SOUND PERCEPTION IN VIRTUAL ENVIRONMENTS

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ABSTRACT

SOUND PERCEPTION IN VIRTUAL ENVIRONMENTS

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Virtual environments have been developing for a long time and are changing the understanding of a space by means of how we design, perceive and use it. This new understanding of space requires people to adapt by gaining a new type of spatial cognition that can help people to combine the possibilities of a virtual space with the physical space they are used to: by making use of their different sensory skills. The aim of this study is to contribute to the literature on the improvement of the auditory perception and cognition of virtual spaces used for education, training, and gaming purposes. This study proposes to offer a realistic representation of soundscapes in virtual environments according to spatial qualities instead of misleading synthetic sounds by integrating acoustical simulations with the immersive environment and questioning the experience of a regular user. The objectives of this study include: Exploring the virtual environments and soundscape approach in the form of a literature review, Combining the design, cognition, and perception of virtual acoustic environments with Schafer's soundscape idea, Comparing and understanding the effects of acoustically simulated and immersive virtual soundscape design methods on auditory perception through changing forms and materials by series of cognitive experiments. The results revealed that the participants achieve more accurate results of source-localization, self-localization, and distance guessing in an immersive environment than in the simulated environment. In addition, they were more aware of the soundwalk route, spent more time on tasks, and evaluated the experience more positively in an immersive environment compared to simulations. Despite the placement of the auralizations from the simulations as sound sources in tested immersive environments, there is still a lack of auditory representation of spatial qualities compared to the accurate calculation of acoustical parameters in a simulated environment.

Keywords: Soundscape, Auditory Spatial Cognition, Virtual Acoustic Environments, Auditory Perception

ÖZ

SANAL ORTAMDA SES ALGISI

Doğan, Aslı Zeynep
Yüksek Lisans, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Arzu Gönenç Sorguç

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Sanal ortamlar uzun süredir gelişmekte ve bir mekanı tasarlama, algılama ve kullanma şeklimizle mekan anlayışımızı değiştirmektedir. Bu yeni mekan anlayışı, insanların farklı duyusal becerilerini kullanarak sanal mekanın olanaklarını alışık oldukları fiziksel mekanla birleştirmelerine yarayacak yeni bir uzamsal biliş kazanarak adaptasyonunu gerektirmektedir. Bu çalışmanın amacı eğitim, oyun amaçlı kullanılan sanal mekanların işitsel algı ve biliş anlamında geliştirilmesi konusunda literatüre katkı sağlamaktır. Önerilen yaklaşım, temelini akustik simülasyon ve çevreleyici ortamların ses manzarası tasarım yöntemleri olarak entegrasyonu konusundaki araştırma boşluğundan almaktadır. Bu çalışma, akustik simülasyonları sanal gerçeklikle bütünleştirerek yanıltıcı sesler yerine, mekansal niteliklere göre gerçekçi temsilini ve kullanıcı deneyimini sorgulamayı hedeflemektedir. Bu kapsamda sanal ortamlar ve ses manzarası yaklaşımı literatür taraması aracılığıyla incelenmiştir. Sanal akustik ortamların tasarım, biliş ve algısını Schafer'in ses manzarası fikriyle birleştirmek, akustik simülasyon ve çevreleyici sanal ortamın etkilerini değişen biçim ve malzemeler üzerinden karşılaştırmak amacıyla bir dizi bilişsel deney tasarlanmıştır. Deney sonuçları, katılımcıların çevreleyici ortamda simülasyon ortamına kıyasla kaynak konumlandırma, kendini konumlandırma ve mesafe tahmininde daha doğru sonuçlara ulaştığını ortaya koymuştur. Ek olarak, katılımcıların sanal gerçeklik ortamında simülasyon ortamına kıyasla daha uzun zaman geçirdiği, deneyimledikleri ses yürüyüşü rotası konusunda daha fazla farkındalığa sahip olduğu ve daha pozitif değerlendirmelerde bulunduğu gözlemlenmiştir. Ayrıca, test edilen sanal gerçeklik ortamlarında ses kaynağı olarak simülasyon ortamından alınan işitselleştirmelerin yerleştirilmesine ragmen, simülasyonların sağladığı hassas akustik parametre hesaplamaları ile karşılaştırıldığında uzamsal niteliklerin işitsel temsilinde eksiklikleri olduğu gözlemlenmiştir.

Anahtar Kelimeler: Ses Manzarası, İşitsel Mekansal Biliş, Sanal Akustik Ortamlar, İşitsel Algı

To All Unique Perspectives

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LIST OF ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
AR	Augmented Reality
ASW	Apparent Source Width
CAD	Computer Aided Design
EDT	Early Decay Time
OBJ	Geometry Definition File Format
HTRF	Head-related Transfer Function
ISO	International Organization for Standardization
LEV	Listener Envelopment
LF80	Lateral Energy Fraction
LG80	Late Arriving Lateral Energy
IVE	Immersive Virtual Environment
MP3	Data Compression Format for Encoding Digital Audio
MR	Mixed Reality
SPL	Sound Pressure Level
T30	Reverberation Time
VR	Virtual Reality
WAV	Waveform Audio File Format

CHAPTER 1

INTRODUCTION

1.1 Background Information

Virtual environments have been developing for a long time and are changing the understanding of a space by means of how we design, perceive and use it. This new understanding of space requires people to adapt by gaining a new type of spatial cognition that can help people to combine the possibilities of a virtual space with the physical space they are used to: by making use of their different sensory skills. The existing studies on virtual environments are clearly dominated by the sense of seeing, which is not enough to result in a convincing immersive environment for the users; therefore, the research on perception and cognition of other sensory experiences is increasing nowadays, especially the auditory experience. The research on auditory perception has been scattered around in many different areas, including medicine, psychology, acoustic engineering, architecture, and urban design. Bringing a human perception-based perspective to sound studies, soundscape is mentioned for the first time in a thesis on urban planning, suggesting that the sonic environment of the cities should be designed and evaluated. (Southworth, 1967) Later, soundscape emerged as a research topic after Schafer, a composer and a writer, mentioned it in his booklet “The New Soundscape”. (1969) The term is explored further in his book “The Soundscape: Our Sonic Environment and Tuning of the World”. (1977) According to Schafer, soundscape is a new research topic that aims to bring together separate study areas of sound that question the relationship between the changing sound environment and people. The author mentions that the term soundscape is derived from the landscape and defines it as “any acoustic field of study”. (1977, p.13) Soundscape research gained popularity in the 1970s after Schafer; however, the sudden increase in the number of studies was not until the 1990s. Most of them aiming at noise control in urban areas; a large number of studies have been conducted on the evaluation of soundscapes until today. The researchers agree that soundscape is strongly involved with human perception; therefore, the evaluation of it should include perceptual dimensions in addition to the acoustical parameters.

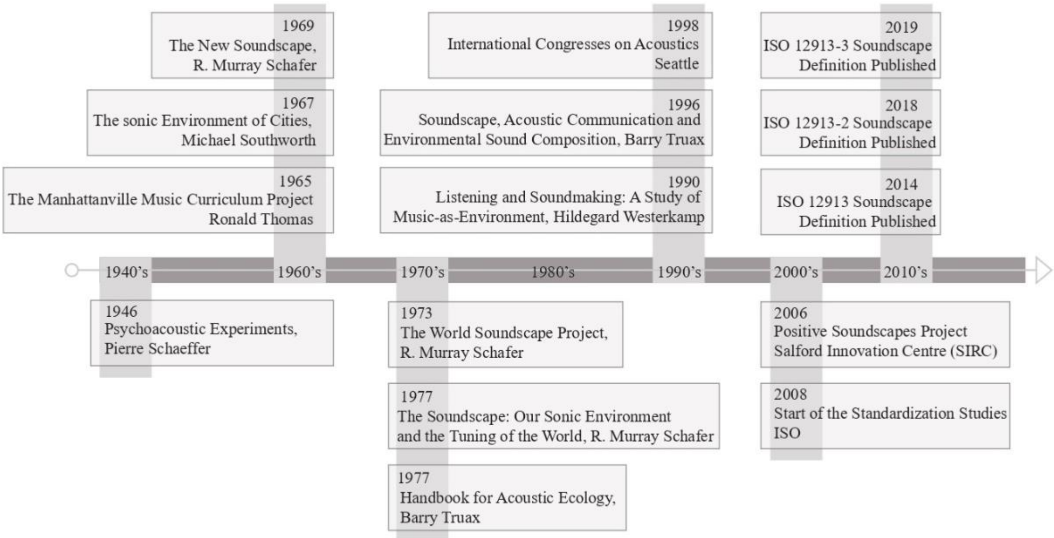


Figure 1-1 Timeline of the Soundscape History (developed by author)

The studies usually use soundwalks, interviews, questionnaires, and recordings for assessment. The latest studies also include the recreation of soundscapes in virtual environments by making use of simulations and auralizations. This approaches resulted in a tendency to design soundscapes virtually as well. Independent from the soundscape research, virtual acoustic environments have already been used for various functions such as assessing building acoustics, rendering of heritage spaces, restorative purposes, experiential art, blind navigation, and source localization. It is obvious that virtual environments are engaged with the auditory sense and have relevant studies on the possible effects on spatial cognition.

1.2 Research Problem & Objectives & Questions

The main aim of this study is to make a contribution to the literature on the improvement of the auditory perception and cognition of virtual spaces which are used for education, training, gaming purposes. This study proposes to offer a realistic representation of soundscapes in virtual environments according to spatial qualities instead of misleading synthetic sounds by integrating acoustical simulations with the immersive environment. In addition, the experience of a regular user instead of a professional will be questioned in auditory simulation environments for design purposes. The proposed approach arises from the noticed research gap on the integration of acoustic simulations and immersive environments as soundscape design methods. The study is also based on the potential of exploring a new kind of spatial experience with a higher level of immersion by a human-centered and more time-based design of sound perception, as well as questioning the place of visual sense that overpowers other senses in virtual environments, which is not inviting or inclusive for everyone. Exploring auditory spatial cognition is not only going to enhance the realism of the virtual environments but also aims to strengthen the idea of universal design by creating virtual environments in which blind or visually impaired people are considered and can strongly experience the space. The objectives of this study include:

- Exploring the virtual environments and soundscape approach in the form of a literature review.
- Combining the design, cognition, and perception of virtual acoustic environments with Schafer’s soundscape idea.
- Comparing and understanding the effects of acoustically simulated and immersive virtual soundscape design methods on auditory perception through changing forms and materials by series of cognitive experiments.

The literature review starts with a short introduction to virtual environments, immersion, space perception and sensory experiences, and spatial cognition. The review continues with basic knowledge on definition, terminology, standardization of evaluation, acoustical parameters, perceptual dimensions, and types of soundscapes. The soundscapes are further explored in the virtual context, creation methods, and cognitive aspects. The cognitive aspects are studied by reviewing the auditory spatial cognition studies on navigation, source localization, and distance perception. The review is concluded with case studies of soundscape based on VR. The research continues with an human-perception based experiment process. For the experiments, virtual soundscape alternatives are designed with changing spatial qualities: form of the room envelope and material selection according to absorption coefficient. The perception of these qualities is studied with two different virtual soundscape design methods. The first method is the auralizations through an acoustic simulator and the second method is the 3D sound environment in Unity combined with VR. The goal of the experiment process is to explore the accuracy of the auditory perception of form and material absorbence and compare two different methods of virtual acoustic environment design, which are a simulation and an immersive experience, by means of distance perception and localization and relate them with the indoor acoustic parameters.

The main questions of this research are:

How can hearing contribute defining a space or conveying spatial information?

What are the objective and subjective parameters of auditory perception in virtual indoor environments?

How can material selection and form affect the perception of sound?

1.3 Hypothesis

The hypothesis of the study is sound events from the perspective of soundscapes are capable of defining a space in a virtual environment and conveying spatial information such as the form, and material difference of the space to the perceiver through the perceptual and cognitive experience however, the simulated environments are not enough for accurate perception without the support of immersive environments.

CHAPTER 2

LITERATURE REVIEW

2.1 Virtual Environments

This study considers virtual environments as the main context of this study. Therefore, it is defined and explored by three qualities of it such as immersion, perception and sensory experiences, cognition.

