2,065. It is used to perform symphonic, chamber and solo (singing) music. In addition to the 450 m^2 adjustable sound-absorbing curtain, there are 74 thick concrete chamber doors around the top of the hall weighing 2.5 tons each that can be opened and closed to increase or reduce reverberance. Another example is the Birmingham Symphony Hall, which is equipped with a reverberation room with a volume of 7,200 m^3 behind and above the organ with concrete doors that can be electronically opened to adjust the reverberation. The top of the hall has sound-absorbing panels that can be raised and lowered. Johnson et al. summarized the experience of these built concert halls, and proposed this concept for the design of 21st century concert halls to meet different musical requirements.

Figure 2.2 Morton H. Meyerson Symphony Center. © Dallas Symphony Orchestra

2.2 SOUND ENVIRONMENTS IN LARGE PUBLIC BUILDINGS

2.2.1 Introduction

Characterizing the acoustic environment of performance spaces such as theatres, concert halls and auditoriums has been one of the main topics of room acoustic research in recent decades (Barron, 2005, Kuttruff, 2000). For spaces where the main function is sound-related (e.g., spaces for listening or performing), it is indeed crucial for clear criteria with measurable parameters to be in place to assess the acoustic quality and performance (Pelorson et al., 1992). For this reason, international standards have been developed over time to harmonize measurement protocols and reporting requirements (International Organization for Standardization, 2009). These standards have gradually been extended to spaces that are not specifically designed for acoustic "performance" but where sounds still play an important role because of the function they can promote (or disrupt), such as educational spaces (Great Britain Department for Education, 2015, Acoustics, 2003), libraries, and open plan offices (International Organization for Standardization, 2012, International Organization for Standardization, 2008a), for which specific guidance has been produced, and restaurants and cafeterias (Tang et al., 1997, Rindel, 2010, Hodgson et al., 2007, Devos et al., 2020).

In parallel, researchers have approached the acoustic characterization of large indoor spaces from a perceptual perspective, that is, investigating how users actually experience them aurally (Aletta and Astolfi, 2018, Kang, 2003, Kang, 2006a). This applies alike to both spaces that are used for acoustic performance and those that are not. There is indeed a growing interest in the emerging field of the "indoor soundscapes" for public buildings and methods to describe them (Torresin et al., 2020b, Torresin et al., 2020a, Yilmazer and Acun, 2018, Dökmeci Yorukoglu and Kang, 2017, Yorukoglu and Kang, 2016, Xiao and Aletta, 2016), where soundscape is defined as the acoustic environment as perceived and/or understood […] in context (International Organization for Standardization, 2014).

However, all the above-mentioned examples imply a listener who is in a fixed position, while for many large public buildings, users experience the space dynamically. Listeners are likely to be exposed to acoustic environments for crowd transit, such as museums and exhibition spaces, shopping malls, or transport stations and hubs. The safety of users and evacuation conditions, rather than acoustic comfort for performance or non-performance purposes, are the main concerns in this context. It is mandatory to use PA and VA systems (British Standards Institution, 2019, British Standards Institution, 2017), which require specific acoustic criteria for proper operation, e.g., RT, signal-to-noise ratio, identification of the position of sound sources, and especially speech intelligibility. Extended guidance exists for acoustic retrofitting in such spaces (Everest and Pohlmann, 2009). However, less is known about these building types in terms of acoustic performance or soundscape (i.e., perceived) quality when they are in operation. In this context, soundscape assessment is not a quantitative parameter but rather an approach to collect perceptual data from users of the space (International Organization for Standardization, 2014). Thus, the research questions underlying this systematic review were as follows: (1) What kind of objective parameters are used to characterize the acoustics of these spaces? (2) What kind of subjective measures (if any) are used to characterize the indoor soundscapes of these spaces? (3) What are the main methodologies used to characterize the acoustics and indoor soundscapes of these spaces? (4) How are the outputs of acoustic and/or indoor soundscape investigations informing the design of such spaces?

The overarching goal is to identify common strategies and empirical approaches that researchers have implemented for these acoustically complex enclosures and provide some methodological indications for future studies.

2.2.2 Materials and Methods

Since **Section 2.2.2** is exploratory, no pre-defined protocol registration was considered for this review. The basic process and data extraction strategies were agreed upon at the earliest research stage. This review was performed and reported in accordance with the PRISMA guidelines for systematic reviews (Liberati et al., 2009).

2.2.2.1 Search strategy and eligibility criteria

Studies were selected if they collected data about the acoustics (or perceptions of acoustics) of large public buildings where users are expected to experience the space dynamically, i.e., users are not "static" (e.g., libraries, offices). For this reason, the definition of the search strategy was driven mostly by building types and functions rather than specific geometrical features, and was the outcome of brainstorming sessions and consultation with colleagues. The general consideration regarding inclusion was to meet the requirement that the case belonged to an appropriate building type for crowd transit (e.g., museums/exhibition spaces, shopping malls, and transportation hubs/stations). Then, the specific inclusion criteria were (1) including at least an objective acoustic measure of the space or (2) including at least a subjective acoustic measure of the space. Only peer-reviewed journal articles published in English were considered.

Studies were identified by searching the Scopus database, manually scanning the reference lists of retrieved items and consulting experts in the field. The following query was submitted to the Scopus database: (TITLE-ABS-KEY (acoustic*) AND

TITLE-ABS-KEY (museum*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (transport* AND station*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (shopping AND mall*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (transit AND space*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (sequential AND space*)) AND (LIMIT-TO (DOCTYPE , "ar")). No time limits were applied to the search. The last search was performed on 8 February 2021. While using two or three databases is a common approach to systematic reviews in medical and life sciences, the Scopus database alone was effective in covering the most relevant literature in built environment studies and acoustics more specifically (Aletta et al., 2018).

The assessment of eligibility was performed independently in a nonblinded standardized manner by colleagues; a few disagreements between reviewers about the inclusion/exclusion of certain items were resolved by consensus.

2.2.2.2 Data extraction

Information was extracted from each included study on (1) the country where the study was conducted/designed; (2) the building type, to describe the main function; (3) the space type, to describe whether the study addressed a single space, multiple spaces, or sequential/adjacent spaces within the building of interest; (4) the objective measure, to describe the investigated acoustic parameter(s); (5) the perceptual attribute, to describe instruments used to collect individual responses regarding the acoustic perception of the space(s); and (6) the methodology, to report on whether the study was based on measurements, software simulations and/or surveys of users.

Considering the differences in the metrics across the selected studies, a quality assessment and quantitative meta-analysis under the quality-effects model were not targeted (Aletta et al., 2018). Therefore, a qualitative approach to data synthesis was adopted to answer the review questions.

2.2.3 Results

The search through the databases and additional manual search returned 1,060 results. After discussion, the abstracts of records were read, and 943 papers were excluded because the topics were irrelevant (e.g., different research fields) and/or they did not address the review research question. Consequently, the full texts of the remaining 117 papers were accessed and 91 were excluded because they did not meet the eligibility criteria (e.g., lack of either objective measurement or subjective survey). The remaining 26 papers were included and eventually considered in the review. **Figure 2.3** summarizes the selection process of the review records.

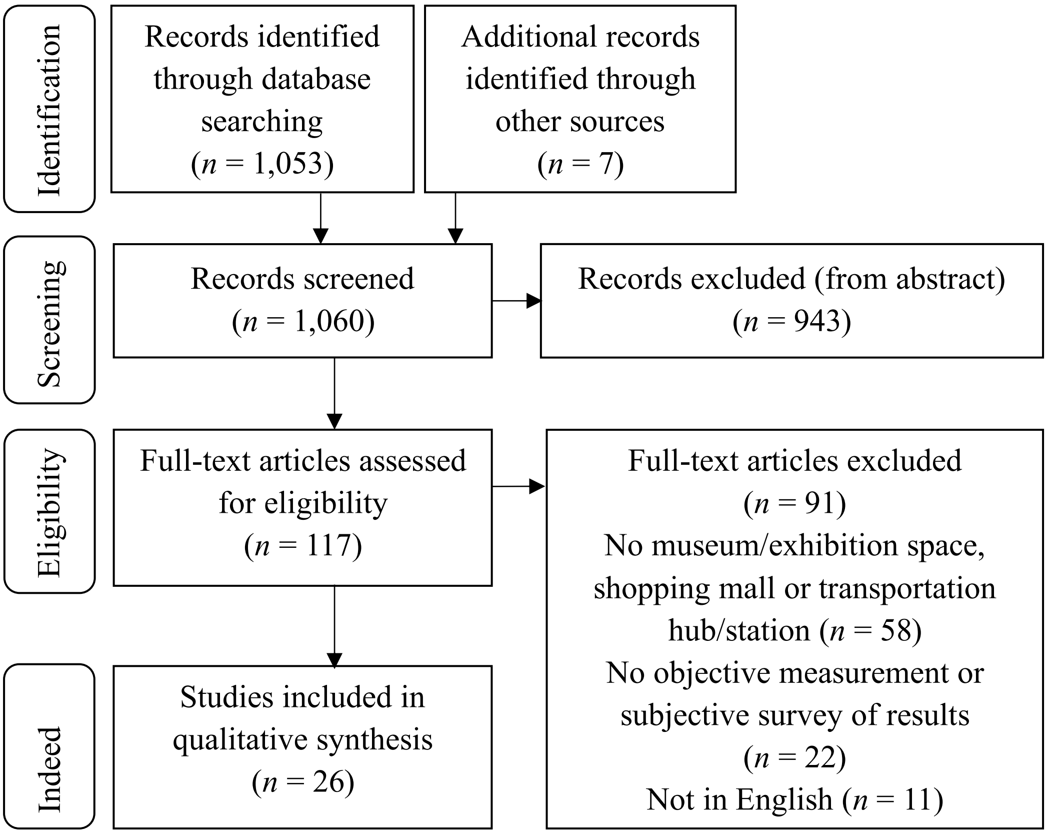


Figure 2.3 The flow of information through the different phases of the systematic review (Liberati, et al., 2009).

Table 2.1 shows the data extracted from the 26 studies considered in this review, reported according to the chronological order of publication. It is important to note that, due to the variance in country, building type, and space type, the sites investigated by each selected study varied in scale.

Table 2.1 The list of studies included in the systematic review in chronological order of publication. The country, building type, space type, objective measure, perceptual attributes, and methodologies were reported. The studies often included several experimental conditions and sound levels. For more specific information, it is possible to refer to the original studies.

Reference	Country	Building Type	Space Type	Objective Measure	Perceptual Attributes	Methodologies
Kanev (2021)	Russia	Shopping Mall	Multiple	$L_{Aeq\text{-}1min}$, T_{20}, T_{30}	-	Measurement
Mediastika et al. (2020)	Indonesia	Shopping Mall	Multiple	$L_{Aeq\text{-}10min}$, L_{Amin}, L_{Amax}	Annoyance: *Comfortable-Uncomfortable, Good-Bad;* Affective Quality: *Clamorous-Quiet, Clear signage-Unclear, Crowded-Empty, Noisy-Calm, Complete-Incomplete, Cool-Warm, Happy-Unhappy, Like-Dislike, Luxurious-Modest, Modern-Ancient, Mute-Loud, Neat-Messy, Safe-Dangerous*; Acoustic Spatiality: *Large-Small, Tight-Loose, Spacious-Narrow, Know the position-Don't*	Measurement, Soundwalk
Orhan and Yilmazer (2021)	Turkey	Museum /Exhibition space	Multiple	$L_{Aeq\text{-}20min}$, L_{Amin}, L_{Amax}	Annoyance: *Disturbing, Positive, Uncomfortable*; Affective Quality: *Appropriate, Calm, Concentrating, Curious, High*	Measurement, Questionnaire
Sü Gül (2021)	Turkey	Museum /Exhibition space	Multiple	SPL, T_{30}	-	Measurement, Simulation
D'Orazio et al. (2020)	Italy	Museum /Exhibition space	Single	$L_{Aeq\text{-}1min}$, SNR	-	Measurement, Simulation
Wu et al. (2020)	China	Transportation hub/station	Multiple	$L_{Aeq\text{-}5min}$, T_{20}	Annoyance: *Uncomfortable-Comfortable*; Affective Quality: *Noisy-Quiet, Loud-Soft*; Room-acoustic Quality: *Clear-Unclear (Intelligibility), Low-High (Loudness), Long-Short (Reverberation)*	Measurement, Questionnaire
Alnuman and Altaweel (2020)	Jordan	Shopping Mall	Multiple	$L_{Aeq\text{-}3min}$, T_{20}, T_{30}	Annoyance: *Comfortable-Uncomfortable;* Room-acoustic Quality: *Quiet-Noisy*	Measurement, Questionnaire
Mónica et al. (2020)	Portugal	Museum /Exhibition space	Multiple	T, C_{50}, EDT, STI, D_{80}	-	Simulation
Wang et al. (2020)	-	Transportation hub/station	Multiple	-	Annoyance: *Acceptance*	Listening test, Questionnaire

Paxton et al. (2018)	-	Museum /Exhibition space, Shopping Mall, Transportation hub/station	Multiple	SPL in the 20 kHz third-octave band	-	Measurement
Martellotta and Pon (2018)	USA	Museum /Exhibition space	Multiple	SNR, T_{15}	-	Measurement, Simulation
Yilmazer and Bora (2017)	Turkey	Transportation hub/station	Multiple	$L_{Aeq\text{-}15min}$, $L_{Aeq\text{-}30s}$	Annoyance: *Annoying-Not annoying, Disturbing-Comfortable;* Affective Quality: *Agitating-Calming, Crowded-Uncrowded, Discordant-Harmonic, Dark-Light, Empty-Joyful, Exciting-Gloomy, Hard-Soft, Heavy-Light, Loud-Quiet, Loud-Soft, Rough-Smooth, Stressing-Relaxing, Sharp-Not sharp, Strange-Common, Unsteady-Steady, Unpleasant-Pleasant*; Acoustic Spatiality: *Far away-Nearby*	Listening test Measurement, Questionnaire,
Thanh Vi et al. (2017)	UK	Museum /Exhibition space	Multiple	-	Annoyance: *Important*; Affective Quality: *Distracting, Meaningful, Random*	Interview, Listening test, Questionnaire
Pon et al. (2016)	USA	Museum /Exhibition space	Single	T_{20}	-	Measurement, Simulation
Urbán et al. (2016)	Slovakia	Shopping Mall	Multiple	T_{30}, flutter echo	-	Measurement, Simulation
Han et al. (2016)	South Korean	Transportation hub/station	Multiple	L_{Aeq}	Annoyance: *Uncomfortable-Comfortable*	Measurement, Questionnaire
Meng and Kang (2013)	China	Shopping Mall	Multiple	$L_{Aeq\text{-}300\text{-}500s}$	Annoyance: *Comfortable-Uncomfortable;* Room-acoustic Quality: *Quiet-Loud*	Measurement, Questionnaire
Dökmeci Yorukoglu and Yilmazer (2012)	Turkey	Shopping Mall	Multiple	$L_{Aeq\text{-}2hr}$	Annoyance: *Quiet-Noisy*	Measurement, Questionnaire

Zimmermann and Lorenz (2008)	Germany	Museum /Exhibition space	Multiple	-	Annoyance: *Irritating*; Affective Quality: *Coherent, Boring, Enriching, Succeed*	Listening test, Questionnaire
Tardieu et al. (2008)	France	Transportation hub/station	Multiple	$L_{Aeq\text{-}10s}$	Affective Quality: *Intimate, Noisy*, *Pleasant, Quiet, Rhythmic;* Acoustic Spatiality: *Closed Space, Confused, Large (Reverberation), Echoes, External, Isolated, Resonances, Small (Reverberation)*	Listening test, Questionnaire
Nowicka (2007)	Poland	Transportation hub/station	Single	EDT, RASTI	-	Measurement, Simulation
Chen and Kang (2004)	UK	Shopping Mall	Multiple	EDT, T, $L_{Aeq\text{-}5min}$	Annoyance: *Annoying-Favourable*, *Uncomfortable-Comfortable*; Affective Quality: *Noisy-Quiet;* Room-acoustic Quality: *Echoing-Dead (Reverberation), Loud-Quiet (Loudness)*	Measurement, Questionnaire
Skarlatos (2003)	Greece	Shopping Mall	Multiple	$L_{Aeq\text{-}3min}$	-	Measurement
Okubo et al. (2001)	-	Museum /Exhibition space	Single	LC, FBR, LRR	-	Measurement
Hopkins (1994)	Canada	Shopping Mall	Multiple	$L_{Aeq\text{-}10s}$	Affective Quality: *Confusing, Exciting, Fun, Fantastic, Glitzy*, *Overcrowded;* Room-acoustic Quality: *Loud*; *Noisy*; Acoustic Spatiality: *Big, Huge, Large*	Measurement, Questionnaire

Ten studies were developed for museums/exhibition spaces; nine studies dealt with shopping malls; six studies focused on transportation hubs/stations; and one study, the results of which are presented in the section on museums/exhibition spaces, covered all three selected building types. Among these, 12 studies reported both physical outcomes and individual responses. One study was performed within large-scale environmental surveys (the acoustic aspects of which were not necessarily the main ones).

For the sake of reporting and discussion, the studies were grouped according to the selected building type of the abovementioned sample; accordingly, the methods and results are described in the following subsections.

2.2.3.1 Museums/exhibition spaces

Orhan and Yilmazer (2021) surveyed the courtyard of the Rahmi M. Koç Museum and its corridor, which is also an exhibition space, as well as another large exhibition space, the Erimtan Archaeology and Arts Museum in Ankara, Turkey, to further generate a systematic categorization of museum content by exploring visitor perceptions. The heights of the investigated spaces of were 3.5 m for the first floor and 10.5 m for the courtyard of the former, and 10.6 m for the latter. $L_{Aeq\text{-}20min}$ was measured on a weekend at 95.6 dB(A) (L_{Amax}: 97.5 dB(A), L_{Amin}: 91.7 dB(A)) in the former and 94.4 dB(A) (L_{Amax}: 96.5 dB(A), L_{Amin}: 93.1 dB(A)) in the latter. It is worth mentioning that these sound levels in public buildings appear to be exceptionally high, but the authors do not provide further details. This study followed the guidance of Standard ISO/TS 12913-2 for semi-structured interviews and used five-point Likert scales for the survey. The investigated perceptual attributes were mainly the appropriate, calm, concentrating, curious, disturbing, high, positive, uncomfortable, etc. The authors concluded that visitor perceptions were based mostly on sound contexts rather than sound levels, even if the measured sound levels were relatively high.

Sü Gül (2021) conducted *in situ* tests in Hagia Sophia of Istanbul, Turkey and simulated the exhibition states with a marble floor. The volume of each individual space ranged from 625 to 95,960 m^3. To determine the sound energy decay that occurs in different states of the space, the researcher considered several decay parameters and degrees of acoustic coupling. Among the many variables, the source-receiver distance and positioning within different sub-spaces appeared to be the underlying determinant of multi-slope sound decay patterns. No subjective surveys were performed in this study.

D’Orazio et al. (2020) selected a highly attended exhibition space in the Archaeological Museum of Florence, Italy, to assess the reliability of a predictive dynamic model. The room was 28.0 m long, 9.30 m wide, and 11.0 m high, and RT averaged over the octave band 500 Hz to 1 kHz was 3.3 s. Objective measures included visitor flow, $L_{Aeq\text{-}1min}$ and the number of visitors inside the spaces during a free-entrance day. The software simulation model involved the SPL attenuation among the visitors, Lombard slope and group size, communication quality related to SNR, and association between the number of visitors and acoustic condition. No subjective surveys were carried out in this study.

Mónica et al. (2020) simulated the Archaeological Museum with transparent roof solutions in Lisbon, Portugal. The volumes of the investigated spaces were 19,600 and 38,145 m^3. The numerical software simulation was presented with selected objective parameters: T was between 1.0 and 4.3 s; C80 was between –8.2 and 2.6 dB; EDT was between 2.1 and 3.4 s; STI was between 0.25 and 0.41; and D50 was between 0.04 and 0.18. No subjective surveys were carried out in this study.

Paxton et al. (2018) investigated ultrasound in selected museums/galleries, shopping centres, and train stations. The difficulties in taking measurements with conventional equipment were highlighted. Tones were identified by SPL in the 20 kHz third-octave band. Five locations were measured in museum/gallery at 34.0, 43.0, and 46.0 dB, with the shopping centre at one location not being measured and two locations being measured in a railway station at 49.0 and 65.0 dB. The characteristics of the tones were consistent with the source being the PA or VA system. The measured results did not exceed existing interim guidelines for public exposure to ultrasound published by the International Non-Ionizing Radiation Committee of the International Radiation Protection Association (INIRC-IRPA, 1984), and existing research suggests that no significant undesirable effects would be anticipated following exposure to ultrasound of this nature for short periods. No subjective surveys were performed in this study.

Martellotta and Pon (2018) measured the absorption coefficients of the Barberini tapestries during a temporary exhibition held in the Cathedral of St. John the Divine in New York City, USA. The largest chapel, St. James, connected by a large opening of 70 m^2 and a much smaller door, had a floor surface of 245 m^2 and a volume of approximately 3,100 m^3. Another two chapels, St. Ambrose and St. Savior, had smaller floor surfaces of 100 and 120 m^2, respectively. The entire floor area of the site was 11,200 m^2, spanning a length of 180 m and a height of 70 m at the crossing and 37 m at the main nave. T_{15} was used, considering the SNR, and significant differences appeared in the high-frequency range, while at low frequencies, T_{15} values with and without tapestries were more similar. Only at 125 Hz were values measured with tapestries inside slightly longer than those measured without tapestries. No subjective surveys were reported in this study.

Thanh Vi et al. (2017) presented a six-week multisensory display using mid-air haptic technology integrated with sound for the Full Stop painting by John Latham at the Tate Britain art gallery in London, UK. The dimensions of the exhibition unit were set at 3.45 m wide and 5.1 long. The authors used a questionnaire with five-point Likert scales and interviews to collect individual responses on the importance of auditory sense to the display, and the resulting mean value was 4.23. In addition, in the interviews, the visitors described other perceptual attributes as the meaningful, distracting, random, etc.

Pon et al. (2016) also targeted the absorption coefficients of the Barberini tapestries, and tested them in a 17.7 m square gallery with a 5.38 m high ceiling in the Meadow Museum in Dallas, USA. Following the guidance in Standard ISO 3382-2, the authors obtained results similar to those of the later study (Martellotta and Pon, 2018): significant differences appeared at high frequencies, while at low frequencies, T_{20} values with and without tapestries were more similar. In the empty room, T_{20} was rather long, and application of the tapestries to the walls caused a dramatic drop in T_{20} at high frequencies and determined a more even distribution of sound absorption and increased diffusion. No subjective surveys were reported in this study.

Zimmer and Lorenz (2008) installed a listening system at the Kunst museum in Bonn, Germany, in the context of an exhibition comprising artworks of the painter August Macke with user evaluations. The questionnaires contained closed questions based mainly on selecting from several predetermined statements and ratings, which were assessed by visitors through “yes,” “no,” and “partly,” and the evaluation of the combination of artwork and auditory information used the coherent, consulting, irritating, boring, enriching, and succeed.

Okubo et al. (2001) took measurements in a multi-purpose hall that contains 2,004 seats and is used for concerts and conventions. It can be altered for exhibitions, with most of the floor area being flattened. The volume ranged from 19,125 to 32,025 m^3, and the RT range was between 1.2 and 1.7 s. Three parameters were measured: the lateral component, the front/back ratio, and the left/right ratio, and the difference in early components was greater than that in late components. No subjective surveys were performed in this study.

2.2.3.2 Shopping malls

Kanev (2021) surveyed two kinds of spaces in shopping malls in Russia perceived as acoustically uncomfortable: one was largest, the central area containing restaurants and a seating area for food stalls, and the other had long corridors or galleries with glass walls containing boutiques, small cafes and local rest areas. The volumes of five cases in the former types of space ranged from 29,500 to 10,600 m^3, with heights between 9.2 and 18.2 m. The volumes of three cases in the latter type of space ranged from 14,500 to 31,000 m^3, with lengths between 112.0 and 234.0 m. The results showed that at middle frequencies, $L_{Aeq\text{-}1min}$ was 7.0 to 10.0 dB(A) higher in the occupied condition than in the unoccupied condition. The normal voice levels at a distance of 1 m were approximately 60.0 dB(A), and the raised voices reached 65.0 to 70.0 dB(A). The largest measured T_{20} and T_{30}, 5.1 s, was found in the largest food court, and the smallest, 2.7 s, was obtained in the smallest gallery. Two thresholds and three ranges of T were proposed for assessments, and the necessity of acoustic absorption materials was suggested for surfaces and volumes. No subjective surveys were performed in this study.

Mediastika et al. (2020) surveyed three shopping malls, the Tunjungan Plaza (retail area 160,000 m^2), the Grand City Mall (retail area 45,000 m^2) in Surabaya, and the Malioboro Mall (retail area 22,000 m^2) in Yogyakarta, Indonesia, with sighted and visually impaired participants. The *in situ* measurements were carried out with indoor soundwalks on three Saturdays, around either lunch or dinner time. $L_{Aeq\text{-}10min}$ was reported to be 70.0 dB(A) (L_{AFmax}: 90.5 dB(A), L_{AFmin}: 60.3 dB(A)). Both off-site and *in situ* surveys were used. A focus group discussion method was assigned for the off-site survey to collect attributes perceived by the participants and then constructed in a closed-ended questionnaire for the *in situ* survey. The questionnaire used three-point Likert scales and was subject-based. For sighted people, three soundscape dimensions were labelled: (1) the pleasantness, including the good, neat, modest, warm, comfortable and like; (2) the space, including the crowded, messy, and tight; and (3) the facilities, including complete and clear signage. For visually impaired people, five soundscape dimensions were abstracted as (1) the pleasantness, including the happy, good, luxurious, modern, comfortable, and like; (2) the space, including the spacious and large; (3) the eventfulness, including the noisy, loud, and clamorous; (4) the danger, including the dangerous; and (4) the direction including the know the position. The researchers concluded that pleasantness and space were the two most prominent factors for both types of participants. Visually impaired people perceived there more favours than sighted people, and they could perceive soundscape dimensions of danger and direction with their hearing sense alone. The relationship between objective and perceptual attributes is of interest. The authors indicated that acoustic perceptions were more influenced by crowds than by SPL. For sighted people, the more crowded the shopping mall was, the higher the perceived SPL. For visually impaired people, the strongest correlation existed between L_{eq} and the noisy.

Alnuman and Altaweel (2020) studied a large shopping mall in the very centre of Amman, Jordan, and chose shopping areas, entrances, food courts, and playing areas to explore the sound environment and its correlation to the acoustic comfort of the workers. $L_{A\mathrm{eq}\text{-}3\mathrm{min}}$ was collected between 10:30 and 12:30, between 13:30 and 15:30, between 16:30 and 18:30, and between 19:30 and 21:30 every day during the entire seven-day period. The values were measured as a minimum of 58.0 dB(A) in the shopping area in the early morning and a maximum of 83.0 dB(A) in the playing area in the evening. An increase was observed when comparing the afternoon and evening with the early morning and midday time; similarly, sound levels for the weekends were higher than those for weekdays. T_{20} and T_{30} were separately measured in the unoccupied condition at 0.9 s in the food court and 1.4 s at the main entrance. The surveys used five-point Likert scales in the questionnaire with the comfortable-uncomfortable and quiet-noisy. $L_{A\mathrm{eq}}$ was found to be correlated with the acoustic comfort and loudness of staff working at these locations.

Urbán et al. (2016) investigated a large vestibule of the Shopping centre Palace in Bratislava, Slovakia. The volume of the main space was 5,750 m^3, and the total surface area of the interior surfaces was 1,850 m^2. It had a round shape with a diameter of 24 m and a dome-shaped, partly transparent roof at a maximal height of 14.5 m. T_{30} and flutter echoes were measured, and the former was found to be 4.3 s at 1 kHz. The software simulation with different solutions based on users’ feedback approached the issues of background noise level, reverberation, and speech intelligibility. Large halls with parallel walls or circular shapes with distances between the walls of approximately 9 m (e.g., 50 ms) will cause audible flutter echoes. No subjective surveys were detailed in this study.

Meng and Kang (2013) studied six shopping malls in China, including Qiu Lin (31,000 m^2), Tong Ji (10,000 m^2), Man Ha Dun (28,700 m^2), Suo Fei Ya (32,000 m^2), Jin An (45,000 m^2) and Hui Zhan (30,000 m^2). $L_{Aeq\text{-}300\text{ to }500s}$ values were averaged between 9 a.m. and noon, between noon and 3 p.m., and between 3 p.m. and 6 p.m. across seasons as 71.3, 73.3, 71.4, 70.8, 68.3 and 69.4 dB(A). The questionnaire used five-point Likert scales exploring the loudness (i.e., quiet-loud) and the acoustic comfort (i.e., uncomfortable-comfortable.) The ratings of the former were 3.36, 3.52, 3.48, 3.32, 3.20, and 3.30, and those of the latter were 3.08, 2.73, 2.96, 2.80, 3.41, and 3.27. The results showed that the loudness was influenced by visit reason, visit frequency, and length of stay. The acoustic comfort was affected by the above factors in addition to the visiting season. The ratings of users waiting for someone were lower for the acoustic comfort, whereas users who went to the malls more than once a month rated it higher. The influences of the period of visiting and the accompanying person were found to be insignificant.

Dökmeci Yorukoglu and Yılmazer (2012) selected an atrium (30,000 m^3) in the food court area of the CEPA shopping centre in Ankara, Turkey, to explore associations between measured noise levels and users' responses. $L_{Aeq\text{-}2hr}$ were obtained between 10.a.m. and noon, noon and 2 p.m., 4 p.m., and 6 p.m., 8 p.m. and 10 p.m. on weekdays and weekends. The results revealed that the average values in the unoccupied condition were 44.0 dB(A), and those in the occupied condition were 63.5 and 68.3 dB(A) for weekdays and weekends, respectively. The peak occurred between noon and 2 p.m. and between 6 and 8 p.m. on weekdays, and the highest value occurred between 4 p.m. and 6 p.m. on weekends. Opening and closing times displayed the lowest values of a day. The questionnaire used five-point Likert scales to investigate noisiness with the quiet-noisy. The subjective ratings of sound levels were demonstrated to correlate well with the measured levels, and noise levels above 67.0 dB(A) led to a sudden increase in ratings.

Chen and Kang (2004) chose three atria in Sheffield's Meadowhall, one of the largest shopping malls in the United Kingdom. $L_{Aeq\text{-}5min}$ was obtained at intervals of one hour for weekdays and weekends. Unsurprisingly, the values of the former were systematically lower than those of the latter. The values were approximately 65.0 to 80.0 dB(A) and reached 72.5 to 76.3 dB(A) because of music and 70.0 to 78.7 dB(A) and 67.8 to 72.0 dB(A) due to PA systems. The highest sound level was 82.6 dB(A) at 12:30 a.m. because of a show. Although the sound levels were rather different, the shapes of the six spectra were similar, with a peak at middle frequencies and a considerable drop at high frequencies. The investigated spaces generally featured long reverberation at all frequencies. The longest one was for a large space, or at middle frequencies, and the shortest one was for a long and narrow space, or at low frequencies. The questionnaire used five-point Likert scales to investigate the annoying-favourable, uncomfortable-comfortable, loud-quiet, noisy-quiet, and echoing-dead. The authors found associations between objective and subjective measures, e.g., level and the acoustic comfort, EDT and communication quality.

Skarlatos (2003) measured noise levels in the commercial centres of Patras, Greece, covering 10 measuring sites five days per week and two hours per day (10.30 a.m. to 12.30 p.m.) at intervals of 10 min to examine whether the noise energy emitted by the source, and the measured noise level were normally distributed. The $L_{A\text{eq-3min}}$ corresponding to the whole sample was 80.24 dB(A), and the 95% confidence interval was between 79.89 and 80.55 dB(A). No subjective surveys were reported.

Hopkins (1994) surveyed the corridors of the West Edmonton mega-mall in Canada. The measurements were taken between 10.a.m. and noon, between 2 p.m. and 5 p.m., and between 7 p.m. and 9 p.m. every day during the entire seven-day period, and sound levels ranged between 58 and 89 dB(A). Weekday mornings and afternoons exhibited the lowest and highest modes, paralleling the daily troughs and peaks in visiting time. The same held true for patron visitation and sound level peaks on Saturday and Sunday afternoons and their troughs on Saturday morning and Sunday night. To ascertain the attributes ascribed to the mega-mall, three off-site surveys were conducted using a written questionnaire. Words elicited from the participants were more likely to be positive, such as the fun, fantastic, and exciting, than negative, such as the overcrowded, confusing, and glitzy, in addition to the spatial descriptors, such as the big, huge, and large. Among the 576 negative words used, the term with the greatest frequency of occurrence was the noisy.

2.2.3.3 Transportation hubs/stations

Wang et al. (2020) took the recordings in nine airports, 14 railway stations, four bus stations, and seven subway stations (a total of 34) to explore the effect of acoustic sequences on noise acceptance; that is, when users are staying or walking in a transport hub, sequential sounds form a sequence of sound sessions. The listening-test surveys, as an aspect of indoor soundscape research, extracted 209 sections of 30 s acoustic units.

The acoustic units were divided into strong, medium, and weak levels and compiled into 37 acoustic sequences, which were then subjected to four tests for acceptance evaluations using a 0-to-10 opinion scale. The effects of the acoustic sequences were demonstrated to improve the sound experience in such spaces.

Wu et al. (2020) investigated the acoustic comfort of six spaces, including the seating area (11,100 m^3), security check (180 m^3), ticket check, ticket lobby (864 m^3), restaurant (172 m^3), and shop (288 m^3), of the Harbin railway station in China. $L_{Aeq\text{-}5min}$ were obtained between 8 a.m. and 6 p.m. at a 1 h intervals. The questionnaire used 5-point Likert scales to survey the uncomfortable-comfortable, noisy-quiet, loud-soft, low-high, long-short, and clear-unclear. The results revealed that the comfort and communication level decreased with increasing SPL, which was below 70.0 dB(A) in the seating area, ticket lobby, and shops. The restaurants were noisiest at 75.1 dB(A), and the acoustic comfort was rated higher than at the ticket check. The mean rating of the acoustic comfort in the railway station was acceptable at 3.65, while the values in the seating area and shop were higher at 3.81 and 3.91, respectively, and those in restaurants were lower at 3.28. The seating area, shop area, and ticket lobby were quieter, and areas with high concentrations of users were “noisy.” T was related to space scale: the larger the space, the longer it is. As it increased, the acoustic comfort and communication level increased. The participants felt the reverberation in the space that it exceeded 4.5 s.

Yilmazer and Bora (2017) selected the park, station entrance, and underground platform of the Akköprü metro station in Turkey. The station is 895 m in length and 216 m in width. The height of the entrance level is 3.19 m, and the height of the platform level is 3.36 m from the base to the suspended aluminium ceiling, and 7.33 m from the metro rails to the top of the metro tunnel. The methodologies involved measurements of $L_{Aeq\text{-}15min}$, soundwalks with noise annoyance and $L_{Aeq\text{-}30s}$, and listening tests on the relationships between space recognition and sound marks. The *in situ* measurements were conducted on Saturday afternoon. The results showed that noise levels were similar, between 55.0 and 60.0 dB(A), in the park and station entrance, while annoyance was higher in the station entrance. L_{Aeq} was lower on the underground platform than at the station entrance, yet the annoyance was close. The listening test asked the participants to describe the recorded space from 17 perceptual adjective pairs and define the sound sources. Only half of the participants were able to correctly determine the function of the spaces; for indoor spaces, they most frequently chose words such as the unpleasant, stressing, and artificial.

Han et al. (2016) investigated six subway stations across seasons in Seoul, South Korea, to explore thermal, air, light, acoustic and passengers' overall comfort. The results concerning the acoustic comfort were reported for only two cases, for which the depths of the concourse were 6.0 and 8.0 m and those of the platform (two-platform form) were 10.2 and 23.1 m. In summer, noise levels were 67.9 and 63.3 dB(A) in the concourses, and 65.3 and 62.9 dB(A) on the platforms. In fall, noise levels were reported to be 64.8 and 63.3 dB(A) in the concourses, and 64.2 and 61.7 dB(A) on the platforms. In winter, noise levels were measured at 65.5 and 61.3 dB(A) in the concourses, and 64.3 and 61.1 dB(A) on the platforms. The questionnaire surveys were conducted between 8 a.m. and 10 p.m. for two days in each season. A five-point Likert scale was used for the comfortable-uncomfortable. As a result, the uncomfortable was selected more than the comfortable comparing to other physical aspects in all three seasons. Since the associations between objective measure and subjective response turned out to be very low, the authors suggested rethinking methodologies of surveying comfort in such spaces with a short visiting time.

Tardieu et al. (2008) sampled six train stations in France: Avignon TGV, Bordeaux St. Jean, Lille Flandres, Nantes, Paris Gare de l'Est and Rennes. The level of each sample was between 65.0 and 70.0 dB(A). The listening tests were composed of several steps, and the first experiment employed a free-categorization task with free verbalizations revealing three main types of acoustical information: sound sources, human activities, and room effects. The perceptual attributes referred to room effects including the close, confused, large, small, external, closed, isolated, echoes, resonances, and personal judgments, including the quiet, noisy, rhythmic, intimate, and pleasant. The results showed that people were able to recognize the type of space (platform, hall, etc.) just by listening to its soundscape.

Nowicka (2007) measured three underground stations in Warsaw, Poland: Metro Politechnika, Metro Wierzbno and Metro Stoklosy. The enclosures were one-platform stations 10.0 to 11.0 m in width. The heights and widths (at the platform level) were the same at 6.0 m and 20.0 m, respectively. The measured EDT increased with the source distance in Metro Stoklosy, while that of the other two stations was independent of the source distance at 500 Hz. RASTI was better in Metro Stoklosy confirming better reverberation with absorptive materials on the ceilings. It was found that a rectangular cross-section led to better RASTI. No subjective survey was reported in this study.

2.2.4 Discussion

2.2.4.1 Objective measure

The most commonly used objective measures were SPL (more specifically often considered L_{Aeq}) and T. The former was reported mainly as the average noise level during visiting time, and the latter was primarily approached by RT measured under the condition without users.

The L_{Aeq} values across building types were normally equivalent to approximately 60.0 to 70.0 dB(A), while the L_{Aeq} intervals across studies were inconsistent. The value reached approximately 90.0 dB(A) in the case of a PA system, music and higher attendance, and was lower than 55.0 dB(A) when the space was not busy, even during opening hours.

Concerning L_{Aeq} intervals (e.g., 1, 3, 5, 10, 15 min, and 2 h), most studies failed to thoroughly explain their reasons for selecting certain intervals. Associations between L_{Aeq} intervals and space scale, space type and sound source were not found. Some studies (Meng and Kang, 2013) chose the measuring duration in accordance with the goals of users, expecting the selected interval to cover their visiting time, which was highly dependent on the usage of the space and individual preferences. The intervals for museums/exhibition spaces and transportation hubs/stations were generally shorter than those for shopping malls: the former could be within 10 min, and the latter could last up to 2 h.

On the other hand, the measured values of RT in museums/exhibitions spaces and shopping malls across locations were between 1.0 and 3.0 s, and those in transportation hubs/stations could be greater than 4.0 s. The larger the spaces are, in general, the larger the values are. Concerning the dynamic ranges for measuring RT (e.g., T_{15}, T_{20}, and T_{30}), T_{20} was more frequently adopted because in some cases the radiated source power was not sufficient to rely on T_{30}.

In clarifying objective items to characterize the acoustics of such spaces, shopping malls are known to exhibit regular sound-level modes daily and weekly, consistent with users' attendance, and the results obtained in different locations with various functions were rich sources of references. The L_{Aeq} range in transportation hubs/stations could be the largest, since some spaces were semi-open or open. However, specific data focusing on user content in terms of the dynamic aspects, such as the number of visitors in museums/exhibition spaces and transportation hubs/stations, are rather difficult to find. Additionally, which interval is most suitable for L_{Aeq} for each building type is not known. The variety of current states may show that having a consistent measure is not a perfect solution. The influence of the space scale and space type should be taken into account together when the intervals are selected. For example, a larger space may have more users and hold more events, in which case the selected L_{Aeq} interval is required to be longer.