Milgram and Kishino defined virtual environment as one of two extreme ends of the "virtuality continuum". The authors offered that while the real and virtual environments define the boundaries of the continuum, all the inbetween stages are within the scope of mixed reality which consists of both real and virtual objects. The author described the virtual objects as objects existing as non-physical essences that are required to be simulated to be perceived. (1994) Another definition of virtual environment is "a computer-generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in, and to interact with that environment". (Schroeder, 1996, as cited in Schroeder, p.2, 2008) Schroeder emphasized that this definition is based on sensory experience; otherwise, the scope of it would be unclear and might include independent subjects like dreams or books. (2008) Luciani supports these two definitions by mentioning virtual environments for needing a computer with the capability of simulation and transducing that can convert digital imagery into sensorially or mechanically perceived experiences. The author also mentioned that virtual environment and virtual reality could have the same meaning if the approach to the position of the human is the same. (2014) This idea is also compatible with Zeltzer's way of understanding the virtual environment, which is based on three components; autonomy, interaction, and presence. The author claimed that if the three components are satisfied at the same level, the end result can be called virtual reality, and to reach this stage, the presence, perception, and sensory experiences of humans must be deeply explored. (1992) According to Ruberto, VR is an archetypal occurrence that clearly reshapes the sense of reality by providing a chance for novel types of “subject-object-concepts.” (Eloy & Kreutzberg & Symeonidou, 2022, p. 9) The author also mentioned that design should aim to explicate prototypal systems in VR, by making use of computer programs and gadgets in questioning the reality and giving rise to the unique perceptual and communicational forms. (Eloy et al., 2022)

2.1.1 Immersion

Highly related to presence (Slater & Usoh, 1993), immersion is defined as the level of ability of a computer to admit a vision of reality to the senses of people in a way that it is “inclusive, extensive, surrounding and vivid.” (Slater & Wilbur, 1997, p. 604) Mentioned as the most significant aspect of VR, immersion is described as making the user part of the virtual environment by captivating all of their sensory perceptions. Accepted as a significant development in technology, VR is used in several different industries like architecture, engineering, entertainment, military, and commercial activities. (Lv, 2020) Schipper and Holmes also agree with these definitions by mentioning that the reason VR and MR tools have been embraced in design industries lately is the convincing nature of immersion by means of presence. The authors also add that the implementation of immersion to the scale of architecture enables designers to better understand what users expect and provide novel layers to their spatial perception, which results in strengthened wayfinding with increased awareness. (Eloy et al., 2022) Serafin, Geronazzo, Erkut, Nilsson, and Nordahl state that even though sound can be highly beneficial for navigating attention, strengthening the presence, and providing time-dependent participation in immersive virtual environments, it is not utilized enough in the area of VR. (2018) Referred as “sense of reality,” the true immersion is still not reached due to the lack of maturement in IVE technologies by means of affecting all senses of the perceiver. (Lv, p.4 2020)

2.1.2 Space Perception and Sensory Experiences

Perception has several definitions according to different fields. Bagok defined it from the perspective of psychology field as an inclusive term that consists of the whole process implemented in order to comprehend the environment and construct a representation of it in mind. The author also highlighted its relation to sensory experiences by defining it from the view of cognitive psychology as all activities conducted in brain aiming to interpret the data coming from the senses. (as cited in Woloszyn, 2018) Berryhill, Hoelscher, and Shipley define spatial perception as the process of handling and implementing the physical relationships objects have with each other, in which the perceiver's own body is accepted as an object as well. (2012) Makaklı noted that the use of VR is an outstanding tool for developing the skills for understanding both physical and virtual spaces, their qualities, thanks to its immersive, interactive, and imaginative character. It is also stated that, instead of accepting VR as a simple tool, it should be considered as a platform to generate unusual spatial experiences and new understandings of spaces. (2019)

It should also be noted that the process of computerization might also result in devitalizing the impressive abilities of the human brain that can work with all senses synchronized and giving in to the bias towards vision’s authority over other senses through the experiencing process of a space. (Pallasma, 2005) Therefore the studies of virtual environments should not focus on only the visual sense, but all of them equally.

2.1.3 Space Cognition

According to Ângulo and Velasco, the immersiveness of VR raise interest in using it in many areas since it provides a good quality of environment fidelity. It has been shown in the experiment conducted by the authors that representation of the design spaces in VR environment and the act of walkthrough ensured architectural students to understand spatial relations and qualities better. (2014) Hu and Roberts mentioned that cognition is heavily dependent on perception due to the fact that it does not occur without a person to perceive and decipher the environment through the sensory experience. The authors also add that apprehending a manufactured environment is not a simple task and requires intricate cognitive activity, including advanced assessment and selection. As a result, providing a 3D and uncostly environment for systematic design operations, VR is mentioned to be a valuable tool for exploring individual responses to the qualities of a designed space. (2020) Damayanti, Redyantanu, and Kossak's study revealed that all sensory systems positively affect the cognition of a virtual space; however, vision and sound are the dominating ones. (2021)

2.2 Soundscapes

This section aims to define the term soundscape and explore its evaluation, types and use in spatial cognition by reviewing the significant studies on the topic. According to ISO 12913-1:2014, soundscape is depicted as; "acoustic environment as perceived or experienced and/or understood by a person or people, in context". (International Organization for Standardization, [ISO], 2014) According to the mentioned depiction, it can be said that soundscape is not limited to the objective acoustical criteria; therefore, it requires observers and their individual perceptions to be highlighted to be understood.

2.2.1 Standardization of Soundscape Assessment

The need for the standardization of soundscape assessment appeared due to the increase in its use for research purposes. Brown, Kang and Gjestland state that attempts for standardization of sound perception and preference started by a Working Group brought together in the scope of ISO/TC 43/SC 1 (2008), which resulted in disagreements among the participants because of the various backgrounds they came from. The authors agree that there is a need for the standardization of soundscape research, which defines the boundaries of the used methodologies, protocol analyses, perception dimensions, sound source types, and the data must be collected for different contexts. It is also added that the terminology to be used must be defined properly. (2011) ISO-12913-1-2014 become the most significant step for the standardization of soundscapes by defining the term and its basic components. (2014) Later it was followed by ISO-TS-12913-2-2018, which defined the assessment criteria of soundscape and the methods for the DATA collection. (2018) Lastly ISO-TS-12913-3-2019 was released to standardize the DATA analysis process of soundscape evaluation. (2019)

2.2.1.1 Terminology of Soundscape

Brown, Kang, and Gjestland claim that there is confusion about term use in existing soundscape literature due to the lack of standardization; therefore, they offer "acoustic environment" to be used as a general term for the soundscape studies. (2011, p.5) According to ISO-12913-1-2014 and ISO-TS-12913-2-2018 terminology of soundscape studies are defined as: "sound sources, acoustic environment, soundscape." (2014, p.1) and "background sound, descriptor, foreground sound, indicator, local expert, noise, soundwalk, total sound". (2018, p.1-2)

2.2.1.2 Methods for Assessment

There were different approaches to how soundscapes should be assessed before the standardizations of ISO. Jennings and Cain (2013) offered a framework for soundscape assessment based on Kano Model aiming to pursue the potential benefit of soundscape field in practice. (Kano & Seraku & Takahashi & Tsuji, 1984) It is designed as three steps such as the composition of soundscape, the evaluation of soundscape as positive or negative, and the application of Kano model for design implementations. Accepting soundscape as only a part of an overall perception of the environment, this framework suggests that the quality of the auditory perception varies among the users according to their engagement level and activities. Therefore, the aim of the soundscape evaluation must serve the positive perception of the whole space, and it requires starting from basic needs and performative criteria. (Jennings & Cain, 2013) Kang, Hao, Yang, and Lavia suggested a framework for the evaluation of soundscapes considering perception assessment with the help of participant surveys and on-site listening tests in addition to the determination of acoustical properties such as level, loudness, sharpness, tonality, roughness, and fluctuation strength. The authors searched for correlations between different variables to provide a numerical representation for the evaluation of soundscapes. (2015) This approach supports the multidisciplinary definition of soundscape and offers a common ground for future studies.

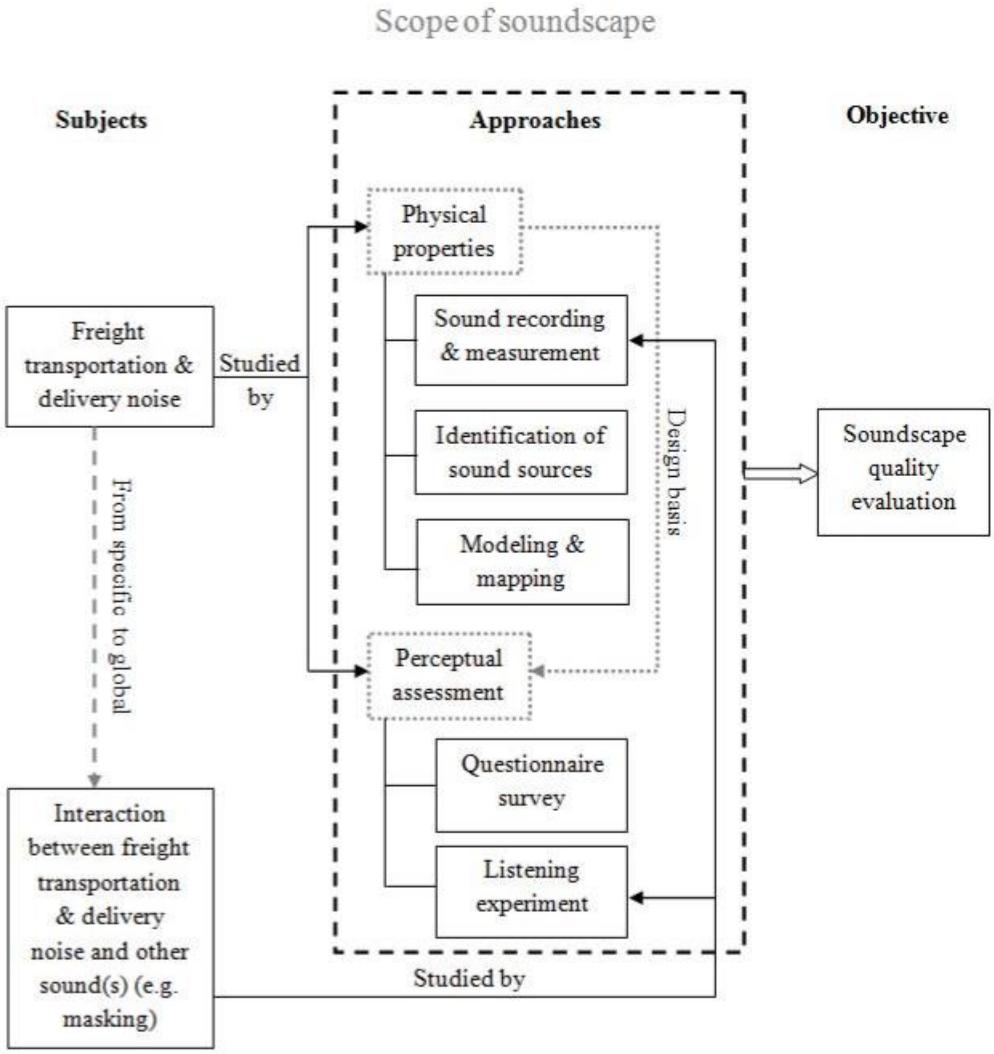


Figure 2-1 Suggested Research Methodology (Kang & Hao & Yang & Lavia, 2015)

Schulte-Fortkamp supports this idea by stating that the evaluation of soundscape requires several different methods, which should be capable of measuring the data from the context, acoustic surroundings, and perception of people. The author also mentioned that soundscape studies should be interdisciplinary and participatory, not only including people from different professions like urban design, acoustic engineering or architecture, but also stakeholders or users of the studied location. (2018) It is stated that the studies conducted on the psychoacoustic parameters of soundscapes are reported to have various methodologies, parameters, and hypotheses. As a result, there is a need for an increase in the number of research in order to reach a reliable standardization of the evaluation parameters. (Engel & Fiebig & Pfaffenbach & Fels, 2021)

The studies trying to fit soundscape assessment to a standard are still continuing, however, the standards defined by ISO are commonly used for the research. According to ISO-TS-12913-2-2018, soundscape research must be inclusive of three main elements such as: “people, acoustic environment, context”. (2018, p.2) Therefore, it requires a hybrid evaluation strategy that brings together several perspectives and varying methods of data collection. It is stated that the evaluation of soundscape must be based on data of individual perception, psychoacoustical parameters, and acoustical parameters. Soundwalking combined with a questionnaire or an interview is accepted as the method satisfying the requirement of individual perceptual data collection, whereas binaural measurements are accepted as the method for obtaining the psychoacoustical parameter information. (ISO-TS-12913-2-2018, 2018)

2.2.1.2.1 Perceptual Dimensions

There are two methods widely adopted for analyzing the perceptual dimension Grounded Theory and Principal Component Analysis (PCA) in the existing soundscape research.