2.2.4.2 Perceptual attributes

The subjective measures used for perceptual attributes were abundant. Most studies collected individual responses through *in situ* surveys, which assessed six aspects, including overall acoustic evaluation, sound noticeability, sound preference, soundscape descriptors, sound descriptors, and control, covering topics in both room acoustics and soundscapes. The subjective items characterizing the acoustics of spaces can be classified into four categories:

- annoyance: the annoying and comfortable, etc., demonstrating the positive/negative effects of sound environments;
- affective quality: the cool and warm, etc., which are associated with the emotional fluctuations of individuals caused by sound or acoustic activities;
- room-acoustic quality: the loudness and reverberation, etc., neutrally describing auditory perceptions of the space; and
- acoustic spatiality: the directionality and large, etc., which are subjective impressions rather than measures related to spatial localization or recognition of the sound environment.

The first two categories (i.e., the annoyance and affective quality) focused on the individual-related changes, and the last two categories (i.e., the room-acoustic quality and acoustic spatiality) were treated objectively. The perceptual attributes the annoying and comfortable may be the basic descriptors that have been most frequently surveyed at present and used to measure levels subjectively in these spaces. The selections of other measures and their results were highly project-specific, and it is reasonable to believe that comparisons across building types could be unsuitable at this stage.

In terms of special considerations related to the dynamics of auditory perception, some perceptual attributes appeared to be concerned with the number of users, such as the crowded-uncrowded, crowded-empty, and unsteady-steady. Additionally, some perceptual attributes were applied with the source noticeability, such as the directionality, far away-nearby, and know the position-don't know the position. However, detailed results of these perceptual attributes were limited compared to reports for the loudness and comfort.

Regarding the spatial features of the sound environments of such large public spaces, some perceptual attributes related to the space scale, such as the large-small, tight-loose, and spacious-narrow, were also of interest in one or two surveys, especially for visually impaired people, in addition to the reverberation and intelligibility.

Most studies confirmed certain associations between objective and subjective measures, although they generally discussed sound levels and annoyance or loudness. Some studies (Wang et al., 2020) considered user-related factors together, such as acoustic sequences in sound levels and users' direction. Some studies (Orhan and Yilmazer, 2021) pointed out that the effects of sound source content were more dominant than those of sound levels in perceptions of such spaces.

Overall, the present deficiencies of perceptual attributes were similar to those of objective measures, i.e., overlooking the effects of space scale, space type, and sound source. In addition, some potential issues could unavoidably arise, such as subjects who are not native speakers answering questions in a foreign language or coming from a person's different professional background (Zimmermann and Lorenz, 2008). However, studies concerning this issue imposed by the gap between a native and non-native English speaker are currently being conducted with numerous efforts (Aletta et al., 2020) by the Soundscape Attributes Translation Project (SATP).

Given that the current application of subjective measures is not standardized for specific building types, four basic perceptual assessments are recommended for each category: (1) the annoying-not annoying; (2) the crowded-uncrowded; (3) the long-short (reverberation); and (4) the far away-nearby. In addition, other perceptual attributes related to how building type affects the crowd are suggested, such as the concentrating for museums/exhibition spaces, the exciting for shopping malls, and the clear for transportation hubs/stations. These perceptual constructs should be the core rather than being included in long lists of items for assessments.

2.2.4.3 Methodologies

The methodologies were mainly four approaches: (1) measurement; (2) questionnaire/interview; (3) listening test; and (4) software simulation. The first two methodologies were applied to collect *in situ* data, and the last two were adopted to interpret or solve issues for which measurement by the former methodologies was considered unreasonable. This review found no experiment using listening tests for shopping malls, as all of evaluations of shopping malls were developed with *in situ* measurements and questionnaires/interviews. However, for transportation hubs/stations, in collecting subjective data, listening tests were more frequently adopted than *in situ* surveys. For museums/exhibition spaces, there were more experiments using software simulation (VorLänder, 2013). Some sites functioned as performing spaces and were simulated for exhibition configurations.

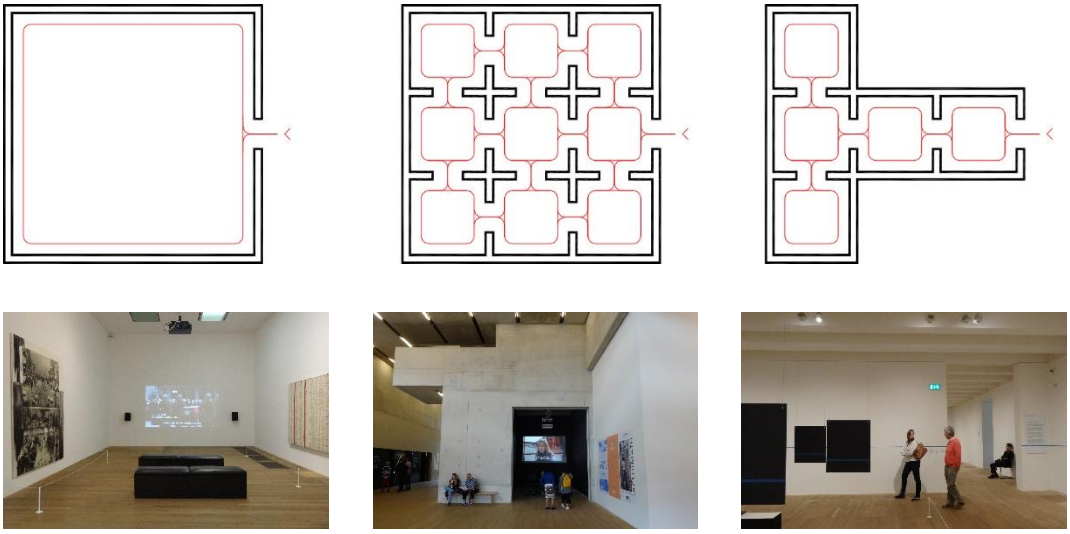
Normally, the methodologies of *in situ* investigation of such a large public environment would inevitably consider survey time and location. The measurements, to obtain the physical outcomes of a site, were conducted in three or four blocks, in the morning, midday, and evening, and it took an entire seven-day period to cover weekends and weekdays, especially for shopping malls. Some studies (Han et al., 2016, Meng and Kang, 2013) lasted for four seasons. The selection of measuring locations was intended to cover a representative sample of the case; otherwise, it was intended to investigate specific research questions, such as space types, or practical problems. The questionnaires and interviews usually used five-point Likert scales, with either open- or closed-ended questions, probably associated with indoor soundwalks. Except for this feature, differences between the three selected building types and others that were not targeted in this review of the methodologies were generally difficult to identify.

Comparatively, the listening test and software simulation methodologies were found to be less focused on the temporal and spatial features of the site. Most studies addressed the prediction accuracy of theoretical solutions in such spaces through software simulation to explore the potentials of using decay and the attenuation of objective parameters. Furthermore, listening tests aimed to identify exploratory factors related and unrelated to the dynamics of the acoustic environment, such as acoustic sequence and users' attendance. These attempts gradually filled the gap in this area.

Overall, these methods potentially advance our understanding of these issues, and they will continue to develop with theoretical advances, technological innovations, and social changes, such as issues associated with COVID-19.

2.2.4.4 Effects on Design

The investigated studies included in this review of research on large public buildings were sorted into three space types: single, multiple, and sequential. **Figure 2.4** illustrates, for example, the configurations of these three space types by museums/exhibition spaces (Tate Modern, UK). An overview of space type and space scale across studies revealed that the investigated spaces of museums/exhibition spaces could be single and multiple. Shopping malls and transportation hubs/stations, either corridors, atria, or platforms, were much larger in scale and more complex as multiple spaces. However, although most studies reported their case selection in terms of room volume or area, the effects of these space factors were not always reflected in the results.



(a) (b) (c)

Figure 2.4 The configurations of space type: (a) single; (b) multiple; and (c) sequential.

Evidence from acoustic and/or indoor soundscapes investigations in such spaces is increasing. Overall, the sound environments of these large public buildings were perceived to be uncomfortable to some extent. Currently, research has indicated that the design of such spaces should focus on the background noise level and sound reverberation. Based on the physical outcomes obtained by measurements and software simulation, some studies (D'Orazio et al., 2020) of museums/exhibition spaces suggested users' control or presented conditional results, e.g., with/without the investigated exhibits, to avoid the detrimental effects of noise level. Some studies (Kanev, 2021) of shopping malls and transportation hubs/stations (Nowicka, 2007) put forward advice on the selection of space scale, shape and acoustic absorption solutions. Feedback from users certainly helped those seeking sufficient acoustic comfort in addition to loudness and speech intelligibility; for example, the results of some studies (Urban et al., 2016) indicated that the difference between large and small space scales was obvious. Counter intuitively, even good objectives sometimes lead to bad subjective outcomes. Studies on objective measures and perceptual attributes are not comparable at this moment. There are fewer objective parameters than subjective parameters; therefore, their association is still basic. In seeking objective parameters or creating a new parameter in this context, it may be possible to take the direction to/from the source factor into account. The integrated design of indoor soundscape design will also promote ensuring that the sound environment of such large public buildings is in tune with the specific functions of such spaces.

2.2.4.5 Limitations

Given the in-depth review, this study could be limited since it eliminated those that did not undergo peer review (e.g., conference papers, book chapters) and those not in English. Furthermore, the search strategies covered targeted public spaces, although efforts were made to avoid overlooking studies that used other definitions of such spaces. After extensive discussions with colleagues, input from other experts in the field was sought to compensate for these limitations.

2.2.5 Conclusions

This **Section 2.2** reports on sound environments in large public spaces for crowd transit. For this purpose, a systematic review in accordance with the PRISMA guidelines was performed. After the screening process, the dataset resulted in 26 items that were sorted into three groups depending on building type (i.e., museums/exhibition spaces, shopping malls, and transportation hubs/stations). Since they had substantially different methodological approaches, the studies were qualitatively analysed. The review presents obvious significant issues related to sound environments between such spaces and other types of functional spaces. The main conclusions are as follows:

- The most commonly used objective measures were SPL and, more specifically, $L_{A\text{eq}}$ and T were often considered. The intervals across studies were inconsistent, and the space scale factor should be taken into account;
- The subjective measures can be classified into four categories: the annoyance, affective quality, room-acoustic quality, and acoustic spatiality. Four basic perceptual assessments for special consideration of dynamic content in the space are accordingly suggested: the annoying-not annoying, crowed-uncrowded, long-short (reverberation), and far away-nearby. The other measures can be project-specific;
- The methodologies involve measurements, questionnaires/interviews, listening tests and software simulations. It is necessary for the first two to consider the temporal and spatial features of such spaces, and the last two will lead to better understanding of users' exposure to such spaces (e.g., acoustic sequence and user amount); and
- The outputs of acoustic and/or indoor soundscape investigations indicate that improvement in the background noise level (e.g., 90.0 dB(A) in museum/exhibition spaces and RT over 4.0 to 5.0 s in shopping malls and transportation hubs/station) is of fundamental importance. Sufficient acoustic comfort for building types can be achieved with the integrated design of indoor soundscapes.

This review qualitatively shows increasing interest in managing sound to enhance users' health and well-being in such large public spaces. Further work on the association between objective and subjective measures is still required. Supplementing such studies with dynamic content will hopefully improve users' experience and indoor environmental quality.

2.3 SUMMARY

Generally, regarding propagation methods in natural or building environments, two fundamental factors affect the magnitude of sound diffraction, i.e., the wavelength of a sound source and opening size. In terms of sound insulation combining direct and flanking transmission, three determinants affect sound attenuation with distance from the source when not only different direct and flanking constructions but also spatial dimension and measurement uncertainty are considered: (1) room volume; (2) room absorption; and (3) source distance. Abundant studies of coupled rooms suggest several crucial contextual and acoustic factors: (1) opening area and position; (2) absorption coefficient and distribution; and (3) room dimension and volume.

According to the systematic review of the sound environments in large public buildings with crowd transit, it is worthwhile to note that both subjective and objective outcomes through survey and measurement obtained in museum/exhibition spaces, shopping malls and transportation hubs are growing. However, information detailing how much better the abovementioned factors will work in current research are still very limited, suggesting insufficient insights and specific details of either sound propagation or noise perception.

In terms of sequential spaces rather than focusing on a single space, some studies have dealt with similar spatial forms, e.g., Hagia Sophia of Istanbul by Sü Gül (2021) the long corridor in a shopping mall by Kanev (2021), and the large-scale public spaces investigated by Paxton et al. (2018), which can be references for sound attenuation and noise control. In addition, some studies have proposed distinct views about the source content and listener response in the museum by Orhan and Yilmazer (2021), or noise acceptance concerning the dynamic changes in sound level (Wang et al., 2020), which is potentially relevant.

3 Methodologies

This chapter introduces the overall methodologies in two categories in RE and VE. One is the objective techniques of airborne sound insulation for *in situ* measurements (Chapter 5) and FEM for predictions (Chapter 6). The second is the perceptual discipline, including questionnaires and soundwalks for evaluations (Chapters 4 and 7).

3.1 OBJECTIVE TECHNIQUE

Standardized building acoustic measurements have been developed for the optimization of sound insulation against noise sources (e.g., airborne and impact sound) for the benefit and well-being of people in spaces such as dwellings, offices and schools. This should minimize disturbing noise from other rooms.

For field measurements, airborne sound insulation can be described in terms of the level difference between the source and receiving rooms. A reference test signal (e.g., pink noise), which can be switched on and off from outside the source room by pressing a button on a supplied wireless remote control, is generated at a range of frequencies in a source room using an omnidirectional loudspeaker, and any resulting sound is detected in an adjacent space with a microphone according to the relevant Standard ISO 16283. Then, the spectra in the source and receiving rooms are measured. The values of background noise and RT would be required for the calculation, and the receiving room is corrected by eliminating background noise and room effect related to room absorption, e.g., if the receiving room is reverberant, the sound level will be higher. In terms of RT, a pink noise signal produced by a dodecahedron loudspeaker is automatically triggered, or an impulse can be generated from a clapping board or bursting balloon. The decay spectra are recorded for the calculation, and the uncertainties of the tests are determined. Tests are typically carried out in the range from 125 Hz to 4 kHz.

Airborne sound insulation is usually measured using broadband noise. However, single frequencies provide a clearer understanding of the effect of different source positions. For field measurements in non-diffuse sound fields, it is necessary to excite the majority of the modes in the source room. For this reason, loudspeaker positions near the corners are used in box-shaped rooms as well as in other shapes of rooms. It is also necessary to take average measurements from more than one source position. However, it must be ensured that the direct sound from a loudspeaker does not cause significant excitation of the walls or floors compared to excitation by the reverberant sound field.

Airborne sound insulation measurements of building façades are categorized according to the relevant Standard ISO 140. The apparent sound reduction index of an individual building element (e.g., window, door) can be measured from outside to inside using SPL measurements with a loudspeaker facing toward the façade. Note that we can only measure the apparent sound reduction index because there will inevitably be some sound transmitted by the rest of the façade, i.e., flanking transmission. By placing a loudspeaker at a sufficient distance from the test element we can assume that the incident sound field comprises plane waves (Hopkins, 2007). The loudspeaker is positioned at an angle, i.e., the angle between the line normal to the centre of the test element and the axis of the loudspeaker that points toward the centre of the test element.

Airborne sound insulation is dependent upon the angle of the incident sound. Hence, differences are to be expected between the sound reduction index measured with a diffuse incidence sound field and with sound incident at a single angle. There is no general rule for conversion between the two types of incident sound. However, for closed windows, $\theta = 45°$ often gives a reasonable estimate of the sound reduction index with a diffuse incidence sound field. The relevant measurement Standard ISO 140 uses $\theta = 45°$, and there are other variables, such as loudspeaker height, that also affect the measurement. There is some evidence that the apparent sound reduction index measured using $\theta = 60°$ instead of 45° gives closer agreement with the value measured in a laboratory (Jonasson and Carlsson, 1986).

On the other hand, various computational methods (e.g., wave approach, geometric acoustics, statistical energy analysis, and diffusion model) have been applied in enclosed spaces with different assumptions and constraints for effective sound field prediction. Geometric acoustics ignores sound wave characteristics, and therefore the simulation of diffraction can be skewed because the modelling in the low-frequency range can be inaccurate when passing over obstacles. For many years, the lack of diffraction has been perceived as a problem for software that is mainly based on geometrical acoustics. It is found that the constant and considerable attempts have been made to include sound diffraction, e.g., CATT-Acoustics (CATT-Acoustics, Gothenburg, Sweden). However, it is worth noting that FEM and similar methods handle hard edges with a finite impedance. They are not diffraction "methods" but ways to solve the wave equation. For the advantage of FEM and to avoid the discussed potential issues, wave theory-based software is considered in this thesis. There are many wave-based techniques, e.g., FEM, boundary element method, and finite difference time domain method. FEM has the advantage of generating a dense grid where needed, such as the corner of a room having a greater influence on sound propagation. Another advantage is to handle coupled rooms. An FEM model for a single frequency is very accurate, but for octave bandwidth, the result contains discrepancies. At this stage, the shape with a rigid wall can be resolved. The most common software is COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden), featuring large-scale advanced numerical simulation by realizing simulations of real physical phenomena. Shi et al. (2018) investigated an original energy-based approach for modelling coupling that was achieved by the continuity of exchanged power between rooms. This approach was validated by comparing the FEM results using COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden).

The disadvantages of FEM are that it remains inefficient in the middle-/high-frequencies especially for large rooms, and requires much more complex input data for the model (e.g., boundary conditions, acoustic impedance, and scattering coefficient) than is generally available. To achieve sufficient prediction accuracy and consistency, the scale of boundary elements should be less than ¼ of the wavelength, and the time step should be short enough to reflect the interference of the wavefront. For example, predicting a sound field in a concert hall with a room volume of 20,000 m^3 would require 1.7 billion elements at 8 kHz, which is too many. Therefore, FEM is mainly used to study the coupling of low-frequency sound fields in small rooms (compared to the wavelength), which is considered to be difficult to apply in performing spaces in a wider frequency range.

Geometrical acoustics and the diffusion equation approach have also been used to model coupled spaces. Summers et al. (2005) applied a modified beam-axis-tracing algorithm. The computation results were confirmed through 1:10 scale-model experiments. Billon et al. (2006) developed a numerical diffusion model to predict the spatial variations in SPL and RT. The model results matched the experimental data. Furthermore, the authors found that although the ray tracing and diffusion models produced similar results, the latter exhibited a significantly lower execution time. Jing and Xiang (2008) used diffusion modelling to produce a visualization of sound pressure distribution and sound energy flow across the coupling aperture of two rooms. Xiang et al. (2009) conducted acoustical measurements on a 1:8 scale model of two coupled-rooms and further quantified the double-slope characteristics of sound energy in coupled rooms. The study addressed issues such as the reversal of energy flow across the coupling aperture and validated the results using experimental scale models. It is important to note that the results of above-mentioned studies are mainly conducted in coupled rooms, which are validated through the physical experiments of the scale model, and have sufficiently confirmed that using scale model can be a potential technique to explore sound fields in sequential spaces. Additionally, it is available for future work to present a wide view and application in architectural acoustics.

3.2 SUBJECTIVE DISCIPLINE

As a broad term describing auditory perception, subjective evaluation of sound quality is particularly useful in performing spaces (e.g., concert halls, conference halls, and recording studios), where high-quality announcement messages and/or music are essential. It essentially addresses the acoustic properties within the room itself by achieving suitable values of the multi-dimensional parameters (e.g., the loudness, clarity, and reverberation).

In addition, collecting perceptual data for a room with a wider purpose than performing involves evaluating the soundscape in a given area based on people's subjective responses. Soundscapes rely on the perception of humans toward an acoustic environment (Kang and Schulte-Fortkamp, 2016). Standard ISO/FDIS 12913-1:2014 (International Organization for Standardization, 2014) defines that both the measurements of physical parameters and the evaluation of perceptual data should be used to determine soundscapes. Recently, Standard ISO/TS 12913-2:2018 (International Organization for Standardization, 2018) was established based on data collection and reporting requirements for soundscapes studies and requires a combination of physical parameters (sound levels and/or binaural measurements) and perceptual data (e.g., soundwalk and/or questionnaire and/or guided interview) providing examples concerning the methods of questionnaire (Method A), soundwalk (Method B), interview (Method C), and binaural measurement.

Questionnaires are one of the most commonly used data-collection methods to understand how people perceive acoustic environments. It is important to inform participants about how their data will be utilized, and it is optional to answer any of the questions. The design of a questionnaire mainly comprises four parts: sound source identification, perceived affective quality, assessment of the surrounding sound environment, and appropriateness of the surrounding sound environment. The results of the questionnaire are usually analysed using statistical software.

Soundwalks, first introduced by Schafer (1994) as an exploration of the soundscapes of a given area using a score as a guide, provide information about existing and proposed acoustic environments. The score comprises a map that draws listener attention toward unusual sounds and ambient sound heard along the way. They initially include a 1 h walk followed by a discussion section, with instant debates at predetermined stops along the route, resulting in highly reliable results. Standard ISO/TS 12913-2:2018 (International Organization for Standardization, 2018) details how to lead a soundwalk, perform binaural measurements, and how the participants are involved. The participants are given at least 3 min to listen to a defined environment using all their senses and complete a sound environment assessment, sound source recognition, and subsequent comments.

These disciplines have been applied in *in situ* and listening tests, as discussed in **Section 2.2**. With the developments of virtual acoustics, when processing these methodologies in VE, software, e.g., the Unreal Engine (Epic Games, Cary, North Carolina), a suite of development tools for real-time technology that provides freedom and control for delivering cutting-edge entertainment, compelling visualizations, and immersive virtual worlds, is widely used.

3.3 SUMMARY

Overall, *in situ* measurement of airborne sound insulation employs level difference between the source and receiving room as a major acoustic parameter (International Organization for Standardization, 2020). Tests use different source positions at the corner of a room (Hopkins, 2007), and an angle of incident sound $\theta = 60°$ rather than 45° may be considered (Jonasson and Carlsson, 1986). FEM can be accurate for nature based on wave theory as a computational simulation prediction method, and COMSOL Multiphysics is used in this thesis. Questionnaires and soundwalks are well-established methods of subjective evaluation, and for experiments conducted in VE, the Unreal Engine is used in this thesis. **Figure 3.1** summarizes the methods used in each chapter.

Methodologies

Chapter 4	Real sound quality evaluation; real soundwalk
Chapter 5	Airborne sound insulation test
Chapter 6	Airborne sound insulation test; FEM
Chapter 7	Virtual sound quality evaluation; virtual soundwalk

Figure 3.1 The methods used in each chapter.

4 Dynamic Perception of Noise as a Stationary Primary Source

As discussed in **Section 2.2**, cognition of noise is important for sound environments in large public buildings. In this chapter, noise perception as a stationary primary source (e.g., a crowd) with a listener in motion is investigated in the building environment. The effects of the primary source across the space are presented using the perceptual attributes developed in room acoustics and indoor soundscape studies. The perceptual asymmetry of the listener directional aspects (i.e., approaching and receding sound sources on the same path) is discussed.

4.1 INTRODUCTION

Acoustic professionals have focused strongly on the subjective evaluation of the sound quality of a stationary sound source and its relation to architectural design with respect to room acoustic studies of performing spaces. Systematic perceptual attributes and acoustic parameters indicating auditory perception, normally under static conditions, have been developed (Ando, 1998, Barron, 1993). Coupled room is one of the strategies for adjusting sound attenuation and reverberation by changing the room volume and absorption for performance. Compared to the rooms common in daily life, the room volume of such a space (e.g., a stage and an audience hall) is usually larger with a larger coupling opening. Therefore, current research and applications are insufficient for the study of sequential spaces, owing to not only the associations between the source and receiving rooms but also the source content.

Although a subjective evaluation of a noise source is uncommon in performing spaces, it is firmly developed based on soundscape studies using numerous qualitative and quantitative techniques, e.g., visitor evaluation based on semantic differentials (Kerrick et al., 1969, Kawai et al., 2004, Axelsson et al., 2010), evaluations of the presence of disturbing characteristics of specific sounds, such as traffic and agriculture (Kogan et al., 2018, Nilsson and Berglund, 2006), and statistical measurement of physical background noises. Although indoor soundscape is a fairly new area of acoustics compared to those conducted outdoors in urban environments, much research has provided a solid conceptual and methodological base for mood and psyche

(Dökmeci Yorukoglu and Kang, 2016). However, although the sites of these studies normally involve multiple sound sources, most of which are environmental signals, the findings are still inadequate. In the case of a stationary primary noise source, they present a limited view of the association between the noise and multiple connected indoor spaces.

The perception difference between sequential spaces and a single enclosure does not rely on spatial information alone but also on listener status. Therefore, listeners should not be assumed to be in a stationary position for a long time, unavoidably having dynamic associations with the sound source and acoustic environment. There exist soundwalk studies (Davies et al., 2013) relevant to this concept, defined as the "expectation," wherein a listener can choose how a location or source will sound. Botteldooren and De Coensel (2006) proposed the expectation as a factor of the reaction and expression of emotion for a soundscape. Bruce and Davies (2014) stated that soundscape evaluation should consider the effect of the expectation, which is primarily influenced by prior experiences of similar spaces and perceived loudness. However, the above studies were mainly developed in outdoor environments, making the results insufficient for indoor applications.

The overarching goal of this chapter is to explore the dynamic auditory perception of noise as a primary sound source for a listener in motion in architectural sequential spaces. Additionally, the potential asymmetry of the directional aspects (i.e., approaching and receding sound sources) was examined. Furthermore, a joint methodology based on room acoustics and indoor soundscape studies of an *in situ* soundwalk in a large-scale building was applied to assess the acoustic environment.

4.2 METHODS

4.2.1 Site Selection

Several representative sites were considered as pilots to appropriately select rooms based on the identified research questions. The conditions of having a source room with only one stationary primary source and having different paths to the source room via a succession of receiving rooms are ideal for the dynamic auditory perception experiments. However, they are a challenge to meet in reality for large public spaces, especially when the primary sound source has to be noise. As such, the site was peculiar in nature and selected for its conditions.

The selected case sites were two exhibition spaces on the fourth floor of the Tate Modern, London, United Kingdom, connected by a concourse on the right and left sides. **Figure 4.1** shows the entire of the interconnecting rooms, concourse, and primary source. Although the contextual factors (e.g., room volume, opening area in the separating partitions, and interior design) were the same for both sides, the only difference could be found in the acoustic factors. The right spaces used a loud stationary primary noise source in room 1 whereas the left spaces were quiet and generalized with multiple sound sources as background noise in the building environments, which makes the two spaces ideal for comparative analysis to examine the performance of the dynamic auditory perception. For ease of understanding, the spaces on the left and right sides were defined as the no-sound-source and sound-source groups, respectively.

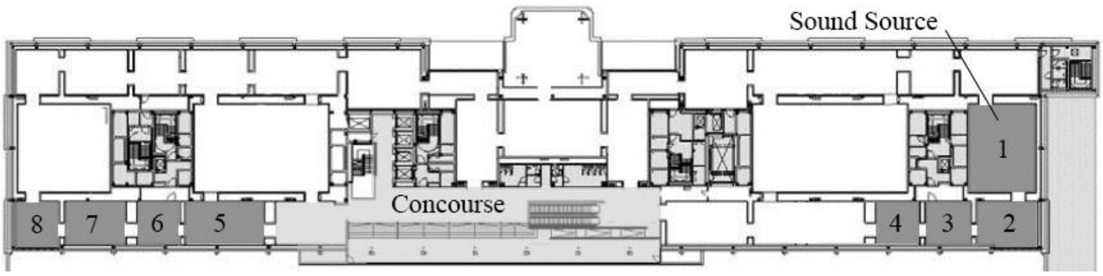
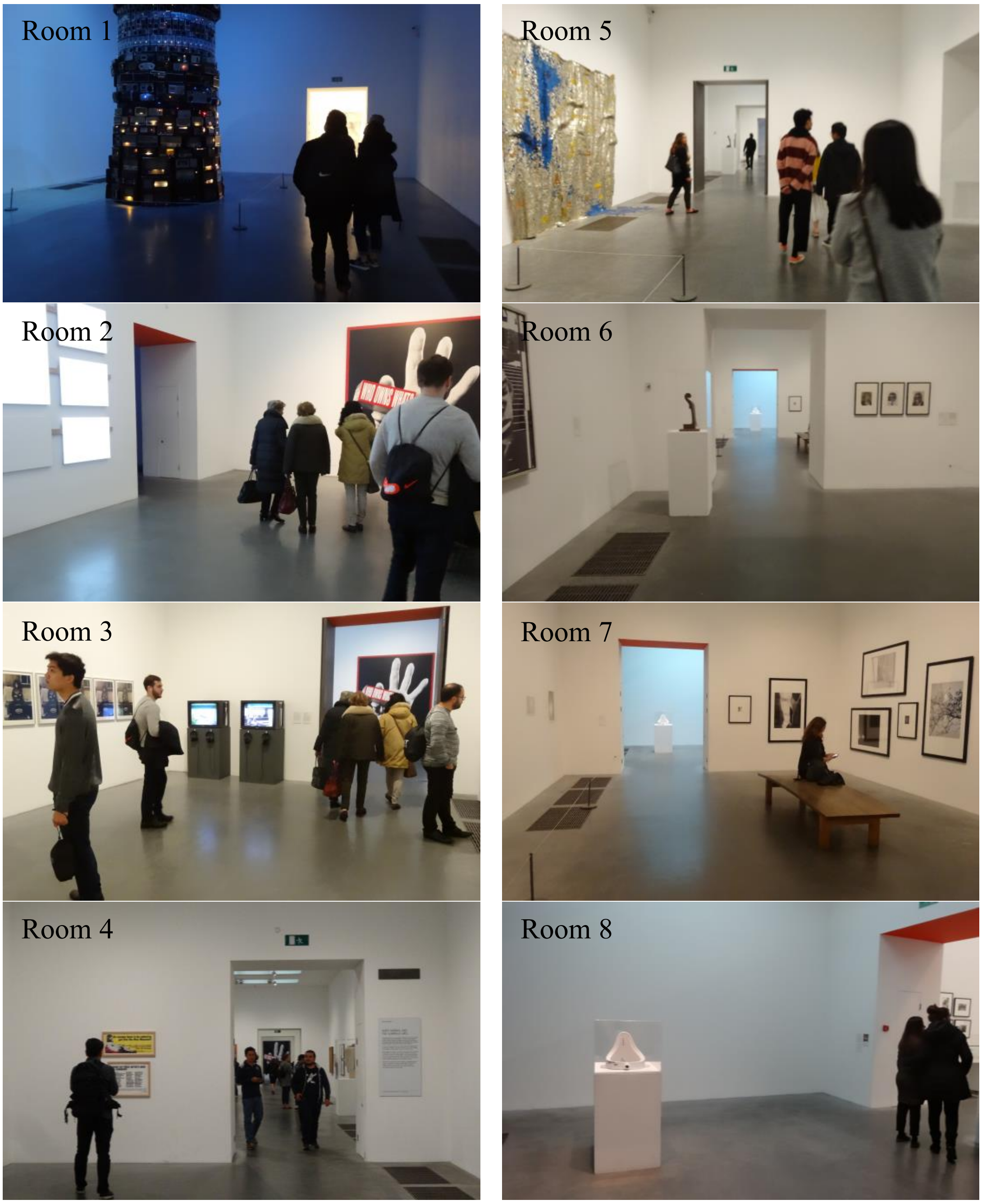


Figure 4.1 The floor plan of the case sites.

Figure 4.2a shows a site photo of the source and receiving rooms in the right site. The primary sound source "Babel, 2001" in room 1 was an artistic sound installation. As a permanent exhibit by artist Cildo Merireles (Meireles et al., 2008), the concept of this work was to depict an imaginary "confusion" with incomprehensible information. It was compiled using hundreds of radios shaped as a cylindrical tower, with a radius and height of approximately 6.0 m and 8.0 m, respectively, which generated unintelligible mixes of music and voices. According to the floor plan, a visitor can pass through the exhibition either in the sequence from rooms 4 to 1 or from rooms 1 to 4 (i.e., starting or ending with the source room). The source room (room 1: 13.0 m × 9.0 m × 9.8 m) was a large box-shaped space with indigo blue lighting and was sequentially connected with three smaller white exhibition units: the first receiving room (room 2: 6.3 m × 8.0 m × 4.9 m), second receiving room (room 3: 6.3 m × 6.3 m × 4.9 m), and third receiving room (room 4: 6.3 m × 6.3 m × 4.9 m). The receiving rooms were normal exhibition spaces with no prescribed sound sources. **Figure 4.2b** shows a site photo of the left site comprising four similar room units without a prescribed sound source, including rooms 5–8 similar to rooms 2–4. Among them, room 5 was the entrance directly connected to the concourse. There were no connecting joints between the walls and floors or the floors and ceilings (Archello, 2022). The interior walls were dry lining walls. The plaster ceilings were flat and unarticulated with considerable machinery and technical facilities concealed above. Artificial illumination coming from glass panels set flush with the ceilings. The floors were of reinforced concrete. The acoustic environments of the sites were subjects to almost uniform interior finishes and the social norm of keeping the voice level down, therefore taken as the baseline condition of sequential spaces.



(a) (b)

Figure 4.2 The site photos for (a) sound-source group as rooms 1 to 4 and (b) no-sound-source group as rooms 5 to 8.

4.2.2 *In situ* Acoustical Measurement

As mentioned above, "Babel 2001" was a permanent exhibit that functioned constantly during visiting hours. The two sites were piloted for a week during visiting hours (i.e., from 10:00 to 18:00 from Sunday to Thursday and from 10:00 to 22:00 from Friday to Saturday). It was observed that although there were only a few visitors in the gallery between 10:00 and 10:30 (unoccupied condition), the numbers of visitors in the no-sound-source and sound-source groups were almost equal between 12:00 and 18:00 (occupied condition). This can be attributed to the fact that the no-sound-source and sound-source groups were located on the same floor of the museum, whereas a difference between weekdays and weekends was observed. As a result, the unoccupied condition offered an environment to gain insight into the effect imposed by the primary noise sound source in sequential spaces, whereas the occupied condition was available for evaluation surveys and conducting corresponding measurements for the no-sound-source and sound-source groups.

The *in situ* measurements were conducted in January 2019. **Figure 4.3** shows the measurements that take place. **Table 4.1** shows the unoccupied results in a room for both groups. A sound level meter XL2 (NTi Audio, Schaaen, Switzerland) was used, and the outcomes were taken in the measuring position close to the centre of the room one after another. The average values are the mean values obtained on three different days (each twice), i.e., six measurements per room (a duration of 1 min in a room). As shown in **Table 4.1** from the $L_{A\text{eq-1min}}$ column, the overall range of $L_{A\text{eq-1min}}$ for rooms 1–8 was 39.7–66.8 dB(A). The $L_{A\text{eq-1min}}$ attenuation for rooms 1–4, i.e., the sound-source group, was 12.2 dB(A), whereas the level difference between rooms was 6.3, 5.1, and 1.8 dB(A), respectively. To determine the temporal variability and low-frequency content, the range of $L_{A\text{10-1min}} - L_{A\text{90-1min}}$ was found to be between 2.0 and 3.6 dB(A), which indicates a small variation presenting an identical sound environment in rooms 1–4; $L_{C\text{eq-1min}} - L_{A\text{eq-1min}}$ was further calculated and was found to be the highest in the third receiving room (room 4), thereby indicating that the acoustic environment in room 4 was dominated by low frequencies. Similarly, $L_{A\text{eq-1min}}$ attenuation for rooms 5–8, i.e., the no-sound-source group, was 7.9 dB(A), and the level difference between rooms was 3.7, 0.3, and 2.9 dB(A), respectively. **Figure 4.4** shows the spectrograms for the rooms in the unoccupied condition for the sound-source and no-sound-source groups, demonstrating that “Babel, 2001” was broadband noise, making the parameters $L_{A\text{eq-1min}}$ and $L_{C\text{eq-1min}}$ valid measurements of the sound field in sequential spaces.

Figure 4.3 The site photo for the measurements that take place.

Table 4.1 The *in situ* acoustic parameters (i.e., $L_{Aeq\text{-}1min}$, $L_{Ceq\text{-}1min}$, $L_{A10\text{-}1min}$, $L_{A50\text{-}1min}$, and $L_{A90\text{-}1min}$) for rooms 1–8 under unoccupied conditions.

Room	$L_{Aeq\text{-}1min}$ [dB(A)]	$L_{A10\text{-}1min}$ [dB(A)]	$L_{A50\text{-}1min}$ [dB(A)]	$L_{A90\text{-}1min}$ [dB(A)]	$L_{Ceq\text{-}1min}$ [dB©]	$L_{A10}-L_{A90}$ [-]	$L_{Ceq}-L_{Aeq}$ [-]
1	66.8±3.0	68.4±2.8	66.6±3.0	64.8±3.1	70.6±2.9	3.6	3.8
2	60.5±3.1	61.9±3.1	60.3±3.1	58.5±3.3	64.8±3.0	3.4	4.3
3	55.4±2.8	56.5±2.8	55.2±2.7	54.0±2.7	59.8±2.4	2.4	4.3
4	53.6±5.8	54.5±0.7	53.5±0.5	52.5±0.3	60.6±2.4	2.0	7.1
5	46.6±1.2	48.1±1.7	46.1±1.0	45.1±0.5	54.9±4.6	3.0	8.3
6	42.9±2.4	44.5±3.4	41.8±1.2	41.1±1.2	55.7±6.0	3.3	12.8
7	42.6±4.0	43.9±4.2	41.3±2.4	40.0±2.0	53.3±5.2	3.9	10.7
8	39.7±1.4	42.0±0.9	38.4±1.7	36.8±1.2	54.9±6.5	5.2	15.3

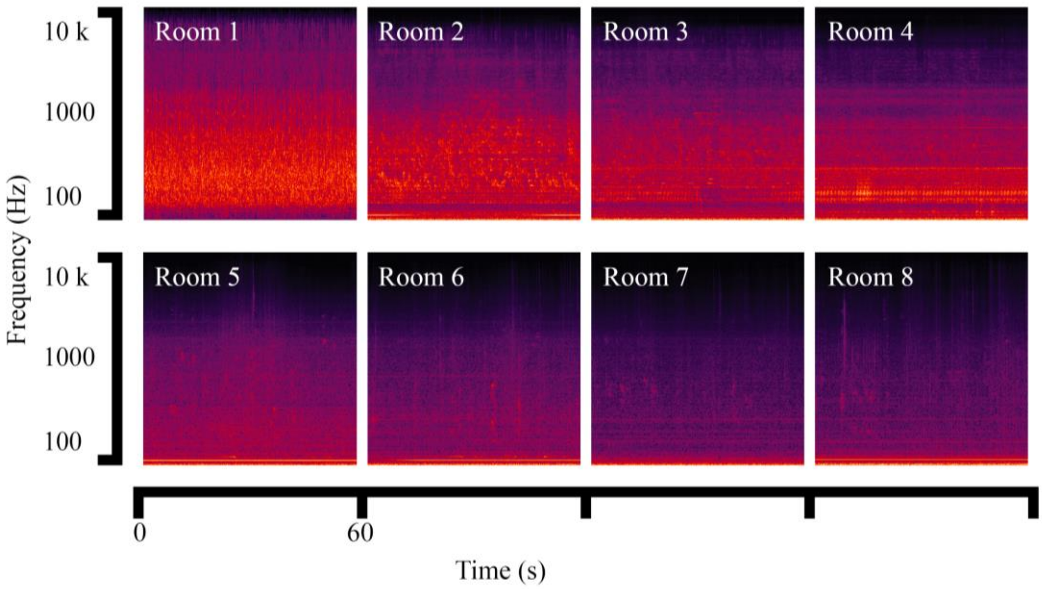


Figure 4.4 The spectrograms in the unoccupied condition for the sound-source group (first row) and no-sound-source group (second row).

Table 4.2 shows the measured results in a room in the occupied condition with the crowd transit for both groups, conducted simultaneously with the subjective evaluation survey of the soundwalk using a binaural recording and analysis kit SQobold (HEAD acoustics, Herzogenrath, Germany) and calculated by ArtemiS SUITE (HEAD acoustics, Herzogenrath, Germany). The average values are the mean values obtained with 108 participants, which are detailed in **Section 4.2.4**. The entire decrease in the SPL with distance for the sound-source group was 8.6 dB(A), and the level difference between rooms was 5.7, 3.8, and –0.9 dB(A), respectively. Similarly, the entire sound level attenuation for the no-sound-source group was 5.3 dB(A), whereas the level difference between rooms was 2.2, 1.6, and 1.5 dB(A), respectively. The downward trend in $L_{A\text{eq}}$ with distance is not as strong as those obtained in the unoccupied condition as shown in the $L_{A\text{eq}}$ column in **Table 4.1**. $L_{Z\text{eq-1min}} - L_{A\text{eq-1min}}$ was further calculated to be equivalent in the receiving rooms (rooms 2−4) for the sound-source group, which was larger than that in the source room (room 1), thereby indicating that the acoustic environment in the receiving rooms was dominated by low frequencies. For the psychoacoustic parameters, the loudness in room 1 and room 5 was highest for each group. The sharpness represents the amount of high-frequency components in a sound, and it is observed that the value of sharpness in the source room (room 1) was highest among the investigated rooms for the sound-source group and equivalent for the no-sound-source group. **Figure 4.5** shows the spectrograms in the occupied condition for both the sound-source and no-sound-source groups, demonstrating that the sound field is dominated by low and middle frequencies.