Axelsson, Nilsson, and Berglund conducted an experiment aiming to standardize the perception dimensions as an appropriate number and relate them with the physical acoustic properties and dominant sound sources by using principal component analysis (PCA) and a listening walk. For the experiment, a variety of urban and indoor soundscapes are evaluated according to 116 decided perceptual attributes and their antonyms, which resulted in three main attributes; Pleasantness, Eventfulness, and Familiarity. The authors also showed that Pleasantness and Eventfulness are correlated with overall level and variability, whereas Eventfulness is inversely related to low-frequency sounds. (2010) For a research carried out in the scope of Positive Soundscape Project, the grounded theory was used on the protocol study of the participants after their soundwalk and listening experiment. The research aimed to explore how participants understand a soundscape and evaluate it as positive or negative. The research revealed that qualities of a positively evaluated soundscape are being informative or in line with the behavior of the participants and having a connection to their memories. By contrast, too loud or inconsistent foreground sounds are mentioned as qualities that make a soundscape be evaluated negatively. It is also revealed that calmness and vibrancy dimensions are the most significant aspects when a soundscape is described. (Davies & Adams & Bruce & Cain & Carlyle & Cusack & Hall & Hume & Irwin & Jennings & Marselle & Plack & Poxon, 2013) Bilen and Can conducted a research aiming to define an approach for the assessment and treatment of acoustical comfort from the perspective of soundscape which tries to explore the level of pleasantness. The evaluation of perception dimensions is maintained with the soundwalk approach, interviews, and questionnaires. The perceptual evaluations were tried to be related to the psychoacoustical parameters measured from the recordings taken simultaneously during the soundwalk. Thirty different adjective pairs are analyzed with a semantic differential test and reduced to 19 statistically relevant ones. It is revealed that %85 of the pairs could be explained with Zwicker loudness, %10 with sharpness, and %5 with roughness. (2021)

2.2.1.2.2 Acoustical Parameters

According to ISO-TS-12913-2-2018, for evaluating a soundscape several acoustical parameters such as: “Equivalent continuous sound pressure level $L_{Aeq,T}$ and $L_{Ceq,T}$, percentage exceedance levels $L_{AF5,T}$ and $L_{AF95,T}$ “ and psychoacoustic parameters such as: “loudness (N), sharpness (S), tonality, roughness (R), fluctuation strength (Fls) should be considered. (2018, p.3) According to Engel, Fiebig, Pfaffenbach, and Fels psychoacoustical parameters are used by researchers for soundscape studies by looking for the possible relations between them and the acoustical parameters. It is mentioned that the most used psychoacoustic parameter in the existing literature is loudness and it is usually related to sound pressure levels by the researchers as an individualized representation of the same information. (2021)

2.2.2 Types of Soundscapes

Brown et al. suggested classifying acoustic environments for soundscape research as outdoor and indoor environments and classified the sound sources accordingly, yet the parts other than the urban acoustic environment empty were left empty, including the indoor environment, and rural, wilderness, and underwater environments. (2011) Early soundscape studies related the term to the landscape. As a result, soundscapes are strongly associated with open spaces, and urban soundscapes dominate the existing literature. Ingold argues that the term landscape cannot be shredded into different senses as if they are separate beings. The author claims that landscape becomes visual when it is recreated with the tools of visual representation such as drawings or photos; therefore, the soundscape can only be validated by its recreation of auditory tools like a recording or a sound art. (2007) For this section, types of soundscapes are classified according to the space quality and divided into two titles: urban soundscapes and indoor soundscapes since the other outdoor environments are out of the scope of this study. According to Aletta and Xiao, there are different approaches to the scale of soundscape, and it is commonly studied on a large landscape scale. However, there are a number of studies on building scale as well. The authors also mention that the researchers working on the sound in indoor spaces are heavily dominated by the influence of room and building acoustics; as a result, soundscape approach is not implemented widely. (2018) Axelsson, Guastavino, and Payne agree and state that most of the existing research focuses on urban parks or plazas, which do not provide spatial diversity or a wide range of context needed for standardization and are only helpful for gaining more insight into similar scenes. The authors also add that it should be possible to exchange information between different studies for the research field to expand and develop. (2019)

2.2.2.1 Urban Soundscapes

Urban soundscapes are usually related to noise and evaluated with the soundwalk method. The studies can mostly be found under the keywords of urban soundscapes, soundscape assessment, and soundwalk. Hong and Jeon suggested soundscape maps as a more helpful alternative to noise maps for urban design research and conducted an experiment aiming to analyze the soundscape of a selected district in Seoul in terms of spatial dependency. The results revealed that perceived sound environments could be affected by the adjacent areas. It is also stated that water sound has positive effects on perception due to the masking of traffic sounds. (2017)

Bahalı and Tamer-Bayazıt mentioned that soundscape is a way of understanding the urban acoustic environment with different types of qualities, including physical, social, or cultural ones. The authors offered a method for the soundscape evaluation, which consists of three stages. For the first stage, the participants report the sounds they expect to hear. The second stage includes the silent soundwalking process with key points, where the participants write the adjectives they use to describe the present sound environments. For the last step, they fill out a questionnaire on a general assessment of soundscapes in addition to their perceptions and classifications of them. The authors applied this process to a route around Gezi Park, and the results indicated that the park is evaluated as comfortable and positive due to the natural sounds present. However, the effect of natural sounds was barely noticeable for the rest of the route. The sound source that affected the route most and was heavily evaluated as positive was the street musicians. (2017) Pérez-Martínez, Torija, and Ruiz also used the soundwalking method to evaluate the soundscape of a touristic location from the perspective of dominant sound sources. It is revealed that if the most dominantly perceived sound is depicted as a pleasant sound by the listeners, the overall perception quality of the soundscape gets higher. The authors also agreed with previously mentioned studies by stating that natural sounds, especially the water sound, were perceived positively. In contrast, the human sounds created by a crowd are perceived as negative aspects of a soundscape. (2018) Mancini, Mascolo, Graziuso, and Guarnaccia also believed that soundscape is a convenient approach to environmental noise assessment and tried to compare the sound pressure level and the perceptual attributes in a university campus to prove that physical attributes might not be enough for noise detection. The study confirmed this idea and showed that there are some locations that are affected by the traffic noise but evaluated positively; therefore, it can be said that the areas with high sound pressure levels are not always perceived negatively. The authors add that natural sounds helped to mask the unattractive car sound and were evaluated positively. Unlike Hong and Jeon, this study found that human sounds are depicted as pleasant and vibrant in the studied context. (2021)

2.2.2.2 Indoor Soundscapes

Dokmeci-Yorukoglu and Kang presented a framework for the evaluation of indoor soundscapes suggesting that the parameters of outdoor soundscapes would not be sufficient for indoors. The authors claim that in order to explore the research area of indoor soundscapes, there is a need to be fed by both urban soundscape approaches and room acoustics since architecture also becomes involved with the sound environment. The framework includes three parameters such as: "built entity, sound environment and contextual experience". (2016, p. 204) The framework is tested on several library contexts, and it resulted in proof of the effect of spatial organizations on psychoacoustical parameters such as sound pressure level and loudness. (2016) Yilmazer and Bora suggest that the existing standardization of soundscape studies is not valid for indoor acoustic environments and there is a need for more studies to be conducted for its standardization. The authors carried out an experiment aiming to look for possible relations between the space enclosure level and spatial recognition through sound perception. The experiment consists of the recordings of each space collected through a soundwalk and presented to the participants in a laboratory environment with headphones followed by a questionnaire. The results of the study showed that auditory perception is dependent on spatial quality since the participants were not able to recognize the closed and semi-open spaces through only auditory data, unlike they did for the open space. Therefore, it is mentioned that the evaluation of sound perception might require new parameters unique to indoor conditions. (2017)

Having a similar approach to Jennings and Cain (2013), Acun, Yilmazer, and Orhan evaluated the indoor soundscape as positive, negative, and neutral in relation to the expectations of the users from the function of a space. They suggested that if the architectural qualities and the auditory elements are in line with the expectation of the perceivers from the building function, the positive evaluation of the soundscape can increase. (2018) Analyzing three more indoor soundscapes and interviewing the users, Yilmazer and Acun supported the idea that people have similar expectations from the design of a soundscape as they do from a physical space. Moreover, they claimed that it is possible to create a lively environment that maximizes the experience of the users by sound if it is used correctly. The authors highlighted that the context and the function of a space crucially affect what is expected from a soundscape and which sounds are preferred. (2018) Torresin, Albatici, Aletta, Babich, Oberman, Siboni, and Kang conducted an experiment aiming to test the reliability of perceptual evaluation models for indoor spaces. The case study was a living room of a residential building that is affected by both interior sound sources and exterior sound sources coming from the urban context filtered by the window. Alternative soundscape arrangements are recorded binaurally and presented to the listeners. The participants evaluated them according to 97 perceptual attributes, and this number is reduced to main three attributes by PCA (principal component analysis), such as comfort, content, and familiarity, similar to the previous studies on urban soundscapes. The suggested evaluation system included a main axis of comfort and content (%87 variance) and a secondary axis of privacy and engagement. The results revealed that a desirable soundscape for an indoor living room would be perceived as comfortable and rich by means of content, a neutral soundscape would be annoying and lack content, and an unwanted soundscape would be annoying and has dense content lastly, a private and controlled soundscape would have both comfort and emptiness. It is revealed that loudness affected comfort negatively, and overall variability affected content positively. In addition, content heavily dependent on external sources or internal music and comfort was negatively influenced by outdoor traffic noise and technological or HVAC sound. (2020) Ercakmak and Dokmeci-Yorukoglu claimed that the standardization of ISO is aimed at urban soundscape research and there is a need for developing a methodology for indoor soundscape research and its application in practice. The authors offer that for the evaluation of an indoor soundscape, architectural characteristics should be examined in addition to people, context, and acoustic environment and tried to associate them with the design phases. These characteristics are described as properties that can affect the sound and its perception and are examplified as function, spatial organization, surface openings, material selection, construction properties, etc. They also mentioned that classification of a sound source in terms of being an interior or exterior source might gain importance. (2021) Jeon, Jo, Santika, and Lee agreed with Dokmeci-Yorukoglu and Kang's approach and tried to combine it with visual parameters and looked for possible audio-visual relations. The authors used several open-plan office environments created with VR tools as the visual context, which is combined with soundscapes simulated according to the measurements of sound pressure levels from on-site recordings. The 3D model of the offices is created and processed with ODEON, in which the materials and acoustical properties are implemented. The participants semantically evaluated the auditory environment by the words loud, variable, and reverberant and the visual environment by bright, orderly, and wide. The overall quality was assessed based on privacy, preference, and work. The study revealed that keeping the reverberation at the minimum level and maintaining a calm environment have positive effects on both work satisfaction and work performance. It is also mentioned that better visual conditions can enhance the satisfaction from the soundscape and speech privacy; as a result, the design of the soundscape and visual conditions should be considerate of each other. (2022)

2.2.3 Virtual Soundscapes & Creation Methods

Virtual environments, mainly VR and AR, become important tools for the creation of experiment scenes. These tools are also accepted in soundscape studies and used for the reconstruction of sound environments virtually, aligned with Schafer's definition of soundscape, which can be the sonic environment of a particular place or even a recording. (Schafer, 1977) Johnson claimed that virtual worlds could be a significant base for creative thought, real-time experience, and novelty to intertwine the synthetic and natural soundscapes into an absolute adventure. The author also added that it could be a tool for removing the limits of time and space and offer an environment for a virtual soundwalk. It can enable the participants to develop an acoustical awareness of the existing sounds around them that they normally do not focus on or experience soundscapes that they cannot reach due to the lack of opportunity. (2018)

Hong, He, Lam, Gupta, and Gan suggest that the use of VR and AR tools for soundscape research keeps increasing thanks to their capability of precisely representing the visual and auditory scenes for perception. (2017)

Reproducing acoustical settings virtually is mentioned to strengthen the capacity of soundscape assessment by means of an accurate inspection of external and independent factors. It is stated that the artificial nature of these acoustic environments gives the opportunity for exploring the cause-effect-based involvements between dependent and independent factors. Nevertheless, the virtuality raises hesitations on the issue of ecological validity. (Hong & Lam & Ong & Ooi & Gan & Kang & Feng & Tan, 2019) Hong et al. suggested that the result of their experiments where the real and recorded soundscape are compared revealed that no remarkable disparity between the two is found in terms of perceptual attributes and source dominance. However, it is reported that the perceptual distance was higher in the artificial soundscape compared to the on-site version. (2019)

In order to understand virtual soundscapes, it is crucial to be familiarized with the methods and tools used for their creation. The scope of virtual acoustics is mentioned to include modeling of the source, the receiver, and the delivery medium. (Savioja & Huopaniemi & Lokki & Väänänen, 2005) Serafin et al. suggest that the devices and softwares for accommodating an immersive and interactive acoustical experience have shown significant progress in the last few years. Speakers and headphones are mentioned as the frequently used devices for transmitting sound immersively, and the headphones have the advantage of managing binaural hearing precisely and leaving out the undesirable sounds of the environment. Nevertheless, the perception of sound might become abnormal due to the proximity to the ear and the confusion of sound location as from inside or outside of the head. HTRF systems also can be used for a realistic hearing experience. (2018) There are three main methods for soundscape creation in virtual environments explored in this study: recording, simulation, and auralization.

2.2.3.1 Recording

Recording is one of the methods used in soundscape studies aiming to carry out controlled experiments. Sound is mentioned to be inseparable from its source, location, and the time it occurred, whereas recording takes out the sound from its context and highlights it as an object. (Solomos, 2018) Davies, Bruce, and Murphy questioned whether a soundscape could be correctly reproduced in a laboratory environment for perceptual evaluation or design, suggesting that there are not enough tools for designing a soundscape compared to the visual ones. The authors conducted an experiment by recording several locations and reproducing them by using a spatial audio system for participants' evaluation. The results revealed that the participants' judgments are in line with each other for different locations and the on-site experiments; therefore, the use of ambisonic reproduction is trustworthy for assessing the perception dimensions of a soundscape. (2014) Hong, He, Lam, Gupta, and Gan add that in order to reach a precise perception of an acoustic environment, timbre and spatial qualities of a recording should be determined carefully, which depends on the devices and methods used for reproduction. (2017) According to ISO 12913-2, there are two frequently used sound reproduction methods in soundscape experiments, such as binaural and ambisonics. (International Organization for Standardization, [ISO], 2019) Binaurals are mentioned to be effective for immersion and fidelity, even though the recordings with them are created in a stationary manner without individualized HTRF's. (Hong et al., 2019) Gerzon defines ambisonics as a technic for recording and duplicating a field of sound surrounding 360 degrees, which means it has the ability to engage all directions incorporating height and depth as well around a point source located in space. (Hong & He & Lam & Gupta & Gan, 2017)

2.2.3.2 Auralization and Simulation

Soundscape simulation is depicted as a tool that makes adjusting a given soundscape or generating a new one possible with the help of several indicators aiming to explore how preference and perception affect the sound environment. (Bruce & Davies & Adams, 2009) It is observed that simulation and auralisation are used in a similar manner in the reviewed literature; therefore, it is better to compare their definitions.

According to Vorländer, auralisation is one of the base keywords of acoustic VR in addition to the simulation and spatial sound reproduction and describes it by the auditory version of visualization, which has a perceivable sound as the end product. The author defines auralisation as “the technique for creating audible sound files from numerical (simulated, measured, synthesized) data.” (2008, p. 103) It is also claimed that auralisation is a significant development for the analysis, synthesis, speculation, and evaluation of sound environments, since understanding a sound event is only possible when one is engaged in a whole experience including more than one sense with respect to the characterization and perception of a sound.

(Vorländer, 2008) Lundén, Gustin, Nilsson, Forssén, and Hellström agree by stating that auralisation is a useful tool for the design of acoustic environments in a participatory manner from the earlier stages since it can solve the problem of communication between the professional and unprofessional by using 3D models for evaluation. (2010) Hong et al. support this idea by accepting auralisation as a post-process that can spatialize the simulated sound sources and add that it helps the reproduction to be more realistic and capacious. (2017) Sudarsono, Lam, and Davies claimed that on-site experiments and acoustical reproduction lack the variety and control of individual sound sources in addition to their impact on the soundscape and perception; thus, they suggested using an acoustic environment simulator. The authors experimented with the simulator by allowing participants to insert and remove static or moving sound sources and reveal the relations between sound objects and perceptual dimensions. Moreover, they feed the simulator with the numerical model of the found relations and get it to predict the perception of given urban soundscape composition. (2017)

2.2.4 Spatial Cognition with Soundscapes

Pallasma states that being independent of the directionality and giving a sense of interiority, the sound is capable of enhancing the cognition and experience of a space. (2005) Several experiments were conducted in existing literature questioning spatial cognition with the use of sound. However, it is observed that these studies usually do not have soundscape as a keyword, even though they use the elements of it without naming them. Keynotes, signals, symbols, and soundmarks are mentioned as the essential parts of a soundscape and are preferred to be mentioned as sound events, which gain their meaning with time, interactions, and context. (Schafer, 1977) Nevertheless, the use of sound in the existing research on spatial cognition usually is in the state of being a sound object, a “laboratory specimen” (Schafer, 1977, p. 121), and does not strongly act as a part of a whole system. It is stated that the mood and the memories of participants heavily affect the understanding of soundscapes; therefore, soundscapes are mentioned to be strongly related not only to basic perception and physical acoustic dimensions but also to high-level cognitive activities. (Davies et al., 2013) As a result, it is not wrong to claim that the integration of the soundscape approach would strengthen the auditory spatial cognition topic. There were two dominating experiment topics in the literature for auditory cognition which are included in this section: source localization and navigation.

2.2.4.1 Navigation

Navigation studies are usually aimed at blind people and can be found under the keywords such as auditory perception, spatial audition combined with visual impairment, or blindness. Most of the related studies use auditory landmarks for navigation or orientation, but they do not use the term soundmark as a keyword like mentioned before. According to Voss, a space can be understood through three dimensions by means of spatial audition such as horizontal, vertical, and depth. The horizontal dimension is mentioned as the one that is usually associated with navigation and location intentions; therefore, it is the most frequently chosen as a research topic. (2016) Viaud-Delmon and Warusfel conducted a study in which, boundaries of the experiment scenes and landmarks in them are created by sound elements. The choice of sounds which are a cicada, a male talking, and a piano, is made aiming for them to be easily distinguishable. Wireless headphones were used for rendering of an auralized virtual acoustic environment updated according to the movements of the participants. 11 participants explored six alternative scenes constructed by sound and tried to find inaudible hidden objects by navigating themselves by the surrounding sound elements. Alternative scenes are used to challenge the participants by changing the distances between the landmarks, removing or rotating landmarks, and replacing landmarks with each other. The success of the task is evaluated by search time, path length, and the number of boundary crossings. Rotation and replacement of the landmarks increased the search time significantly, whereas removing one did not cause significant change. The results revealed that it is possible to find a target without making use of any visual information; moreover, the search time decreased through the repetition of trials in general, showing that participants started to learn to navigate themselves better with more experience. It is also emphasized that auditory cognition enables perceivers to create an allocentric representation of space since they are open to relying on cues that are out of vision and touch. (2014) Even though this study mentions the word soundscape in the text, they do not include it as a keyword or use it effectively for the experiment scene design. Another research also hypothesized that sound is a useful tool for navigation and reorientation tasks due to its ability to transfer information from a distance without the need for touch and is more flexible by means of traveling around surrounding objects. Aiming to test their hypothesis, the authors directed an experiment where 24 participants were instructed to find an object within the given scene by only using their sense of hearing. Later they were disoriented by rotating and asked to find their way back to the object's location to put it back. The study resulted in a reliable success rate of wayfinding by sound, even if there are ambiguous sources. It is also mentioned that using a rhythmic sound instead of a continuous one that can blend in the environmental sounds helped the participants to encode the scene better. (Nardi & Twyman & Holden & Clark, 2020) The consideration of environmental sounds could be one of the turning points for these studies to become a soundscape studies if explored with more depth. Unlike the previously mentioned research, Woloszyn brought together the terms soundscape and spatial cognition in an experimental navigation study in VR aiming to reconstruct an existing soundscape in an immersive environment for community evaluation by planting existing sound sources to the virtual model with respect to their hierarchical relations with each other and time. The method used is mentioned as virtual soundwalking in a worldline which supports the anthropocentrism of a space. It enhances the variational qualities of a soundscape by creating the opportunity for personal choices of movement, perception of comparable distances between sources from the scale of a human, and time-based interactions. (2018) Even though this study takes auditory cognition one step further by means of integrating soundscape, the understanding of soundscape is an extension of a landscape, which does not provide much for indoor spaces or sound-based spatial design. Aiming to test the reliability of auditory navigation without any visual stimuli in VR environments; Fialho, Oliveira, Filipe, and Luz designed an experiment setting called "Soundscape VR". (2021, p.3) It works with a head-mounted display combined with a game engine and uses 3D sounds for spatial navigation. The experiment was conducted with different difficulty settings, which included a crosswalk simulation, an object location with obstacles, and wayfinding in a maze. 3D sound provided by the headphones of the VR set was based on echolocation and represented the distance of an obstacle or an object. The performance of the participants was evaluated according to the time spent on the task, the number of times they hit an obstacle, and the number of prompts given during the task. The research results showed that the developed setting is a qualified tool for the aim of the research. It is also revealed that the performance of the participants showed an increase over time, affected by their experience and familiarity with the tasks. (Fialho & Oliveira & Filipe & Luz, 2021) Nardi, Carpenter, Johnson, Gilliland, Melo, Pugliese, Coppola, and Kelly's study questioned whether it is possible to comprehend geometrical information of a space by making use of sounds of an array of speakers. For the experiment, an octagonal space with rectangularly arranged four landmark sounds (a male reading poem, a piano melody, a bird sound, and keyboard typing) is explored by the blindfolded participants. The choice of sounds was based on the semantic significance and appropriateness of a room soundscape. Their task was to find a hidden object attached to one of the boundaries of the space and place it back in the same location after being disoriented. It is mentioned that the participants were clearly instructed to use what they hear instead of other navigation methods. The participants managed to complete the task successfully. The experiment results were evidence of the ability to encode geometrical information by differentiable soundmarks. It is also revealed that when the geometry of the configuration is learned by the participants, the information can be used for navigation even if the soundmarks are replaced with identical ones. (2022)

2.2.4.2 Source Localization

Geronazzo, Bedin, Brayda, Campus, and Avanzini paired the sound with haptic sense and questioned if a map with only these two senses is enough to comprehend an unknown scene before experiencing it. The reason for pairing the two was mentioned as including both proximal and distal senses in order to supply local and global information on location at the same time. The participants were required to explore the map with a virtual cube defined as a haptic object and find out the location and size of it in a variety of conditions, including one or more feedbacks such as tactual information, 2D or 3D anchor sounds. The research showed that tactual information resulted in a higher level of spatial cognition compared to 2D anchor sound; however, the result was the opposite when the anchor sound was 3D. (2016) The study by Aggius-Vella, Campus, Finocchietti, and Gori focused on the spatial qualities of the sound around the body and searched for the perceived differences between the body parts. An experiment is conducted on 26 participants, in which they were asked to identify the location of several sound sources presented at different positions and different heights such as head level, chest level, or feet level. The results suggested that participants were able to localize the sounds coming from their backspace more accurately compared to the front if the level of source is at chest or foot level. In addition, the participants were more likely to think that a source was at the back when they were not able to see the source and felt unsure. The authors related this with the lack of other sensory stimuli at the back, making hearing the only sense to be relied on for understanding space. (2017) Battal, Occelli, Bertonati, Falagiarda, and Collignon conducted an experiment to compare the spatial hearing capabilities of sighted and blind individuals to understand if vision has an effect on source localization. Seventeen blind and seventeen sighted participants were instructed to predict the location of several different sound sources realized by a series of speakers placed in the horizontal and vertical planes. The results showed that the visual sense is not necessary for the development of spatial hearing abilities and increases the tendency to rely on the auditory sense. It is mentioned that, since blind participants performed better for the sounds coming from rear space, which is not affected by visual stimuli for both groups, it can be said that spatial auditory sense can be developed by training and experience. (2020)