Table 4.2 The *in situ* acoustic parameters (i.e., $L_{Z\text{eq-1min}}$ and $L_{A\text{eq-1min}}$) and perceptual parameters (i.e., the loudness and sharpness) for rooms 1–8 for the subjective survey in the occupied condition.

Room	$L_{A\text{eq-1min}}$ [dB(A)]	$L_{Z\text{eq-1min}}$ [dB]	Loudness [sone]	Sharpness [acum]	$L_{Z\text{eq}} - L_{A\text{eq}}$ [-]
1	68.3±2.4	72.9±2.0	24.8±3.6	2.8±0.2	4.6
2	62.5±2.8	70.5±1.6	17.1±2.9	2.3±0.2	8.0
3	58.8±3.0	68.1±1.6	13.1±2.3	2.2±0.8	9.3
4	59.7±3.4	68.0±1.8	13.5±2.7	1.9±0.1	8.3
5	59.1±4.7	71.1±2.8	13.1±3.6	1.9±0.2	12.0
6	56.9±4.8	67.5±2.9	11.3±3.3	1.8±0.1	10.6
7	55.3±5.5	65.9±2.2	10.4±3.4	1.9±0.1	10.6
8	53.8±5.7	67.5±2.5	9.6±3.6	1.9±0.2	13.7

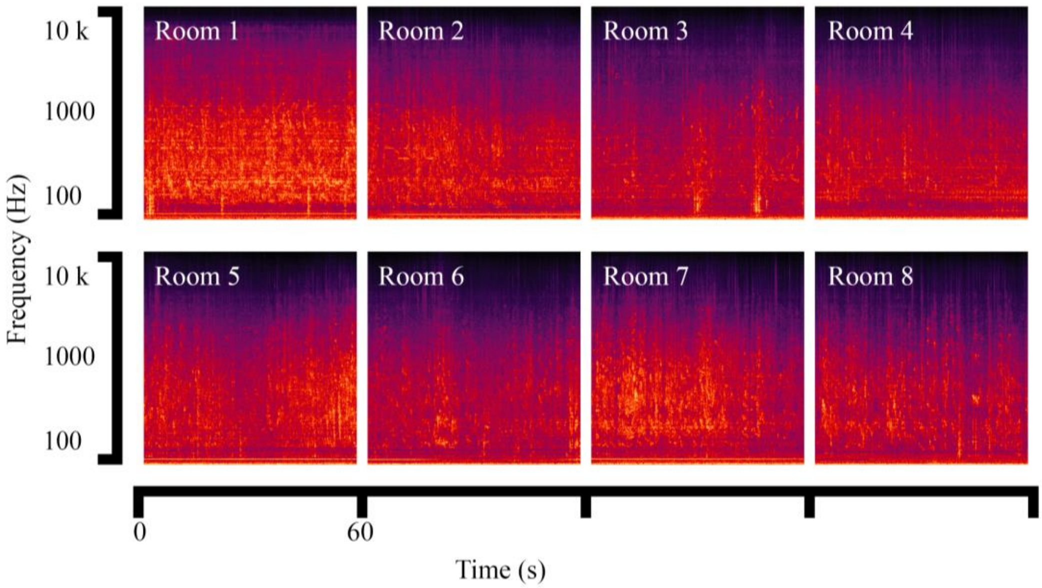


Figure 4.5 The spectrograms in the occupied condition for the sound-source (first row) and no-sound-source (second row) groups.

It is worthwhile to note that the measured $L_{Aeq\text{-}1min}$ for the source room (room 1) was kept low with “Babel, 2001” and did not exceed 70.0 dB(A) in the occupied condition, as shown in **Table** . Meanwhile, $L_{Aeq\text{-}1min}$ for the far receiving rooms (rooms 3 and 4) was approximately 60.0 dB(A) functioning as normal museum/exhibition spaces in occupied conditions, as shown in **Table** . Therefore, the motivation and assumption of this chapter was fulfilled under the condition that the source or receiving rooms that are close to the primary source are auditorily comfortable, whereas the receiving rooms far from the primary source were quiet, but the primary sound source could be distinguished.

4.2.3 Perceptual Attribute

The subjective data were collected using questionnaires based on assessments for each individual room (i.e., four sheets with the room number arranged sequentially for the participant to complete one experiment) involving 12 perceptual attributes extracted from the studies of room acoustics and soundscape, along with the soundwalks in the occupied condition.

For room acoustics, five independent subjective dimensions were proposed for assessing the spaces for listening and performing purpose including clarity, reverberant response, impression of space, intimacy, and loudness, as suggested by Hawkes and Douglas (1971). Eight perceptual attributes, namely, the loudness, “clarity,” reverberation, “spaciousness,” “listener envelopment,” “intimacy,” “warmth,” and “stage support,” frequently used for music and voice content, as defined by Beranek (1996), were considered. For indoor soundscape, Kang (2006b) categorized four factors, namely relaxation, communication, spatiality, and dynamics, by strengthening their necessities to investigate listener responses. Because the site functioned as a museum/exhibition space, the annoyance and directionality were chosen to describe the specific context of affective quality and acoustic spatiality of the built environments. In addition, previous studies chose the acoustic comfort and overall impression as important attributes (Zhang and Kang, 2007, Kang and Zhang, 2010) and were considered for the evaluation of the general indoor soundscape.

The questionnaire comprised 12 questions: (1) How loud is it? (2) How could individual notes be clearly distinguished from another? (3) How do you feel reverberant in the sound environment? (4) How do you feel spaciousness in the sound environment? (5) Are you immersed in the sound environment? (6) Are you intimate with the sound environment? (7) Are you cozy with the sound environment? (8) Can you clearly hear yourself and other sound? (9) Are you comfortable with the sound environment? (10) Can you identify the direction of the sound? (11) Are you annoyed with the sound? (12) Are you satisfied with the whole sound environment? Each question was related to each perceptual attribute listed above. As suggested by ISO/DIS 12913-2 (International Organization for Standardization, 2018), five-point unipolar continuous category scales were used: (1) “not at all,” (2) “slightly,” (3) “moderately,” (4) “very,” and (5) “extremely,” and verbal labelling was provided below each scale.

4.2.4 *In situ* Subjective Survey

The *in situ* subjective surveys were conducted in January 2019 under ethical approval from the UCL (see Appendix A). Additionally, the administration at the Tate Modern supported the field experiments under the condition that there was no disturbance to the art gallery. Therefore, all of the participants were randomly approached and asked for consent in the concourse during their departure, rather than inside the art gallery. They were visitors to the exhibition who had completed their visitations to the investigated spaces. Consequently, it was observed that after understanding the experimental content in the listening area, the participant did not focus on the exhibits during the experiment, which they were assumed to have done previously.

The procedures of the soundwalk were carefully explained to the participants, with the detailed instructions provided. They were required to voluntarily walk along a prescribed path and rate the marked positions at the centre of a room. Moreover, participants were accompanied by the researcher until the experiment ended, and the researcher recorded their instant exposures to the acoustic environments simultaneously for approximately 1 min at the designated spots in the rooms using the binaural recording and analysis kit SQobold (HEAD acoustics, Herzogenrath, Germany).

The direction of the path for each participant was clarified before the experiment. All of the participants of the no-sound-source group moved from rooms 5 to 8, whereas those of the sound-source group were further subdivided into approaching-sound-source and receding-sound-source groups, which moved either toward (rooms 4 to 1) or away from the primary source (rooms 1 to 4), respectively. Therefore, a total of three sets of data were collected, each comprising 36 different participants between the ages of 18 and 60 years. This meets the sample criterion of normal distribution, which states that a sample size should be larger than 30. Overall, 108 subjects each completed four questionnaires for four rooms, resulting in 432 valid questionnaires.

4.3 RESULTS

4.3.1 Effect of Noise as a Stationary Primary Source

As shown in the floor plan in **Figure 4.1**, the differences in room dimension between rooms 2–4 and rooms 6–8 were very small, and therefore, the two sites were comparable. The visitors were able to go through the exhibition spaces by taking the route either from rooms 4 to 1 for the sound-source group or from rooms 5 to 8 for the no-sound-source group. To examine the effect of the primary sound source "Babel, 2001" on the investigated perceptual attributes, a comparison between the results of the approaching-sound-source group (rooms 4–2) and no-sound-source group (rooms 6–8) was undertaken.

According to the MANOVA results between the two groups, the differences in the mean rating in a room were statistically significant only for the loudness and spaciousness ($p < 0.01$), and reverberation ($p < 0.05$). This indicates that the effect of the primary noise source was larger for the listener perception on acoustic spatiality compared to that on room-acoustic quality, annoyance, and affective quality, as discussed in dynamic content in large-scale public buildings. **Figure 4.6a, b, and c** show the mean ratings in a room for the loudness, reverberation, and spaciousness, respectively. Compared to the no-sound-source group, the mean ratings of the approaching-sound-source group were higher in each room for the loudness. For the reverberation, the mean ratings of the approaching-sound-source group were 20% higher in room 2, whereas the values in rooms 4 and 3 were equivalent to those in rooms 6, 7, and 8. For the spaciousness, the mean ratings did not show any clear patterns for either group (e.g., correlation with the source-receiver distance).

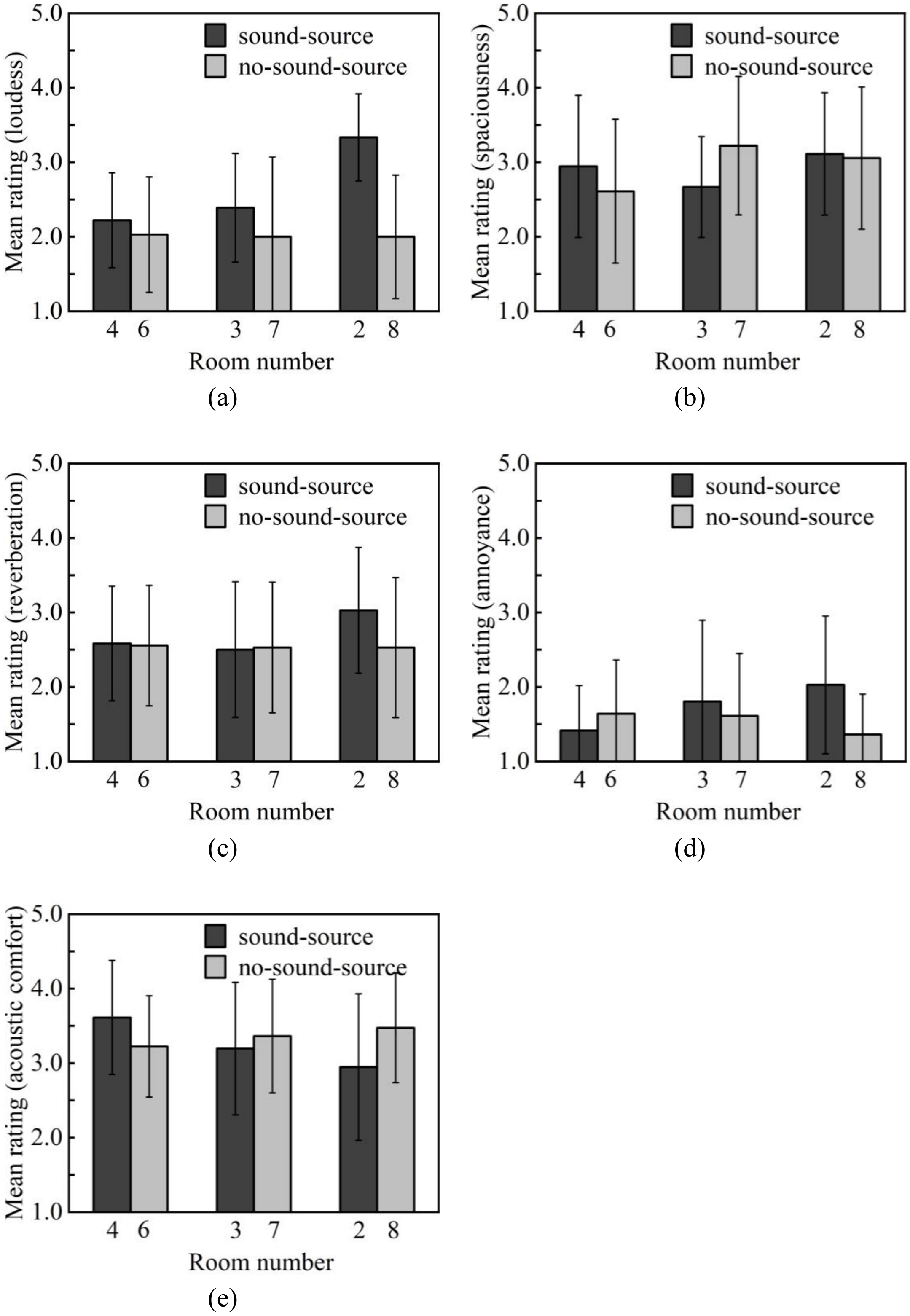


Figure 4.6 The mean rating in a room of the approaching-sound-source and no-sound-source groups for the (a) loudness; (b) reverberation; (c) spaciousness; (d) annoyance; and (e) acoustic comfort.

Furthermore, according to the ANOVA tests (p) within each group, a significant difference ($p = 0.021$) was observed for the spaciousness of the no-sound-source group. However, significant differences were only observed in the evaluation for the loudness ($p = 0.000$), annoyance ($p = 0.000$), and acoustic comfort ($p = 0.006$) of the approaching-sound-source group, thereby indicating that the effect of the primary noise source between the connected rooms (rooms 4–2) was more distinguishable for the listener perception on annoyance and affective quality compared to that for room-acoustic quality and acoustic spatiality. **Figure 4.6a, d and e** show the mean rating for the loudness, annoyance, and acoustic comfort, respectively. The values of these three perceptual attributes of the approaching-sound-source group were between 2.2–3.3, 1.4–2.0, and 3.6–2.9, respectively, with the largest increment of 30%.

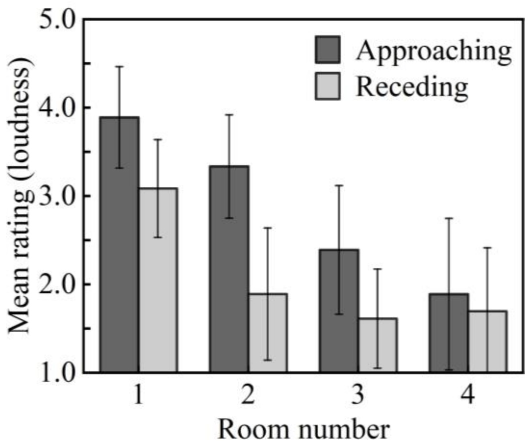
It is worthwhile to note that methodologically, a listener in motion is demonstrated to perceive changes in three perceptual attributes (i.e., the **loudness**, **reverberation**, and **spaciousness**) in the presence of a stationary primary noise source, while the remaining nine perceptual attributes (e.g., the warmth and intimacy, as well as the annoyance and acoustic comfort) are not demonstrated to be effective in noise assessments, at least with $L_{A\text{eq-1min}}$ in a room between 63.0–60.0 dB(A) and 57.0–54.0 dB(A). However, although the difference in room dimension between the rooms was small, a gradual rise in sound level for a listener in motion resulted in the dynamic perception differences in the **loudness**, **annoyance**, and **acoustic comfort** owing to the attenuation of the primary noise source in the receiving rooms, at least with $L_{A\text{eq-1min}}$ in a room attenuating from 63.0 dB(A) to 60.0 dB(A).

4.3.2 Effects of the Approaching and Receding Noise Sources

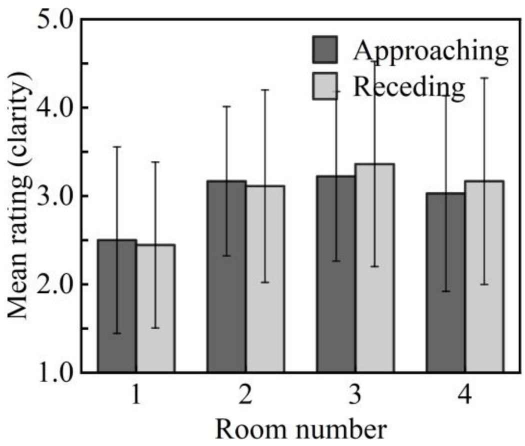
To explore the perception characteristic of approaching or receding noise sources, ANOVA tests (p) were separately conducted within the approaching-sound-source or receding-sound-source groups. According to the results of the approaching-sound-source group, as shown in **Table 4.3**, the differences for the loudness, clarity, reverberation, spaciousness, listener envelopment, intimacy, and annoyance were statistically significant ($p < 0.01$). However, for the receding-sound-source group, statistically significant differences ($p < 0.01$) were only observed for the loudness, clarity, and listener envelopment. This indicates that the perceptual difference between the rooms in the reverberation and spaciousness and intimacy and annoyance greatly decreased as the listener was receding from the noise sources. **Figure 4.7** shows the mean ratings in a room of the loudness, clarity, reverberation, spaciousness, listener envelopment, intimacy, and annoyance for the approaching-sound-source and receding-sound-source groups.

Table 4.3 The ANOVA tests (*p*) within the approaching-sound-source group or receding-sound-source group. * $p < 0.05$, ** $p < 0.01$ (two-tailed test of statistical significance).

Perceptual attribute	Approaching-sound-source	Receding-sound-source
Loudness	0.000**	0.000**
Clarity	0.009**	0.005**
Reverberation	0.005**	**0.916**
Spaciousness	0.013*	**0.206**
Listener envelopment	0.000**	0.000**
Intimacy	0.007**	**0.366**
Warmth	**0.646**	**0.467**
Stage support	0.000**	0.000**
Acoustic comfort	0.011*	**0.730**
Directionality	**0.528**	**0.118**
Annoyance	0.001**	0.043*
Overall impression	**0.087**	**0.098**



(a)



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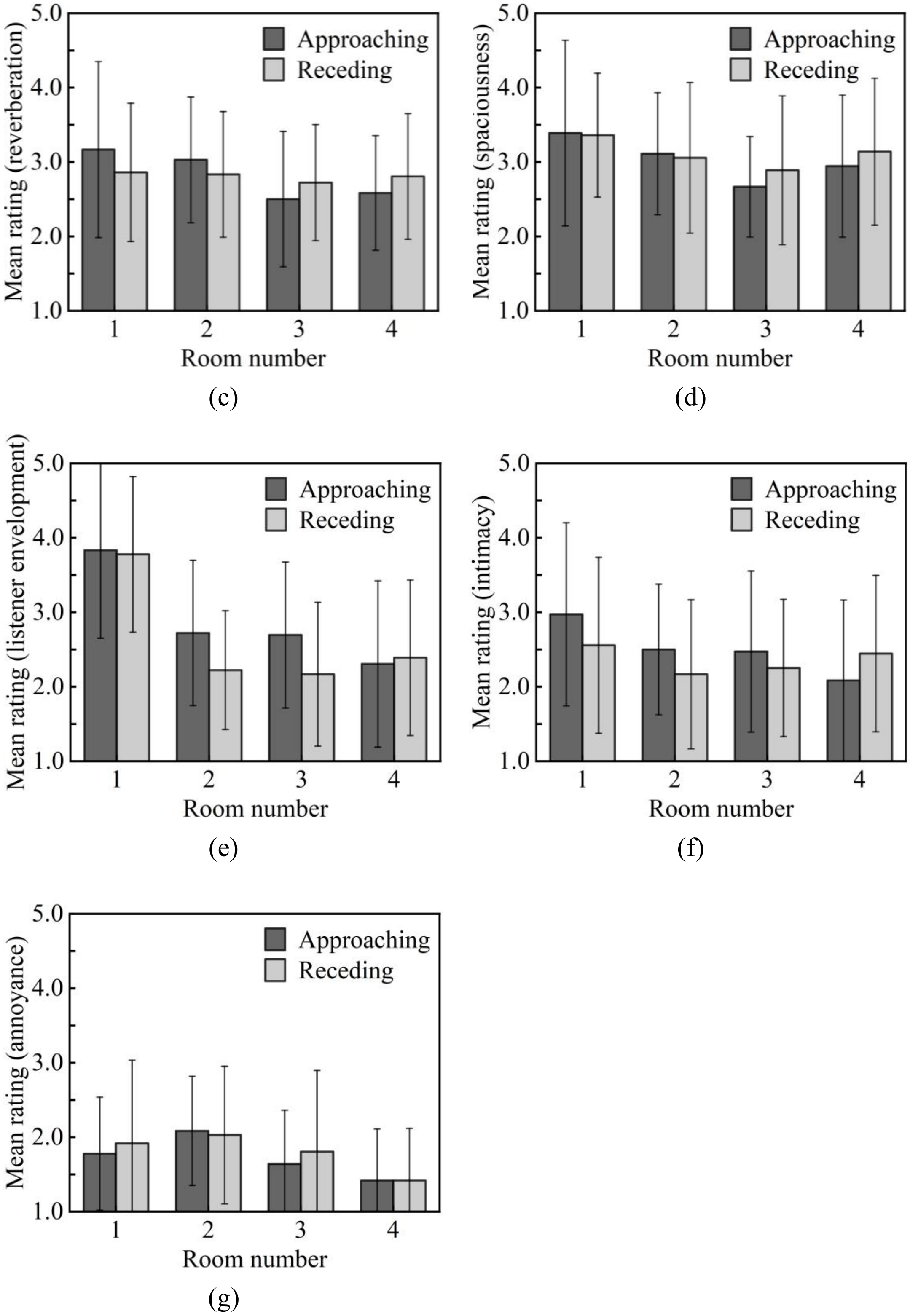


Figure 4.7 The mean rating in a room for the approaching-sound-source and receding-sound-source groups for the (a) loudness; (b) clarity; (c) reverberation; (d) spaciousness; (e) listener envelopment; (f) intimacy; and (g) annoyance.

It is worthwhile to note that the **warmth**, which comes from concert hall acoustics, for the approaching-sound-source and receding-sound-source groups is not demonstrated to be effective for noise assessment at least in museum/exhibition spaces. However, the **directionality** and **overall impression** can also be inappropriate, as they come from soundscape, at least with $L_{A\text{eq-1min}}$ in a room from 69.0 dB(A) to 60.0 dB(A).

Furthermore, the perception difference between approaching and receding sound sources was explored, as shown in **Table 4.4**. According to independent *t*-tests (*p*) between the approaching-sound-source and receding-sound-source group, the differences for the loudness were statistically significant ($p < 0.01$) in all of the rooms. In addition, significant differences were observed for the listener envelopment in room 2 ($p = 0.020$) and room 3 ($p = 0.023$). The asymmetry of the directional aspects of approaching and receding sound sources were demonstrated by the loudness and listener envelopment using broadband noise. As shown in **Figure 4.7**, the loudness proved to be stronger in all of the rooms with the highest mean rating difference at 1.5 in the first receiving room (room 2), whereas the listener envelopment was stronger in the middle portion of the spaces with an equivalent difference at 0.5 in the first receiving room (room 2) and second receiving room (room 3), when a listener approached the noise sources.

Table 4.4 The independent *t*-tests (*t* and *p*) between the approaching-sound-source and receding-sound-source groups. * $p < 0.05$, ** $p < 0.01$ (two-tailed test of statistical significance).

Perceptual attribute		Room 1	Room 2	Room 3	Room 4
Loudness	*t*	6.054	9.127	4.950	3.319
	p	**0.000****	**0.000****	**0.000****	**0.001****
Clarity	*t*	0.236	0.242	−0.524	−0.498
	p	0.814	0.810	0.602	0.620
Reverberation	*t*	1.218	0.976	−1.092	−1.134
	p	0.228	0.332	0.279	0.261
Spaciousness	*t*	0.111	0.256	−1.144	−0.848
	p	0.912	0.799	0.257	0.399
Listener envelopment	*t*	0.211	2.384	2.330	−0.322
	p	0.833	**0.020***	**0.023***	0.748
Intimacy	*t*	1.465	1.503	0.945	−1.455
	p	0.147	0.137	0.348	0.150
Warmth	*t*	1.329	−0.356	0.202	0.673
	p	0.188	0.723	0.841	0.503
Stage support	*t*	−1.190	−1.769	−1.651	0.516
	p	0.238	0.081	0.103	0.607
Acoustic comfort	*t*	−0.820	−0.964	0.629	1.311
	p	0.415	0.338	0.532	0.194
Directionality	*t*	0.817	−0.405	−0.180	0.289
	p	0.417	0.687	0.858	0.773
Annoyance	*t*	−0.704	0.243	−0.805	0.000
	p	0.484	0.809	0.424	1.000
Overall impression	*t*	0.127	−0.379	0.152	−0.404
	p	0.899	0.706	0.880	0.687

4.4 DISCUSSION

4.4.1 Perceptual Attribute of Noise—the Asymmetry of the Loudness and Listener Envelopment

The loudness, which is the most basic perceptual attribute, indicates the perception of the volume of a sound source related to the middle frequency content (Howard et al., 2009). Neuhoff (1998) pointed out that naturally occurring continuous broadband noise can be attributed to multiple sound sources (e.g., crowd noise), which is less common, and the perceived asymmetry of a rising or falling sound level occurred with harmonic sounds but not with broadband noise in listening tests. Considering the fact that “Babel, 2001" was noise comprising mixes of music and voice, this chapter demonstrates that the asymmetry of the directional aspects also occurs with broadband noise for the loudness when background noise and reverberations are present, but not in a quiet environment.

The dynamic localization of noise can be more significant in an indoor environment compared to a natural environment owing to the crucial issues in the organization of traffic flows concerning people's perception toward approaching or receding from a large crowd common in large-scale public spaces. This is also akin to the "cocktail party" effect, wherein a group of people gathering in one space are considered as multiple sound sources. As people approach the crowd, they might overestimate the crowd (e.g., the number of people) by perceiving an increasing sound level. The overestimation would be the largest in the receiving room connected to the source room rather than in the source room as shown in **Figure 4.7a.**

On the other hand, the listener envelopment is defined as a sense of immersion concerning the diffusion of space (Howard et al., 2009). The results of the listener envelopment suggest that there could be two very different immersive experiences for noise perception emerging on the same path. Once the direction of traffic flow inside the sequential spaces is confirmed, it becomes necessary for the designer to pay attention to this perception difference. Furthermore, it is also reasonable to believe that the perceptual priority of a rising sound level could be exaggerated in VE.

4.4.2 Limitations and Future Work

As the baseline condition of sequential spaces, all of the openings of the case sites were identical and located at the same position in the separating partition. Whether a non-uniform opening along the direction of sound attenuation would lead to different results is not known. However, answering such a question could be very difficult and time consuming in RE. Therefore, the research has inspired the idea of a validation of sequential spaces in VE. Additionally, the subjective survey obtained binaural recordings of the participants, which will be explored. Future work could investigate the situations in which the primary sound source is not noise, e.g., speech that is understandable. The effect of different sound source type in determining which source type has the highest perceptual priority of a rising sound could potentially be studied. Moreover, the masking effect of background sound on the highly affected perceptual attributes could be explored.

4.5 CONCLUSIONS

This chapter explored the dynamic auditory perception of noise as a stationary primary source for a listener in motion in sequential spaces by investigating typical exhibition spaces with a noise-like sound source at an acceptable volume in real-world scenarios. Based on the subjective evaluation, 12 perceptual attributes of room acoustics and soundscape were employed with soundwalks. Further to the earlier work in perceived asymmetry of a rising or falling sound level with harmonic sounds (Neuhoff, 1998), it is concluded that

- $L_{A\text{eq-1min}}$ in the source room was approximately 70.0 dB(A). The primary noise source changed the loudness, spaciousness and reverberation in at least three receiving rooms with individual volumes of approximately 200 m^3 (600 m^3 in total). The differences in the loudness, annoyance, and acoustic comfort between the rooms were attributed to noise attenuation. Both the loudness and reverberation decreases with increasing source distance;
- the differences in the reverberation, spaciousness, intimacy, and annoyance between the rooms significantly decreased for receding from the sound sources compared to approaching sound sources. The warmth, directionality and overall impression were not effective in noise assessments, at least with $L_{A\text{eq-1min}}$ attenuating from 69.0 dB(A) to 60.0 dB(A); and
- the loudness and listener envelopment in the same room showed disparity between the approaching and receding sound sources. The loudness was larger for the approaching sound sources in all of the rooms, and the listener envelopment was only larger for the middle portion of the sequential spaces.

5 Practice Influence on Performance of Sound Attenuation

To separate into individual rooms, sequential spaces use partitions with openings in identical constructions, whose condition changes with the needs of users. As discussed in **Section 2.1**, a decrease in the SPL with distance involves propagation methods of sound diffraction and insulation. Coupled room theories adjust the room volume by connecting more rooms or dividing more rooms, the source position and room absorption in the application of performing spaces. This chapter presents such strategies in spaces more common in our life, e.g., educational spaces, to explore either consistency or inconsistency in sound attenuation with distance from the source when different strategies are adopted in practice.

5.1 INTRODUCTION

Normally, there is a certain difference in performance of sound insulation between an *in situ* and laboratory separating partition because we cannot build perfect buildings. Flanking should be taken into account, or the element tested in a laboratory could have a much different surface area to the actual element. The same construction measured in a laboratory obtains the same result every time but varies from room to room and project to project when measured *in situ*. However, reports on combining direct and flanking transmissions through a number of separating partitions, i.e., sound attenuation of a stationary source in sequential spaces, are difficult to be find.

Regarding a long distance from a source, long space theory shows that the SPL decreases continuously with increasing source distance; additionally, the RT increases with increasing source distance, and the shape of decay curves is not linear, namely, the SPL does not reduce linearly with increasing time (Kang, 2002). Without separating partitions, the form of sequential spaces is similar to that of long spaces. However, the dominant and obvious path is to propagate directly through separating partitions although sound also transmits through the floor and façade, which involves the sphere of sound diffraction and insulation concerning the wavelength of the sound source and opening dimension. Regarding the separating partition between rooms, researchers have conducted measurements in two coupled rooms that lack diffuseness. The SPLs were demonstrated to have small differences in a room but complicated distribution around the opening, which indicates that the opening area in a separating partition is decisive to the acoustic coupling (Harris and Feshbach, 1950). Recently, the blocked pressure and surface impedance of separating partitions have gained interest as measures to predict sound attenuation and reverberation of such spaces (Du and Pavic, 2019). Classical statistical energy analysis theory is common and efficient for predicting the high-frequency noise and vibration of engineering systems. Examples of applications to sequential spaces can be found in train coaches (Sadri et al., 2016, Forssen et al., 2012). Therefore, there are reasons to believe that sound fields in sequential spaces comprise many coupled spaces that exhibit individual acoustic characteristics, which are imposed by their individual distance from the source and opening dimensions.

In situ sound insulation of a separating partition (i.e., the noise level in a source room minus the noise level in a receiver room) usually termed D_w, is considered a performance standard that can be physically measured after completion of construction. The value demonstrates compliance with building regulations, e.g., for schools in the United Kingdom (Great Britain Department for Education, 2015), depending on the sound insulation capabilities of a particular wall, ceiling, or component, which can be measured in a laboratory and assigned a sound reduction index of a single element termed R_w (International Organization for Standardization, 2021). A laboratory test measures the wall performance in isolation from any other sound flanking paths. In the case of an infinitely high mass surrounding constructions with no flanking, it is theoretically not possible to achieve the same D_w and R_w. If a wall is only built to the underside of a ceiling and not to the slab, a significant flanking path exists around the wall.

For spaces that are not uncommon in our lives, the open or closed condition of an opening, e.g., a window or door, could be frequently changed by users when such an element is attached to a separating partition, which could potentially lead to a totally different outcome across the space. This is also akin to a well-developed strategy in coupled room studies adjusting the room volume in application of performing spaces. Furthermore, the source position in use is not fixed. It is also noted that for the measurements of field-airborne sound insulation, the major modes in the source room must be excited by more than one source position near the corner of box-shaped rooms (Hopkins, 2007). Additionally, acoustic absorption varies when the boundary conditions change, e.g., external sources are introduced, or sound passes through an opening to external free spaces. There are also possibilities in practice, i.e., different numbers of separating partitions are used to divide the entire space, or the shape of the room is changed, concerning the individual room volume of the spaces. Studies in spaces such as churches have achieved outstanding *in situ* outcomes to examine the prediction accuracy in computational simulations (Gül, 2021), and moreover, the scope of these studies can be extended when the conditional applications discussed above are studied and deemed feasible from an operational point of view.

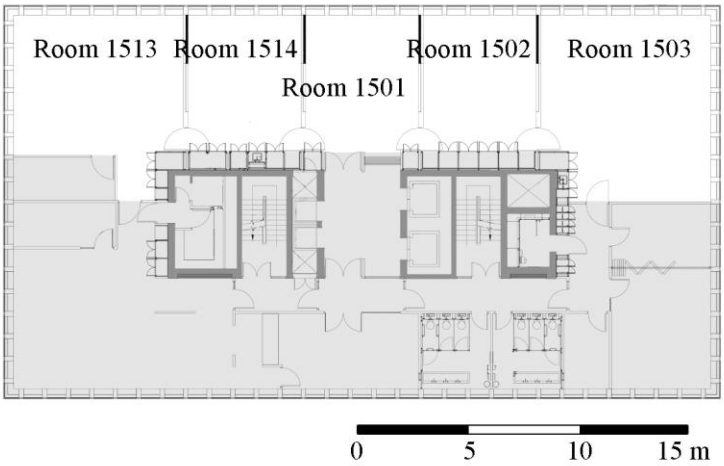
The overarching goal is to examine the *in situ* performance of sound attenuation and reverberation with distance from the source in sequential spaces by exploring the potential effect of four factors that could be commonly adjusted in accordance with the functional space, i.e., the connected room volume, individual room volume, source position, and acoustic absorption. A total of nine *in situ* measurements were taken in three case sites to shed some light on the conditional environment to assist clients and design teams.

5.2 METHODS

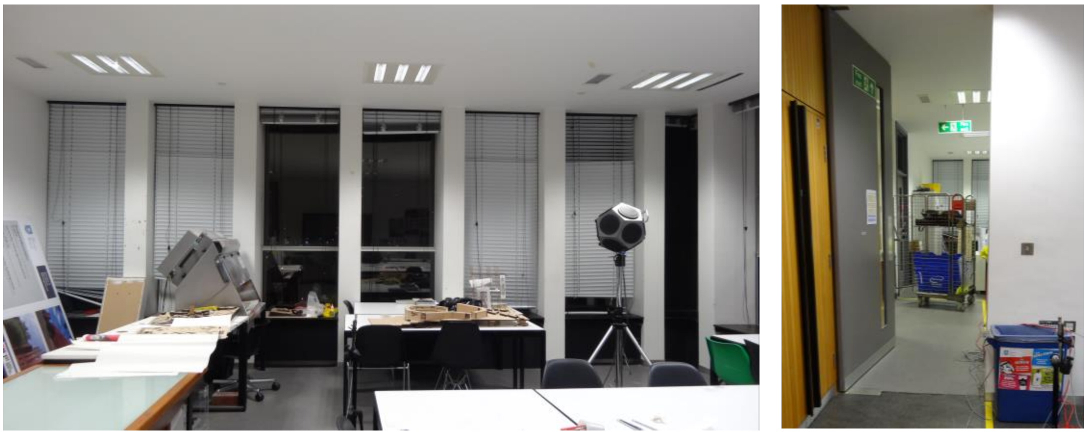
5.2.1 Site Selection

Three sites were selected to explore the discussed research questions. Note that all of the sites functioned as educational buildings. The length and width of an individual room were found to be similar, but not the height. Detailed configurations of each experiment are presented with measured results in **Section 5.3**, illustrated by the experimental setups (**Figure 5.6**, **5.9**, **5.11**, and **5.15**).

Site 1: The selected site was the fifteenth floor of the Arts Tower of the University of Sheffield, built in the 1960s by architects Gollins, Melvin, Ward, and Partners as a high-rise university tower block. It was used as an open plan space by students, while the other floors of the building were separated into individual staff offices. The layout of site 1 is presented in **Figure 5.1**a. The investigated space consisted of five box-shaped rooms with two room volumes, e.g., rooms 1513 and 1503 were the two larger rooms in the corners (6.5 m × 7.5 m × 3.9 m); rooms 1514, 1501, and 1502 were the three smaller ones in the middle (6.5 m × 5.0 m × 3.9 m). The widths and heights of the openings, with a heavy wooden door, were 1.0 m and 3.9 m, respectively, as shown in **Figure 5.1**b.



(a)

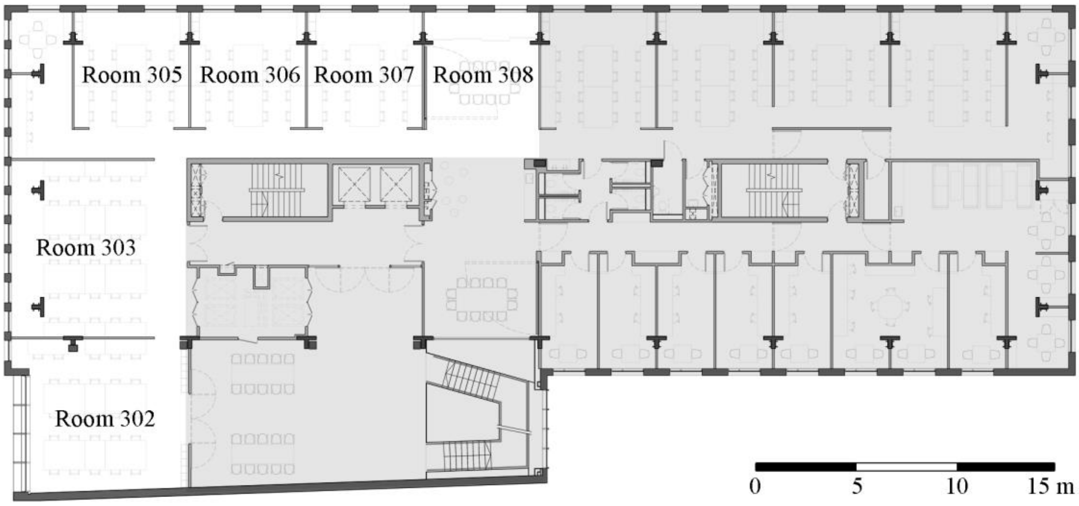


(b)

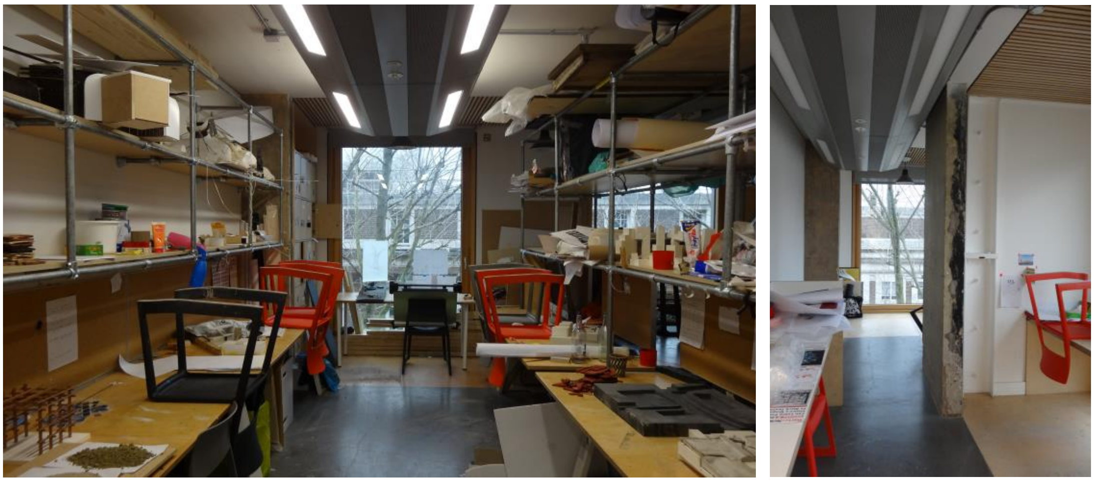
Figure 5.1 The site 1 configuration: (a) floor plan and (b) site photo.

The floor slab of the investigated space used reinforced concrete structure. The non-load-bearing separating partitions and ceilings were made of smooth plaster with lightweight constructions. The façade used sliding windows installed on glazed curtain walls of both glass and lightweight panelling for safety in high-rise buildings. As shown in **Figure 5.1b**, different numbers of tables, chairs, cabinets, and other furniture were randomly arranged in a room.

Site 2: The third floor of 22 Gordon Street of the Bartlett School of Architecture, UCL, known as Wates House, rebuilt in 2016 by Hawkins\Brown, is a representative design for educational buildings. The layout of site 1 is presented in **Figure 5.2a**. The space investigated at site 2 comprised six box-shaped spaces with two room volumes. Rooms 302 and 303 were the two larger rooms (9.0 m × 9.0 m × 2.7 m), while rooms 305, 306, 307, and 308 were smaller (6.0 m × 7.5 m × 2.7 m). The openings for walkways were 1.5 m in width and 2.7 m in height.



(a)

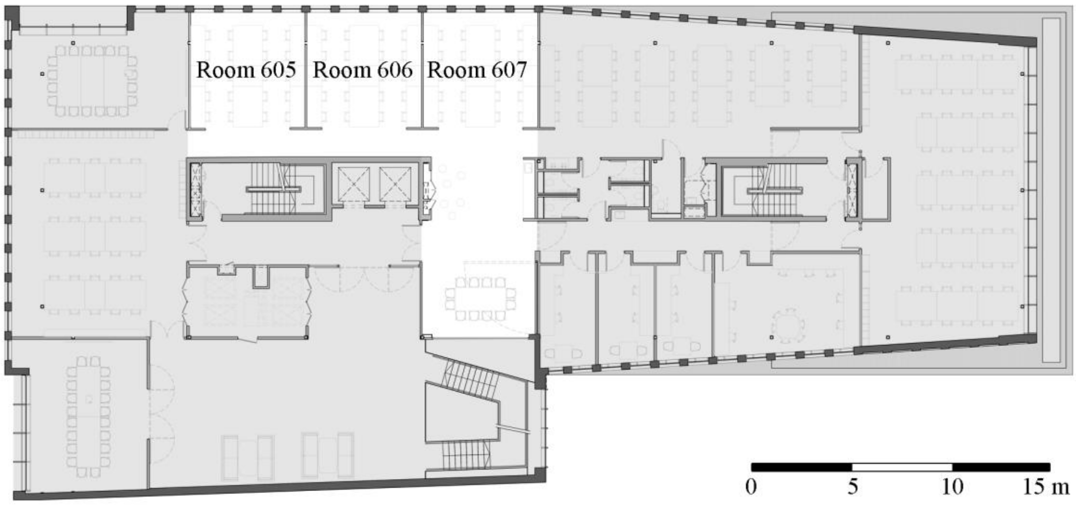


(b)

Figure 5.2 The site 2 configuration: (a) floor plan and (b) site photo.

Figure 5.2b shows that the interior finishes in a room were consistent and featured the same furniture. The floor slab of the investigated space used a reinforced concrete structure. The non-load-bearing separating partitions and ceilings were made of smooth plaster with lightweight constructions. The façade of the space used hopper windows with small opening angles.

Site 3: The sixth floor of the same building as site 2 was selected. The investigated space comprised three rectangular rooms with a slope roof. Rooms 605, 606, and 607 were similar to rooms 306, 307, and 308 at site 2, and the roof direction was perpendicular to the sound attenuation. The interior finishes and constructions were the same as those at site 2 as shown in **Figure 5.3**.



(a)

(b)

Figure 5.3 The site 3 configuration: (a) floor plan and (b) site photo. © UCL

5.2.2 Experimental Setups

To assess the effect of four factors, a total of nine *in situ* measurements were conducted across the three sites. The results were analysed using four comparative studies. **Table 5.1** tabulates the experimental details, including the sites, source positions, connected volumes, and boundary conditions and **Figure 5.4** shows the configuration of the experiments at each site; these have also been detailed with the results in **Section 5.3**. The experimental conditions and procedures of the four studies are summarized as follows.

- Study a (connected room volume): an open or shut door in the separating partitions at site 1;

- Study b (individual room volume): an equivalent room volume was divided by different numbers of separating partitions in the same construction at sites 2 and 3.
- Study c (source position): source position A was far from an opening in the corner; source position B was located along the openings; source position C was placed at the side corner near an opening; all of these were placed in the same source room at site 1;
- Study d (acoustic absorption): an open/shut façade windows in some receiving rooms at site 2.

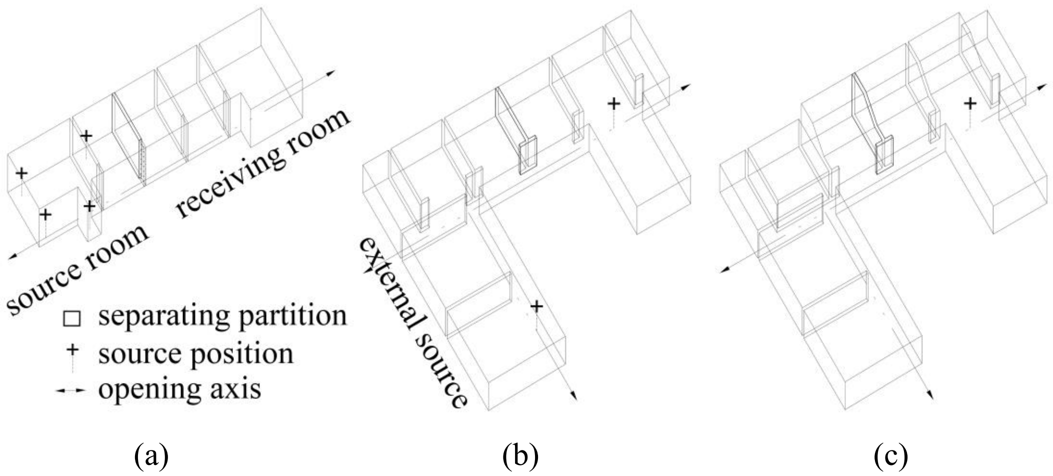


Figure 5.4 The experimental configurations at the three sites. (a) site 1; (b) site 2; and (c) site 3.

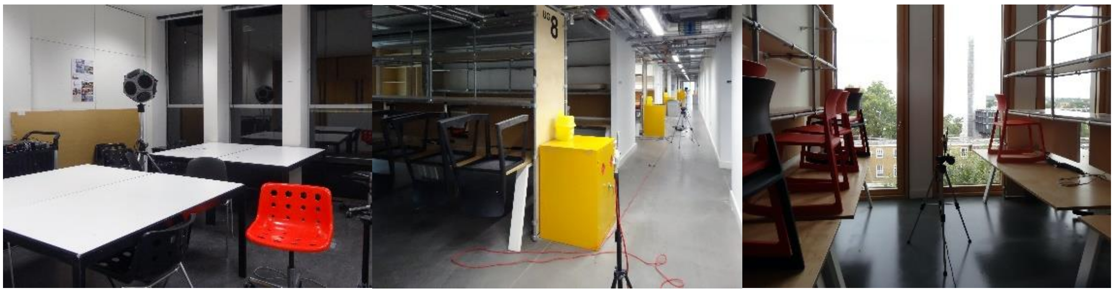
Table 5.1 The experimental details of Measurements 1–9, including the site, source position, connected volume, and boundary condition of Studies a–d.

Study	Measurement	Site	Source position	Connected volume	Window
a	1	1	1514 (A)	1514+1501+1502	Closed
	2			All	
	7				
b	6	2	308	All	Closed
	8		302		
	9	3	607		
c	3	1	1513 (A)	All	Closed
	4		1513 (B)		
	5		1513 (C)		
d	6	2	308	All	Closed
	7				303+302 open

5.2.3 Measurement Technique

In situ measurements for the three sites were completed in July and August 2019, during summer break of the schools in unoccupied conditions, and the interiors of each room were consistent and regularly cleaned.

For each measurement, a single sound source and a certain number of receivers (one in a room) across the rooms were simultaneously involved as shown in **Figure 5.5**. A total of eight measuring positions (microphone locations) arranged diagonally along the room and running along the openings were the same in each investigated room as shown in the experimental plans in **Figure 5.6**, **5.9**, **5.11**, and **5.15**. In the source room, the test signal was generated by a signal generator Minirator MR-PRO (Nti Audio, Schaaen, Switzerland), amplified by a power amplifier (Inter M Co., Gyeonggi-do, Korea), and fed into an omni-directional dodecahedron loudspeaker mounted at a height of 1.5 m above the floor. On the other hand, one calibrated measured omnidirectional microphone (01dB type-1, Limonest, France) connected to an audio recorder MixPre-10 II (Sound Device, Reedsburg, United States) was set at the same measuring position in each investigated receiving room so that the measurement could cover the entire site simultaneously rather than locally, i.e., a total of five, six, and three receivers for sites 1, 2, and 3, respectively, on tripods at the height of 1.2 m above the floor in accordance with (International Organization for Standardization, 2021), which is normal for concert halls, considering that the investigated rooms usually functioned with subjects sitting for educational purposes; Furthermore, the difference between the results obtained through the tripod height of 1.6 m, i.e., when subjects stand in the space, and 1.2 m was considered to be limited.



(a) (b) (c)

Figure 5.5 The measurement photos. (a) site 1; (b) site 2; and (c) site 3.

The measure for the measurements is SPL to obtain comparable sound attenuations and reverberations. Additionally, the “relative average SPL in a room” and “level difference between rooms" are the two main acoustical parameters used to quantify the performance of an element in this study. The relative average SPL refers to the calculated value in a target room, which is the average SPL in the target room minus the average SPL in the source room, as it was the highest value across the space and therefore normally started from 0.0 dB. The level difference between rooms is a calculated value, which is the average SPL in the source or receiving room minus the average SPL in another receiving room.

RT was measured in all spaces in accordance with the requirements of Standard ISO 3382 for the engineering level of accuracy (International Organization for Standardization, 2012, International Organization for Standardization, 2009). It means that sound sources, sound receivers, their locations, as well as the number of measurements were selected in accordance with the recommendations of Standard ISO 3382. Interrupted stationary pink noise was generated and stopped abruptly to obtain calibrated impulse responses. The recorded files by omnidirectional microphones (01dB type-1, Limonest, France) were analyzed using ArtemiS SUITE (HEAD acoustics, Herzogenrath, Germany). The measure of T_{20} was used rather than T_{30} because the maximum sound level for the most remote location from the source could not have been greater than or equal to 35.0 dB more than the background noise level. RT is usually calculated at 125–2000 Hz. For speech, the 500–1000 Hz range is taken as a reference. Since all of the selected sites functioned as educational buildings, to better characterize RT with a single value of T instead of six octave band values, T_{m} at middle frequencies was used as follows:

$$T_{\mathrm{m}}=\frac{T_{500\mathrm{Hz}}+T_{1000\mathrm{Hz}}}{2} \tag{5.1}$$

where $T_{500\mathrm{Hz}}$ and $T_{1000\mathrm{Hz}}$ are the T at 500 Hz and 1 kHz, respectively.

5.2.4 Statistical Analyses

To assess the difference between the physical measurements, SPSS Statistics 26 (IBM United Kingdom Limited, Portsmouth, UK) and OriginPro 2021 (OriginLab Corporation, Northampton, MA) were utilized to analyse the independent *t*-tests. Values are different in the various room as the physical measurements have a known uncertainty, and thus difference should have been obvious. However, the attempts to use the independent *t*-tests to assess the difference in this chapter is not for the interest of testing uncertainty. It is used to show that for the results obtained in the various room, the situation of each room varies. For example, the *t*-test results reveal that when comparing two physical measurements obtained in the spaces composed of rooms A, B and C, the differences in SPL distribution are statistically significant for room A, but not for rooms B and C. Additionally, the *t*-test results also reveal that even a single value of average SPL in a room can be equivalent for two rooms, the SPL distribution in a room can be different.

5.3 RESULTS

5.3.1 Effect of the Connected Room Volume

To explore the effect of the connected room volume, the experimental setups for Measurements 1 and 2 shown in **Figure 5.6** were used. The doors between rooms (rooms 1514 and 1513; rooms 1502 and 1503) enabled open or shut conditions of rooms 1513 and 1503; that is, rooms 1514–1502 stayed connected for Measurements 1 and 2, while rooms 1513 and 1503 were separately closed for Measurement 2. The source was positioned in room 1514. The connected volume driven by source A increased from at least three to five rooms, i.e., from approximately 360 to 795 m^3 in Measurement 2 compared to that in Measurement 1.

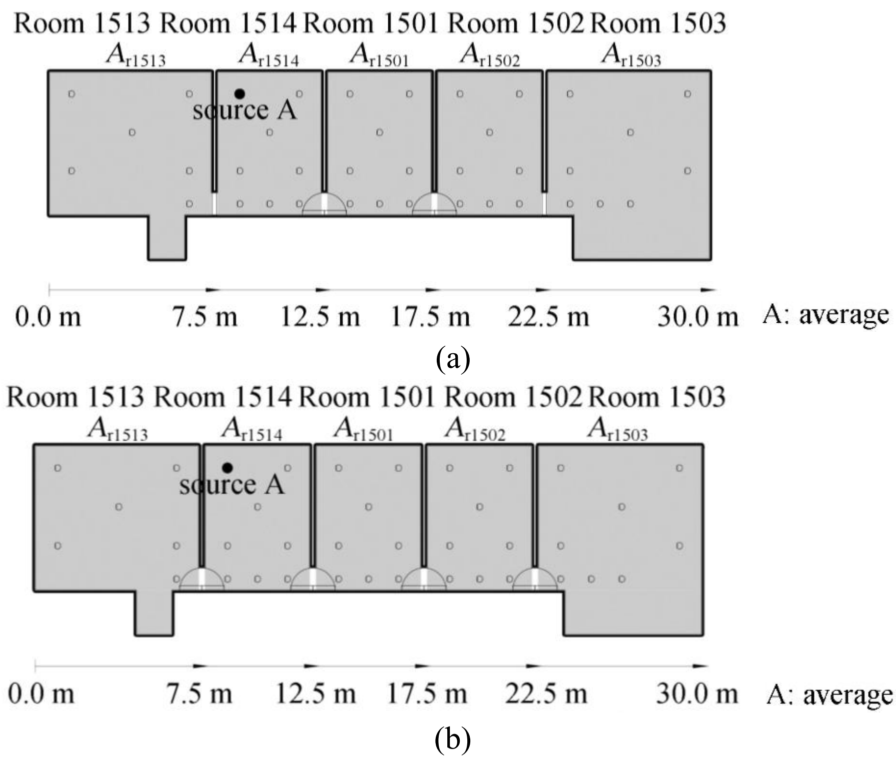


Figure 5.6 The experimental setups for (a) Measurement 1: shut condition of rooms 1513 and 1503 and (b) Measurement 2: open condition of rooms 1513 and 1503.

Figure 5.7 shows the relative average SPL in a room for Measurements 1 and 2. The differences between the two measurements were demonstrated by changes of a single average value of A_{r1513} and A_{r1503} in rooms 1513 and 1503. The results reveal that the difference in the receiving rooms (rooms 1513 and 1503) was much larger compared to those in the source room (room 1514) and receiving room (rooms 1501 and 1502), which is very limited to 1.0 dB. To further explore the effect of the connected room volume on SPL distribution in a room, according to paired *t*-tests (*p*), no significant difference was observed in the source room (room 1514) except at 4 kHz (p = 0.029) between Measurements 1 and 2, as shown in **Table 5.2**. In contrast, SPL distribution in a room was statistically significant ($p < 0.001$) in the two receiving rooms in which the opening condition was changed (rooms 1513 and 1503) except for the third receiving room (room 1503, p = 0.011). Furthermore, no significant differences were observed in the first receiving room (room 1501) and second receiving room (room 1502). Therefore, it is concluded that the effects imposed by the connected room volume were more prevalent in those blocked spaces than in those that stayed connected and at high frequencies.

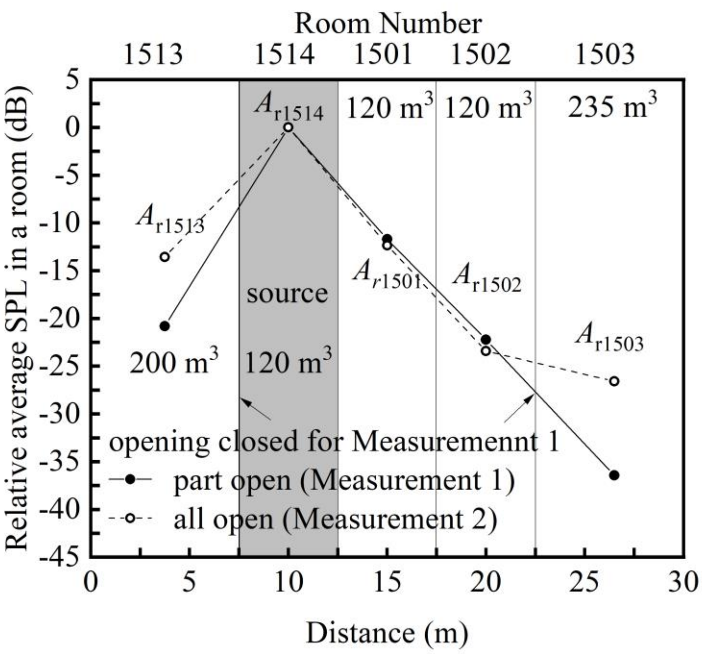


Figure 5.7 The relative average SPL in a room (*A*) for Measurements 1 and 2.

Table 5.2 The paired *t*-test (p) of SPL distribution in a room between Measurements 1 and 2. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ (two-tailed test of statistical significance).

[Hz]	Room 1513 [-]	Room 1514 [-]	Room 1501 [-]	Room 1502 [-]	Room 1503 [-]
125	0.004**	0.882	0.773	0.707	**0.011***
250	0.005**	0.366	0.082	0.070	0.000***
500	0.000***	0.059	0.119	0.181	0.000***
1000	0.001**	0.258	0.087	0.176	0.000***
2000	0.001**	0.093	0.467	0.271	0.000***
4000	0.000***	**0.029***	0.531	0.178	0.001**

5.3.1.1 Level difference between rooms

Table 5.3 shows the level difference between rooms (D) and the differences in D between Measurements 1 and 2 ($\Delta D_{\mathrm{M1,2}}$). The results show that $D_{\mathrm{r1514–1513}}$ decreased by a value of $\Delta D_{\mathrm{M1,2}}$ at 9.4 and 10.5 dB at middle frequencies, i.e., 500 Hz and 1 kHz, respectively, owing to the change in the open or shut condition for the openings. In contrast, $D_{\mathrm{r1502–1503}}$ was larger for Measurement 1 than for Measurement 2 by a value of $\Delta D_{\mathrm{M1,2}}$ at 15.1 dB at 500 Hz and 13.4 dB at 1 kHz. In contrast, $\Delta D_{\mathrm{M1,2}}$ values for $D_{\mathrm{r1514–1513}}$ and $D_{\mathrm{r1502–1503}}$ at low and high frequencies, i.e., 125 Hz and 4 kHz were much closer compared to those of middle frequencies.

Table 5.3 The level difference between rooms (*D*) and the difference in *D* between Measurements 1 and 2 ($\Delta D_{M1,2}$).

[Hz]	Measurement [-]	$D_{r1514–1513}$ [dB]	$D_{r1514–1501}$ [dB]	$D_{r1501–1502}$ [dB]	$D_{r1502–1503}$ [dB]	$D_{r1514–1502}$ [dB]
125	1 (Smaller connected volume)	17.7	13.0	11.3	9.4	24.3
250		22.2	12.7	11.3	16.5	24.0
500		22.6	10.9	11.2	16.7	22.1
1000		23.8	10.8	10.7	16.8	21.5
2000		23.5	10.3	10.6	16.0	20.9
4000		22.7	9.1	10.2	15.8	19.3
125	2 (Larger connected volume)	10.4	12.0	11.4	3.1	23.5
250		**15.7**	**14.3**	**11.8**	5.2	26.1
500		13.2	11.4	12.1	1.6	23.5
1000		13.3	11.0	11.3	3.4	22.3
2000		13.1	10.5	11.4	4.2	21.9
4000		12.4	8.7	11.6	4.6	20.3
125	$\Delta D_{M1,2}$	**7.3**	1.0	–0.1	**6.3**	0.9
250		6.5	–1.6	–0.5	11.3	–2.1
500		**9.4**	–0.5	–0.9	**15.1**	–1.4
1000		**10.5**	–0.2	–0.6	**13.4**	–0.8
2000		10.4	–0.2	–0.8	11.7	–1.0
4000		**10.3**	0.4	–1.4	**11.2**	–1.0

The width of the openings was 1.0 m, and therefore, the effect of diffraction was further explained by the results that $D_{r1514–1513}$ was smaller at low frequencies, i.e., 125 Hz, than at middle and high frequencies for both Measurements 1 and 2. Additionally, it is observed that the value at 250 Hz was greater. For Measurement 2, when the door is all open, $D_{r1514–1513}$ was larger than $D_{r1501–1502}$ for 3.9 dB at 250 Hz, where the values of the middle and high frequencies were equivalent or even smaller, indicating that the decrease in SPL with distance from the source was smaller at low frequencies and greater at high frequencies due to the diffraction, but it is prevalent with a wavelength close to opening dimension imposed by the sequential openings as shown in **Table 5.3**.

As shown in **Table 5.3**, $D_{r1514–1502}$, i.e., the level differences between the rooms that stayed connected for Measurements 1 and 2 (rooms 1514–1502), were 22.1 and 23.5 dB at 500 Hz, 21.5 and 22.3 dB at 1000 Hz, respectively, which generally had a value of $\Delta D_{M1,2}$ under 2.0 dB. Therefore, although the SPL distribution in a room changed in the receiving rooms, the effect of the connected room volume, as connecting larger space volume driven by the source, was again proven to be limited in those rooms that stayed connected and only profound in those that were blocked.

As shown in **Figure 5.6**, the ratio of room volume between rooms 1514 and 1501 was 1, which was larger than that between rooms 1514 and 1513 (approximately 0.6). Correspondingly, the results of Measurement 2 show that $D_{r1514–1501}$ was slightly smaller than $D_{r1514–1513}$, except those at 125 Hz for 1.6 dB, when the sound transmitted through two separating partitions with the same construction but with different room volume ratios. The effects of the room volume ratio between the source and receiving room were then demonstrated: room volume is an important determinant for *in situ* sound insulation because sound energy condenses in a smaller room, which leads to a higher sound level in a receiving room, and consequently a smaller level difference between rooms. In the case of a settled source in room 1514 (e.g., an HVAC or human speech), considering the condition that the room volume is larger for room 1513 than for room 1501, to achieve an equal sound level in these two receiving rooms, a higher design value is recommended for level difference between rooms 1514 and 1501.

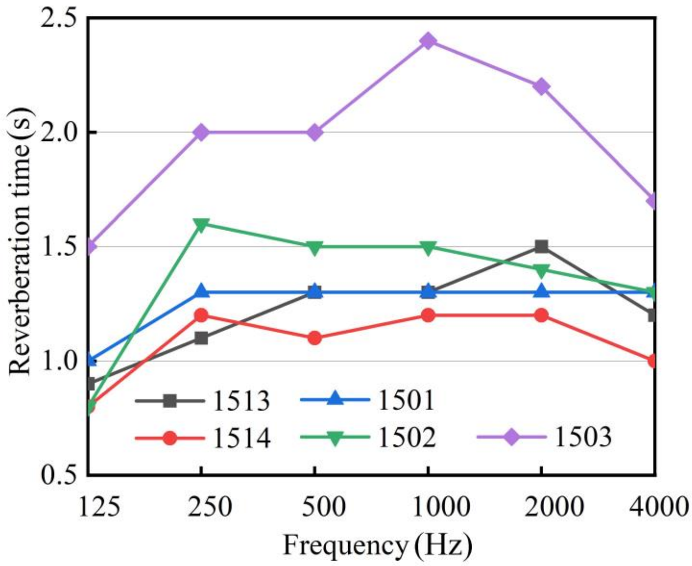
5.3.1.2 Reverberation Time

The average RT (T_{20}) in a room obtained by Measurements 1 and 2 are shown in **Figure 5.6**. **Table 5.4** shows the reported values of the "expanded uncertainty" expressed at approximately the 95% confidence level using a coverage factor (k = 2). The uncertainties were estimated in accordance with Standard ISO/IEC GUIDE 98-3:2008 (International Organization for Standardization, 2008b) to characterize the quality of the measurements. When estimating uncertainty in measurement, the expanded uncertainty is the last calculation. Typically, the calculation only requires multiplying the uncertainty by a desired coverage factor. When the data represent a normal distribution, the k factor reflects the number of standard deviations used when calculating a confidence level. The values of the expanded uncertainty were not significant compared to the just-noticeable difference characterizing the sensitivity of listeners to small changes in the acoustical attributes, which in this case should be lower than 5%, as discussed in Standard ISO/IEC GUIDE 98-3:2008 (International Organization for Standardization, 2008b). Thus, the variation caused by measurements was nearly unobservable. The quality of the measurements was demonstrated as to be acceptable.

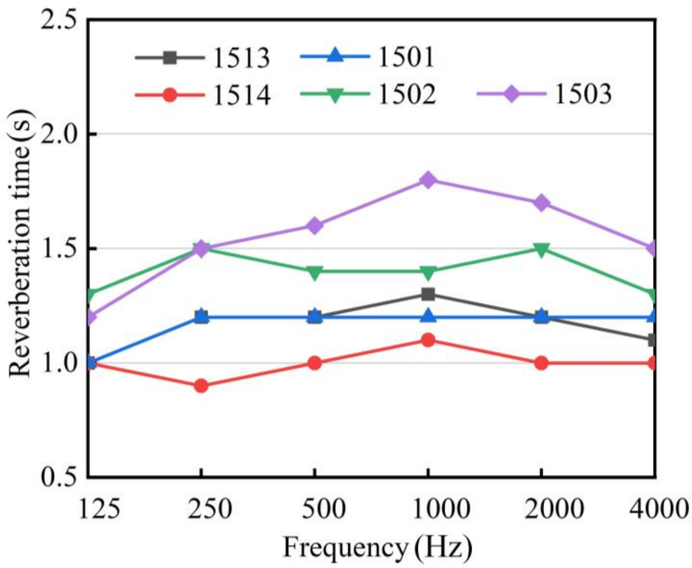
Table 5.4 The expanded uncertainty at the 95% confidence interval of the average RT (T_{20}) in a room for Measurements 1 and 2.

	Measurement 1 (Smaller connected room volume) Room					Measurement 2 (Larger connected room volume) Room				
	1513	1514	1501	1502	1503	1513	1514	1501	1502	1503
[Hz]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
125	0.05	0.07	0.07	0.05	0.08	0.05	0.09	0.07	0.05	0.07
250	0.07	0.08	0.05	0.04	0.04	0.07	0.05	0.07	0.07	0.08
500	0.06	0.05	0.04	0.04	0.07	0.07	0.08	0.07	0.05	0.07
1000	0.06	0.04	0.06	0.07	0.05	0.07	0.09	0.10	0.08	0.08
2000	0.07	0.07	0.05	0.07	0.08	0.04	0.07	0.09	0.07	0.04
4000	0.04	0.05	0.05	0.05	0.04	0.07	0.10	0.07	0.09	0.09

As shown in **Figure 5.8**, lower values of average T_{20} in a room were observed across the space for Measurement 2 than those for Measurement 1. The lowest values were found at 1.0 and 1.1 s in the source room (room 1514) at 500 Hz and 1000 Hz, and the highest values were obtained at 2.0 and 2.4 s for Measurement 1 in the third receiving room (room 1503) at 500 Hz and 1000 Hz. An increase in RT with distance from the source is similar to those of long spaces. **Table 5.5** shows the calculated average T_m in a room for Measurements 1 and 2. The values of T_m in the two receiving rooms (rooms 1513 and 1501) were equal in both measurements, although the two rooms varied in room volume, and for Measurement 1, the openings were close.



(a)



(b)

Figure 5.8 The measured average RT (T_{20}) in a room. (a) Measurement 1 and (b) Measurement 2.

Table 5.5 The calculated average RT (T_m) in a room for Measurements 1 and 2.

Measurement	Room 1513 [s]	Room 1514 [s]	Room 1501 [s]	Room 1502 [s]	Room 1503 [s]
1	1.3	1.2	1.3	1.5	2.2
2	1.2	1.1	1.2	1.4	1.7

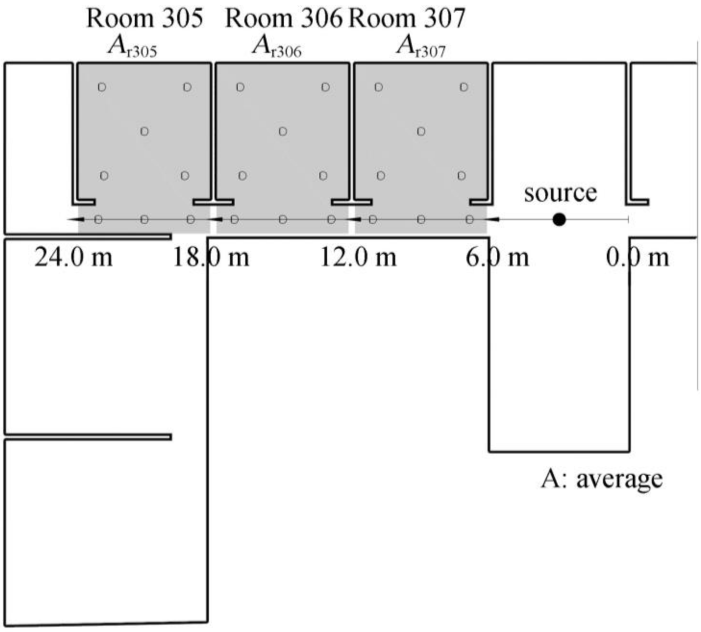
According to the paired *t*-tests (p) of T_m in the measuring positions in a room between Measurements 1 and 2, statistically significant differences were observed in the first and third receiving rooms (room 1501, $p = 0.001$ and room 1503, $p = 0.002$), while no significant differences were observed in the source room (room 1514), first receiving room (room 1513), and second receiving room (room 1502), which indicates that the reverberation in room 1501 was affected by the increase in the connected room volume. However, as shown in **Table 5.5**, the values of average T_m in a room rise 1.0 s for Measurement 1 and 0.6 s for Measurement 2. The difference of 0.1 s in the source and receiving rooms (rooms 1513–1502) was much smaller than for the third receiving room (room 1503), which reached 0.5 s when room 1503 was connected in Measurement 2.

Note that the results of RT mentioned above can be surprising. A common coupling effect frequently used in performing spaces, e.g., concert halls with adjustable RT, is if coupled spaces are reverberant, RT increases when the door in between is open; however, if it is absorbing, then an opposite effect is observed. Therefore, the RT was expected to increase rather than decrease once the door was opened in Measurement 2.

However, this did not occur because this coupling effect is not the same as that of the comparisons between Measurements 1 and 2. When the source was placed in room 1514 connecting a smaller room volume, i.e., rooms 1514–1502 for Measurement 1, sound reflected when the absorbing opening between rooms 1514 and 1513 and between rooms 1502 and 1503 was blocked by a door. Therefore, the connected rooms driven by the source were dominated by the direct component, becoming more condense, and therefore, attained a higher RT. Furthermore, in the first receiving room (room 1513), although the decay started with a lower value of SPL than that in the source room (room 1514), the separating partition between the source and receiving rooms (rooms 1514 and 1513) with a blocked opening rather than an absorbing one, acted more like a plane sound source, which also potentially led to a higher RT. This also explains why the value of T_{20} was higher for the receiving rooms (rooms 1513 and 1501) than for the source room (room 1514), whereas rooms 1514 and 1501 were almost identical in room volume and absorption, because the aligned receivers were additionally closer to the separating partition functioned as an additional “sound source.”

5.3.2 Effect of the Individual Room Volume

As shown in **Figure 5.9**, the two sets of rooms at site 2 (rooms 305–307 and rooms 302–303) were equivalent in length (approximately 18.0 m) and comparable in volume. The former was separated by two separating partitions (three individual room volume, each: 218.7 m^3, entire: 427.4 m^3), while the latter was separated by only one partition (two individual room volumes, each: 121.5 m^3, entire: 364.5 m^3). In addition, the room volume was larger with three slope roofs (two individual room volumes, each: 182.3 m^3, entire: 364.6 m^3) in the rooms at site 3 (rooms 605, 606, and 607) that were similar to the rooms at site 2 (rooms 305, 306, and 307). Measurements 6, 8, and 9 were compared to assess the effect of individual room volume as dividing the entire space with different numbers of separating partitions, or using different shapes.



(a)

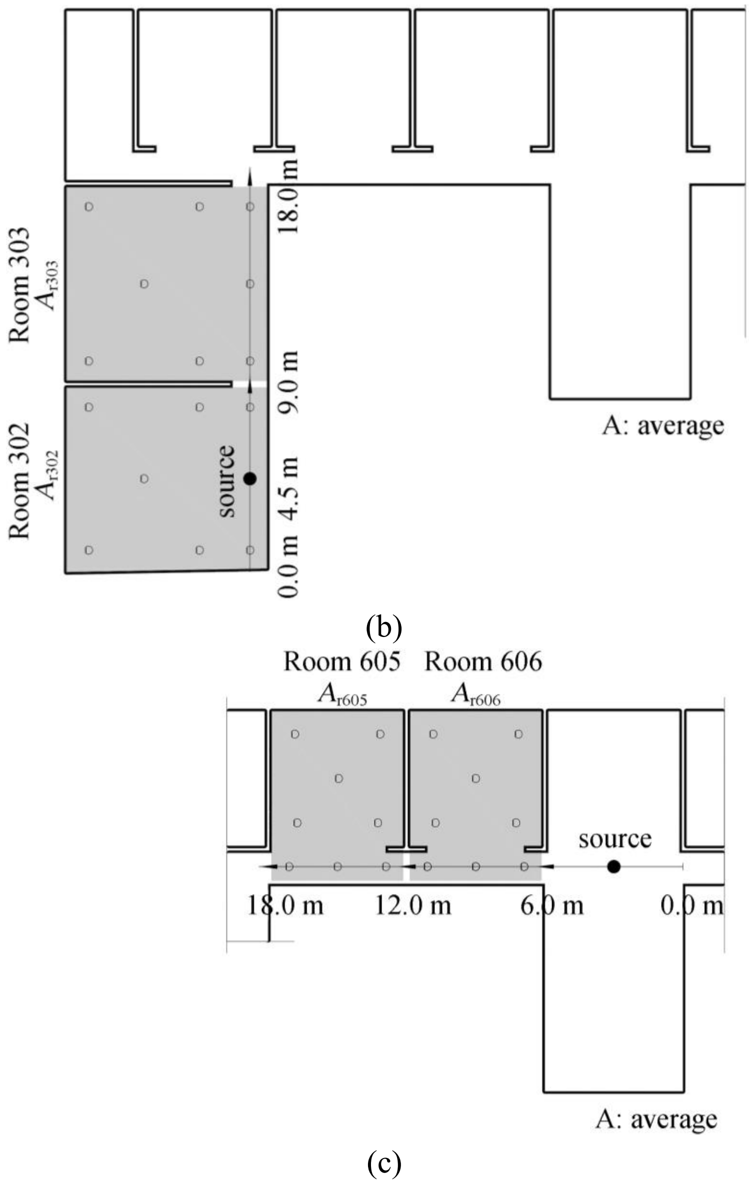


Figure 5.9 The experimental setups for (a) Measurement 6; (b) Measurement 8; and (c) Measurement 9.

According to the ANOVA tests (p), the comparison of the SPL in the measuring position among Measurements 6, 8, and 9 showed statistically significant differences (p = 0.001) among rooms 307, 302, and 606. In addition, a statistically significant difference (p = 0.000) was found when comparing rooms 305, 303, and 605. This indicates that the effect of the individual room volume is prominent in the SPL distribution in a room.

Figure 5.10 illustrates the relative average SPL in a room for Measurements 6, 8, and 9. Note that the level difference across rooms 305, 306, and 307 for Measurement 6 was 17.0 dB, equivalent to that across rooms 302 and 303 for Measurement 8.

Furthermore, the level difference between adjacent rooms (rooms 308 and 307; rooms 307 and 306; and rooms 306 and 305) was 7.5, 4.9, and 4.7 dB, respectively. Therefore, for Measurement 6, the ratio of the level difference for a separating partition along the source distance was approximately **1.5:1:1**. Comparatively, the level difference between adjacent rooms (rooms 302 and 303; and rooms 303 and 305) was 10.0 and 6.7 dB, respectively. Consequently, the ratio for Measurement 8 was also **1.5:1**. Additionally, although the level difference across the space for Measurement 9 was much smaller than those for Measurements 6 and 8 by 4.5 dB on average, the level difference between adjacent rooms (rooms 607 and 606; and rooms 606 and 605) was 6.0 and 4.0 dB, respectively; the ratio along the source distance was also **1.5:1**. As a result, when the entire space was divided into equal room volumes with different numbers of separating partitions in the same construction, the ratio of the level difference was fixed for the first and second separating partitions, e.g., **1.5** in this case. The level differences of successive separating partitions along the source distance were generally equal.

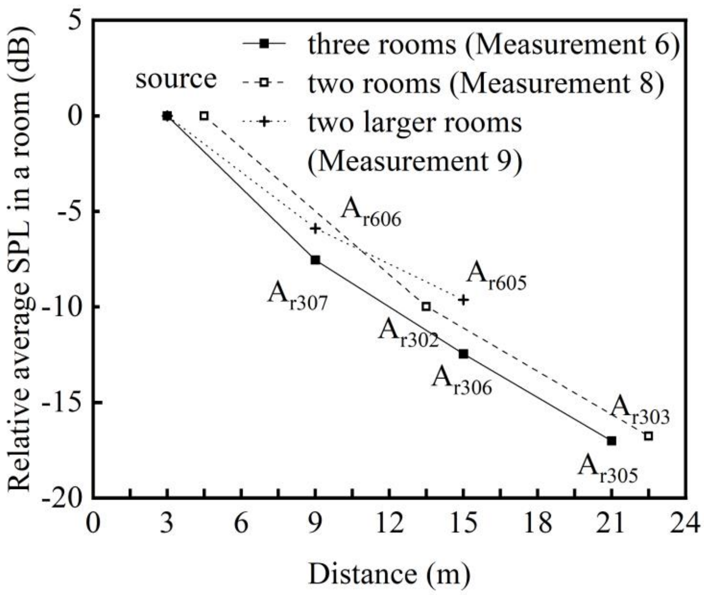


Figure 5.10 The relative average SPL level in a room for Measurements 6, 8, and 9.

5.3.3 Effect of the Source Position

Three source positions on the corners of room 1513 were considered as shown in **Figure 5.11**. Source A (Measurement 3) was located on the left corner, 8.2 m away from the opening; source B (Measurement 4) was placed on the end of the opening axis, 6.5 m away from the opening; source C (Measurement 5) was positioned on the right corner, 2.6 m away from the opening.