2.2.5 Cases of VR in Soundscape Studies

This section aims to bring together the previous studies in literature, which include the use of VR technologies in soundscape research. The VR based soundscape studies usually focus on how sound affects the presence of the virtual environment. Kern and Ellermeier aimed to understand the effect of soundscape in the realism and presence in VR environments. The authors used a natural soundscape as the background sound and real time foot-steps as the impulse sound for two experiments. The Unity software is used for spatializing the soundscape. The results of the first experience showed that the background sounds strongly affected the presence and realism whereas the foot-steps did not show a significant difference. For the second experiment they improved the algorithm detecting the foot-step detection and improved the experiment setup which resulted in no significant effects on presence, realism, or involvement for both background and impulse foot-step sounds. (2020) Serafin, Geronazzo, Erkut, Nilsson, and Nordahl mentioned auditory cues as a crucial aspect of spatial representation in virtual reality and the presence of the environment, different than the visual cues that dominate, by its temporariness and omnidirectionality. It is also added that the simulation methods for providing realistic sound propagation to understand the relationship of sound, geometry, and receiver and the hardware to deliver the sound correctly are improving. Thanks to the use of headphones, it is possible to experiment with binaural hearing and HTRF (head related transfer functions) and improve the distance perception of sounds. Nevertheless, the effectiveness and reliability of these methods are questioned in the immersive VR context which requires real time modifications according to the participant’s active involvement. (2018) Llorca-Bofí and Vorländer agree with the questionability of sound in VR environment by stating that the researchers of architecture are having hard time representing and understanding the qualities of space by VR that requires consultancy from different fields, especially auditory perception due to the research gap. The authors offered a framework for combining visual and acoustical modeling by matching their details levels to each other, however, it is mentioned that the existing visual and acoustical modeling methods have different working logic and need more reliable integration strategies. (2021) According to Milo and Reiss, professionally practicing architects would also like to take part in understanding sound propagation through the integration of acoustic features to the existing representation tools they use and are interested in how the geometry or the material of a space would influence the reaction of the space to a potential sound source. (2019) As a result, it can be said that the integration of sound perception with VR environments still needs improvement for providing a better base for soundscape experiments. On the other hand, there are studies that validated VR as an adequate tool for soundscape research. Xu, Oberman, Aletta, Tong, and Kang state that immersive virtual reality is accepted as a valid research tool for multisensory experiments in several fields varying from acoustics to psychology. It is also added that even though it is not easy to reach an adequate number of subjects in experiments, the ecological validity of the tool keeps increasing over time in parallel to the developments in VR technologies. (2021) Rajguru, Obrist, and Memoli claimed that VR is the ideal tool for auditory perception based research due to its convenience for precisely controlling the sound and combining it with visual information. However, according to the authors, there is not enough research in current literature that understands soundscape from the perspective of spatialization, and the existing ones are usually limited to site recordings presented with headphones. (2020) Echevarria-Sanchez, Van- Renterghem, Sun, De Coensel, and Botteldooren used VR for assessing the soundscape design alternatives for an existing bridge. (2017) The significance of the Echevarria-Sanchez et al.'s experiment was the use of movement freedom VR provides for the participants by means of walking (Rajguru et al. 2020) and rotating their heads (Serafin et al. 2018), which are mentioned as important contributors to the accuracy of source localization in VR settings in literature. The headphone-aided virtual walk was conducted through the 3D environment Unity software offers both visually and aurally, in the form of a camera movement with a constant speed that participants experience but cannot control but, are free to look any direction. The results showed that VR environment is sufficient enough for comparing soundscape alternatives and rated as realistic by the subjects. (Echevarria-Sanchez et al., 2017)

2.2.6 Critical Review

The literature suggests that there is a growing interest in the evaluation of soundscape studies in virtual environments however, the reliability of the tools used is not clear. Immersive environments lack the ability to convey spatial information such as materials, or objective and subjective acoustical parameters, whereas acoustic simulation tools lack to provide a representation of first-person perception. Even though the studies on soundscape and its evaluation in virtual environments are increasing rapidly, there is a research gap for the integration of realistic simulation of spatial and acoustic qualities with the representation in immersive environments. Therefore, the integration of two soundscape creation methods should be studied in more detail, for providing a reliable solution for future research such as spatial cognitive training, education purposes, perception-based spatial design, and spatial perception of blind or visually impaired people.

CHAPTER 3

METHOD OF INQUIRY

According to the standing point clarified in previous chapter, an experiment process is designed to compare and understand the affects of acoustically simulated and immersive virtual soundscape design methods on auditory perception through changing forms and materials. For the acoustically simulated soundscape design method, each virtual space is organized with a grid system and a soundwalk route is designed on this system. Auralizations of the grid points which are in the soundwalk route are used as sound events. For the immersive method, the auralization of the furthest grid point is used as the sound event, aiming to represent the effects of spatial qualities of the space on perceived sound, such as the form, material absorption and size.

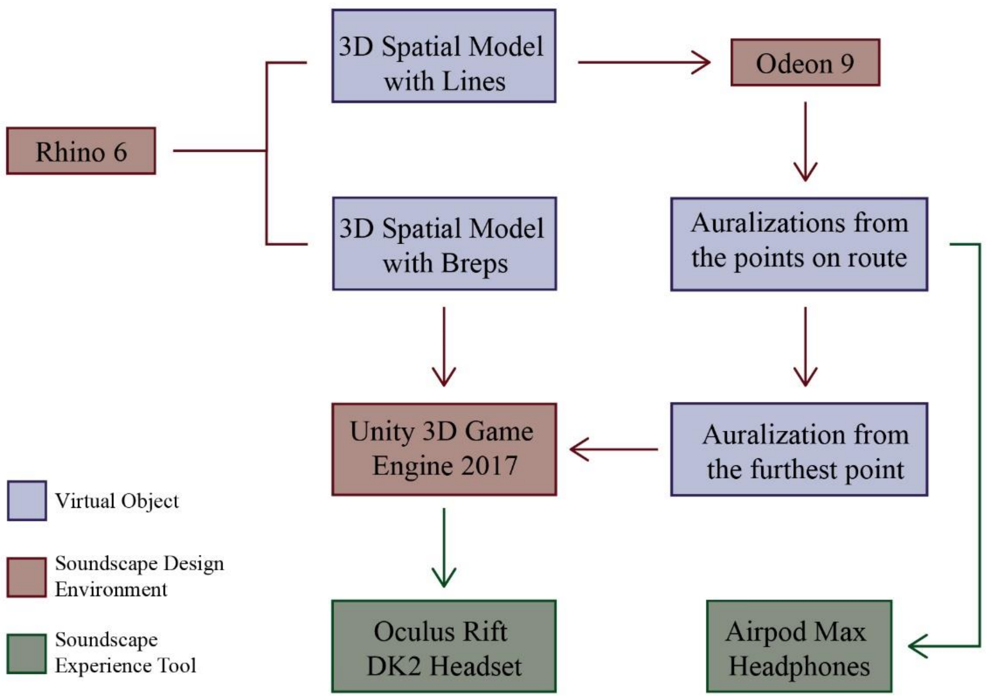


Figure 3-1 Workflow of the Virtual Soundscape Design Methods (developed by the author)

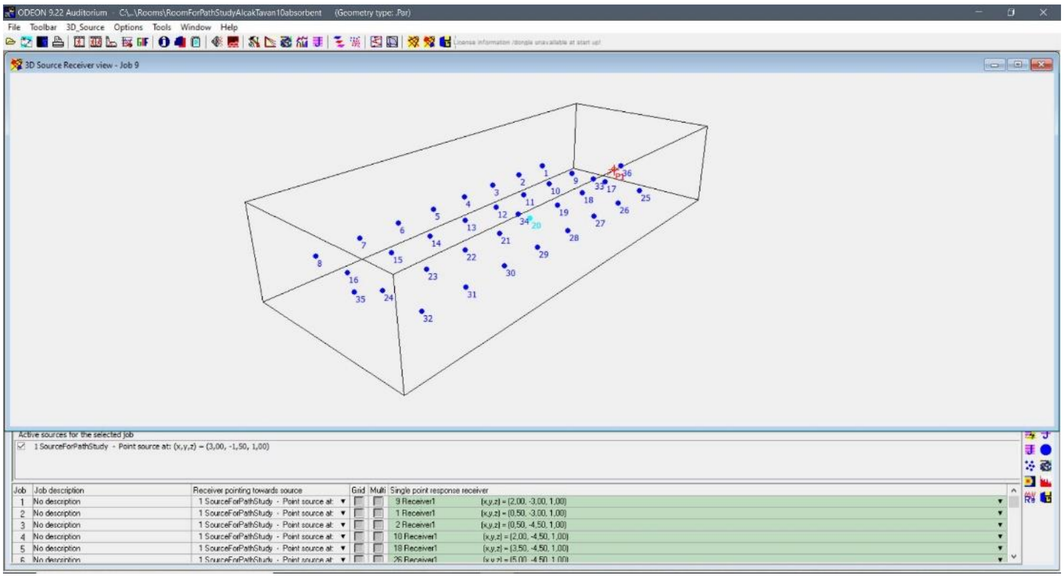


Figure 3-2 Virtual Soundscape Design Method 1: Odeon - Room Acoustic Simulator

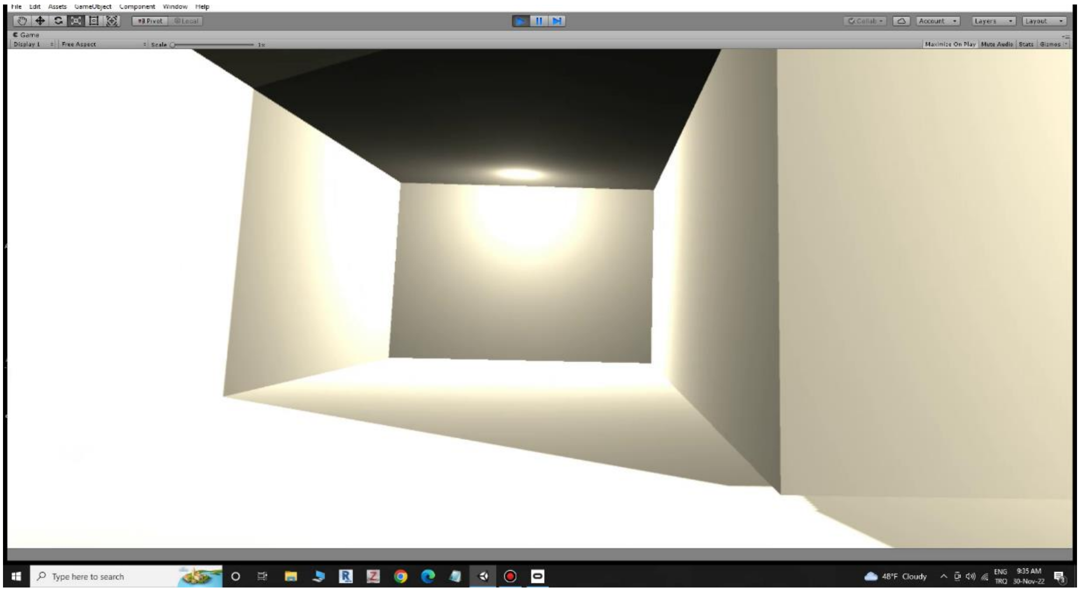


Figure 3-3 Virtual Soundscape Design Method 2 : Unity - Immersive Gaming Engine

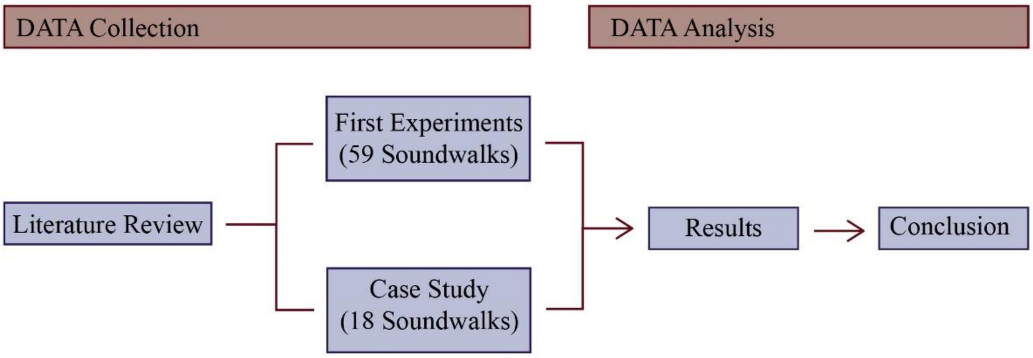


Figure 3-4 Workflow of the Study (developed by author)

The experiment process includes two series of experiments. First experiments are conducted to compare two soundscape design methods for the rooms with different forms and material selections within a cognitive study including source localization, self localization and distance guessing. 20 participants joined and 59 soundwalks are conducted in a total of 15 soundscapes with varying forms, material absorptions and soundscape design methods. The second experiments are in the form of a case study based on a physical space that the participants have different levels of familiarity. It is aiming to explore how the perception changes when the same sound event is tested in a detailed and familiar virtual space. Case Study process is conducted with 09 participants and 18 soundwalks are conducted in 2 soundscapes.