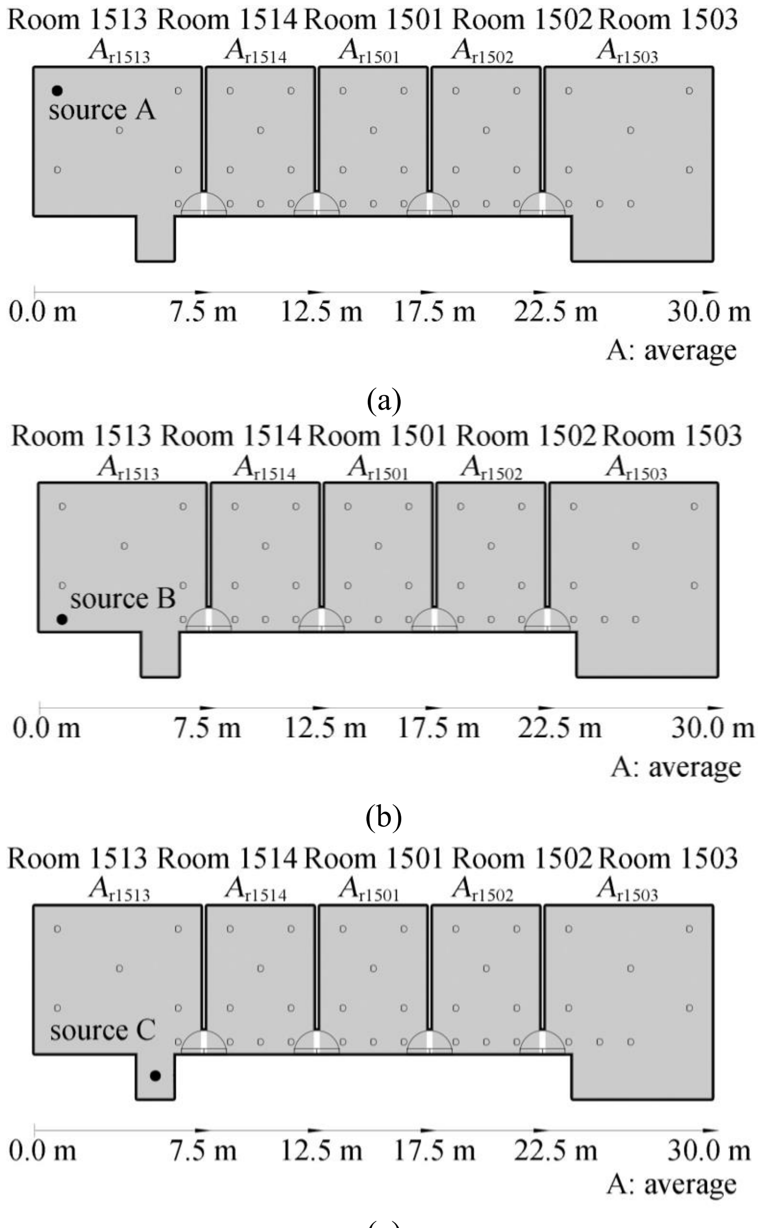


Figure 5.11 The experimental setups for (a) Measurement 3: source position A; (b) Measurement 4: source position B; and (c) Measurement 5: source position C.

To evaluate the effect of the source position on SPL distribution in a room, according to the ANOVA tests (p) as shown in **Table 5.6**, significant differences (p = 0.018) were found in the source room (room 1513), and statistical significances ($p < 0.01$) were delivered in all the receiving rooms (rooms 1514–1503) at 500 Hz. However, there was no significant difference in the source room (room 1513) at 1 kHz. In contrast, significant differences were only found in the first (room 1514, p = 0.002) and fourth (room 1503, $p = 0.000$) receiving rooms at 1 kHz. Furthermore, there was no significant difference across the space at 125 Hz. Therefore, it is concluded that the distinct between the results obtained by different source positions on the SPL distribution in a room is more prevalent in the frequencies with a wavelength close to the opening size and in the room with a larger distance from the source in the high-frequency range due to sound diffraction.

Table 5.6 The ANOVA test (p) of SPL distribution in a room between Measurements 3, 4, and 5. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (two-tailed test of statistical significance).

[Hz]	Room 1513 [-]	Room 1514 [-]	Room 1501 [-]	Room 1502 [-]	Room 1503 [-]
125	0.716	0.103	0.204	0.816	0.157
250	**0.016***	**0.009****	**0.011***	**0.066**	**0.005****
500	**0.018***	**0.000*****	**0.005****	**0.000*****	**0.000*****
1000	0.606	0.002**	0.231	0.054	0.000***
2000	0.087	0.185	0.012*	0.001**	0.000***
4000	0.000	0.011*	0.021*	0.000***	0.000***

Figure 5.12 shows the relative average SPL in a room for Measurements 3, 4, and 5. The results reveal that the entire level difference across the space was smallest at 25.3 dB for Measurement 4 and largest at 30.5 dB for Measurement 3. These results indicate that a smaller source-opening distance causes a smaller entire level difference across the space, and if the sound source is located along the opening, the entire decrease in the SPL with distance across the space would be small. **Figure 5.13** shows the SPL in the measuring position along the openings for Measurements 3, 4, and 5. Good agreements were obtained with the results in **Figure 5.13** by the measuring positions along the openings.

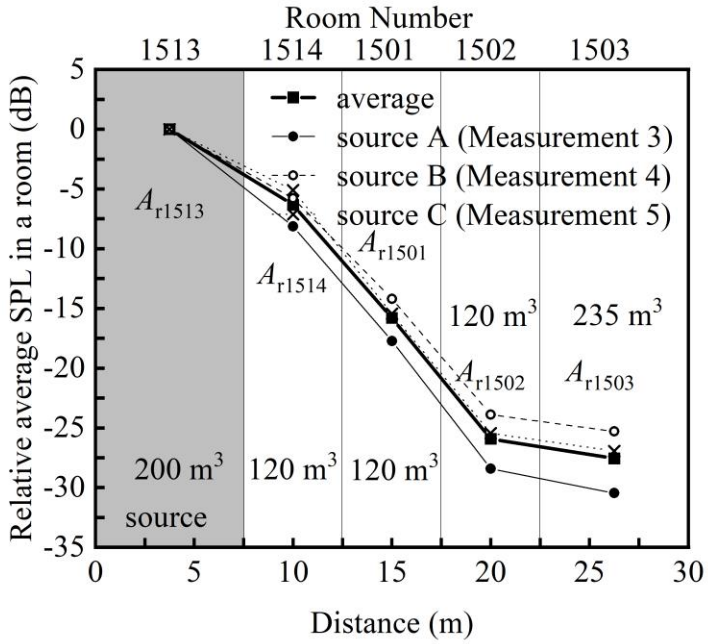


Figure 5.12 The relative average SPL in a room (A) for Measurements 3, 4, and 5.

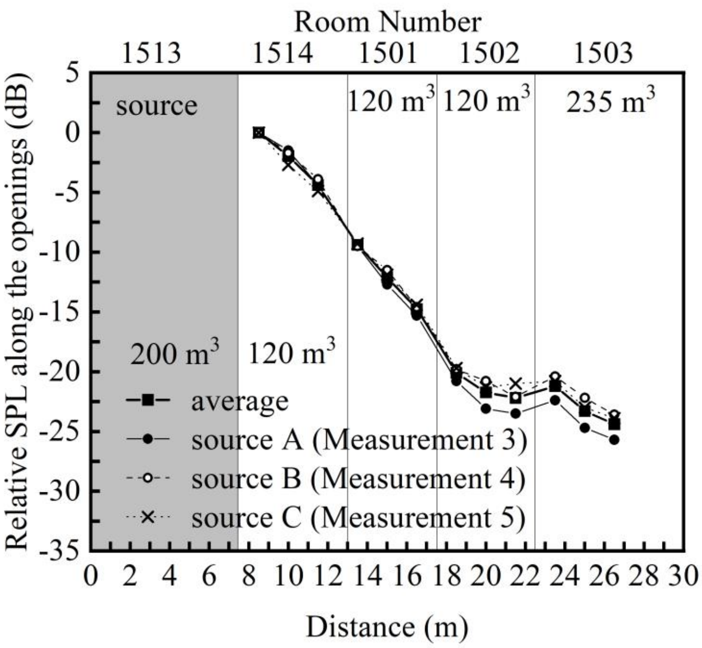


Figure 5.13 The relative SPL along the openings for Measurements 3, 4, and 5.

As highlighted by the bold line in **Figure 5.12**, the measured average SPL in a room for Measurements 3, 4, and 5 was averaged as a single value (*A*) to represent the average SPL in a room when the sound source was placed in room 1513. **Table 5.7** illustrates the level difference between rooms (*D*) and the difference in *D* among Measurements 3, 4, and 5 ($\Delta D_{M3,4,5}$). The results show that $D_{r1513\text{–}1514}$ were much smaller than $D_{r1514–1501}$ and $D_{r1501–1502}$. The larger decrease in the SPL in a room with distance across the space was obtained in higher frequencies as a result of sound diffraction, although the value at 125 Hz was also large probably due to resonance.

As shown in **Table 5.7,** the standard deviation among the three measurements was greatest at 2.4 dB at 250 Hz for $D_{r1513–1514}$ and greater for $D_{r1514–1501}$, $D_{r1501–1502}$, and $D_{r1502–1503}$ at 4 kHz. Furthermore, the values of $\Delta D_{M3,4,5}$ were generally greater for $D_{r1514–1513}$ than for $D_{r1513–1514}$ in the low-frequency range at 125 Hz and 250 Hz, as the size of the opening is 1.0 m and the wavelength of 500 Hz is 0.7 m. Therefore, the effect of the source position on the level difference between rooms seemed to be reflected in those separating walls with a larger source-receiver distance at high frequencies and with a smaller source-receiver distance at the frequencies with a wavelength close to the opening, which could also be related to sound diffraction.

Table 5.7 The level difference between rooms (D) and the difference in level difference among Measurements 3, 4, and 5 ($\Delta D_{M3,4,5}$).

[Hz]	$D_{r1513–1514}$ ($\Delta D_{M3,4,5}$) [dB]	$D_{r1514–1501}$ ($\Delta D_{M3,4,5}$) [dB]	$D_{r1501–1502}$ ($\Delta D_{M3,4,5}$) [dB]	$D_{r1502–1503}$ ($\Delta D_{M3,4,5}$) [dB]	D_{rAll} [dB]
125	7.8±1.5 (3.6)	10.0±0.9 (2.0)	12.5±1.1 (2.6)	3.6±0.9 (2.2)	33.9
250	5.1±2.4 (5.5)	10.1±1.0 (2.4)	9.3±0.3 (0.6)	4.7±0.4 (1.1)	29.2
500	5.5±0.5 (1.2)	9.3±1.4 (3.4)	9.1±1.0 (2.3)	0.5±0.3 (0.6)	24.4
1000	6.5±0.9 (2.2)	9.7±0.8 (2.0)	9.6±0.4 (0.9)	1.1±0.3 (0.8)	26.9
2000	6.8±0.5 (1.2)	9.6±1.1 (2.6)	9.3±0.6 (1.4)	0.7±0.8 (1.7)	26.4
4000	6.7±0.8 (1.8)	8.1±1.3 (3.0)	9.3±1.1 (2.5)	0.7±1.4 (3.1)	24.8

To evaluate the effect of source position on SPL along the openings, **Figure 5.14** shows the decrease in the SPL with distance along the openings at 125–4000 Hz. The entire level difference across the space at 125 Hz was the largest. Regarding the results at 250 Hz, the entire level difference across the space was generally close to those obtained by higher frequencies. However, the difference was mainly delivered in rooms 1514 and 1501, i.e., the rooms with smaller distances from the source. The results at 500 Hz and higher frequencies were generally very similar.

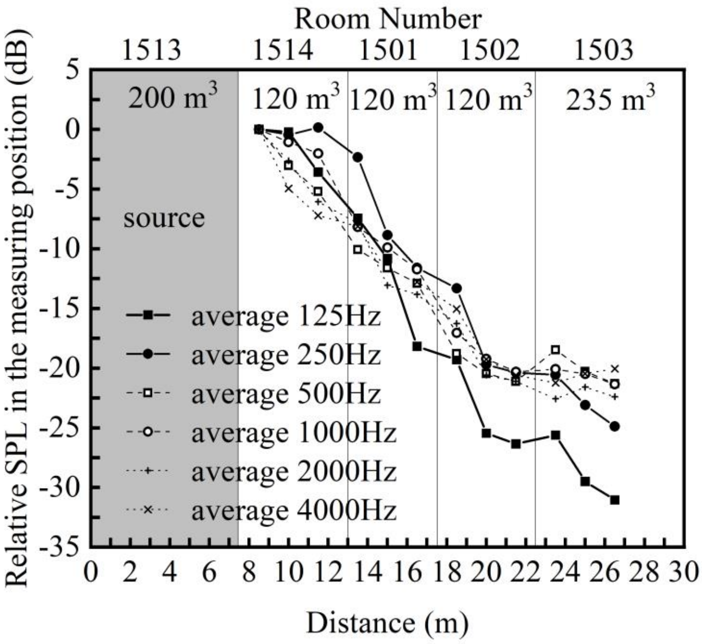
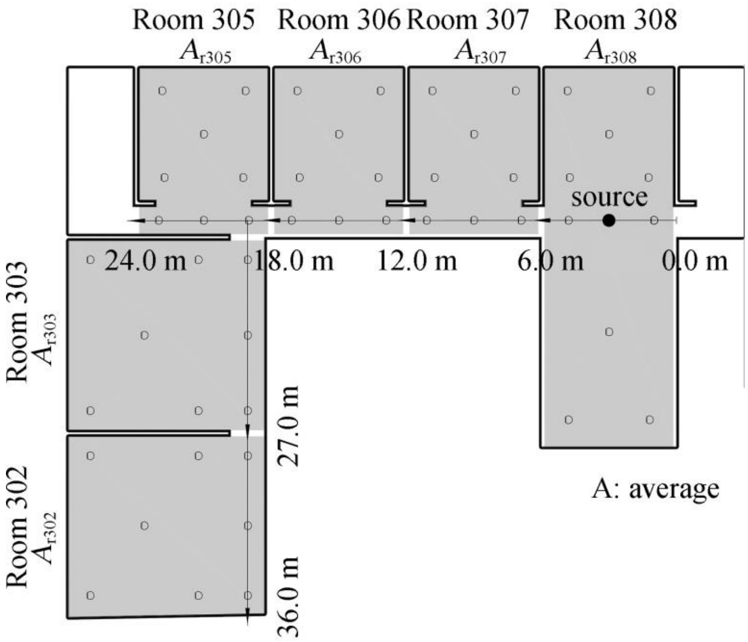


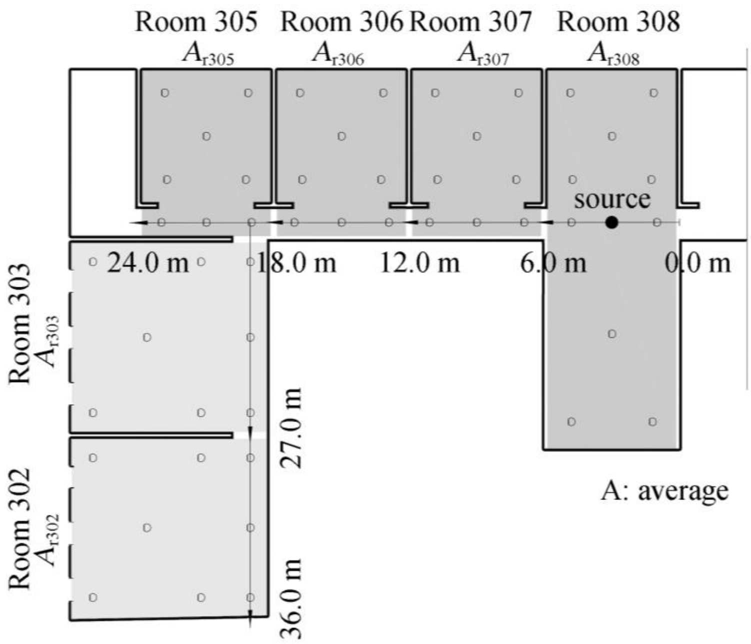
Figure 5.14 The relative SPL in the measuring position along the openings for Measurements 3, 4, and 5.

5.3.4 Effect of the Acoustic Absorption

To assess the effect of the acoustic absorption, six windows on the façade of the receiving rooms (rooms 302 and 303) were open in Measurement 7 as shown in **Figure 5.15**. As discussed above, the site uses a side-hung window opened at a narrow angle. The total areas of the windows are approximately 18 m^2 in room 302 and 18 m^2 in room 303. The sound absorption equivalent to an open window of 1 m^2 is 1 Sabin. The added total absorption is estimated to be 50% × area of windows = 18 Sabin.



(a)



(b)

Figure 5.15 The experimental setups for (a) Measurement 6 and (b) Measurement 7.

According to the paired *t*-tests (*p*) comparing the SPL in a room between Measurements 6 and 7, there was no significant difference in the receiving rooms (room 307, $p = 0.767$; room 306, $p = 0.612$; room 305, $p = 0.168$). However, statistically significant differences were observed in the receiving rooms (room 303, $p = 0.006$; room 302, $p = 0.000$). **Figure 5.16** shows the relative average SPL in a room for

Measurements 6 and 7. It is observed that $D_{r308-307}$, $D_{r307-306}$, and $D_{r306-305}$ were equivalent in the two measurements. The values for Measurement 6 were greater than those for Measurement 7. When sound passed through three rooms, meeting the corner at the location of room 305, the attenuation of levels ceased only for Measurement 6. However, for Measurement 7, $D_{r305-303}$ and $D_{r303-302}$ were equivalent to the level difference obtained in the previous three rooms (rooms 308 and 307; and rooms 307 and 306), e.g., $D_{r308-307}$. Therefore, increasing the acoustic absorption through partial changes in boundary conditions of sequential spaces, has been proven to unnecessarily interplay the overall level difference across the space. Especially for spaces designed in a corner type, the effects were confined to the changed part of the connected spaces.

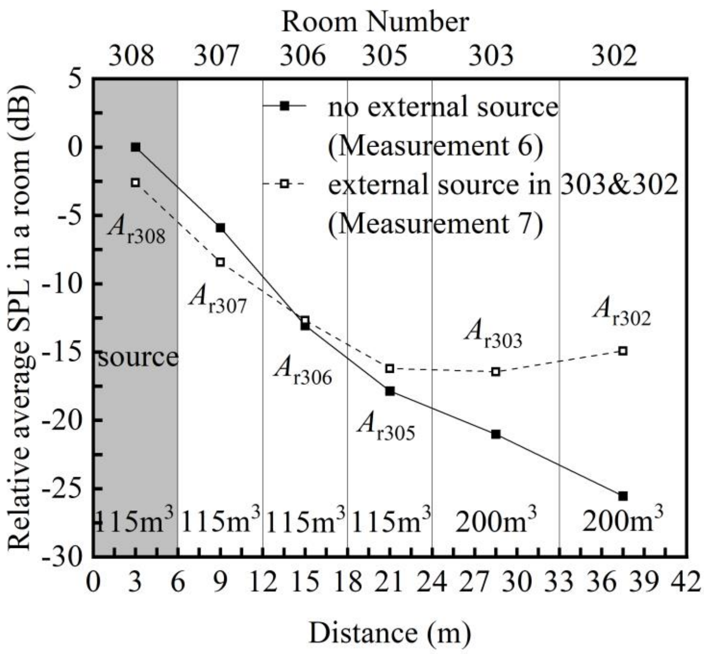


Figure 5.16 The relative average SPL in a room (A) for Measurements 6 and 7.

Table 5.8 shows the difference in the average SPL in a room (ΔA) between Measurements 6 and 7. The larger differences were found to be the values at 250 Hz and 500 Hz. It is found that the changes in the average SPL in a room was prevalent in the frequency range in which the wavelength is close to the opening size, i.e., 250 Hz and 500 Hz in the rooms with smaller distances from the source.

Table 5.8 The difference in the average SPL in a room (ΔA) between Measurements 6 and 7.

[Hz]	ΔA_{r307} [dB]	ΔA_{r306} [dB]	ΔA_{r305} [dB]	ΔA_{r303} [dB]	ΔA_{r302} [dB]
125	5.4	0.9	0.5	1	–2.5
250	4.5	3.1	2.3	2.2	–1.3
500	5.4	1.1	0.9	2.7	0.4
1000	2.6	0.2	–0.3	0.2	0.9
2000	1.8	–0.2	0.1	–1.4	–0.8
4000	2.3	0.3	0.4	0.2	–1.6

5.4 DISCUSSION

5.4.1 The Distinction for R_w and D_w by Room Volume and Source Distance

Acoustic professionals and design teams select the elements of walls, floors, glazing, and doors based on a sufficient R_w rating to achieve the targeted *in situ* D_w. R_w can vary significantly between separating partitions, even if they require the same D_w. However, no project ends up with thousands of wall types, although performing the calculations wall-by-wall correctly is important in achieving a successful, cost-effective design. Moreover, in practice we normally adopt conditional source positions for different requirements.

Take the separating partition between rooms 1513 and 1514 as an example. A clear difference can be found between a separating partition with either a closed or open door, demonstrated by Measurements 1 and 2, which was approximately 11.0 dB in the frequencies at 500 Hz and 1 kHz. Furthermore, under the same entire room volume, when the source was placed in room 1514 for Measurement 2, $D_{r1514–1513}$ with an open door it was approximately 13.0 dB; comparatively, when the source was placed in room 1513 for Measurements 3, 4, and 5, $D_{r1513–1514}$ with an open door was approximately 5.0 dB. This disparity imposed by the source position reaches 8.0 dB, showing that the ratio of the room volume of the source and receiving room is important: for the former, the room volume is 200 m^3 (room 1513); for the latter, the room volume is 120 m^3 (room 1514). The smaller the receiving room is, the greater is the concentration of sound energy, the higher the SPL of the receiving room is, the smaller is the level difference between rooms, and therefore, a higher R_w is required. Therefore, the temptation to $R_w = D_w + 8.0$ dB could be a possible comfortable safety margin only considering the effect of room volume of source and receiving room.

Take another look at the separating partition between rooms 1514 and 1501. $D_{r1514-1501}$ in both Measurements 1 and 2, where the source was placed in room 1514, was approximately 12.0 dB in the frequencies at 500 Hz and 1 kHz. In contrast, in Measurements 3, 4, and 5, when the source was placed in room 1513 and the source distance increased by approximately 5.0 m, it was approximately 8.0 to 10.0 dB with an open door. This disparity imposed by the source position reached 4.0 dB, showing that the effect of source distance was observable: the larger the source distance is, the smaller is the sound energy in the adjacent "source" room, the smaller the sound energy to transmit through, the smaller is the level difference between rooms, and therefore, a higher R_w is required. Therefore, the temptation to $R_w = D_w + 4.0$ dB could be possible to avoid the time-consuming measurements and calculations only considering the effect of source distance.

Therefore, both the room volume of the source and receiving room, and the source distance should be considered when performing the correction between R_w and D_w in sequential space.

5.4.2 Limitations and Future Work

Although the microphone locations in an experiment covered all of the rooms simultaneously, limitations are imposed by the measurement techniques (e.g., the number of working sources and receivers in a room to be involved simultaneously). Additionally, although the sites were perfectly cleaned by the relevant departments presenting a relatively stable state during the measurements, there are issues to be addressed in handling the effect of customized furniture on the results, which is critical for a detailed analysis for specific positions in space (e.g., the SPL distribution within the opening area). Therefore, future work will involve simplifying the room to a generic condition.

5.5 CONCLUSIONS

The decrease in SPL with distance from the source and an increase in T were explored using *in situ* measurements analysing the influence of room volume, source position, and acoustic absorption, i.e., three strategies in coupled room studies. The major findings of this chapter are

- significant changes were not observed for the SPL distributions in the rooms that remained connected after the room volume increased by opening the door. For the original connected space, the average **SPL** in a room **stays** within 2.0 dB, while the average $\boldsymbol{T_{20}}$ in a room in the middle-frequency range **decreases** after increasing the connected room volume because of the effect of plane source by a separating partition. The $\boldsymbol{T_{20}}$ range across the rooms increases, and the larger the source distance is, the more significant were the changes in the value of T_{20}. Therefore, increasing the connected room volume only profoundly affects the added connected room;
- the performance of the same separating element (*in situ* level difference ***D***) between the source and first receiving room is magnified to approximately **1.5** times their sequential values between the receiving rooms. In the case of a settled sound source, the design for the first receiving room should consider this effect;
- a larger ratio of room volume between the source and receiving room resulted in a smaller level difference between rooms, therefore, a higher designed value for level difference is recommended;
- a larger source–opening distance resulted in a larger decrease in the SPL with distance across the room unless the sound source was placed in line with the openings indicating a smallest decrease across the room. The effect of the source position on SPL distribution is more prevalent in the frequencies with a wavelength close to the opening dimension, and in the room with a larger distance from the source in the high-frequency range due to sound diffraction, further showing the necessity of measuring the level difference with different source positions (Hopkins, 2007); and
- increasing room absorption only affects the level difference in local space rather than the rest of the connected rooms. The change of average SPL in a room is prevalent in the frequency range in which the wavelength is close to the opening size.

6 Parametrization Efficiency on Performance of Sound Attenuation

In Chapter 5, the spatial and source information in practice (e.g., connected room volume, individual room volume, source position, and acoustic absorption) was varied in accordance with user need. During the design phase, such information (e.g., opening dimension and position) can also be modified to achieve a certain level of sound attenuation performance based on computational simulations. A corresponding strategy to find the design values based on predicted values will be studied. This chapter explores the parametrization efficiency for sound attenuation with distance, showing the consistency or inconsistency between different assumptions and constraints.

6.1 INTRODUCTION

The modelling of sound fields in sequential spaces is necessary for noise control and acoustical design in large-scale public building. It is not practical to adopt thousands of specific separating partition types in the design of these projects; instead, the construction is assumed to be identical across all spaces. However, the sound field is nevertheless complex because of the influence of the interaction on their contextual and acoustic factors. Although recent research in this area has been conducted through objective approaches (D'Orazio et al., 2020, Pon et al., 2016, Tang et al., 1997), mainly reporting L_{Aeq} values measured in well-established acoustic projects in occupied conditions, the sound field predictions have generally been calculated in the absence of the relevant spatial and source information in the context of sound attenuation across the space as discussed in **Section 2.2**. Therefore, the fundamental strategies that should be followed to achieve specified sound field performance targets, especially during the design phase, remain unknown to professionals.

Various room acoustic studies of coupled spaces have been conducted to explore how the contextual and acoustic factors adjust these spaces modulating the degrees of coupling effects under different assumptions and constraints. Regarding the contextual factors (e.g., opening dimension and position), Harris and Feshbach (1950) studied how the opening dimension and position affected the frequency using wave theory. Meissner (2010) investigated the effects of mode degeneration and localization by assuming low absorption, which led to weakly coupled modes. Based on the field eigenfunction representation, Poblet Puig and Rodrıguez-Ferran (2013) analyzed the sound transmission through openings between cuboid-shaped rooms and proposed that the opening position and room dimensions are both crucial determinants of the coupling effects between rooms. Regarding the acoustic factors (e.g., absorption coefficients and positions), Fitzroy (1959) presented an empirical expression considering nonuniform absorption in the three orthogonal directions for rectangular rooms with several measurements. By modelling a rectangular room with one absorbing wall, Maa (1940) showed that the absorption depends not only on the absorptive material but also on its position and the shape of the room . McMullan (1991) pointed out that the absorption provided by absorptive materials significantly affects the sound quality (acoustics) within a room but has little effect on the amount of sound passing in or out of a room (sound insulation). These studies, although limited to spaces of two coupled rooms, demonstrated the potential of parametrization with respect to the contextual and acoustic factors for sound field modification. However, the efficiency of such techniques in controlling the sound passing across several rooms remains to be determined.

For effective sound field prediction for coupled rooms, computational simulation techniques (e.g., FEM, geometrical acoustics, and the diffusion equation) have gradually become more accepted and accurate. An energy-based modelling approach was investigated by Shi et al. (2018), in which coupling was achieved by enforcing the continuity of the power exchanged between rooms and was then validated through comparison with the results obtained using the FEM. Geometrical acoustics-based simulations have also been validated (Bradley and Wang, 2005, Aspöck and Vorländer, 2019). Jing and Xiang (2008) produced a visualization of the sound pressure distribution and sound energy flow across the coupling aperture between two rooms using diffusion modelling. Billon et al. (2006) developed a numerical diffusion model to predict spatial variations in SPL. Both numerical methods (Leblanc and Chardon, 2014, Ortiz et al., 2013, Koch, 2005, Seybert et al., 1990) and analytical models (Jin et al., 2016, Wang et al., 2015, Yu et al., 2014, Kim and Kim, 2001, Kim and Kim, 2002) have been utilized to determine the acoustic quantities of interest for openings and room absorption. In particular, the FEM is a routinely used tool in most acoustic studies (Leblanc and Chardon, 2014). The ray and beam tracing methods can be correctly applied to spaces of arbitrary shapes, either empty or furnished. The sound field is composed of noninteracting sound rays reflected from surfaces with dimensions much larger than the sound wavelength. However, the accuracy of these methods for large source–receiver distances or complex boundary conditions has been demonstrated to be insufficient (Nijs et al., 2002, Anderson and Bratos-Anderson, 2000).

In the case of environmental noise, plane waves can be used to simulate sounds in the far field, e.g., outdoor sounds incident on the windows on the façade of a building. A source of surface transportation noise (e.g., a busy highway) is usually modelled as an incoherent line source (Arenas, 2007). This is akin to the indoor noise coming from other rooms far from the investigated space (e.g., a crowd). As an acoustic opening may attenuate noise from different dominant incidence angles (e.g., traffic noise on the upper floors of a high-rise building or crowd noise from a source room with oblique boundaries), the performance should be investigated for different noise source incidence angles. For instance, an incidence angle of 60° corresponds to an approximate position on the 20th floor of a building relative to a surface-level road 50 m away from the building (Lam et al., 2018). In addition, there are typically additional noise sources (e.g., HVAC systems and human speech) in large-scale public spaces (e.g., museums), which are frequently simplified as omnidirectional or directional point sources in predictions models, whose effects at a particular location or in a particular area must be considered.

Consequently, this research focuses on a parametric study using FEM-based prediction as a case study. Compared with other well-established room acoustics programs, the FEM can better consider the effects of diffraction, which are essential in sequential spaces. The results can serve as a reference for practical applications, especially during the design phase. *In situ* measurements were conducted in selected exhibition spaces to confirm the accuracy of the predictions by validating the FEM results. The overarching aim is to explore the efficiency of using contextual and acoustic factors, i.e., opening dimension and position, absorption coefficient and distribution, to predict the performance of sound attention through rectangular openings in sequential spaces in parametric studies. In addition, the effects of source factors are investigated by considering the directional radiation from openings and additional sources. Finally, the influence of increasing the number of rooms to enlarge the scale of the entire space is analysed.

6.2 METHODS

6.2.1 Simulation Configuration

The simulations were conducted in the FEM software COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden). The density of the mesh was set to provide a minimum of six elements per wavelength at 4 kHz for all frequencies tested (⩽ 4 kHz) to ensure consistency as well as accuracy. PML (Koch, 2005) absorbing boundary conditions were adopted to compute the acoustic resonances in three-dimensional open cavities with other general boundaries. The air aperture of an open cavity could be theoretically considered as an equivalent structural component with a small thickness, neglecting the physical properties of the opening (Yu et al., 2014). However, a three-dimensional model would need far more elements to fully represent the connected spaces to provide physical insight and practical guidelines and would be highly time consuming. Instead, a two-dimensional model runs reasonably well for various geometrical conditions and covers a higher range of frequencies with practical modelling efficiency.

Figure 6.1 illustrates a hypothetical two-dimensional model representing a cross section of five rectangular rooms with initial dimensions of a width of w_{sp} = 5.0 m and a length of l = 8.0 m separated by solid walls with rigid boundary conditions and connected by openings with a width of w_{op} = 2.0 m. The opening/partition area ratio, i.e., the ratio of the width of the opening to the width of the entire separating partition, is d_{op} = 40%, and the openings are located in the middle of each separating partition. The openings on the end walls on the left and right sides are enclosed with PMLs to emulate free-field conditions. The thicknesses of all separating partitions are set to 0.2 m, because this value is commonly used in practice. The sound insulation of the rigid walls is not modelled. For a coherent sound source, the sound incident on the opening is assumed to be plane waves with an initial incidence angle of θ = 0° indicating that the source is located at the same height level as the investigated spaces.

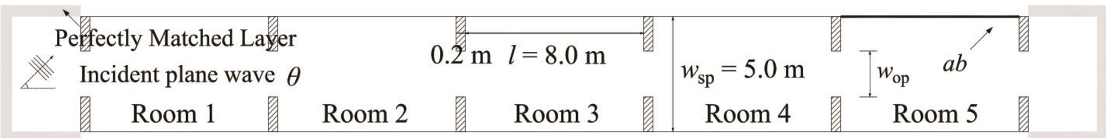


Figure 6.1 The two-dimensional FEM prediction model (in m).

6.2.2 Simulation Parameters

As discussed in **Section 6.1**, the performance across the space was investigated with respect to three aspects, i.e., contextual factors (opening dimension and position, number of rooms), acoustic factors (absorption coefficient and distribution) and source factors (directional radiation from the opening and an additional source).

For the contextual factors, one of the parameters is the opening/partition area ratio d_{op}, which is defined as follows:

$$d_{op} = w_{op}/w_{sp} \quad (6.1)$$

where w_{op} is the width of the opening and w_{sp} is the width of the separating partition. The value of d_{op} was varied from 0% to 100% representing the conditions ranging from a small opening to an opening spanning the entire width of the separating partition. In particular, d_{op} values of 20% and 40% are considered to correspond to small and large openings, respectively. As the effects of the space and source information, e.g., source position, are most predominant in the frequencies with a wavelength close to the opening dimension due to sound diffraction as discussed in Chapter 4, considering d_{op} = 20%, i.e., w_{op} = 1.0 m, 250 Hz, 500 Hz, 1 kHz and 2 kHz are used in this Chapter.

Another parameter representing the contextual factors is the opening/partition position ratio p_{op}, the maximum of which is defined as follows:

$$p_{op} = (1 - d_{op})/2 \quad (6.2)$$

The value of p_{op} varied from 0% to $(1 - d_{op})/2$%. The value of 0% indicates that the opening is in the middle of the separating partition, and the maximum value of $(1 - d_{op})/2$% means that the opening is located on one side of the separating partition attached to the sidewall running along the length of the rooms. Therefore, the value of $p_{op} \times w_{sp} = (w_{sp} - w_{op})/2$ represents the relative distance between the centre of the opening and the centre of the separating partition in the prediction model. For example, if the width of the opening w_{op} is 2.0 m and the width of the separating partition w_{sp} is 5.0 m, then d_{op} is 40%. If p_{op} is 30%, then the value of $p_{op} \times w_{sp}$ is 1.5 m, indicating that when the opening is attached to side wall, i.e., the center of the opening is 1.5 m away from the center of the separating partition.

Finally, the number of connected rooms across the space is denoted by N. The range of N investigated in this chapter is from 1 to 10.

Regarding the acoustic factors, one parameter is the absorption coefficient ab, which is applied uniformly to the boundaries of each room and ranges from 0 to 1.0. In particular, the *ab* values of 0.01 and 0.5 are defined as low and high room absorption, respectively. Another parameter is termed the “absorption distribution” in this chapter. The distribution of absorption at the boundaries is represented by two conditions, i.e., uniformly or nonuniform (only along the sound attenuation direction).

Regarding the source factors, one parameter is the directional radiation from the opening, i.e., the incidence angle on the transparent boundary θ. Oblique noise incidence cases are analogous to noise impinging on openings at different floors of a building; for example, an incidence angle of 60° corresponds to an approximate position on the second floor of a building when a walkway is on the first floor, 5.0 m away from the wall of the atrium. Another parameter is termed the “directional radiation from an additional source” in this chapter, referring to the placement of an omnidirectional or directional point source in the corner of room 1.

6.2.3 Validation Between Measurements and Simulations

6.2.3.1 Validation Configuration

The simulation results were validated by comparison to *in situ* measurements from selected rooms in the right portion of the Tate Modern in London, United Kingdom, as detailed in **Chapter 4**. The reason that the outcome obtained in **Chapter 4** is suitable for validation is because the investigated rooms in the Tate Modern were simple and contained very limited furniture, thus meeting the baseline conditions for sequential spaces. It is worthwhile to note that the outcome in **Chapter 5** was not used for validation because it was obtained under the conditions in which the investigated spaces contained furniture. It would not be possible to build the furniture into the simulation sufficiently precisely, and the attempt to do so would consume too much calculation time due to the amounts of furniture to be detailed.

The two-dimensional FEM computational model was built in accordance with the real spatial dimensions, as illustrated in **Figure 6.2b**. The boundary conditions for a given space were specified considering its relation to the subsequent spaces; otherwise, the sound energy would be much greater if it were to be considered as an enclosed space because of the reflections. Moreover, because the height of room 1 was not comparable to those of rooms 2–4, only the boundary conditions of rooms 2–4 were modelled, and the areas representing the source room (room 1) with the primary source “Babel, 2001” and the other spaces of the museum, which were not detailed at this stage as they were not investigated, were bounded with PMLs. To simulate the reflected sound in the source room (room 1) attenuating across the opening between the source room (room 1) and the adjacent receiving room (room 2), the noise incident on the separating partition was assumed to be a plane wave of $\theta = -90°$ (Crocker and Arenas, 2021). The opening was located slightly toward the side wall rather than in the middle of the separating partition in the initial plan. The value of d_{op} was 32%. The value of p_{op} was 8%, and therefore, $p_{op} \times w_{sp}$ was 0.5 m. The value of *ab* was initially set to 0.02 to match the low room absorption.

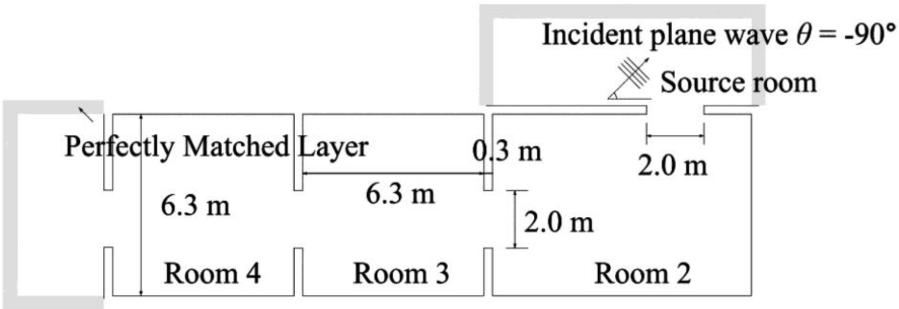


Figure 6.2 The two-dimensional FEM validation model (in m).

6.2.3.2 Prediction Difference with the Measurement

To examine the prediction sensitivities of the validation model when changing the sound absorption coefficient, one baseline condition (*ab* = 0.02) as discussed in **Section 6.2.3.1** and two additional conditions (*ab* = 0.01 and *ab* = 0.03) are considered to assess the predictions differences with the measurement. **Figure 6.3** shows the normalized measured average SPL and the average SPL computed results under each of the three conditions. For the baseline condition (*ab* = 0.02), the measured (black line) and the simulated (blue line) results consistently agree across all tested frequencies, i.e., 250 Hz, 500 Hz, 1 kHz, and 2 kHz, within a difference range of 2.0 dB. Therefore, it can be concluded that the sound attenuation with distance from the primary source across rectangular openings can be simulated. Nevertheless, the “best” performance for a single frequency was observed to be 500 Hz, and the “best” performance for a room was observed to be room 3 within a difference of 1.0 dB. Additionally, the greatest difference with the measurement was found to be room 4 at 1 kHz.

For two additional conditions (*ab* = 0.01 and 0.03), the decrease in the SPL in a room is almost the same for both investigated values of *ab* with the difference being limited to 3.0 dB, especially at 250 Hz. However, in further improving the accuracy of prediction model, the results reveal that the differences for sensitivities gradually increase with distance from the source, i.e., larger in room 4 than in room 3, and are larger in the high-frequency range, i.e., 1 kHz and 2 kHz. In general, the results corresponding to *ab* = 0.01 (green line) and 0.02 (blue line) are closer to the real observation than those corresponding to *ab* = 0.03 (red line).

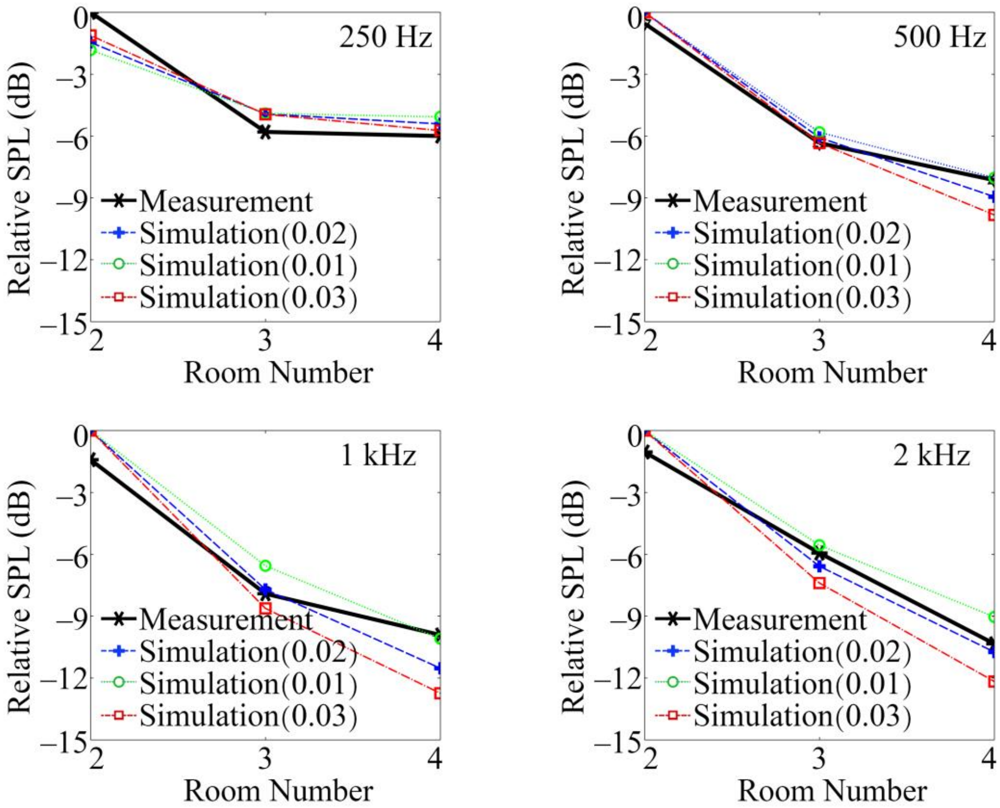


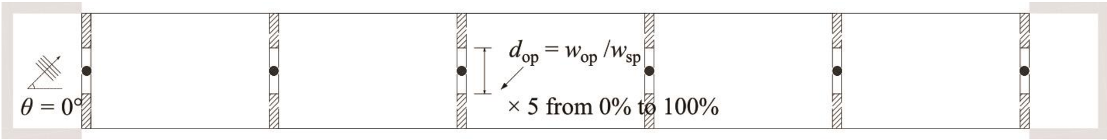
Figure 6.3 Comparisons of three validation simulations with the corresponding measurements of the relative SPL in a room when simulating different room absorption coefficients over a range of frequencies.

6.2.4 Simulation Experiments

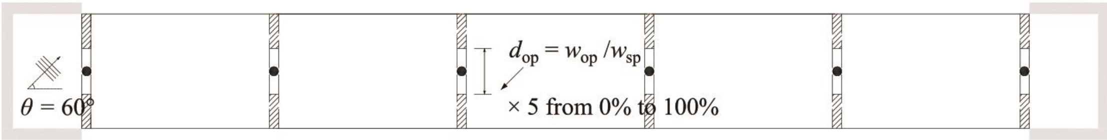
The underlying research questions were addressed on the basis of the chosen parameters, and the efficiency of the parametrizations in simulating the performance across the connected spaces was investigated through seven comparative studies: (1) Study 1 (opening dimension): parameter d_{op}; (2) Study 2 (directional radiation from the opening): parameter d_{op} with θ = 60°; (3) Study 3 (directional radiation from an additional source): parameter d_{op} with the introduction of an additional source; (4) Study 4 (opening position): parameter p_{op}; (5) Study 5 (absorption coefficient): parameter *ab* with two opening dimension values of d_{op} = 20% and 40%; (6) Study 6 (absorption position): parameter *ab* with a nonuniform absorption distribution; and (7) Study 7 (number of rooms): parameter *N*. **Table 6.1** shows the simulation input and **Figure 6.4** shows the experimental configuration for each study. Note that all openings and walls in the model, which are marked with circle and broad-brush lines, respectively, were changed simultaneously in each simulation.

Table 6.1 The parametrizations of three contextual, acoustic, and source factors and the simulation input used in COMSOL.

		Contextual factor			Acoustic factor		Source factor	
		Opening/partition area ratio (%)	Opening/partition position ratio (%)	Number of rooms	Absorption coefficient	Absorption position	Angle of opening incidence	Directional radiation from an additional source
Study		d_{op}	p_{op}	N	ab	[-]	θ	[-]
1	a b	0–100	0	5	0.01 0.5	Uniform	0°	No
2	a b	0–100	0	5	0.01 0.5	Uniform	60°	No
3	a b	0–100	0	5	0.01	Uniform	0°	Omni directional
	c d	0–100	0	5	0.5	Uniform	0°	Directional
4	a b	40	0– $(1 - d_{op})/2$	5	0.01 0.5	Uniform	0°	No
5	a b	20 40	0	5	0 to 1.0	Uniform	0°	No
6	a	20 40	0	5	0 to 1.0	Nonuniform	0°	No
7	a b	40	0	1–10	0.01 0.5	Uniform	0°	No

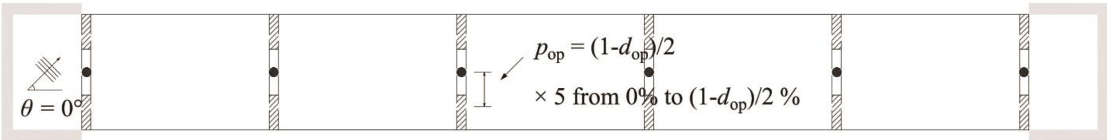


(a) Opening dimension

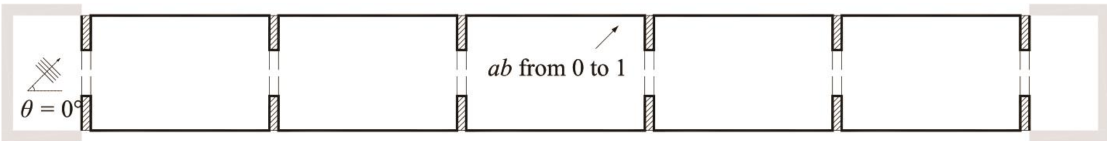


(b) Directional radiation from the opening

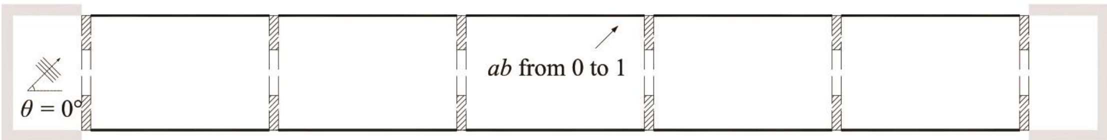
(c) Directional radiation from an additional source



(d) Opening position



(e) Absorption coefficient



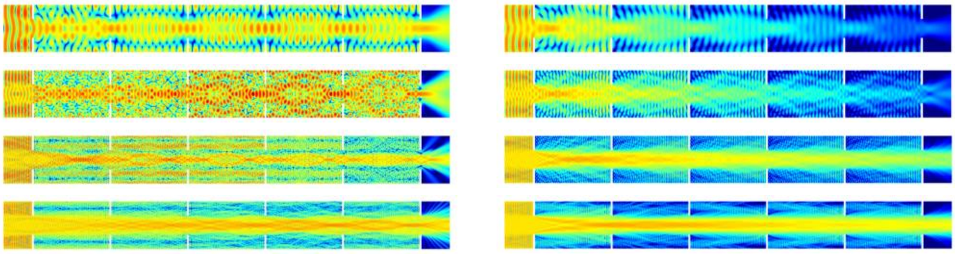
(f) Absorption distribution

Figure 6.4 The experimental plans for (a) Study 1: opening dimension; (b) Study 2: directional radiation from the opening; (c) Study 3: directional radiation from an additional source; (d) Study 4: opening position; (e) Study 5: absorption coefficient; and (f) Study 6: absorption distribution.

6.3 RESULTS

6.3.1 Effect of the Opening Dimension

Figure 6.5 visualizes the SPL distributions for example simulations of the initial model (i.e., d_{op} = 40%) at a range of frequencies for two room absorption conditions (i.e., *ab* = 0.01 and 0.5.) The sound attenuation across the space exhibits different patterns, and the transmitted field on the right is decreases as the frequency increases from 250 Hz to 2 kHz.

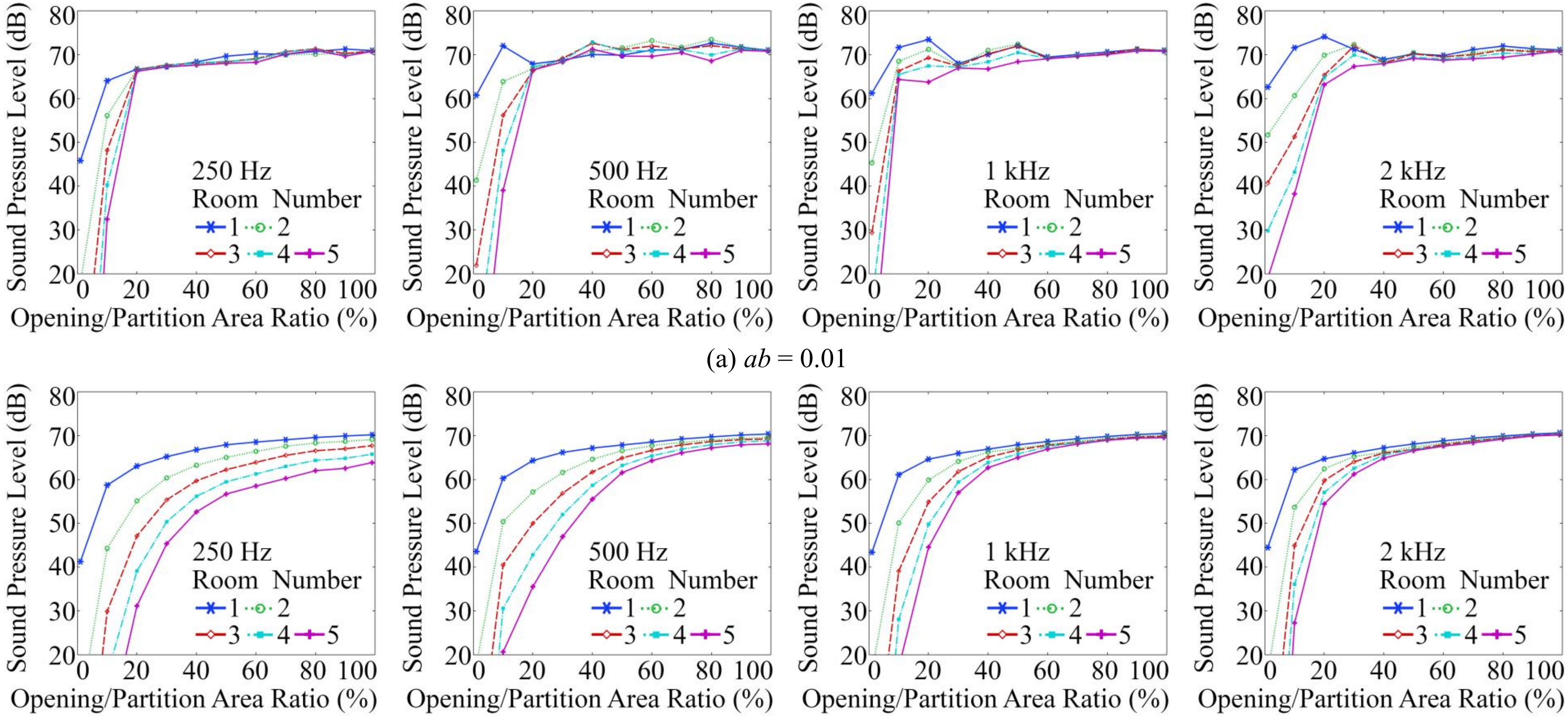


250 Hz
500 Hz
1 kHz
2 kHz

(a) (b)

Figure 6.5 SPL distributions of the initial model at a range of frequencies: (a) *ab* = 0.01 and (b) *ab* = 0.5.

Adjusting the opening dimension could be one of the most direct ways to control sound attenuation by modifying contextual factors. To understand the effect of the opening dimension under two acoustic absorption conditions, low and high room absorption conditions were defined as *ab* = 0.01 and 0.5, respectively. **Figure 6.4a** shows the experimental plan for this study, and **Figure 6.6a** and **b** show the average SPL in a room for d_{op} values from 0% to 100% for the two room absorption conditions. The results reveal that the sound field patterns imposed by the parameter d_{op} are inconsistent for low and high room absorption, indicating that when adjusting the value of d_{op} during the design phase, it is also necessary to consider the room absorption conditions.



(b) *ab* = 0.5

Figure 6.6 The average SPL in a room for d_{op} values from 0% to 100% for two *ab* values at $\theta = 0°$: (a) $ab = 0.01$ and (b) $ab = 0.5$.

In the case of low room absorption, as shown in **Figure 6.6a**, the average SPL in a room attenuates with increasing source–receiver distance, i.e., the level decreases from the highest in room 1 to the lowest in room 5, up to a certain value of d_{op}. The level differences between rooms are large at low d_{op} values whereas at high d_{op} values, they are very small. The value of d_{op} above which the levels become unpredictable is smaller at lower frequencies, e.g., 20% d_{op} at 250 and 500 Hz and 40% at 2 kHz. However, from d_{op} = 0% to 20%, i.e., w_{op} = 0 to 1.0 m, the changes in the average SPL in a room at 250 Hz (close to the wavelength) is different from those in the higher frequencies than 500 Hz especially in room 1 due to sound diffraction as shown in **Figure 6.6a**.

However, the average SPL in a room corresponding to an increasing d_{op} appears to increase up to a certain value of d_{op} and then to decrease in an unpredictable pattern until the value of d_{op} at which the levels are identical across all spaces. Moreover, the level differences are uncorrelated with d_{op}, which could be due to coupling effects between the rooms, i.e., strong, medium, and weak. For low room absorption and a small opening (d_{op} = 0–20%), the coupling effect is weak, i.e., the spaces are acoustically separated with limited sound flow, and the non-diffuse sound field is confined to the area near the opening; therefore, even a small change in the opening dimension could result in significant differences in the sound levels. On the other hand, for a large opening (d_{op} > 60%), the separated spaces act as a single space, and any change in the opening dimension does not significantly affect the sound levels. In addition, when the opening dimension is in the medium range (d_{op} = 20–60%), the non-diffuse sound field near the opening area could be the largest compared to cases of small and large openings.

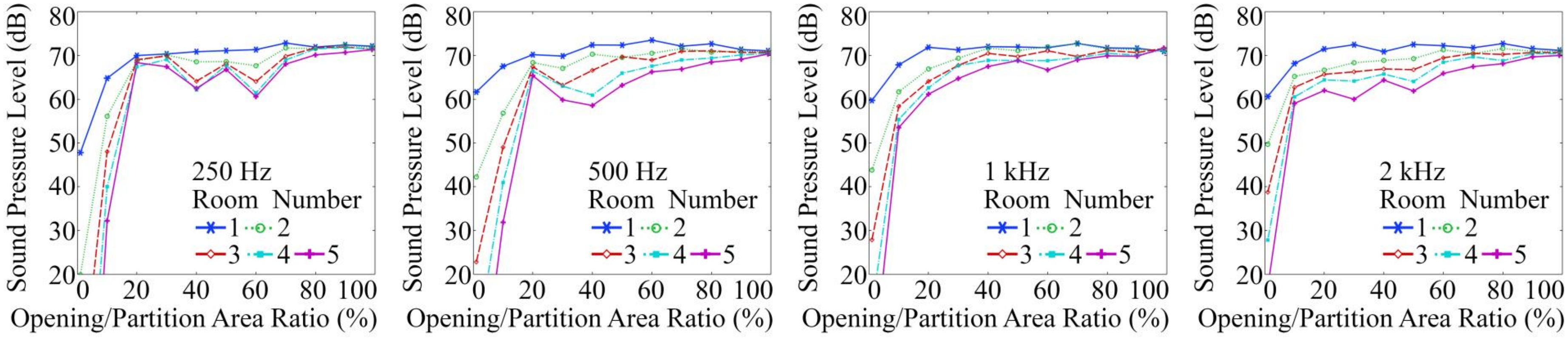
As shown in **Figure 6.6b**, in the case of high room absorption, the average SPL in a room clearly attenuates from highest to lowest from room 1 to room 5, and the values gradually increase with increasing d_{op}. These patterns are similar at all frequencies. The level differences between rooms gradually kept and continuously decrease before stabilizing. With increasing d_{op}, the efficiency of reaching a stable value is greater at higher frequencies than at lower frequencies. The reason could be that as d_{op} increases, the sound flow from the other side of the spaces decreases. Once d_{op} reaches a certain value, the levels are no longer affected by d_{op}, and the separating partitions can be regarded as acoustically transparent as an effect of diffraction. For high room absorption, the distribution of the sound energy becomes more uneven with increasing

d_{op}, and the attenuation in the sequential rooms increases close to a free-field conditions. Interestingly, similar results are also obtained with a smaller room length (l = 5.0 m).

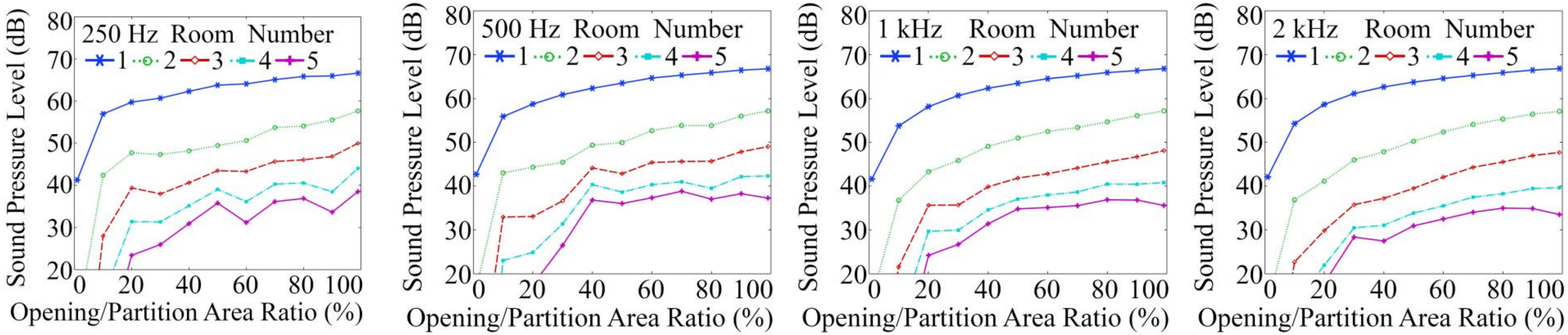
6.3.2 Effect of the Directional Radiation from the Opening

An incidence angle of θ = 60° was defined to simulate the sound field when the source and receiving rooms are not at the same height level, e.g., for a room on the second floor near an atrium. **Figure 6.4b** shows the experimental plan for this study, in which the parameter d_{op} was again varied to examine the effects of an oblique sound incidence angle on the opening.

Figure 6.7a and **b** show the results obtained at θ = 60° corresponding to those obtained at θ = 0° in **Figure 6.6a** and **b**. The results also reveal that from d_{op} = 0% to 20%, i.e., w_{op} = 0 to 1.0 m, the changes in the average SPL in a room at 250 Hz (close to the wavelength) is different from those in the higher frequencies than 500 Hz especially in room 1 due to sound diffraction as shown in **Figure 6.7a**. Additionally, the average SPL in room 1 is the same, while those in rooms 2–5 are considerably reduced compared to those at θ = 0°. The differences between low and high room absorption are also more significant at θ = 60°. In the case of low room absorption, as shown in **Figure 6.7a**, the average SPLs at θ = 60° are still somewhat random but clearly attenuate from room 1 to room 5. The level differences between rooms are larger than those at θ = 0° at all the frequencies. In the case of high room absorption, as shown in **Figure 6.7b**, trends in which the average SPL in a room increases and the level difference decreases to a stable value with increasing d_{op} are shown, similar to those at θ = 0°. However, the stable value of the level difference increases, being, e.g., close to 10.0 dB at θ = 60° rather than close to 0 dB as at θ = 0°. The level differences between rooms nearer the sound source are more significant because of the direct sound component. The coupling effect is also more evident at θ = 60°. Especially under the condition of low room absorption for opening dimension in the medium range, the level differences between rooms are significant, indicating a more obvious non-diffuse sound field near the opening. Additionally, for rooms with high room absorption, the level differences between rooms are larger than those at θ = 0°.



(a) $ab = 0.01$



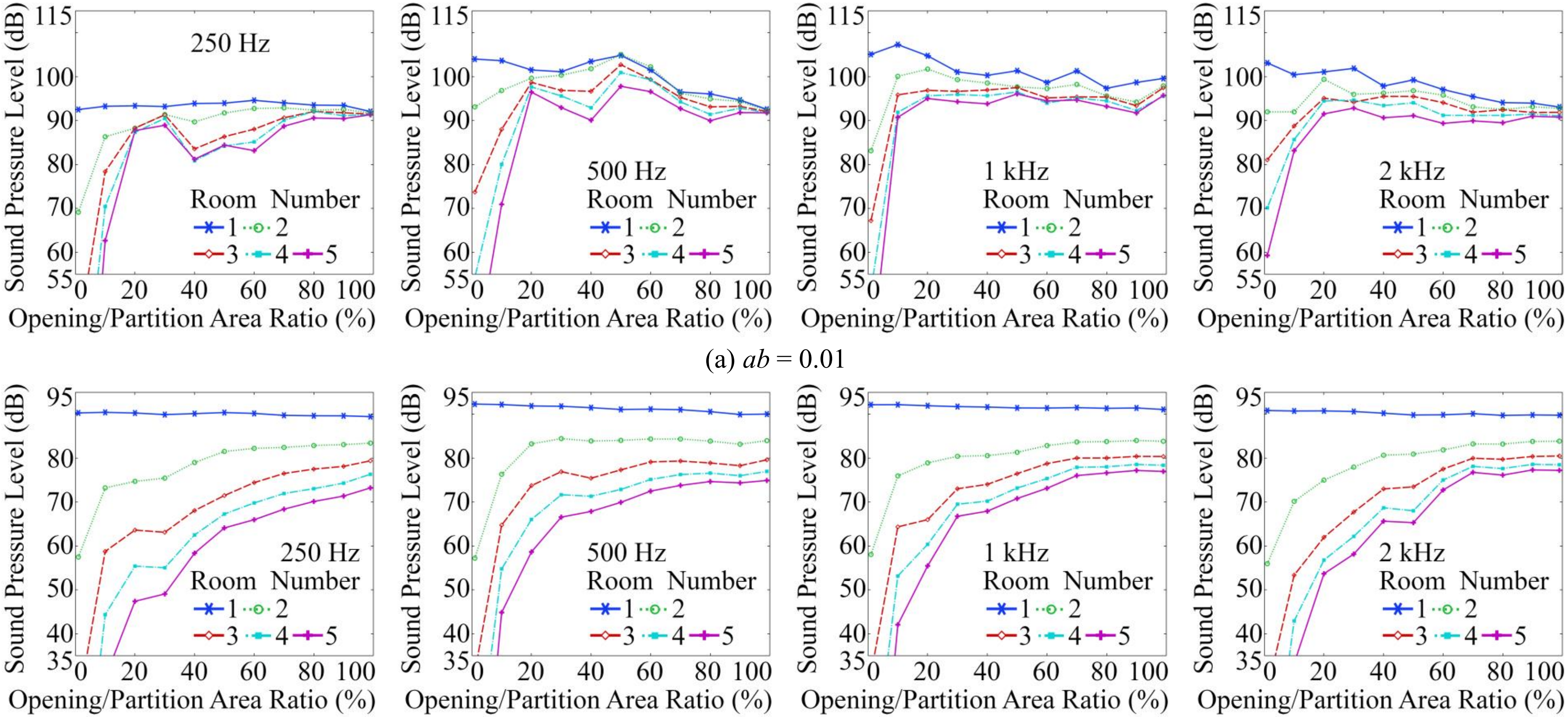
(b) $ab = 0.5$

Figure 6.7 The average SPL in a room for d_{op} values from 0% to 100% with two ab values at $\theta = 60°$: (a) $ab = 0.01$ and (b) $ab = 0.5$.

In regard to the directional radiation from the opening, for both low and high room absorption, the level differences between rooms are larger when the source room is located at a different height level than the receiving room compared to the case in which both are at the same level, indicating greater attenuation across the space. The level differences between rooms are significantly higher for those rooms closest to the source compared to the successive level differences between rooms. This tendency is not observed when the source and receiving rooms are located at the same height level, indicating a distinct gap in listener perception (e.g., loudness) between the source and first receiving rooms.

6.3.3 Effect of the Directional Radiation from an Additional Source

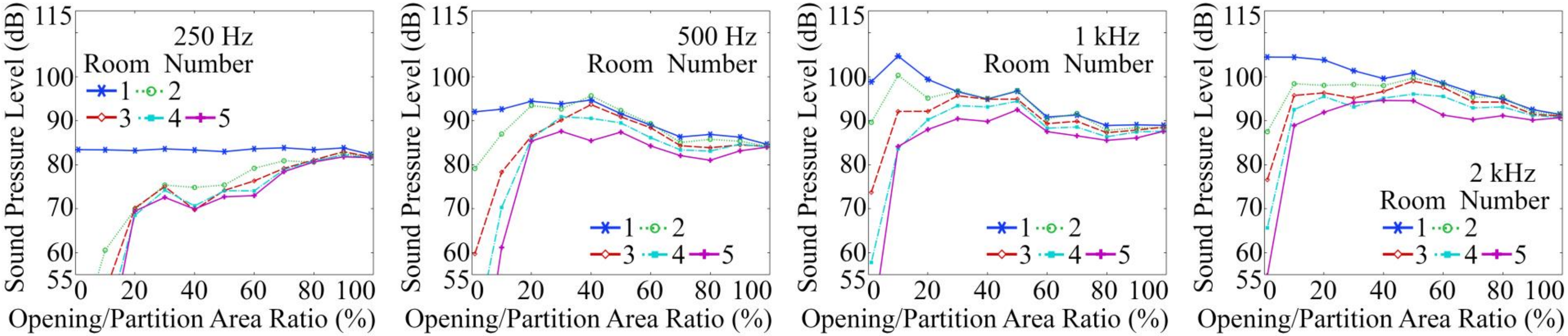
To study the effect of an additional omnidirectional or directional source, a point source in room 1 was investigated while varying the parameter d_{op}, as shown in **Figure 6.4c**. **Figure 6.8a** and **b** present the average SPL in a room with an omnidirectional point source (source A) in room 1. The results reveal that with increasing d_{op}, only the average SPL in room 1 gradually decreases, whereas it increases in rooms 2–5. Because the sound level in room 1 is high, the magnitude of the change caused by increasing d_{op} is not large, especially at low frequencies. In contrast, the sound level in room 5 is the lowest; therefore, the magnitude of the corresponding change caused by increasing d_{op} is large. The closer a room is to the source, the smaller the change in its sound level. Similar results are obtained with a directional point source (source B) in room 1, as shown in **Figure 6.9**.



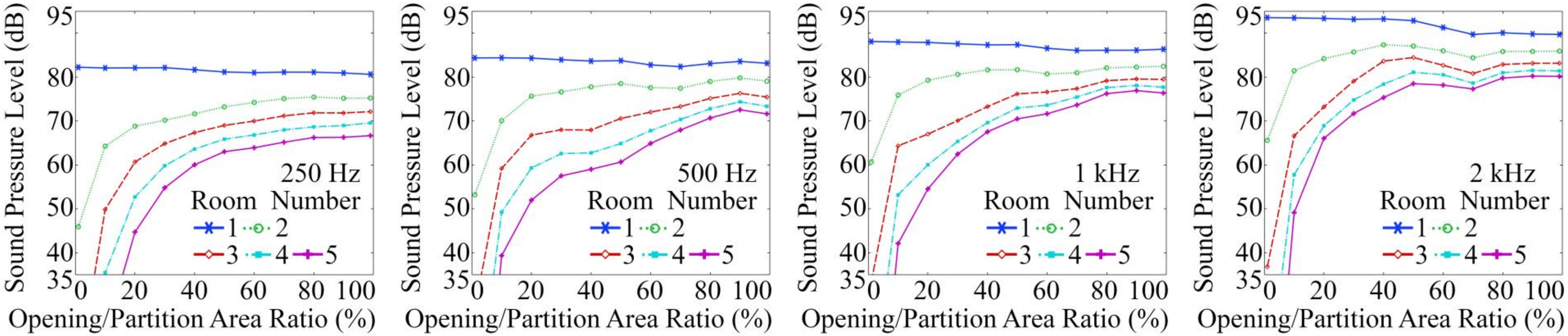
(a) ab = 0.01

(b) ab = 0.5

Figure 6.8 The average SPL in a room for d_{op} values from 0% to 100% with two ab values and with an omnidirectional point source in room 1: (a) ab = 0.01 and (b) ab = 0.5.



(a) ab = 0.01



(b) ab = 0.5

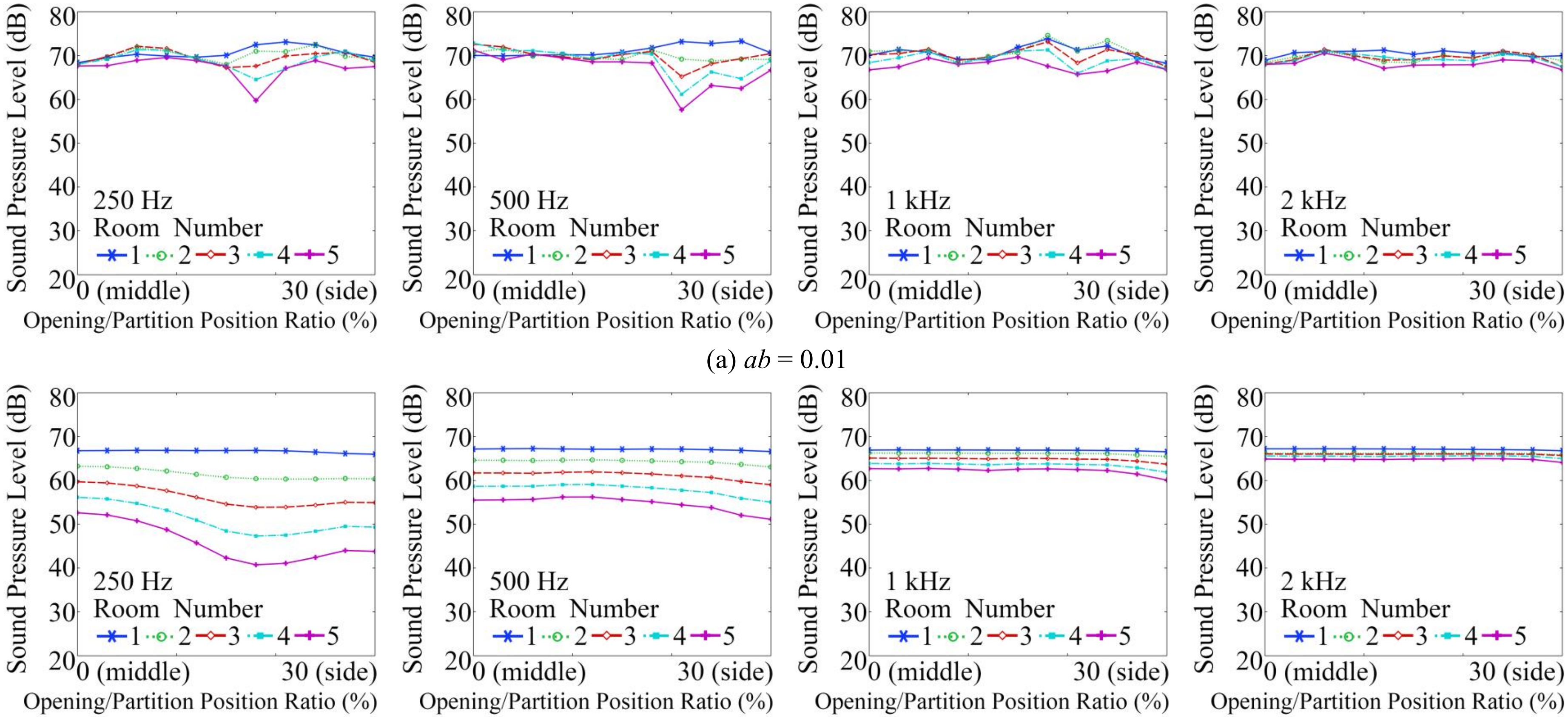
Figure 6.9 The average SPL in a room for d_{op} values from 0% to 100% with two ab values and with a directional point source in room 1: (a) ab = 0.01 and (b) ab = 0.5.

With an additional source (e.g., an HVAC system or human speech) at a particular location, the level differences between rooms increase, indicating greater sound attenuation across the space. However, only the average SPL in the room that contains the additional source exhibits a decrease rather than a sharp increase with increasing opening dimension, whereas those in the other rooms increase, indicating inconsistent behaviour between the source and receiving rooms. Therefore, to achieve a lower average SPL with an additional source, enlarging the opening dimension is effective for reducing the sound level in rooms with low absorption, but this effect will be very limited for rooms with high absorption.

6.3.4 Effect of the Opening Position

The opening position, whether in the middle of the separating partition or against the sidewall, clearly defines how people move between spaces. Additionally, it can divide the room volume into two functional parts. **Figure 6.4d** shows the experimental plan of this study.

Figure 6.10 shows the average SPL in a room for p_{op} values from 0% to 30% (corresponding to the maximum $p_{op} = (1 - d_{op})/2\%$ for $d_{op} = 40\%$) under the two considered room absorption conditions (high and low). The step size in distance between the considered opening position values is $p_{op} \times w_{sp}/10 = 0.15$ m. The results reveal that the sound field patterns with varying p_{op} under low and high room absorptions are fundamentally different. In the case of low room absorption, as shown in **Figure 6.10a**, the average SPL in a room varies randomly with increasing p_{op} as the opening moves from the middle to the side of the separating partition; however, attenuation with increasing source-receiver distance can be observed. The range of the changes in the sound level in room 1 is the smallest, and that for room 5 is the largest. The level differences between the rooms are uncorrelated with p_{op}. In the case of high room absorption, the average SPL in a room remains unchanged with increasing p_{op}, and the level differences between rooms decrease with increasing frequency, as shown in **Figure 6.10b**. The reason why the opening position has a limited impact on the sound field for high room absorption could be the relative lack of reflections, which are more prevalent in a room with low absorption.



(a) $ab = 0.01$

(b) $ab = 0.5$

Figure 6.10 The average SPL in a room for p_{op} values from 0% to $(1-d_{op})/2$% with two ab values at $\theta = 0°$: (a) $ab = 0.01$ and (b) $ab = 0.5$.

Therefore, the influence of the opening position, whether in the middle of the separating partition or attached to the sidewall, on sound attenuation performance suggests a technique for professionals to utilize it to determine the path for listeners. In the case of low room absorption, the sound field is significantly affected by even small changes in the opening position, whereas for rooms with high absorption, the average SPL in a room will remain at the same level irrespective of the opening position.

6.3.5 Effect of the Absorption Coefficient

Adjusting the absorption coefficient could be one of the most straightforward post-construction means of implementing noise control. To determine the effect of the absorption coefficient in connected spaces, a study was conducted in accordance with the experimental plan shown in **Figure 6.4e**.

Figure 6.11 shows the average SPL in a room for *ab* values in the range from 0 to 1 with d_{op} = 20% and 40%. The results reveal that the patterns for small and large opening dimensions are consistent. However, note that the average SPLs in rooms 2−5 for d_{op} = 40% are significantly lower than those for d_{op} = 20%, whereas those in room 1 are roughly equivalent for both d_{op} values. In general, the average SPL decreases within a certain range as *ab* increases. The larger the source–receiver distance is, the larger the magnitude of the sound level change. It is also observed that the rate of change is higher at smaller *ab* values than at larger values. Thus, increasing *ab* to modify sound attenuation could be more efficient at smaller *ab* values than at larger ones. As expected, the level differences between rooms at d_{op} = 20% (i.e., a small opening size) are much larger at all frequencies than those at d_{op} = 40% (i.e., a large opening size). For both d_{op} values, the level differences between the rooms gradually decrease with increasing frequency.

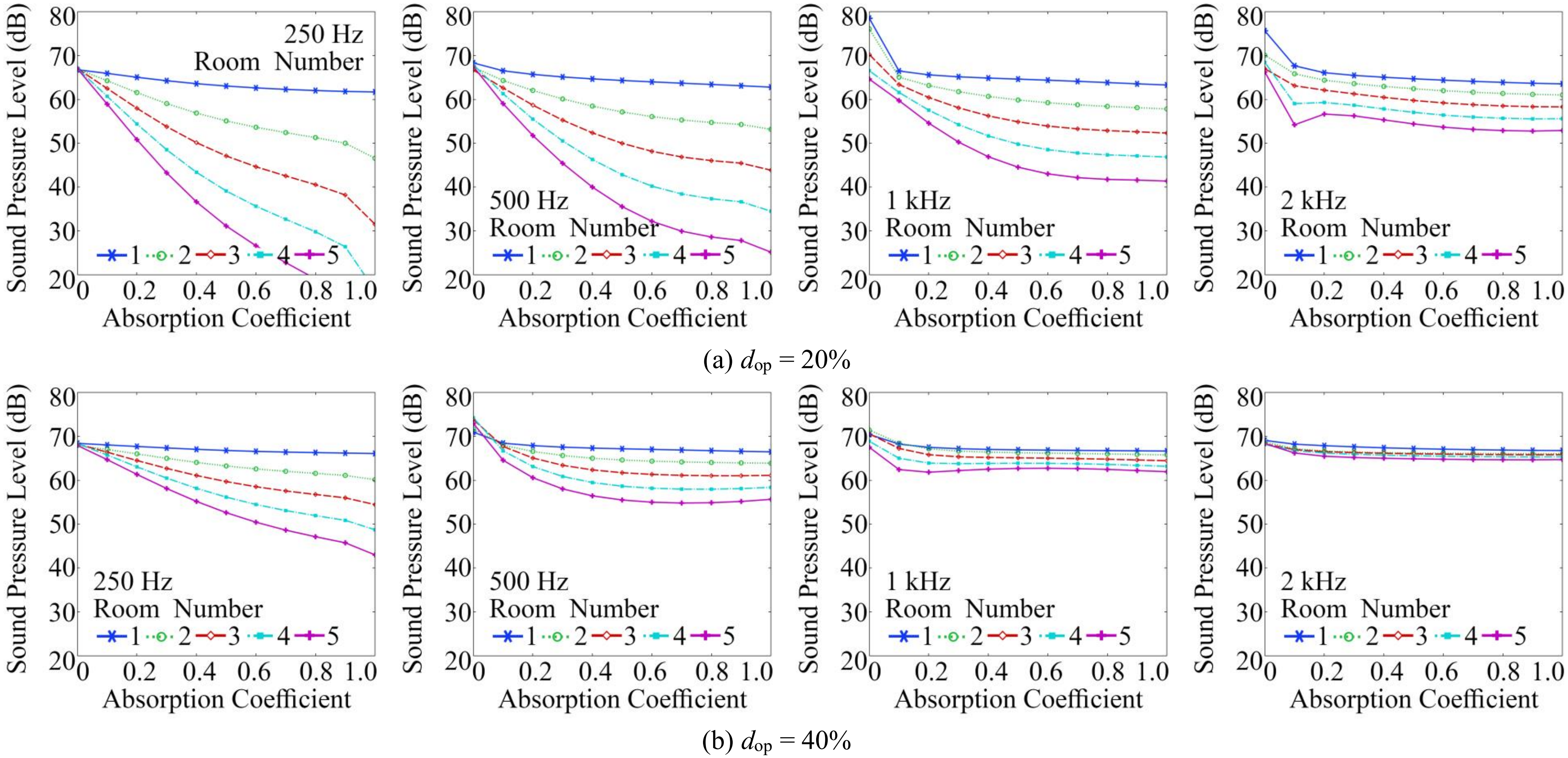
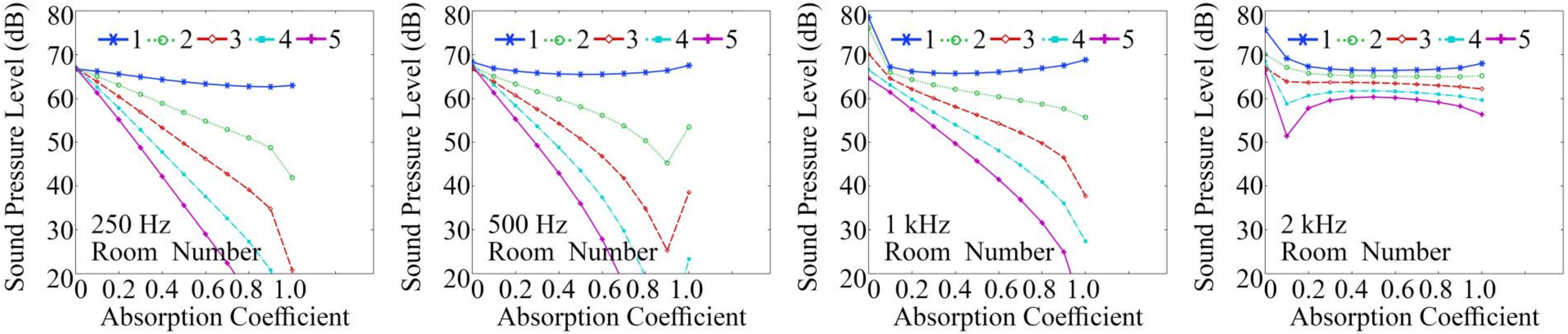


Figure 6.11 The average SPL in a room for *ab* values from 0 to 1 with two d_{op} values at $\theta = 0°$: (a) d_{op} = 20% and (b) d_{op} = 40%.