3.1 Hypothesis

The hypothesis of the study is sound events from the perspective of soundscapes are capable of defining a space in a virtual environment and conveying spatial information such as the form, and material difference of the space to the perceiver through the perceptual and cognitive experience however, the simulated environments are not enough for accurate perception without the support of immersive environments.

3.2 Research Questions

The main questions of this research are:

How can hearing contribute defining a space or conveying spatial information?

What are the objective and subjective parameters of auditory perception in virtual indoor environments?

How can material selection and form affect the perception of sound?

3.3 Design of the Experiment

Lehnert states that sound signal has an effect on source localization and perceived timbre, however, it is not the only effect that determines the perception of a sound event of a receiver. The physical qualities of the space, geometry and acoustic properties of the surfaces that surround the sound event also have an effect and it is called spatial impression. The author also add that basic dimensions that indicate spatial impression are reverberance and spaciousness. (1993) Sabine defines reverberation as an acoustical character of a room and claims that if the volume of space and the absorption coefficients of its components are known, it can be calculated. (1964) According to Beranek, spaciousness, also referred as ASW, is the perception of an enlarging effect on a sound source due to its reflections from lateral surfaces. Beranek depicts listener envelopment (LEV) as the perception of being surrounded by the reverberance of the sound and it is highly related to the late arriving lateral energy (LG80). (2010) Morimoto, Jinya, Nakagawa, and Sakagami suggest that the spatial impression of a listener depends on apparent source width (ASW) and listener envelopment (LEV). (2007) Aiming to understand auditory spatial cognition better, the objective and subjective parameters affecting spatial impression should be examined.

The subjects of the experiment process are two spatial qualities: the form of the room envelope and the absorption coefficient of the surface materials. The perception of these qualities is studied with two different virtual soundscape design methods. The first method is the auralizations through an acoustic simulator and the second method is the 3D sound environment in virtual reality. The goal of the experiment process is to understand the auditory perception of mentioned qualities and compare two different methods of virtual acoustic environment design ,which are a simulation and an immersive experience, by means of distance perception and localization and relate them with the indoor acoustic parameters.

In this study, the virtual acoustical environments are examined from the perspective of soundscape approach which is human-centered and does not only depend on acoustical calculations. Therefore, the experiments include virtual soundwalks followed by a protocol study including questionnaires, interviews and mind maps, which allow collecting individual perceptual data from the participants.

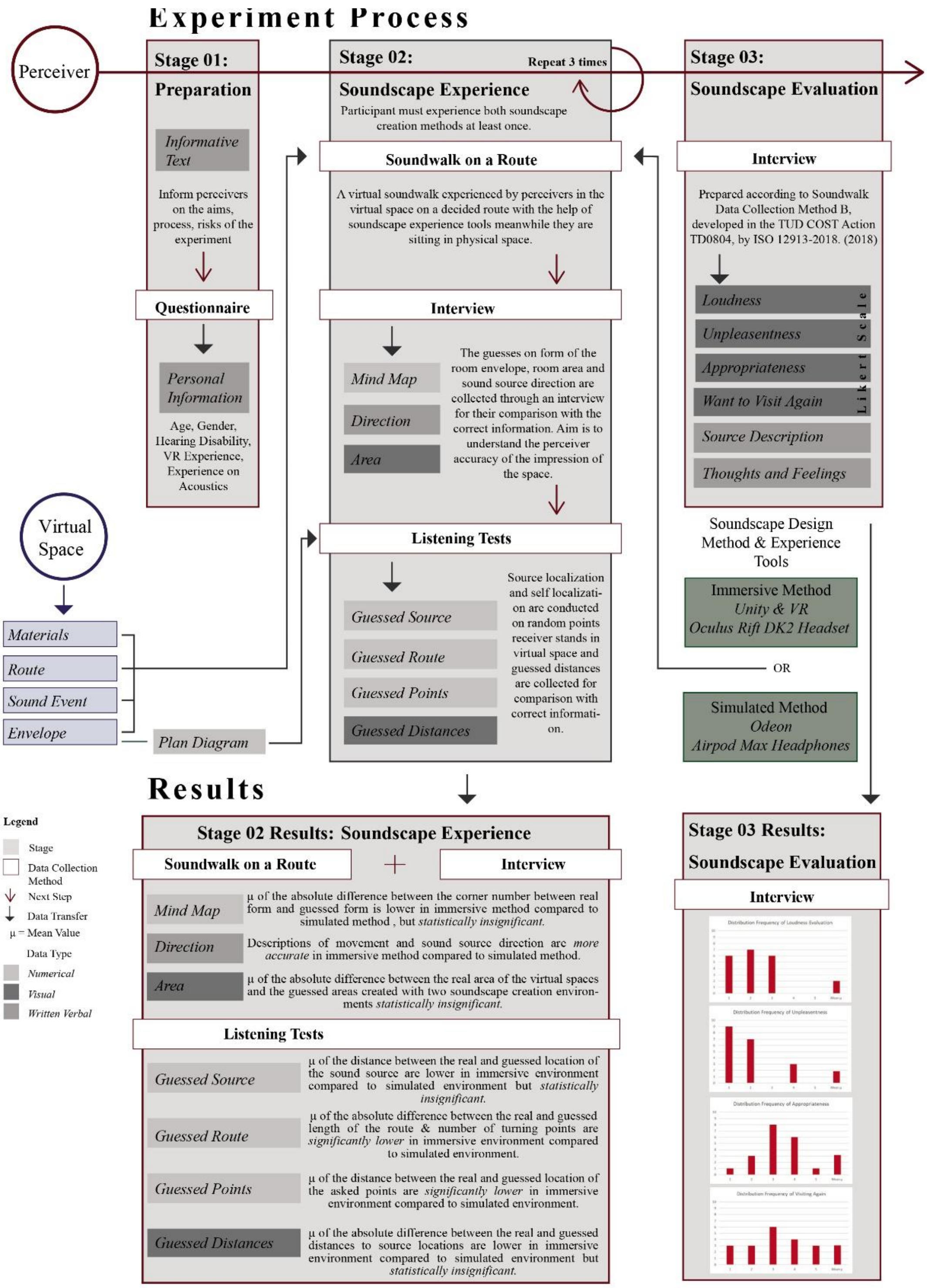


Figure 3-5 Pipeline Process of the First Experiments (developed by the author)

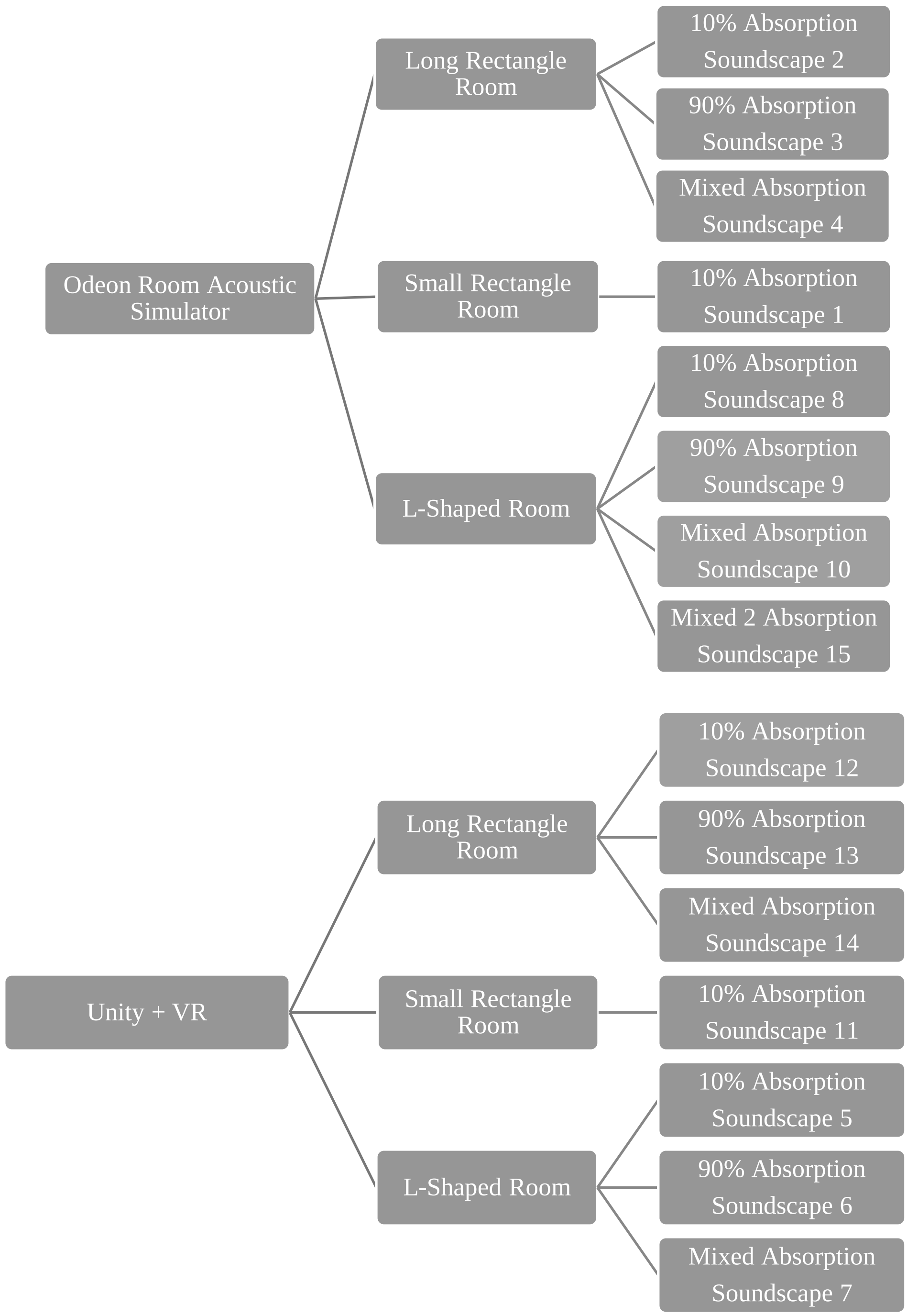


Figure 3-6 All Soundscape Alternatives

3.3.1 Participants

20 participants joined the study and subjected to 3 pairs of soundwalks and a listening tests. The participants are volunteered members of METU who do not have hearing disabilities. The ages of the participants differ between 18-55 with a 26,4 average. The participants reported having different levels of familiarity with the used equipment and softwares. 60% of the participants have previous experience with VR whereas the rest mentioned trying it for the first time. All of the participants were familiar with using headphones. None of the participants had previous professional or academic experience in acoustics.

3.3.2 Acoustic Environment: Rooms

Since form of the room envelope affects the perceived space, simple alternative forms are selected as rooms and created in both environments. Three different virtual rooms are designed: a small rectangular room (10 m x 6 m x 4 m height), a long rectangular room (15 m x 6 m x 3 m height) and an L-shaped room (13 m x 4 m and 10 m x 6 m arms with 3 m height). Two rectangular rooms are aimed to understand the perceptual changes between two rooms with different sizes which will affect reverberation time due to the volume change. The small rectangle room is included for having a first impression of the sound source. The reasons for including a long rectangular room are based on the fact that narrow rectangular rooms produce powerful lateral reflections (Long, 2014) which can be related to spaciousness by lateral energy fraction (LF) (Veneklasen & Hyde, 1969, as cited in Long, 2014) and the basic acoustical calculations are not valid for the rooms that have one dimension significantly longer than the others. As a result, the acoustical quality of these spaces must be studied by different approaches. (Kang, 1997) The L-shaped room is included to search for the possible perceptual changes in acoustics that appear according to the form of the room envelope since it might change the distribution of the sound and affect early decay time (EDT). Soundscape can be a relevant approach for these spaces since it brings together different types of measurements. It is important to see if the participants can notice a change of form, or draw a mental image of the room by making use of its soundscape.

Two of the room envelope types are produced with three different virtual material choices aiming to look for how the absorption coefficient of the surface materials might affect the soundscape of a room. In order to make their difference easily noticeable, materials with extreme absorptions are chosen such as %10 absorption and %90 absorption. The third type of material choice is achieved by the use of both materials together. Inluding the mixed material alternative serves for confusing participants by mixing up their directional perception by creating different reverberations from two sides. The options for the Long rectangle room are fully covered with 10% absorbent material, fully covered with 90% absorbent material and the reciprocal surfaces of the envelope covered with two different materials symmetrically. For the L-Shaped room, there are four material conditions, since the room is not symmetrical and chosen surface for different materials might change the results. Small Rectangle room is not the subject of the material experiment and is only designed with one material choice: % 10 absorption. Since the acoustic environments of the experiment are completely virtual weather and wind conditions or time information are not useful for this study as ISO/TS 12913-2018 offers. (2018) The experiment is conducted with a synthesized impulse clapping sound and its repetition, which is perceived differently according to each sound source location, receiver location, form of the room envelope, and absorption coefficient of the surface materials.

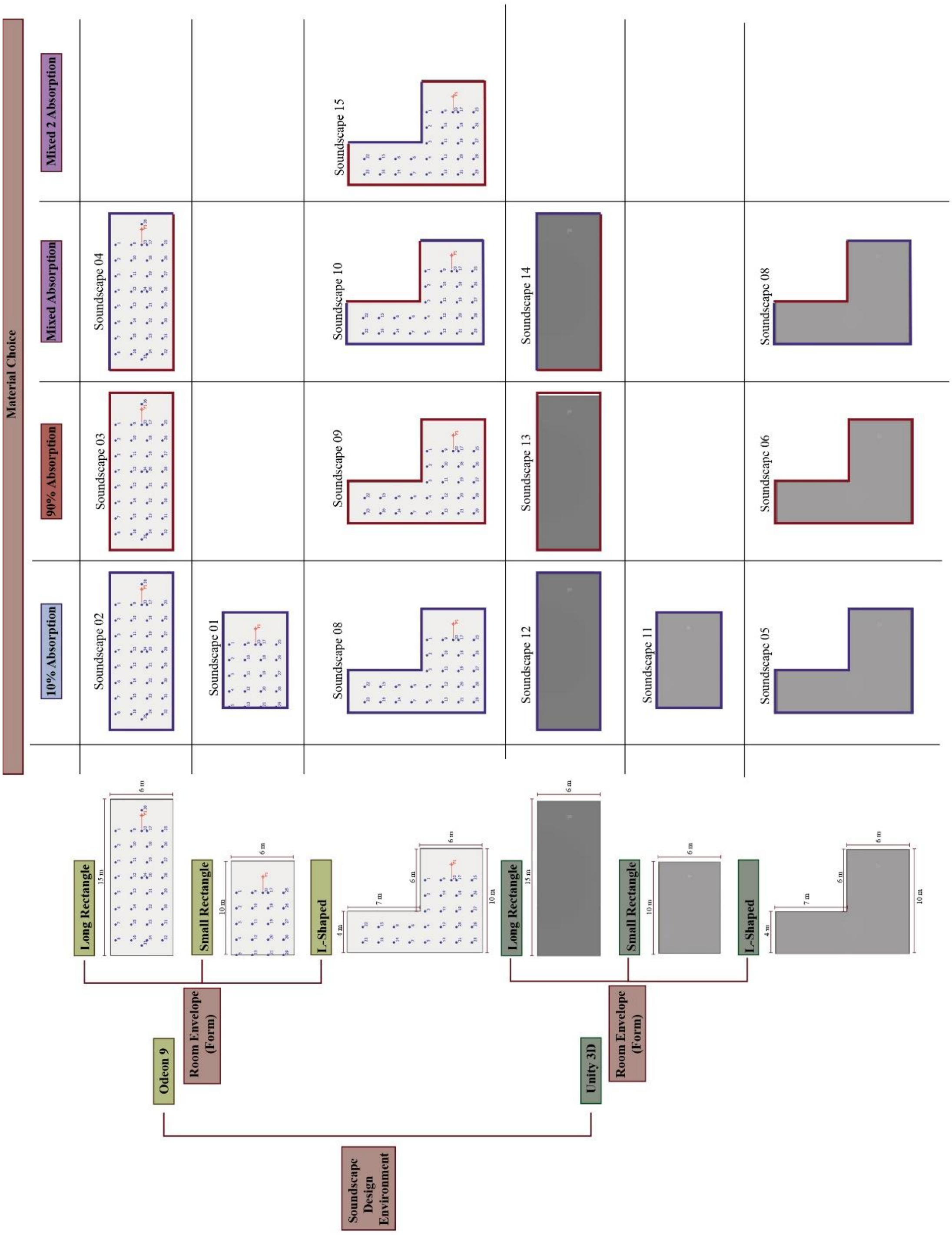


Figure 3-7 Soundscape Matrix (developed by author)

3.3.3 Setup: Virtual Soundscape Design Methods

There are two virtual soundscape design methods used for the experiment: Room acoustic simulator ODEON 9 and virtual reality paired with Unity 3D Game Engine 2017. An Airpod Max is used for delivering the soundscape from the simulator. An Oculus Rift DK2 head-mounted display is used as the main technical equipment for virtual reality. The computer used for the experiment is HP Z820 Base Model Workstation and has the qualities as 16 GB RAM and NVIDIA GeForce GTX 2070 graphics processor. The two design methods are used for making a comparison through the experiment.

3.3.3.1 Acoustic Simulator

The first method of virtual acoustic environment design is a room acoustic simulator software ODEON 9 Auditorium, which creates auralization of a located sound source within the designed rooms. Boundaries of the designed rooms are created with a 3D modeling software, Rhino 6 as polylines and exported into ODEON environment as. CAD files. For the first method, the spaces are organized with horizontal grids and a path is defined along the grids. Receivers are located on the grids that intersect with the defined path. The receiver height is decided as 1 meter. For each receiver, auralization of the sound source is conducted and exported as .WAV files. The files are then transformed into .MP3 files due to the convenience. Room acoustic parameters of each room are calculated in Odeon environment from the grid in the furthest row to observe the effect of the room size and form of the envelope better. The calculations and decay curves of Soundscape 01 are shown below. The calculations for the rest of the soundscapes are presented in the appendix.

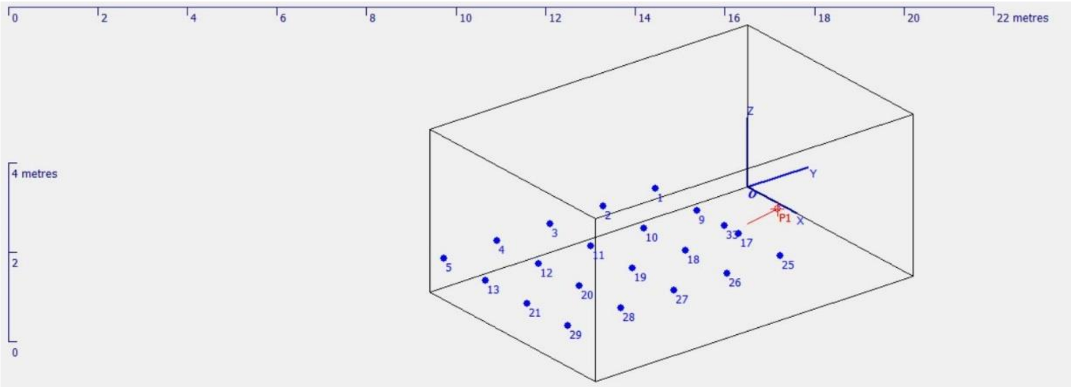


Figure 3-8 Small Rectangle Room in Odeon Environment (10 m x 6 m x 4 m height)

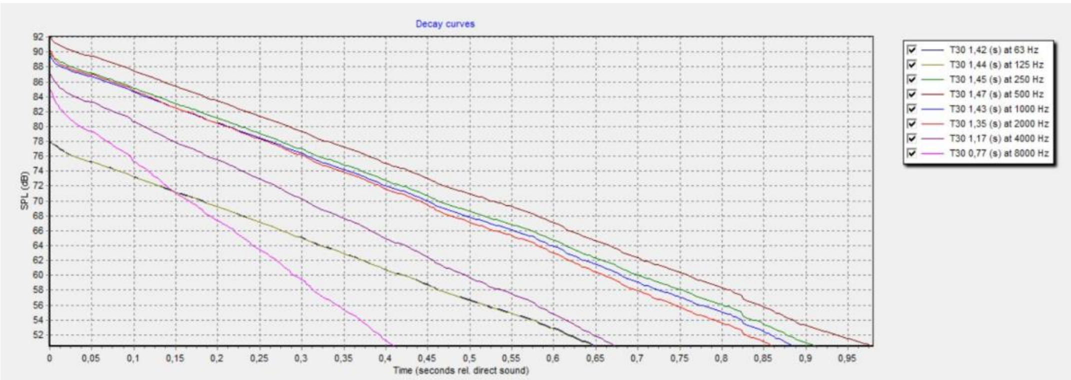


Figure 3-9 Soundscape 01 Decay Curves (Small Rectangle Room %10 Absorption)

Table 3-1 Soundscape 01 Room Acoustic Parameters (from the grid in the furthest row) (Small Rectangle Room %10 Absorption)

Soundscape 01 - Small Rectangle Room %10 Absorption								
Receiver Number: 13 Receiver1			(x,y,z) = (2,00, -9,00, 1,00)					
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	1,42	1,45	1,48	1,46	1,45	1,32	1,07	0,76
T30 (s)	1,42	1,44	1,45	1,47	1,43	1,35	1,17	0,77
SPL (dB)	78	77,9	89,9	92,1	89,7	90,4	87,1	85,1
C80 (dB)	1,6	1,6	1,7	1,6	2,1	2,9	3,9	7,4
D50	0,47	0,47	0,48	0,47	0,51	0,56	0,6	0,74

(Table 3-1 continued)

Ts (ms)	91	91	90	90	83	73	61	36
LF80	0,258	0,253	0,241	0,265	0,246	0,222	0,208	0,197
SPL(A) = 96,2(dB)								
LG80* = 81,0(dB)								
STI = 0,58 (Theoretical based on T30, STI = 0,54)								

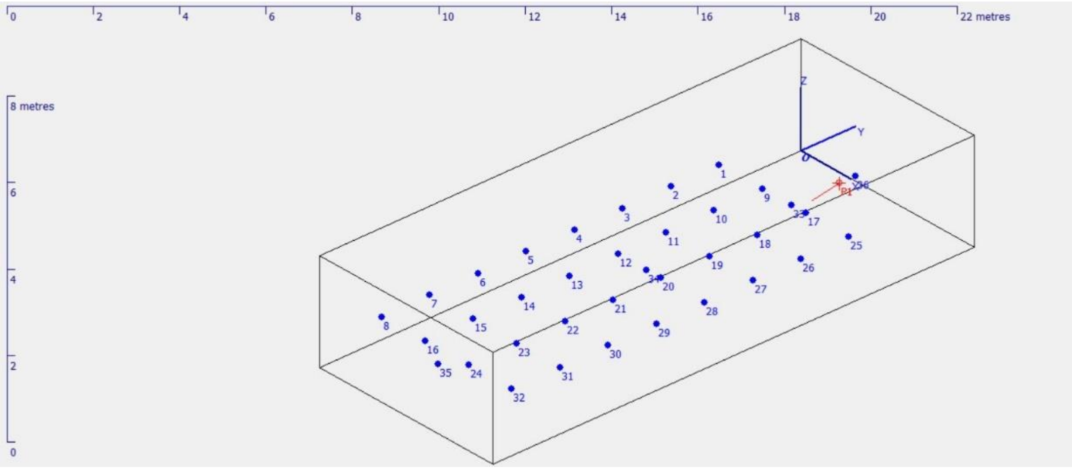


Figure 3-10 Long Rectangle Room in Odeon (15 m x 6 m x 3 m height)