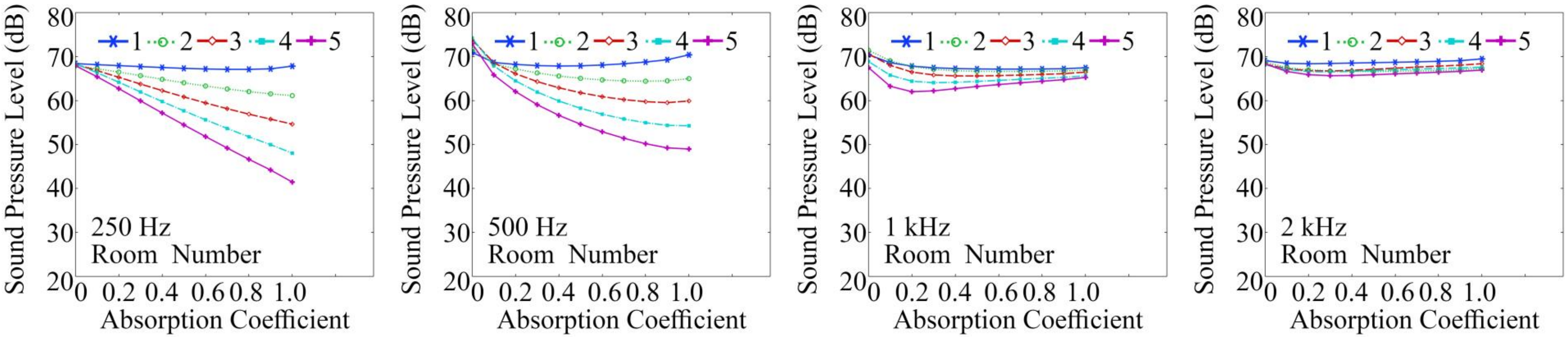
6.3.6 Effect of the Absorption Distribution

Instead of changing the absorption coefficient, another simple approach is to adjust the absorption distribution. **Figure 6.4f** illustrates the experimental plan used to determine the effect of the absorption position. In this experiment, the absorptive areas were placed along the length of the sequential spaces, i.e., along the sound attenuation direction, while keeping the entire absorption amount equivalent to that of the plan shown in **Figure 6.4e** (in which the absorption was evenly distributed in each room).

Figure 6.12 shows the average SPL in a room for *ab* ranging from 0 to 1. The results show that, under the assumption of an equivalent amount of absorption in each room, the difference in the average SPL in a room between the case in which the absorptive areas are positioned only along the direction of sound attenuation (non-uniform distribution) and the case in which they are evenly distributed in the room (uniform distribution) when d_{op} is small, whereas it was negligible for a large d_{op}. Therefore, it is concluded that the effect of absorption distribution between uniform and non-uniform is presented by a small opening size. It is observed that, for a larger d_{op} = 40% , i.e., w_{op} = 2.0 m, as shown in **Figure 6.12b**, the average SPLs in a room in the higher frequencies, i.e., 1 kHz and 2 kHz, increase with increasing *ab* over the entire range of 0–1, rather than remain at the same level as seen in **Figure 6.11a** for uniform absorption.



(a) d_{op} = 20%

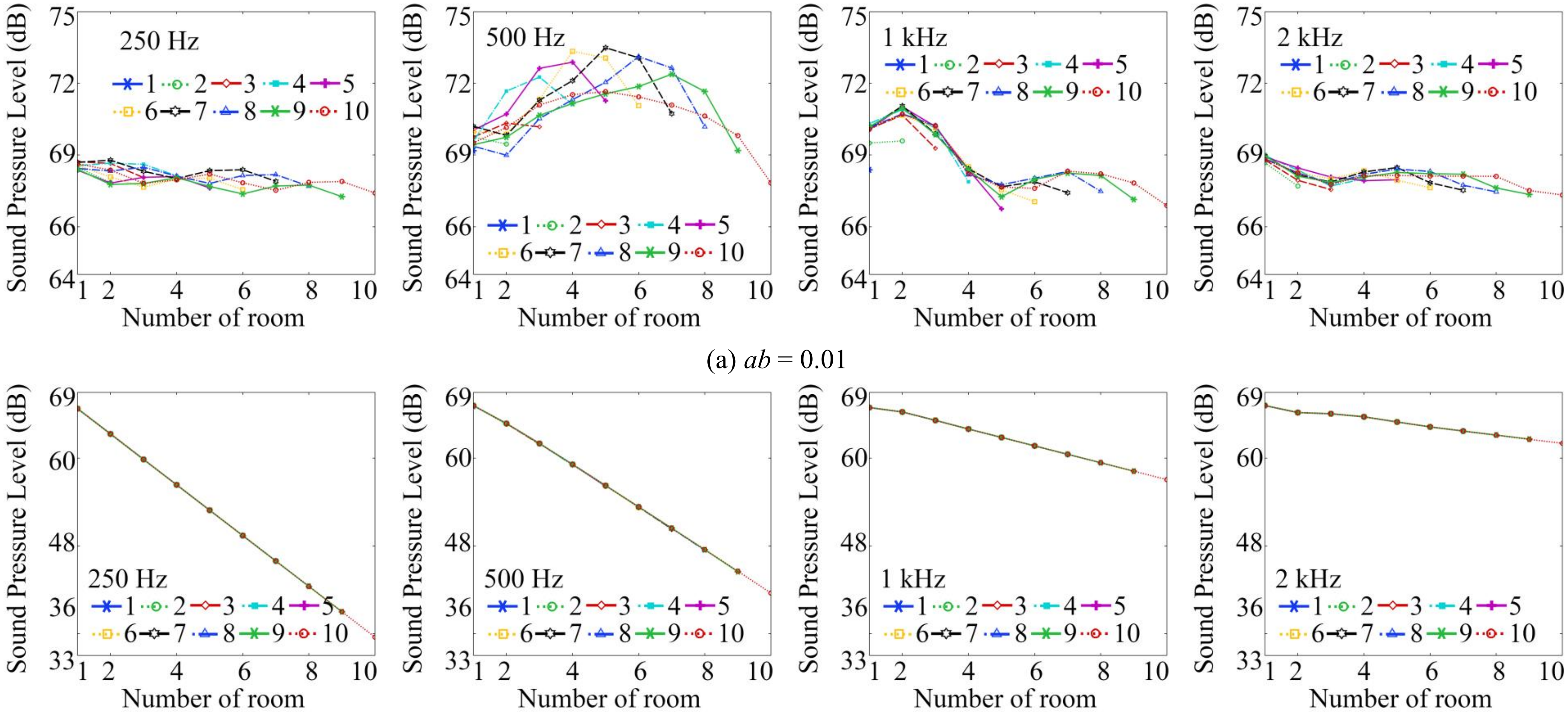


(b) d_{op} = 40%

Figure 6.12 The average SPL in a room for *ab* values from 0 to 1 with two d_{op} values at $\theta = 0°$ for nonuniform absorption: (a) d_{op} = 20% and (b) d_{op} = 40%.

6.3.7 Effect of the Number of Rooms

This chapter has essentially focused on large-scale spaces consisting of a number of small rooms. **Figure 6.13** shows the average SPL in a room for *N* ranging from 1 to 10 under two room absorption conditions. The results reveal that with increasing *N*, the average SPLs in the existing and added rooms change inconsistently depending on the room absorption conditions. In the case of low room absorption, as shown in **Figure 6.13a**, the average SPLs in the existing and added rooms are different for different *N*. However, the pattern of sound attenuation is similar irrespective of *N*. In the case of high room absorption, as shown in **Figure 6.13b**, not only the pattern of sound attenuation but also the average SPL in a room remain the same at all frequencies, while the level range decreases with increasing frequency. It is interesting to note that with increasing *N*, the average SPL in room 1 changes for low room absorption but remains constant for high room absorption.



(a) *ab* = 0.01

(b) *ab* = 0.5

Figure 6.13 The average SPL in a room for *N* ranging from 1 to 10 with two *ab* values: (a) *ab* = 0.01 and (b) *ab* = 0.5.

6.4 DISCUSSION

6.4.1 Design Decision under Certain Assumptions

Schemes in which all the parameters that have been varied are summarized in **Table 6.1**. Correspondingly, the results that can be used for reference during the design phase by professionals are presented in **Table 6.2**. Possible practical applications are presented in the Application column of **Table 6.2**. Many previous studies have generally described how sound spreads and how it can be discouraged from spreading. In this study, practical aspects of the results were determined under different assumptions, as summarized in the Assumptions column of **Table 6.2**. For most of the investigated schemes, such as the contextual factors, the assumptions of low or high room absorption and either a small or large opening dimension must be considered when applying the results.

Generally, the greater the distance a room is from the source, the larger the magnitude of the level changes that can be achieved by modifying various parametric factors, as shown in the results for the opening dimension obtained in Studies 1, 2, and 3. Considering the just-noticeable difference (JND) in the first receiving room, it is observed that most outcomes greatly exceed the target JND, which is 0.25 dB at the most sensitive levels (greater than 60 dB) and frequencies (1–4 kHz) (Long, 2014), except for the first receiving room in the case of high room absorption and with the presence of an additional source. Practically, as a design objective is often to achieve an ideal sound attenuation, Kang (2002) noted that in practice, because design objective is often to achieve ideal sound attenuation, the absorbers used as surface treatments must be evenly placed in long spaces. The results of Study 6 similarly demonstrate that for an equivalent amount of absorption, consistent performance is not ensured between uniform and nonuniform distributions, especially in the case of a small opening dimension. It is also worth noting that according to McMullan (1991), increasing the sound absorption in a room has little effect on the sound passing between rooms. This finding is further confirmed in Study 5, which shows that increasing the sound absorption in a room has little effect on the sound passing between rooms for rooms with high absorption, whereas such adjustments made to rooms with low absorption could result in greater changes.

Table 6.2 The results of each scheme showing the assumptions that should be considered as well as the applications and guidelines that should be used by professionals in the design phase.

Scheme	Assumptions	Main results	Application
Opening dimension	Room absorption: low/high	The average SPL in a room increases as the opening/partition area ratio increases for rooms with high absorption until the level difference between rooms stabilizes.	If a large opening is required, one should expect a high average SPL and a small level difference between rooms for rooms with high absorption, while no such pattern is found for rooms with low absorption.
Directional radiation from the opening	Room absorption: low/high	The level difference between the rooms is larger for oblique incidence than for horizontal incidence, particularly for rooms close to the source.	If the receiver and source are at different heights, the level differences between rooms are larger than if the source and receiver are at the same height and larger for rooms closer to the source.
Directional radiation of the additional source	Room absorption: low/high	With an additional source, the average SPL in a room either remains the same or decreases by approximately 10 dB with an increasing opening/partition area ratio. The level difference between the rooms becomes larger with an additional source.	To reduce the average SPL in the presence of an additional source (e.g., an HVAC system and human speech), increasing the opening dimension could be useful; however, the average SPLs in other rooms as the opening dimension increases, especially for rooms with high absorption.
Opening position	Room absorption: low/high	Changes in the opening position affect the average SPL in a room only for rooms with low absorption and not for those with high absorption.	To determine the path of crowd noise across spaces, the opening position needs to be considered only for rooms with low absorption.
Absorption coefficient	Opening dimension: small/large	Adjustments made within small absorption coefficients result in greater changes in the average SPL than those made to large absorption coefficients.	The strategy of absorption adjustment as a remedial measure yields limited benefits for rooms with high absorption.
Absorption position	Opening dimension: small/large	For a given absorption amount, the differences in the average SPL in a room between the cases of uniform and nonuniform absorption distributions is larger for a smaller opening dimension.	Ensuring an equivalent amount of absorption between cases of uniform and nonuniform distributions does not ensure consistent performance, especially for rooms with small openings.
Number of rooms	Room absorption: low/high	The average SPL in the first receiving room remains constant for high room absorption. The maximum difference between cases with different absorption coefficients is approximately 6 dB, depending on the number of rooms.	In the case of increasing the scale of the entire space (e.g., the number of rooms), to avoid interference in the first receiving room, high room absorption is necessary.

6.4.2 Limitations and Future Work

Although the FEM is relatively stable and effective, the amount of calculation time required confines the predictions to two-dimensional modelling in the validity tests. Future work could involve more efficient methods that could enable three-dimensional simulations to be conducted under high-frequency conditions to allow issues, such as the height of the spaces to be investigated. Additionally, the Schroeder Cut off frequency can be calculated in the case of a three-dimensional predication model as it deals with either wave energy or low frequency, or ray energy which is the middle and high frequency, that establishes when modality dominates the predictions further explaining the results at low frequencies. Moreover, there are other related aspects to consider in the future, e.g., rooms with circular and irregular shapes, and rooms that are connected at the corners.

6.5 CONCLUSION

In this chapter, the prediction accuracy for sound attenuation in sequential rooms was examined by validating the results of FEM simulations through comparison to *in situ* measurements collected in exhibition spaces. Then, a parametric study was carried out by considering the contextual factors (opening dimension and position, number of rooms), acoustic factors (absorption coefficient and position) and source factors (directional radiation from the opening and an additional source) to determine the effects on the average SPL in a room. It is concluded that

- for rooms with high absorption, the average SPL in a room is higher and the level difference between rooms is smaller with a larger opening dimension, whereas for rooms with low absorption, the changes in the average SPL are more complicated. The opening position has a significant impact only for rooms with low absorption;
- the level difference between rooms is larger for oblique radiation than for horizontal radiation, especially for rooms close to the source. With an additional source (e.g., an HVAC system or human speech) in a room, the average SPL is maintained or reduced by approximately 10 dB with increasing opening dimensions for rooms with high or low absorption, respectively. In contrast, the average SPLs in other rooms increase with

increasing opening dimension for rooms with high absorption, but there is no clear trend for rooms with low absorption;

- the changes of the average SPL in a room achieved by adjusting the absorption are more significant for cases of small absorption coefficients. For a given amount of absorption, the difference in the average SPL in a room between uniform and nonuniform absorption distributions is greater with a smaller opening dimension; and
- with the addition of more connected rooms, the effect on the average SPL in the first receiving room is lesser when the absorption in the added rooms is high (e.g., with an absorption coefficient of 0.5). Furthermore, the maximum difference between cases of absorption coefficients is approximately 6 dB, depending on the number of rooms.

7 Approaching and Receding Sound Sources of a Listener in Motion

As demonstrated in Chapter 3, listeners adjust their temporal and spatial noise perception on a directional basis. The asymmetry of approaching and receding sound sources in the loudness and listener envelopment occurs with broadband noise. This chapter additionally explores the dynamic auditory perception in context of music and human voice.

7.1 INTRODUCTION

The characteristics of the dynamic sounds that people hear during normal movement, i.e., clearer, and louder or un-clearer, and quieter on their chosen path, are important for a variety of topics. For instance, well-defined traffic flow patterns are desirable in large-scale buildings with multiple spaces, e.g., museums and stores. In contrast to natural environments, the direction of a listener in motion within a building is crucial, as the sound propagates through architectural sequential spaces on the same path. Several visual and non-perceptual factors, e.g., lighting, events, PA, and VA systems (British Standards Institution, 2019, British Standards Institution, 2017), influence traffic flow patterns for acoustic, aesthetic, and functional purposes. However, investigations on the dynamic auditory perception for multiple sound sources and background noise are seldom reported.

To start with the perceived difference between two sound signals, whether identical or not, Cremer and Müller proposed two methods for evaluating the subjective loudness (Cremer and Müller, 1982). One method is a reiterative approach wherein the signals are controlled by the subject. Beginning with a signal A_1, which is louder than signal A_2, the subject gradually lowers the loudness of signal A_1 until it becomes weaker than signal A_2. Second method is to set a reference signal, wherein the subject listens to steadily stimulated signals A_1, A_2,…,A_n and is required to compare each signal to the reference signal. Thereafter, the loudness of signal A_n is evaluated as either larger or smaller than the reference signal. Cremer and Müller suggested that the latter method is more reliable because the results obtained by the former method could be different if the order is reversed, i.e., the quieter signal A_2 approaches the louder signal A_1. To some extent, this raises the perceptual disparity between the rising and falling sound levels as a key question in the study of acoustics.

To understand the dynamic sounds in the context of the frequency spectrum, waveform amplitude, or both, a series of technical measures have been proposed to estimate the loudness of fluctuating sound. These measures, including the energy-equivalent level of a steady sound (L_{eq}) and the 95th percentile of the loudness distribution N_5 (Zwicker and Fastl, 1999), assume that all temporal portions of a sound contribute equally to overall loudness (Ellermeier and Schrödl, 2000). However, this conjecture was demonstrated to be incorrect in previous studies in which the listeners' judgments of the global loudness of a level-fluctuating noise with a duration of 1 s are influenced more by the first 100–300 ms of the sound than by its middle portion (Pedersen and Ellermeier, 2008, Dittrich and Oberfeld, 2009, Rennies and Verhey, 2009). The temporal weighting of the loudness presents a pattern similar to the primacy effect in the short-term memory (Baddeley, 1966, Oberfeld and Plank, 2011). The beginning of the temporal sound has higher weights, indicating that the first portion contributes more to the perceived loudness of the sound than the middle portion. Also, the end portion has higher weights to a lesser extent than the middle portion as a recency effect (Dittrich and Oberfeld, 2009, Rennies and Verhey, 2009). The rising and falling sounds has been demonstrated to have different perceptions (Neuhoff, 1998). This evidence suggests that the changes in the loudness for each portion or rising and falling tones in architectural sequential spaces, could be a complex and nonlinear phenomenon.

For the building environment, Bruce and Davies (2014) suggested that prior experiences of similar spaces and the perceived loudness affect the expectation of the soundscape through the soundwalks in urban environments. Through numerous listening tests, Wang *et al*. (2020) explored the noise acceptance by evaluating the recordings taken in transportation spaces with the acoustic sequence, i.e., when the listener was either stationary or walking in spaces where the sounds form sequences. The acoustic units were divided into strong, medium, and weak levels. Wang *et al.* concluded that all of the acoustic sequences exhibited "attenuation effects." The high-acceptance units offer an "enhancement effect," wherein the acceptance increases after a high-level acceptance. The low-acceptance units display a "boost effect," in which the acceptance increases after a low-level acceptance. These approaches have reported outcomes that potentially explain how people deal with the familiarity of a sound source or sequence. However, visual information plays an important role in calibrating the auditory space and, therefore, the lack of spatial information during the experiment raises concerns in practice. Several applications are being developed by using the virtual and augmented reality revolution to explore the visual content along with the acoustic spatiality. Although there are continuing discussions on the validity between the RE and VE, the success of virtual soundwalks (Oberman et al., 2020), dynamic auditory perception (Rungta et al., 2017), and a convincing virtual acoustic environment, which is guided with a real-world sound field, could provide a reference for further studies in this regard.

As part of the spatial information, the auditory distance perception related to the rising and falling tones, enabling the location of the objects, is important in the spatial awareness. However, the research relative to the studies on the directional aspect of the sound localization remains scarce (Kolarik et al., 2016). The primary cues are the sound level, reverberation, and frequency. Also, the effect of the background noise and multiple sound sources could have remarkable relevance to the distance judgments (Guth et al., 2013). However, the effects of noisy environments on auditory distance perception are unknown except for the study of Mershon *et al.* (1989), which reported that the perceived auditory distance for the sound sources decreased as the background noise level increased for a distance between 0.75 and 6.0 m in rooms with a high or low reverberation effect. Moreover, the auditory distance information is useful in segregating the sound sources in complex acoustical conditions when the background noise or reverberations are present, helping focus attention and improve the identification of the sound source, including in “cocktail party” situations (Kidd et al., 2005, Kolarik et al., 2016, Haykin and Chen, 2005).

The overarching aim of this chapter is to explore the dynamic auditory perception of a listener in motion, i.e., approaching and receding sound sources, with a stationary primary sound source in acoustically complex enclosures, i.e., large sequential public spaces where background noise or reverberations are present. Also, the effect of the sound source type is explored. In this chapter, the soundwalks were conducted in VE, which are validated with the soundwalks in RE. The research contains the implication that none of the paths are sufficiently loud in dB to cause auditory discomfort, which could yield path avoidance behavior.

7.2 METHODS

7.2.1 Site Selection

The right side of the **Chapter 4** case site (i.e., sound-source group) was chosen. To clarify the effect of the primary sound source in the source and receiving rooms, as discussed in **Chapter 4**, for the unoccupied condition, the value of $L_{A\text{eq-1min}}$ in the source room (room 1) was 66.8 dB(A), and the values in the receiving rooms (rooms 2−4) were 60.5, 55.4, and 53.6 dB(A), respectively. Precisely, the entire level attenuation for the sound-source group was 12.2 dB(A), whereas the level difference between rooms was 6.3, 5.1, and 1.8 dB(A), respectively. For the occupied condition, the $L_{A\text{eq-1min}}$ in each room were the mean values of the objective results of the corresponding subjective evaluations conducted simultaneously. The value of the source room (room 1) was 68.3 dB(A), and that of the receiving rooms (rooms 2−4) were 62.6, 58.8, and 59.7 dB(A), respectively. Precisely, the entire level attenuation for the sound-source group was 8.6 dB(A), whereas the level difference between rooms was 5.7, 3.8, and −0.9 dB(A), respectively.

7.2.2 Virtual Reproduction

The VE was constructed using the Unreal Engine (Epic Games, Cary, North California), in accordance with the acoustical and contextual attributes obtained in the RE. For the contextual attributes, the room shape, scale, and interior finishes (e.g., the material of the floor, wall, and ceiling) corresponded for the RE and VE were therefore replicated. On the other hand, the consistency of the content detail of the exhibits is pursued to an acceptable extent under the assumption that the auditory perception of the participant during the experiment is not affected by the differences in the contextual attributes of the exhibits between the RE and VE. However, “Babel, 2001” was well presented visually in the VE for its importance and specification. As shown in **Figure 7.1**, the radios were arranged by the size at different levels using uniform materials, and the lighting on them was replicated to the authors’ best efforts with the specifics.

Figure 7.1 (Left) The site configuration of two experiment paths (approaching/receding sound sources) with the start/end and rating points in the VE. The corresponding photos/renderings of the source (left) and receiving room (right) are depicted for the (top) RE and (bottom) VE.

There is considerable value in validating the acoustic spatiality, consisting of the primary source “Babel, 2001” which attracts worldwide visitors, rather than modelling what would be possible to build in large spaces, such as factories. More importantly, the underlying goal of this research, discussed in the Section 7.1, is also to explore the effects of the multiple sound sources and background noise, seeking a wider application of the dynamic auditory perception in the VE. As a result, the baseline condition for the validation between the RE and VE was selected as the occupied condition.

To reproduce the primary sound source “Babel, 2001” in the VE, the recordings taken in the source room at the site were not used as the clips for the laboratory listening test for two reasons. First, the content of “Babel, 2001” was constantly changing, therefore, the representation of the recorded sample was not considered sufficient. Another reason is that considering the effect imposed by the reverberation, the recordings could be too generalized and, additionally, the background noise could vary for each position on different days. The reproduction method should be more generic for the validation. **Figure 7.2a** shows the spectrograms of the site recordings, obtained under the unoccupied condition in the source room (room 1). The character of the primary source, as described on the Tate Modern webpage (Barson, 2011), is an analog audio streaming “a cacophony of low, continuous sound,” barely audible to the human ear. It originates from the early 16th century Babel (see the Tower of Babel (2021b)), where, according to the biblical story, God made all of the builders speak different languages. The installation is reported to be a collection of 800 radios (2021), and every moment of "Babel, 2001" is unique. Therefore, an environment with multiple voice and music sounds in the source room (room 1), i.e., the cocktail party effect, is relevant to the context.

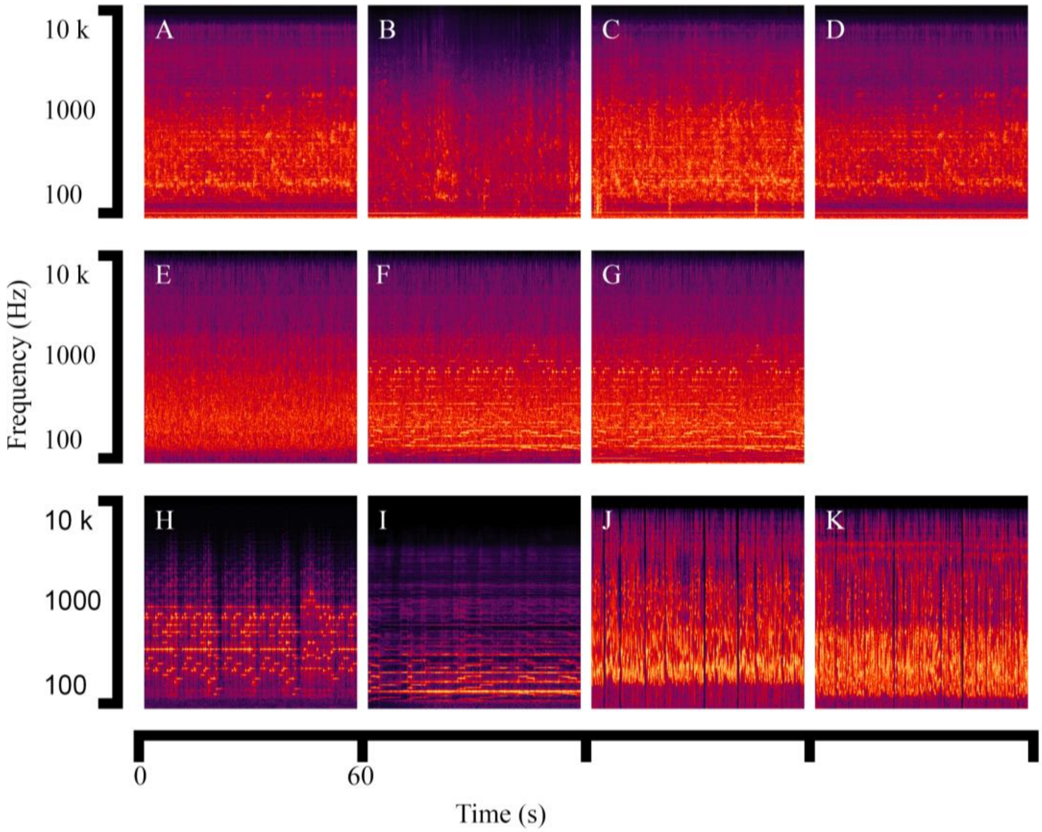


Figure 7.2 The spectrograms, including the site recordings (first row), samples for the validation between the RE and VE (second row), and samples for the virtual experiment (third row), are shown for the (a) unoccupied condition in the source room (RE); (b) background sound of the occupied condition (RE); (c) occupied condition in the source room (RE); (d) mixes of the unoccupied condition in the source room and background sound of the occupied condition; (e) mix of ten pairs of voices (VE); (f) mixes of ten pairs of voices, piano, and cello (VE); (g) mixes of ten pairs of voice, piano, cello, and background sound (VE); (h) piano (VE); (i) cello (VE); (j) female (VE); and (k) male (VE).

To begin the process of recreating an analog source in digital form, featuring a mixed content of human voices and music, the criteria of using the minimum amount of music and voice sources that could efficiently reproduce the stationary primary source in the VE were established. A sufficient number of voice sounds were required to simulate the situation of two or more people speaking at the same time. The selection of the samples is not specified except for the subject matter based on the broadcasts with female or male voices. **Figure 7.2e** shows the spectrograms of the sound signals for ten pairs of female or male voices for 60 s. As the paired number of speakers increased to 10, i.e., 20 people simultaneously having conversations in the source room (room 1), there was no distinguishable pattern in the time-frequency plane. Furthermore, this number of sound sources greatly exceeded the number used to simulate the cocktail party effect, which is usually between three and eight sources. The specifications for the music sample were developed on the high-/low-frequency basis. A piano (**Figure 7.2h**), and a cello sample (**Figure 7.2i**), were chosen as they are not emotional or famous enough to be distinguished. **Figure 7.2f** shows the spectrograms of the mixes of the sound signals for ten pairs of female or male voices, piano, and cello. In a naturally occurring auditory scene, music provides examples in which the levels of the different instruments are not carefully calibrated, thus, each instrument can often overwhelm the others. Therefore, the two selected instrument sounds varied in their frequencies and could create a new type of fused sound to be perceived by a listener.

In terms of the background signal to simulate the crowd transit, a 3-min binaural recording was used. This recording was captured in a normal exhibition space under the equivalent geometric and interior conditions of room 4, with no audio resource, located in another exhibition space on the same floor as the selected site, and looped across the source and receiving rooms. **Figure 7.2b** shows the spectrograms of the site recordings. The mixes of the unoccupied condition in the source room (room 1) and the occupied condition in the other room (**Figure 7.2d**) were similar to those obtained in the occupied condition in the source room (**Figure 7.2c**), demonstrating that the building conditions of the recorded room were mostly identical to those of the site. The content contained the various sounds of footsteps and conversations in the Tate Modern, such as the clicking of high heels and children's voices.

Figure 7.2g shows the spectrograms of the mix of samples representing "Babel, 2001" in the VE, which is generally similar to the site recording (**Figure 7.2c**). Two distinct attenuation distance curves were applied to appropriately define the acoustic properties of the frequency content. For the acoustical attributes, four audio volumes and reverberations were created in accordance with the individual boundary conditions of each room. These four audio volumes were separately set to approximately 6.0-, 4.0-, and 0.0- dB reductions in the sequence from rooms 1 to 4, ensuring the level difference between adjacent rooms in the sequence measured in the RE to be correspondingly reflected in the VE. In addition, only the volume of the third receiving room (room 4) was filtered by 800 Hz to satisfy the low-frequency propagation, concerning the effect of the source distance. The simulated sound level coming out of the headphones of the primary source "Babel, 2001" in the source room (room 1) was approximately 67.0 dB(A) calibrated by a sound level meter (Nti Audio XL2, Schaaen, Switzerland), which was corresponded to the measured sound level in the RE. Meanwhile, the level of background noise was separately considered approximately to be 55.0 dB(A), and was set to be equivalent across the rooms.

7.2.3 Listening Test

The listening tests for the VE were conducted in a design laboratory (4.0 m × 10.0 m × 4.0 m) in January 2021. The background noise in the quiet laboratory was measured as below 35.0 dB(A) with no distinguished background noise, inferring the participant especially using active-noise cancelling headphone (Bose QuietComfort 35, Framingham, MA). The calibration of the sound volume was undertaken before being presented to the subjects in the test. The VE, as shown in **Figure 7.1**, was shared on a monitor, which was streaming with the laptop. Such an environment can be recreated with a game engine implemented in immersive virtual reality. The reason for presenting the recreated environment to the test subjects via a monitor was to avoid any unknown effects of the virtual reality tools because a more general criterion was targeted for the auditory perception to achieve the research goal. All of the subjects were invited, and a randomized double-blind experiment was performed to categorize them into two groups (i.e., approaching-sound-source group or receding-sound-source group). Each group contained 20 participants.

The subject was informed that the listening tests comprised several rounds with varying visual and audio stimuli in a random playback sequence. They were sitting in front of the monitor while taking the listening test using headphones. Before the experiment, no self-reported hearing problems were declared by the participants. A brief guidance on the procedures, including the task assignments and device control with the keyboard and mouse, was provided prior to conducting the virtual experiment. Once started, the subject was no longer accompanied by the researcher physically, and they were under the partial control of the VE. They were restricted to a prescribed path, which was basically designed as a line moving across the space at a default walking speed. It should be noted that the subjects were allowed to observe the virtual space by rotating the mouse when they were in motion. Meanwhile, they could use the keyboard to call out/off the questionnaire. They provided the ratings using a mouse when they stopped at the centre of each space, as illustrated in **Figure 7.1**. A completion interface, directing the subjects into the next test, appeared as they completed the questionnaire at the end of the sequence either in the source room (room 1) for the approaching-sound-source group, or in the third receiving room (room 4) for the receding-sound-source group. There was a mandatory halt between the two tests at the start location for 10 s in silence to avoid any distraction imposed by prior experiences before being allowed to voluntarily start the new test. The total time duration required for each subject to complete the tests was typically less than 1 h.

7.2.4 Soundwalk Subjects

Seventy-two visitors, aged between 18 and 60 years old (mean age = 27), were involved in *in situ* survey, and a total of 216 valid questionnaires were collected. Forty subjects aged between 18 and 22 years old (mean age = 20), were voluntarily recruited for the listening test. As discussed in **Section 4.2.4**, prior to the soundwalk, all of the participants in the RE had exposure to the acoustic environment rendered by the primary source. Comparatively, all of the participants in the VE did not have any prior knowledge and field experience of the site, which was verified after the completion of the experiment. In addition, they were restricted to the preset route, which made it almost impossible to pay further attention to the details of the exhibits. The differences between the subjects were to ensure the objectivity of both of the results in the RE and VE, which could be potentially affected by the exhibits.

To avoid the possibility of age-dependent limitations, this chapter only used the results from those participants between 18 and 22 years of age rather than the entire sample of the broader group. The number of subjects in the RE and VE satisfied the sample criterion of a normal distribution (i.e., greater than 30). However, although the ages of the subjects in the RE and VE were within the same range, according to the one sample *t*-test (p) between the subjects aged between 18 and 22 years old and those between 18 and 60 years old in the RE, the former group containing 28% of the participants from the latter group, the age-dependent effects in the broader group were significantly limited. The results revealed that there were significant differences for the spaciousness in room 3 ($p = 0.040$) and listener envelopment in room 4 ($p = 0.024$). In addition, it was observed that almost every perceptual attribute, especially the loudness, reached the value of $p = 1.000$. Therefore, the results of this chapter could be reasonably extended to a wider age range.

7.2.5 Data Analysis

To assess the difference in the perceptual attributes, independent *t*-tests were used. In addition, to measure the similarities, the distance correlation analysis was conducted using the distance similarity measures by the Pearson correlations, solved using SPSS Statistics 26 (IBM United Kingdom Limited, Portsmouth, UK) and OriginPro 2021 (OriginLab Corporation, Northampton, MA). This method can be used to perform statistical tests such as computing similarities between pairs of automobiles based on certain characteristics, e.g., engine size and horsepower, gaining a sense of which automobiles are similar to each other and which are different from each other (IBM Corporation, 2021). In this chapter, this method was used to measure the similarities between the pairs of evaluations based on the perceptual attributes.

7.2.6 Validation between the RE and VE

To ensure an acceptable correspondence between the RE and VE, this chapter used three conditions in the VE, varying with the volume of the primary source or the reverberation of the rooms, as shown in **Table 7.1**. The first VE condition was pre-set as the baseline according to the virtual reproduction as discussed above. According to the independent *t*-tests (p) of the loudness between the RE and VE (first), for the approaching-sound-source group, the results of room 4 (p = 0.007) exhibited statistically significant differences; for the receding-sound-source group, there were statistically significant differences in room 1 (p = 0.000) and room 2 (p = 0.008). In addition, the mean rating of the loudness under the VE (first) was demonstrated to be much larger than that of the RE, especially for the receding-sound-source group, as shown in **Figure 7.3**.

Table 7.1 The experimental details of each experiment in the VE.

Primary source	Background sound	VE condition	Experimental phase
“Babel, 2001” (validation)	Yes	First	
“Babel, 2001”	No	First	VE-1
Piano/cello/female/male	Yes/no	First	
“Babel, 2001” (validation)	Yes	Second/third	
“Babel, 2001”	No	Second	VE-2
Piano/cello/female/male	Yes/no	Second	

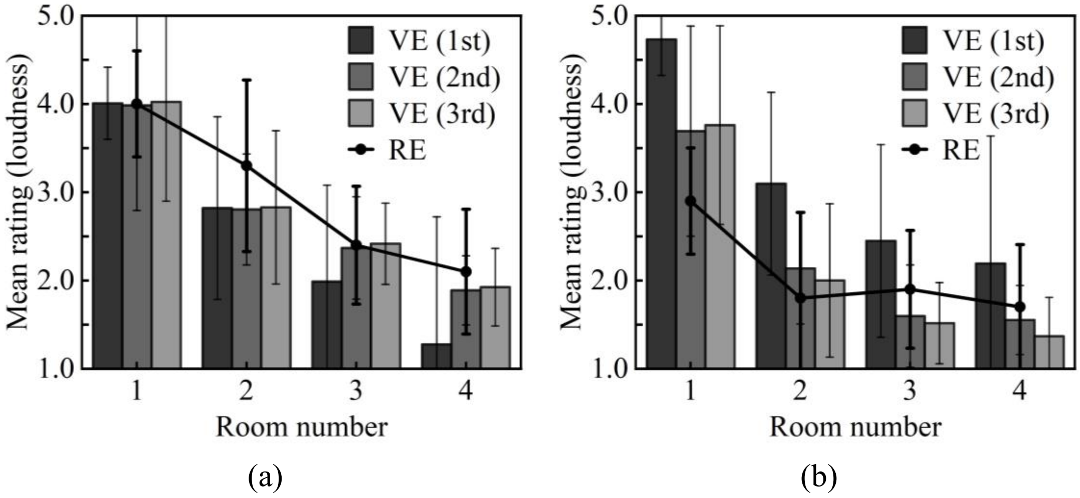


Figure 7.3 The mean ratings and standard deviations of the loudness in the RE and three VEs are shown for the (a) approaching-sound-source group and (b) receding-sound-source group.

Consequently, the second condition reduced the volume of the primary source by 10.0 dB to pursue a better validity. The reduction of 10.0 dB is defined by the research of Sudarsono (Sudarsono and University of Salford, 2017) which shows that when participants are given the opportunity to adjust the sound level of a soundscape reproduction in the laboratory with the pantophonic system, they tend to adjust the sound level to −9.5 dB below the actual level. According to the independent *t*-tests (*p*) of the loudness between the RE and VE (second), no significant difference was found in all four of the investigated rooms. It was also observed in **Figure 7.3** that the mean ratings of the VE (second) were closer to those of the RE when compared to the result obtained by the VE (first). In addition, following the VE (second), the VE (third) increased the decay time of each room by 0.5 s to explore the potential reverberation effect. The results for the evaluation of the loudness were generally the same as those obtained by the VE (second), and there was only a significant difference in the source room (room 1: $p = 0.050$) between the RE and VE (third).

The VE subjects were unaware of "Babel, 2001" as a piece of well-established art, whereas the RE subjects were those who supposedly had prior experiences of the exhibit. According to the subsequent feedback sheet provided after the completion of the experiment in the questionnaire, the VE subjects documented that they experienced confusion with the "chaotic" acoustic environment.

Notably, the mean rating of the loudness was equal to 4.0 in the source room (room 1) for the approaching-sound-source group, whereas the ratings for the receding-sound-source group were exceptionally high (4.7) in the VE (first) compared to those in the RE (2.9). This indicates that a distinction of the methodology between the RE and VE for the receding-sound-source group cannot be ignored. The VE subjects were automatically placed in the source room (i.e., the loudest room), whereas the RE subjects walked through the rooms before physically arriving at the source room because they were recruited in the concourse. Some of the VE subjects expressed their unpleasantness and fright upon suddenly listening to "Babel, 2001" for the first time. Such complaints were seldom received and documented by participants in the approaching-sound-source group. The values of the receiving rooms were generally smaller in the VE than those in the RE. The listener's sudden exposure to the primary source in the VE dominated the loudness perception.

Three distance correlation analyses were conducted with the approaching-sound-source group to measure the similarities between the RE and VE, as listed in **Table 7.2**. Although the VE (first) was preset as the baseline in this chapter, the VE (second) was the "best performer" among the three for exhibiting greater similarities with the RE. Moreover, the loudness, reverberation, and stage support were well-developed throughout the three conditions; clarity and warmth were considerably improved by decreasing the volume of the primary source in the VE (second). Enlarging the reverberation effects in each room did not lead to differences for the loudness, intimacy, and warmth, and imposed detrimental effects on the clarity and directionality. There were statistically significant differences for certain perceptual attributes in some of the rooms. However, according to the independent *t*-tests (p) of each of the perceptual attributes in each room, no significant differences ($p < 0.05$) were observed for the evaluation of the loudness (room 1, $p = 0.964$; room 2, $p = 0.147$; room 3, $p = 0.939$; room 4, 0.561) and the reverberance (room 1, $p = 0.570$; room 2, $p = 0.723$; room 3, $p = 0.900$; room 4, 0.078) in each investigated room between the RE and VE (second).

Table 7.2 The proximities of the ratings by the approaching-sound-source group by the distance correlation similarity tests (*r*) between the RE and three VEs when using "Babel, 2001".

Perceptual attribute	VE (first)	VE (second)	VE (third)
Loudness	**0.988**	**0.965**	**0.965**
Clarity	**0.196**	**0.749**	**0.000**
Reverberation	**0.773**	**0.840**	**0.882**
Spaciousness	0.255	0.323	0.468
Listener envelopment	−0.217	−0.827	−0.395
Intimacy	−0.804	−0.838	−0.838
Warmth	−0.738	−0.233	−0.233
Stage support	0.963	0.966	0.986
Acoustic comfort	0.607	0.475	0.498
Directionality	0.169	−0.192	−0.911
Annoyance	0.541	0.569	−0.635
Overall impression	−0.549	0.394	−0.578

7.2.7 Virtual Experiment

The experimental details of each test in the VE, including the validation and experiment, are listed in **Table 7.1**. For each of the two sequenced experimental phases, VE-1 and VE-2, the participant completed five pairs of experiments, varying with the primary source (i.e., "Babel, 2001", piano, cello, female, and male) with or without background sound in either first or second VE condition. Additionally, one validation for "Babel, 2001" with background sound in the third VE condition was conducted in VE-2. The validation and experiments were not separately conducted and were arranged in a random order, which was unique for each participant. For the VE (first and third) conditions, only the results of the validation (i.e., using "Babel, 2001" as the primary source) are presented in this chapter. Note that all of the results shown in the **Section 7.3** were obtained with the VE (second) condition in this chapter. The clips of the primary source used in the experiments had been already applied in reproducing "Babel, 2001". **Figure 7.2h, i, j,** and **k** show the spectrogram of each primary source.

7.3 RESULTS

7.3.1 Effects of the Approaching and Receding Sound Sources

Figure 7.4 shows the mean rating for the evaluation of the loudness of the approaching-sound-source and receding-sound-source groups by different source types tested without or with a background signal. The results revealed that people had very different auditory perceptions in the same actual space. **Table 7.3** has further calculated the mean rating differences in the loudness between the approaching-sound-source and receding-sound-source groups without background sound. As shown in **Table 7.3** by the columns of $A - R$, the mean ratings of the approaching-sound-source group were larger than those of the receding-sound-source group for all of the investigated spaces. This means that the sound with a gradual increase in the level across the space (i.e., approaching sound source) receives a higher importance in the perceived loudness (defined in this chapter as the approach effect) no matter where the listener is located. The increased perceptual disparity was observed to be equivalent in the source room (room 1) for the music and voice with similar mean rating difference of 0.6−0.8. However, this mean rating difference was found to be larger in the receiving rooms (rooms 2−4) according to the different source types, and greater at the high-level receiving room (the one near the source room), that is, in the first receiving room (room 2), the mean rating difference was equivalent for the piano, female, and male voices source (1.6) except for the cello (1.0). In the second receiving room (room 3), the mean rating difference was smaller for the cello than for the piano and smaller for the female than for the male, as shown in **Table 7.3**. Also, according to the independent *t*-tests (p) of the mean rating tested without background sound between the approaching-sound-source and receding-sound-source groups, there were significant differences ($p < 0.01$) in the first receiving room (room 2) and the second receiving room (room 3) for all of the investigated sources. However, no significant differences ($p < 0.01$) were observed in the source room (room 1) and third receiving room (room 4). This also indicates that the greatest perceptual priority by the approaching sound source occurred in the receiving rooms near the source room, not in the source room.

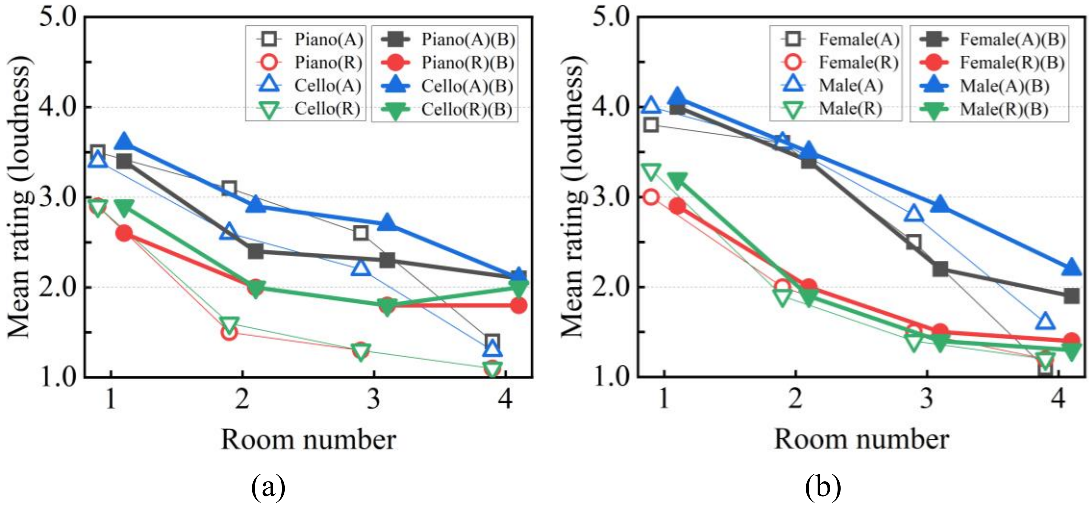


Figure 7.4 The mean ratings of the loudness for the approaching-sound-source group (*A*) and the receding-sound-source group (*R*), tested without or with background sound (*B*) are shown for (a) music and (b) voice.

Table 7.3 The mean rating differences in the loudness between the approaching-sound-source group (*A*) and the receding-sound-source group (*R*), tested without background sound with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (two-tailed test of statistical significance).

	Piano	Cello	Piano − cello		Female	Male	Female − male	
Room	$A - R$	$A - R$	A	R	$A - R$	$A - R$	A	R
1	0.6	0.5	0.0	0.0	0.8	0.7	−0.2	−0.3
2	1.6^{**}	1.0^{*}	0.5^{*}	0.0	1.6^{***}	1.6^{**}	0.0	0.0
3	1.3^{**}	0.9^{**}	0.4^{*}	0.0	1.0^{**}	1.4^{***}	−0.3	0.0
4	0.3	0.2	0.0	0.0	−0.1	0.4^{*}	-0.5^{**}	0.0

To explore how background noise affects the judgments in this context, **Table 7.4** further calculated the mean rating differences in the loudness between the approaching-sound-source and receding-sound-source groups with background sound. As shown in **Table 7.4** by the columns of $A - R$, the mean ratings were also larger for the approaching-sound-source group than for the receding-sound-source group, which means that the discussed approach effect was maintained with the masking. Comparing **Table 7.4** and **7.3**, the mean rating difference between the rising and falling level slightly increased by approximately 0.2 in the source room (room 1) with background sound. Furthermore, in the first receiving room (room 2), the mean rating differences were stationary except for the piano, which decreased by 1.3. In the second receiving room (room 3), the mean rating differences were kept at the same level for the cello and male, whereas those of the piano and female decreased by 0.6 and 0.3, respectively. Therefore, the masking effect on the impairing perceptual priority of a rising sound did not occur in the source room but did occur in its connected receiving room. Also, according to the results of the independent *t*-tests (*p*) shown in **Table 7.4**, no significant differences ($p < 0.01$) were observed in the first receiving room (room 2) and second receiving room (room 3) in columns of the piano $A - R$ anymore, demonstrating that the masking effect was greater for the piano than for the cello.

Table 7.4 The mean rating differences in the loudness between the approaching-sound-source group (*A*) and the receding-sound-source group (*R*), tested with background sound (*B*) with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (two-tailed test of statistical significance).

	Piano	Cello	Piano − cello		Female	Male	Female − male	
Room	$A - R$	$A - R$	A	R	$A - R$	$A - R$	A	R
1	0.8	0.7	−0.2	0.0	1.1^{*}	0.9	0.0	−0.3
2	0.3	0.9^{*}	-0.5^{*}	0.0	1.4^{**}	1.6^{***}	0.0	0.0
3	0.5	1.0^{*}	−0.4	0.0	0.7^{*}	1.5^{***}	−0.7	0.0
4	0.4	0.1	0.0	−0.2	0.6	0.9^{**}	−0.3	0.0

In terms of the other perceptual attributes (e.g., reverberation), the mean ratings were also larger for the approaching-sound-source group than for the receding-sound-source group in most cases, except for a small value of −0.2 for the female in the source room (room 1) and the second receiving room (room 3) as shown in **Figure 7.5** and **Table 7.5**. The perceptual difference in the source room (room 1) was identical to that of the loudness (0.7) for the music, however, the perceptual difference for the voice was much lower (0.2). This also indicates a disparity in perceiving reverberation and loudness for the voice, that is, in the case of the different loudness, the reverberation could be identical when a listener enters or leaves the source room. However, according to the results of the independent *t*-test (*p*), as shown in **Table 7.5** and **7.6** by all of the columns of $A - R$, in general, the asymmetry of the directional aspects in the reverberation is hard to distinguish because no statistically significant differences ($p < 0.01$) was observed.

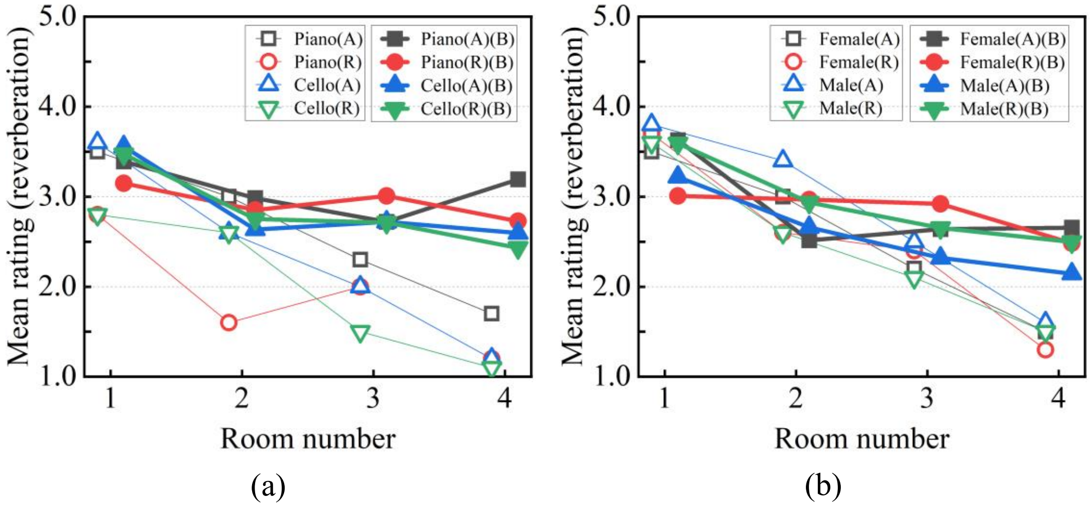


Figure 7.5 The mean ratings of the reverberation for the approaching-sound-source group (*A*) and the receding-sound-source (*R*), tested without and with background sound (*B*), are shown for (a) music and (b) voice.

Table 7.5 The mean rating differences in the reverberation between the approaching-sound-source group (*A*) and the receding-sound-source group (*R*), tested without background sound with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$ (two-tailed test of statistical significance).

	Piano	Cello	Piano − cello		Female	Male	Female − male	
Room	*A* − *R*	*A* − *R*	*A*	*R*	*A* − *R*	*A* − *R*	*A*	*R*
1	0.7	0.7	0.0	0.0	−0.2	0.2	0.0	0.0
2	1.3**	0.0	0.4	−1.0*	0.4	0.8	−0.4	0.0
3	0.3	0.5	0.3	0.5	−0.2	0.4	−0.3	0.3
4	0.5*	0.1	0.5**	0.0	0.1	0.1	0.0	−0.2

Table 7.6 The mean differences in the reverberation between the approaching-sound-source group (*A*) and the receding-sound-source group (*R*), tested with background sound with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$ (two-tailed test of statistical significance).

	Piano	Cello	Piano − cello		Female	Male	Female − male	
Room	*A* − *R*	*A* − *R*	*A*	*R*	*A* − *R*	*A* − *R*	*A*	*R*
1	−0.2	0.1	−0.3	−0.2	−0.6	0.4	−0.6	0.4
2	−0.1	0.1	0.1	0.3	0.5	0.3	−0.2	0.1
3	0.3	0.0	0.1	−0.1	0.3	0.3	−0.2	0.1*
4	−0.5	−0.2	−0.1	−0.9	−0.2	0.4	−0.1	−0.1

To measure the approaching effect for a global view of all of the perceptual attributes, **Table 7.7** shows the distance correlation similarity tests (*r*) between the approaching-sound-source and the receding-sound-source groups for all of the investigated source types. The results showed that the greatest similarity was delivered by “Babel, 2001” in the source room (room 1, $r = 0.976$), whereas the lowest similarity was obtained by the piano in the first receiving room (room 2, $r = -0.245$). The similarities of the piano were lower than those of the other three sources, and those of the cello seemed to be similar to “Babel, 2001”. This suggests that the perceived changes between the rising and falling levels for the noise could be less distinguishable, especially when compared to high-frequency music. The asymmetry of the directional aspects most occurred with music but not with broadband noise and voice, especially at the high levels. Furthermore, the greatest similarity with the background sound was also exhibited by “Babel, 2001” in the source room (room 1, $r = 0.992$), and the lowest similarity was also obtained by the piano in the second receiving room (room 3, $r = 0.508$).

Table 7.7 The correlation distance similarity tests (*r*) between the approaching-sound-source and receding-sound-source groups with the investigated source types.

	Without background sound					With background sound				
Room	Babel	Piano	Cello	Female	Male	Babel	Piano	Cello	Female	Male
1	**0.976**	0.065	0.870	0.839	0.853	**0.992**	0.645	0.955	0.804	0.918
2	0.800	**−0.245**	0.820	0.574	0.543	0.809	0.691	0.819	0.775	0.641
3	0.568	0.671	0.591	0.859	0.810	0.849	**0.508**	0.901	0.682	0.768
4	0.885	0.486	0.936	0.728	0.836	0.846	0.742	0.800	0.754	0.603

7.3.2 Effect of the Sound Source Type

As shown in **Figure 7.4**, for the approaching-sound-source group, the overall range of ratings of the loudness was equivalent for the piano and cello, and slightly smaller for the female than for the male. This suggests that the rising intensity piano and cello have comparable perception, whereas rising intensity male could have perceptual priority to the female. Additionally, as shown in **Table 7.3** by the columns of piano − cello and female − male, the mean rating was identical between the piano and cello in the source room (room 1), while different by 0.5 in the first receiving room (room 2) and 0.4 in the second receiving room (room 3). On the other hand, the mean rating between the female and male was slightly different in the source room (room 1; −0.2), the second receiving room (room 3; −0.3), and third receiving room (room 4; −0.5).

These results suggest that the largest difference imposed by the sound source type for a rising level sound did not occur in the source room but did occur in the receiving rooms.

Comparatively, as shown in **Figure 7.4**, for the receding-sound-source group, the overall range of the ratings of the loudness was equivalent for the piano and cello, and opposite to the results of the approaching-sound-source group, was slightly larger for the female than for the male. Therefore, it is found that when a listener approaches or recedes from the sound source, the perceptual priority of the female and male could be different, that is, for the female when receding from the sound source. On the other hand, as shown in **Table 7.3** by columns of piano − cello and female − male, the mean ratings were equivalent for the piano and cello and for the female and male in most of the investigated rooms except for a difference of 0.3 between the female and male in the source room (room 1). This indicates that in the case of the receding sound sources, the loudness difference across the various sound source types are needed to be more concerned in the source room (i.e., when the sound is loud or close to the listener). It is observed that the loudness in the room connected to the source room (room 2) received a sharp drop (defined in this chapter as the plummet effect), that is, it was rated as 2.9 in room 1, which is particularly high compared to the ratings in rooms 2−4, which range from 1.1 to 1.5 as shown in **Figure 7.4**. However, this plummet effect was weaker for the voice, that is, the value of room 2 was larger than that of the music for approximately 0.5, which made the difference between rooms 1 and 2 smaller. Note that the plummet effect was not observed in the approaching sound sources and was on a sound source type basis, for which music was larger than voice.

Table 7.8 calculated the mean rating differences in the loudness between the conditions without and with background sound for either the approaching-sound-source group or the receding-sound-source group. As shown in the columns of $A - A(B)$ and $R - R(B)$, the ratings of the rising piano decreased, and those of cello increased due to the masking. The magnitudes of the music were greater in the receiving rooms but not the source room. Also, although no significant differences ($p < 0.05$) were observed in rooms 1 to 3 according to the results of the independent t-tests (p) as shown in **Table 7.8** and the mean rating differences were very small, the masking effect could be larger for the female than for the male. As shown in **Figure 7.4**, the discussed plummet effect for a falling sound was kept under the masking, although the difference between the source room (room 1) and first receiving room (room 2) becomes smaller because of the increase in the first receiving room (room 2).

Table 7.8 The mean rating differences in the loudness between the conditions without and with background sound (*B*) for either the approaching-sound-source group (*A*) or the receding-sound-source group (*R*) with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$ (two-tailed test of statistical significance).

Room	Piano		Cello		Female		Male	
	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$
1	0.1	0.3	−0.2	0.0	−0.2	0.1	−0.1	0.1
2	**0.7***	**−0.5**	**−0.3**	**−0.4**	0.2	0.0	0.0	0.0
3	0.3	−0.4	−0.5	−0.4	0.2	0.0	0.0	0.0
4	−0.7*	−0.7	−0.8**	−0.9**	−0.8**	−0.2	−0.6*	−0.1

In terms of the reverberation, as shown in **Table 7.5** by the columns of piano − cello and female − male, for the approaching-sound-source and receding-sound-source groups, in the source room (room 1), there was no mean rating difference for the piano and cello, and for the female and male, whereas the mean rating difference in the receiving rooms (rooms 2−4) could be observed. **Table 7.9** shows the mean rating differences in the reverberation between the conditions without and with background sound. It is worthwhile to note that the masking effect of background sound imposed on the reverberation was limited in the source room (room 1), according to the results of the independent *t*-tests (*p*) because no significant differences ($p < 0.05$) were observed, although the mean ratings increase to a greater or lesser degree. Meanwhile, the masking effect was also limited for the voice in the receiving rooms (rooms 1−3).

Table 7.9 The mean rating differences in the reverberation between the conditions without and with background sound (*B*) for either the approaching-sound-source group (*A*) or the receding-sound-source (*R*) with the independent *t*-test (*p*). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (two-tailed test of statistical significance).

Room	Piano		Cello		Female		Male	
	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$	$A - A(B)$	$R - R(B)$
1	**0.3**	**−0.6**	**0.1**	**−0.7**	**0.5**	**0.0**	**0.2**	**0.4**
2	0.1	−1.4**	−0.1	−0.1	−0.2	−0.1	0.4	−0.1
3	−0.7	−0.7*	−1.2**	−0.8**	−0.2	−0.7	−0.2	−0.2
4	−1.0*	−2.0***	−1.2***	−1.5**	−1.0	−1.3**	−0.9*	−0.6*

To measure the perceptual priority between the piano and cello, as well as the female and male, with all of the perceptual attributes, **Table 7.10** shows the distance similarity correlation tests for the approaching-sound-source and receding-sound-source groups. The results revealed that either a rising or falling voice was similar for the female and male. However, the similarity between the piano and cello for the approaching-sound-source group was 0.682, whereas the similarity of the receding-sound-source group was −0.604 in the source room (room 1). This indicates that the rising music could be perceptually identical, whereas the perception of the falling music could be distinctly different between the piano and cello.

Table 7.10 The correlation distance similarity tests (*r*) between the music (piano and cello) and voice (female and male) sources tested with or without background signals for the approaching-sound-source group (*A*) and the receding-sound-source group (*R*).

	Without background sound				With background sound			
	Music		Voice		Music		Voice	
Room	*A*	*R*	*A*	*R*	*A*	*R*	*A*	*R*
1	**0.682**	**−0.604**	0.973	0.964	0.685	0.325	0.936	0.886
2	0.463	−0.205	0.886	0.955	0.433	0.607	0.960	0.856
3	0.042	0.268	0.916	0.964	0.769	0.849	0.837	0.886
4	0.659	0.681	0.851	0.956	0.598	0.947	0.453	0.898

It is interesting to note that the similarity between the music decreased with increasing source distance for the approaching-sound-source group, and this pattern was opposite to the pattern for the receding-sound-source group, of which the similarity gradually increased with increasing source distance. This suggests an increasing symmetry between the music (defined in this chapter as the convergence effect); that is, when approaching the sound source, the perception difference between the piano and cello gradually grows from unsimilar to similar, surprisingly, and when receding from the sound source, the perception difference between the piano and cello also gradually grows from unsimilar to similar. This increasing symmetry was also observed under the masking effect. Furthermore, as shown in **Table 7.10**, the masking effect considerably increased the similarities between the piano and cello for the receding-sound-source group, which indicates that the masking effect was larger for the falling music than the rising music.

7.4 DISCUSSION

7.4.1 The Distinction of Spatial Information for the Approaching and Receding Sound Sources

The results in this chapter show that it could be insufficient to confirm the validity of the listening tests when dealing with the dynamic auditory perception for the approaching and receding sound sources by disregarding the actual spatial information, especially in indoor space. The condition of a room as a source or receiving room is important. For instance, the perceptual difference between the approaching and receding sound sources was greater for the receiving rooms than for the source room. This indicates a potential challenge to apply the guidelines in a natural environment as the source room does not experience the greatest perceptual differences in this context. When a listener enters or leaves the source room, the perception of the source room is not greatly different; however, the perception of the room connected to the source room is highly dependent on a directional basis. The plummet effect, although many stimulus parameters have yet to be investigated, suggests that the ratios of the room volumes between the source and receiving rooms could have an impact on the perceptual priority of a rising intensity sound. Additionally, the ratings of the receiving rooms (rooms 2−4) were observed to be equivalent for the falling tones, which is not observed by the rising tones, as shown in **Figure 7.4**. It is worthwhile to note that because the spatial information of rooms 2−4 was almost identical, the effect of the expectation is demonstrated to be stronger for a falling level than for a rising level.

Another distinction to consider with the spatial information for the dynamic auditory perception is that it makes the experiment more realistic by increasing the time of the experiments. Most experiments with only listening dimensions were using the sound sequence within 100 ms to 2 s, or intervals (e.g., 30 ms). However, in this chapter, the time taken for each participant in the VE to complete one survey in each room was much longer (e.g., 1 min) akin to the RE. Therefore, the conclusions in this chapter, e.g., the range of the loudness for the voices was larger for the approaching-sound-source group than for the receding-sound-source group, and the rating difference between rooms 1 and 2 was larger for the receding-sound-source group than for the approaching-sound-source group, are the results of a longer-term temporal effect with the interaction with the actual spatial information.

7.4.2 Limitations and Future Work

As developed in **Section 2.2.4.2**, there can be some unavoidable issues regarding soundwalk subjects who are not native speakers answering the English questionnaires in a foreign language or subjects coming from a person's different professional background that can potentially influence the subjective evaluation in both RE and VE. However, the word selected in the questionnaire is not uncommon and not difficult to be understood. Additionally, the subjects mostly come from well-educated backgrounds, and before the experiments, they indicated that they are able to read and understand the questionnaire. It is worthwhile to note that numerous efforts are made concerning this potential translation issue with the studies (Aletta et al., 2020) by the Soundscape Attributes Translation Project (SATP).

The chapter has inspired a series of options for future work. For instance, this research was developed under the assumption that the background noise for each room was identical; however, future work could explore the situations where one room has a particularly high level of background noise. Another avenue for further research could be exploring the situations in which the process of rising levels in the approaching sound source in sequential spaces is interrupted or restarted by additional sound events. Finally, the asymmetry patterns demonstrated in this chapter are a fundamental phenomenon of a stationary single sound source and background noise, using samples of no specific content. Apart from voice and music, which are common sounds in indoor building environments, it would also be interesting to explore specific environmental sound sources, such as birds or water.

7.5 CONCLUSIONS

This chapter reported on auditory perception in large sequential public spaces with a listener in motion and a stationary primary sound source. Thus, virtual experiments were performed with *in situ* surveys for the validation. The headphone reproduction of 10.0 dB less than the actual sound level was demonstrated to be necessary to imitate the feeling of being at the actual location in the indoor spaces. Confirming the earlier work, the existence of significant differences in the auditory perception was determined within these spaces to understand how the approaching and receding sound sources are perceived on the same path, and three major effects were found. In indoor building environments, such differences could create an overestimation of the source, and the rising intensity can signal movement toward the source. This bias was not necessarily stronger at higher levels (i.e., the source room), suggesting that the rising loudness is more critical either close to a sound source or loud in the receiving rooms. The results indicate the importance of the dynamic rising loudness, and an asymmetry of the dynamic intensity change.

For the effects of the approaching and receding sound sources, it is concluded that

- the rising levels when approaching the sound source were rated higher in each room (**approach effect**), and changed more than the falling levels, despite having the same actual change in the level. This indicates that a change in the direction is an important factor in the perception of the dynamic loudness. The rattlesnake uses something similar to deter mammals (Forsthofer et al., 2021). None of the findings are predicted by the traditional psychophysical laws derived by simulating a static listener, indicating that there are differences between the static and dynamic loudness perceptions. Furthermore, the difference between the rising and falling levels was greater for the receiving rooms than the source room and greatest for the room connected to the source room;
- the masking effect impairing the perceptual priority of the rising sound was profound in the receiving rooms but not in the source room itself;
- the results of the loudness could not be extended to that of the reverberation; and
- the overall asymmetry of directional aspects occurring with broadband noise and voice was not as distinguishable as with music, but for some perceptual attributes, e.g., the loudness, the perception disparity does exist.

For the effect of the sound source type, it is concluded that

- a gradual changing level was perceived to change in an equivalent manner in the loudness between the piano and cello. For the female and male, it is on a directional basis which was larger for the approaching sound source. The difference between the sources was greater for the room connected to the source room rather than the source room itself. The rating of the room connected to the source room received a sharp drop (**plummet effect**), which was only observed for the receding sound source. The magnitude was dependent on the source type, of which the music magnitudes were larger than the voice magnitudes;

- the masking effects on the loudness and reverberation were limited, although they were larger for the receiving rooms than for the source room and for the female than for the male; and
- the rising music could be perceptually identical, whereas the perception of the falling music could be distinctly different between the piano and cello. An increasing symmetry of the overall perception between the different source types was observed (**convergence effect**) either by the approaching or receding sound source.

Overall, the results suggest that the modal and technical measures of the perceptual attributes, which do not account for the directional aspects, are oversimplifications. The prediction of the perceptual attributes (e.g., the loudness) can be improved by considering the dependence of the perceptual importance on the spatial position and direction toward the sound source.

8 Conclusions and Future Work

8.1 MAIN CONTRIBUTIONS

The aim of this study was to find the characteristics of the dynamic auditory perception of a primary sound source and sound attenuation with distance from the source in practice with respect to sequential spaces. Four valuable contributions are concluded as follows.

The first contribution is the determination of reliable perceptual attributes to rate a noise source in the large public building environments. A stationary noise source (e.g., a crowd) changes the dynamic auditory perception for the loudness, spaciousness, and reverberation; the warmth, directionality, and overall impression are at least less effective for assessments. **Two reliable perceptual attributes (i.e., the loudness and listener envelopment) are identified to be different significantly in the same room** between approaching or receding noise sources according to the experiments at actual locations. The study is further proceeded to discover the asymmetry of dynamic auditory perception on specific sound sources in the low-/high-frequency range, e.g., human voice (i.e., female and male) and music (i.e., piano and cello), which is imposed by the direction toward sources, using experiments conducted in virtual environments.

The second contribution is the development of knowledge in the asymmetry of dynamic auditory perception under the validation of virtual acoustics for sound level adjustment. It is found that a soundwalk experiment using a headphone can give the similar perception with the *in situ* experiment where sound level adjustment should be implemented. **The sound level of reproduction should be adjusted to 10.0 dB below the actual level to imitate the perception of the actual experience.** The previous work was confirmed that perceptual priority increases with a rising level. Additionally, **three key effects** emerged from my experiments: **the approach** (i.e., generally higher for the loudness in a room when approaching source room), **plummet** (i.e., significant fall for the loudness in a receiving room when leaving a source room, which is larger for music than for voice) and **convergence** (i.e., gradually similar for the overall impression of different types of voices and music along sound attenuation.) The asymmetry of the overall impression of directional aspects occurring with noise and voice is not as distinct as that with music.

The third contribution is the determination of evidence on sound attenuation with distance from the source in practice. This study tries to understand the distinction in average sound pressure level in a room and level difference between the rooms, when using uniform construction for each separating partition, but adopting different conditions in accordance with the needs of users. First, **increasing connected room volume leads to the same average SPL and the smaller average T_{20} in the originally connected rooms;** second, **level difference between the source and first receiving room is magnified to approximately 1.5 times level difference between sequential receiving rooms;** third, **a larger source distance to the opening leads to a greater entire attenuation, but if a source is positioned along the openings, the decrease will be the smallest;** fourth, **the distinction imposed by source position and room absorption is prevalent in the low-frequency range whose wavelength is close to the opening dimension.**

The fourth contribution is the prediction models, which explains the interaction between sound attenuation and factors of space (i.e., contextual, acoustic, and source). This study has built up the relationship between the parameters (i.e., opening dimension and position, directional radiation from the opening and an additional source, absorption coefficient and distribution, and number of the rooms) and sound attenuation, which is developed with wave-based FEM. The simulation is also validated in this study by comparing the simulation with the *in situ* measurement in a museum as a baseline. The simulation is then applied to analysed the decrease or increase in the SPL with distance. New knowledge is contributed in designing spaces with uniform openings. **For a high absorptive space,** first, **the average SPL in a room increases with an increasing opening area to a certain value, and stays irrespective of the opening position;** second, **the average SPL in a room with an additional source is maintained or reduced with an increasing opening area, whereas the average SPL in other rooms increase. Oblique radiation from the opening** (e.g., the source and receiver are not located at the same height) **leads to a larger level difference between the rooms than for horizontal radiation.** Changes to low absorption coefficients have more significant effects. For a given absorption amount, the difference in the average SPL in a room between uniform and nonuniform absorption distributions is greater with a smaller opening area.

8.2 IMPLEMENTATION

The implementations of this thesis should be related to the design decision and guidelines for practitioners in the architectural design, architectural acoustics, noise control, and relevant theories of building physics in large-scale public spaces on sound measure, prediction and evaluation.

A baseline for sequential spaces in a large worldwide architectural practice can compose four to five rooms with a stationary primary noise source at **70.0 dB(A)** in a highlighted source room (approximately room volume = 1,150 m^3) with lightweight construction and low room absorption, and the width of openings is 2.0 m. The decrease in sound pressure level with distance from the source is confined to three receiving rooms (approximately room volume = 60 m^3 each, entirely 200 m^3) in the range of **13.2 dB(A)** in the unoccupied condition; **8.6 dB(A)** in the occupied condition. Adjustment to **10.0 dB** lower than the actual sound level will be required to make for a realistic reproduction in virtual environments.

Guidelines for practitioners to improve and design sequential spaces are that applying the strategies of distinct dynamic auditory perception in the directional aspects, as well as the practical consideration of sound attenuation with distance from the source in large-scale public space are keys to the goal of delivering better, more efficient acoustical environment that are coordinated around the needs of the individual. It is essential to enable early intervention and preventative work for safety and well-being.

As dynamic auditory perception is a vital element in improving design outcomes for all, "if the circulation in the space is required," you should

- value an essential distinction existing in perception between approaching or receding sound sources and the importance of a listener's direction toward sound sources in the building environment;
- take the over-estimation of actual condition of noise (e.g., a crowd) into account as it is clearly unavoidable in perceiving a rising level, and make a safety correction for the condition (e.g., the number of people in a room) by adjustments to a smaller value than the required one if the circulation is dominated by approaching sound sources; and
- design an approaching source room as either attraction or deterrent, and be clear of the circumstances when people may be at risk of a sudden,

significant lost in cognition of sound source when leaving a source room into a receiving room for a comfortable safety margin.

To feel confident about making design decisions related to sound attenuation with distance from the source, it is important that you

- understand a decrease of **11.0 dB** for level difference between the rooms when a door can be opened connecting a larger room volume;
- apply good practice with a decrease of **8.0 dB** for level difference between the rooms when the sound source can be located in the larger room of a source or receiving room; and
- consider and calculate **1.5 times** the level difference between the rooms when estimating the one between the source and first receiving room, if same construction is applied to all of the separating partition.

8.3 LIMITATIONS AND FUTURE WORK

Many methods and tools for measurements, predictions and evaluations developed in RE and VE support innovations in this thesis. Therefore, limitations can be found in the data collections, field measurements, and digital techniques of existing solutions.

In terms of data collection *in situ*, binaural devices were used to record the acoustic environment of each participant. Therefore, abundant results can be related for further analysis either for the author or future researchers in the field. Because the participants for subjective evaluation are not professionally trained for acoustical experiments, their understanding of the perceptual descriptors may vary in accordance with their personalities. Future work may also invite target participants with acoustic professional backgrounds. The appropriate datasets of the subjective and objective outcomes obtained in this thesis, e.g., the soundwalk survey conducted in the museum, or the *in situ* physical measurements conducted in educational buildings are underdeveloped, which will be made available for access in the future, along with the further exploration and resources to help any future researchers progressing their work.

Regarding objective physical measurement, although the microphone locations for one measurement simultaneously covered all of the rooms in the investigated spaces, limitations can be found in the number of working sources and receivers operating at the same time. Second, although the selected site of the educational building is ideal for room dimension and composition as a baseline condition of sequential spaces, the customized furniture could not be moved out for the experiments. Additionally, all of the rooms in the selected site use interior finishes with low absorption. Future work involves more examples, e.g., rooms for high absorption.

For digital techniques, the large amount of calculation using FEM limited the research and only two-dimensional modelling was validated. Effective methods allowing for three-dimensional simulations are planned in future work so that many potentials (e.g., the cross section of the spaces) can be explored. Although VE was presented to the participants in the listening tests, to avoid the unknown impact imposed by the tools, no virtual reality headset equipment was associated with the display of a monitor. Additionally, some techniques in neuroscience, e.g., electroencephalography, were not used to assist the listening test. Future work will involve deepening and broadening the content of these aspects.

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Appendices

APPENDIX A

ETHICAL APPROVAL

Ethical approvals for the subjective experiments were obtained by UCL The Bartlett School of Environment, Energy and Resources (BSEER) Research Ethics Committee as follows.

CHAPTER 4:

Title of Study:

Acoustic Subjective Evaluation in Sequential Space

Name(s) of BSEER reviewer(s):

Jonathon Taylor

Date: 07/01/2019

CHAPTER 7:

Title of Study:

Acoustic Subjective Evaluation in Sequential Space 2

Name(s) of BSEER reviewer(s):

Francesco Aletta

Date: 13/10/2020

THE BARTLETT SCHOOL OF ENVIRONMENT, ENERGY AND RESOURCES

Consent Form for Visitor
Acoustic Subjective Evaluation in Sequential Space

Participant Identification Number for the project: Please initial box

1 I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction. ☐
2 I consent to participate in the study. I understand that my personal information (provide information on what personal information specifically will be collected) will be used for the purposes explained to me. I understand that according to data protection legislation, 'public task' will be the lawful basis for processing. ☐
3 I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified *(unless you state otherwise, because of the research design or except as required by law)*. I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications. ☐
4 I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise. ☐
5 I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research. ☐
6 I understand the direct/indirect benefits of participating. ☐
7 I understand that the data will not be made available to any commercial organisations but is solely the responsibility of researcher(s) undertaking this study. ☐
8 I agree that my anonymised research data may be used by others for future research. No one will be able to identify you when this data is shared. ☐

Name of participant Date Signature

Researcher Date Signature

If you have questions or want more information on the research, please contact the researcher and the supervisor:

- **Researcher:** Tingting Yang, tingting.yang.18@ucl.ac.uk, +44(0)78 6495 9890.
- **Supervisor:** Professor Jian Kang, j.kang@ucl.ac.uk, +44(0)20 3108 7338.

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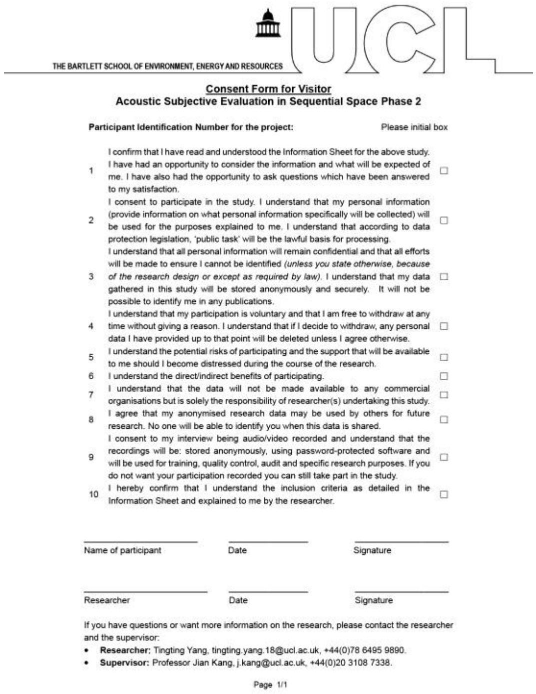

THE BARTLETT SCHOOL OF ENVIRONMENT, ENERGY AND RESOURCES

Consent Form for Visitor
Acoustic Subjective Evaluation in Sequential Space Phase 2

Participant Identification Number for the project: Please initial box

1 I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction. ☐
2 I consent to participate in the study. I understand that my personal information (provide information on what personal information specifically will be collected) will be used for the purposes explained to me. I understand that according to data protection legislation, 'public task' will be the lawful basis for processing. ☐
3 I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified *(unless you state otherwise, because of the research design or except as required by law)*. I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications. ☐
4 I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise. ☐
5 I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research. ☐
6 I understand the direct/indirect benefits of participating. ☐
7 I understand that the data will not be made available to any commercial organisations but is solely the responsibility of researcher(s) undertaking this study. ☐
8 I agree that my anonymised research data may be used by others for future research. No one will be able to identify you when this data is shared. ☐
9 I consent to my interview being audio/video recorded and understand that the recordings will be: stored anonymously, using password-protected software and will be used for training, quality control, audit and specific research purposes. If you do not want your participation recorded you can still take part in the study. ☐
10 I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher. ☐

Name of participant Date Signature

Researcher Date Signature

If you have questions or want more information on the research, please contact the researcher and the supervisor:

- **Researcher:** Tingting Yang, tingting.yang.18@ucl.ac.uk, +44(0)78 6495 9890.
- **Supervisor:** Professor Jian Kang, j.kang@ucl.ac.uk, +44(0)20 3108 7338.

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APPENDIX B

LIST OF RELATED PUBLICATION

The results of Chapter 2 have been published in Applied Sciences.

- Yang, T., Aletta, F. and Kang, J., 2021. Sound Environments in Large Public Buildings for Crowd Transit: A Systematic Review. *Applied Sciences*, 11(9), 3728. doi: https://doi.org/10.3390/app11093728

The results of Chapter 4 have been published in Applied Acoustics.

- Yang, T. and Kang, J., 2020. Subjective evaluation of sequential spaces. *Applied Acoustics*, 161, 107139. doi: https://doi.org/10.1016/j.apacoust.2019.107139

The results of Chapter 5 have been published in Applied Acoustics.

- Yang, T. and Kang, J., 2021. Sound attenuation and reverberation in sequential spaces: An experimental study. *Applied Acoustics*, 182, 108248. doi: https://doi.org/10.1016/j.apacoust.2021.108248

The results of Chapter 6 have been published in Building and Environment.

- Yang, T. and Kang, J., 2022. Acoustic modeling of sequential spaces: A parametric study. *Building and Environment*, 212, 108733. doi: https://doi.org/10.1016/j.buildenv.2021.108733

The results of Chapter 7 have been published in the Journal of the Acoustical Society of America.

- Yang, T. and Kang, J., 2022. Perception difference for approaching and receding sound sources of a listener in motion in architectural sequential spaces. *The Journal of the Acoustical Society of America*, 151(2), pp.685-698. doi: https://doi.org/10.1121/10.0009231