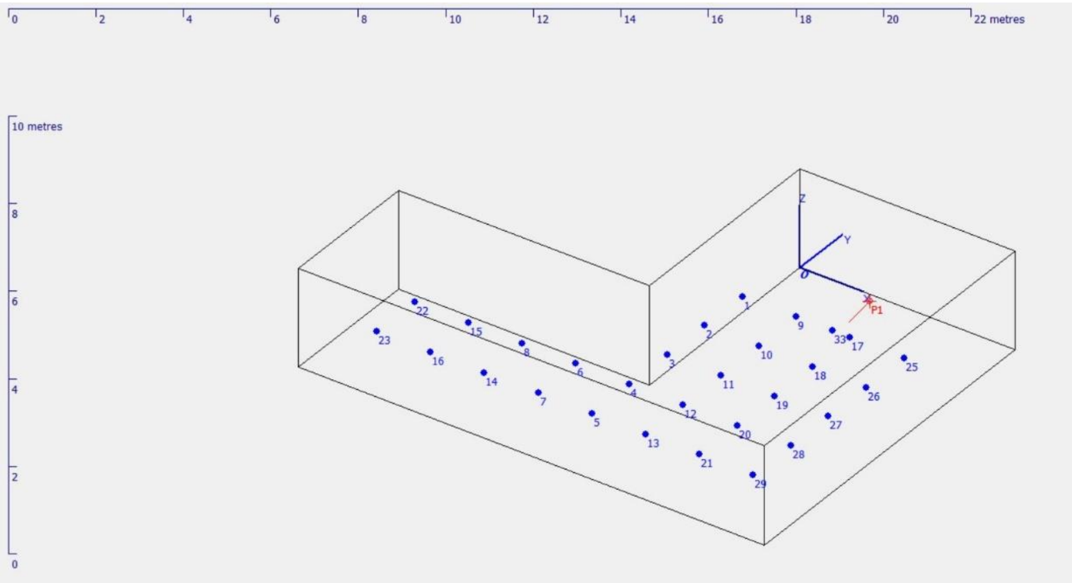


Figure 3-11 L-Shaped Room (13 m x 4 m and 10 m x 6 m arms with 3 m height)

3.3.3.2 Virtual Reality

The second method requires the same designed rooms to be visually modeled with thick surfaces Rhino 6, then exported to the Unity 2017 environment as .OBJ files. One of the auralizations created in the acoustical simulator is placed in the same location in the given room as an audio source to represent the effects of spatial qualities of the space accurately on perceived sound, such as the form and material absorption. Using the auralization created with the acoustic simulator according to the designed virtual space in VR environment is an attempt for offering a realistic immersive virtual environment in terms of soundscape instead of a misleading abstraction of the auditory space. The auralization for the furthest grid point in the virtual room is chosen to represent correct room size and the maximum distance within the space to the sound source by involving all reverberations the spatial qualities cause. Chosing a closer grid point would result in misrepresentation of the room size and the distances by ignoring the distrubition of the sound in the space. For the second method, a moving camera, that also acts as an audio receiver, follows the same path designed for the previous environment. The receiver and camera height is decided as 1 meter. This time the same audio source plays on a loop as the camera moves, perceived according to the spatial sound environment of Unity software. The main advantages of this method are the accessibility of participants to visual information from the first-person perspective in addition to the freedom of head movements.

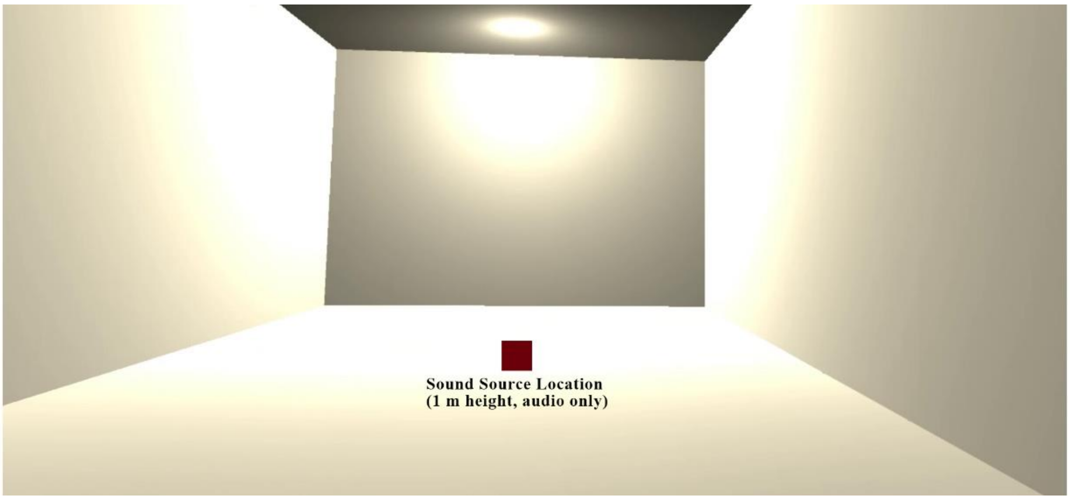


Figure 3-12 Small Rectangle Room in Unity VR (10 m x 6 m x 4 m height)

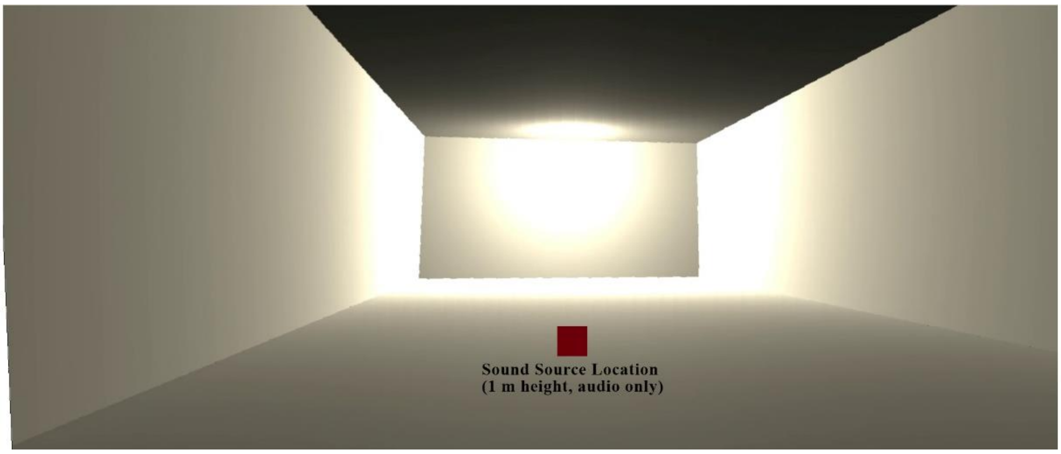


Figure 3-13 Long Rectangle Room in Unity VR (15 m x 6 m x 3 m height)

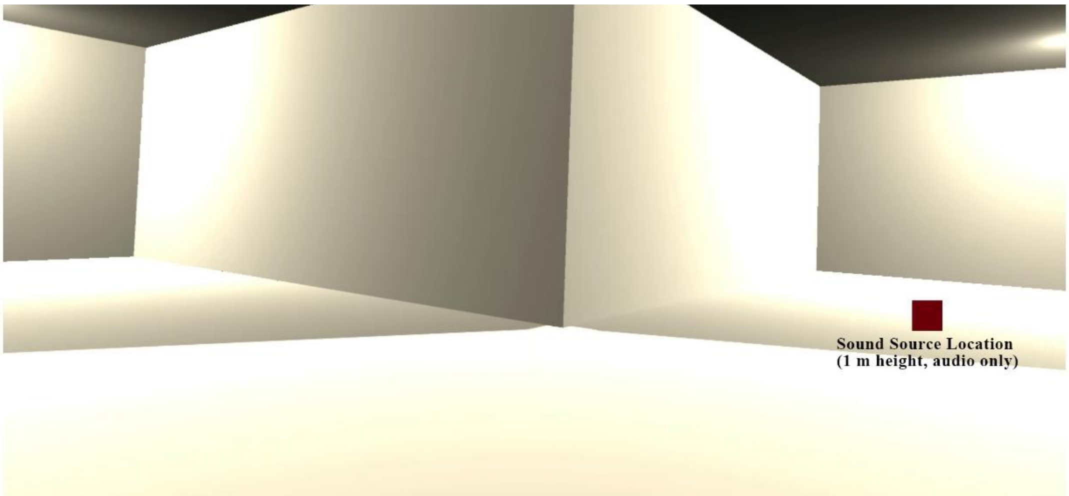


Figure 3-14 L-Shaped Room in Unity VR (13 m x 4 m and 10 m x 6 m arms with 3 m height)

3.3.4 Data Collection

Soundwalking is interpreted as virtual soundwalks followed by virtual listening tests for both soundscape design methods. After the soundwalking, written interview questions are asked about the sound source distance, sound source localization, self localization, and room size as well as drawing a mind map for evaluating the accuracy of spatial impression the participants. The soundscape evaluation data collection is conducted according to Soundwalk Data Collection Method B, developed in the TUD COST Action TD0804 explained in ISO/TS 12913-2018 (2018)

3.3.4.1 Sessions

There are a total of 15 soundscapes with different spatial qualities. (3 forms of room envelope x 3 material selection options x 2 design methods + 1 extra) The experiment consists of four sessions including a preparation, three virtual soundwalks and matched listening tests with an interview, and lastly an evaluation questionnaire. The participants join the process one by one. The sessions are designed as randomized blocks in a way that each participant must experience both design methods for different soundscapes, since having spatial information on the environment from the previous soundwalk might mislead the results of the experiment by favoring the second soundscape design method. The interview language is Turkish.

3.3.4.1.1 Preparation

Firstly, the participants read and sign the informatory text and fill in a questionnaire for their personal information including their name, age, gender and profession, the experience of using VR, or professional knowledge of acoustics if any. The questionnaire also collects information on their hearing abilities, physical or mental disabilities, and health-related factors that might cause any kind of risk to the participants or the experiment.

3.3.4.1.2 Virtual Soundwalking & Listening Tests

Soundwalking is conducted in the form of an audio receiver following a decided virtual route. The participants do not move physically, but rather experience the repeating soundscape as if they are moving in a virtual space. The soundwalk of an acoustic simulator environment is experienced through headphones, whereas the soundwalk of VR environment is experienced through a VR headset which can also provide visual information and allow head movements. Each soundwalk will be followed by a listening test and short interview questions about their experiences.

3.3.4.1.2.1 Soundwalk with Acoustic Simulator - Headphones

This session is designed as matched pairs. The participants experience one soundwalk on the decided path, later they are subjected to a listening test with randomized locations on the path. This session aims for the participants to observe how the perceived sound changes according to a regular movement. The participants listen to the acoustic environment with headphones, having no prior knowledge of the virtual space.

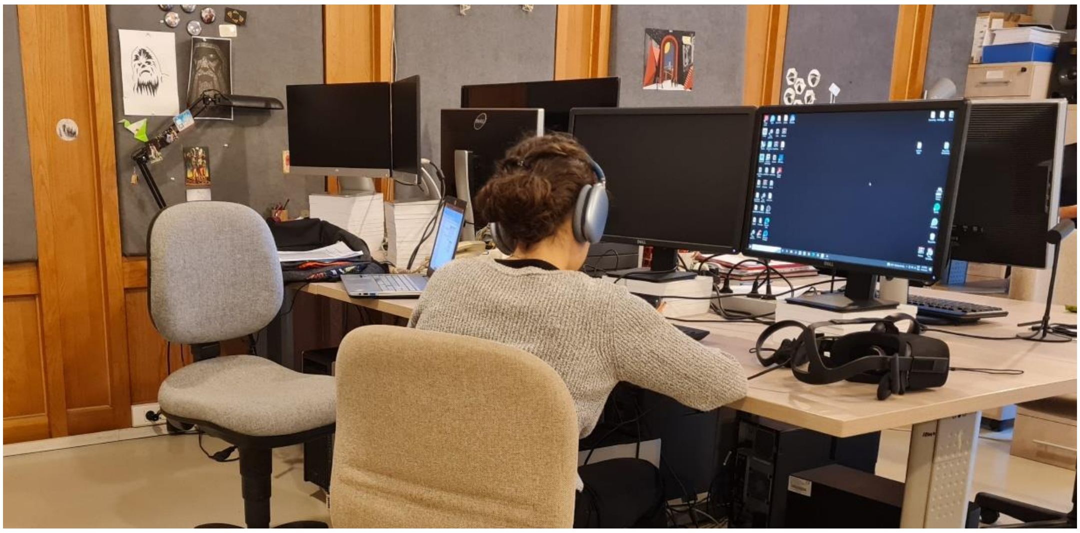


Figure 3-15 Virtual Soundwalk Session in Odeon with Airpod Max Headphones

The participants can repeat this process a few times to be sure. Later, the participants are asked to report their perception of the direction of the sound and how the distance from the sound source changes through the movement.

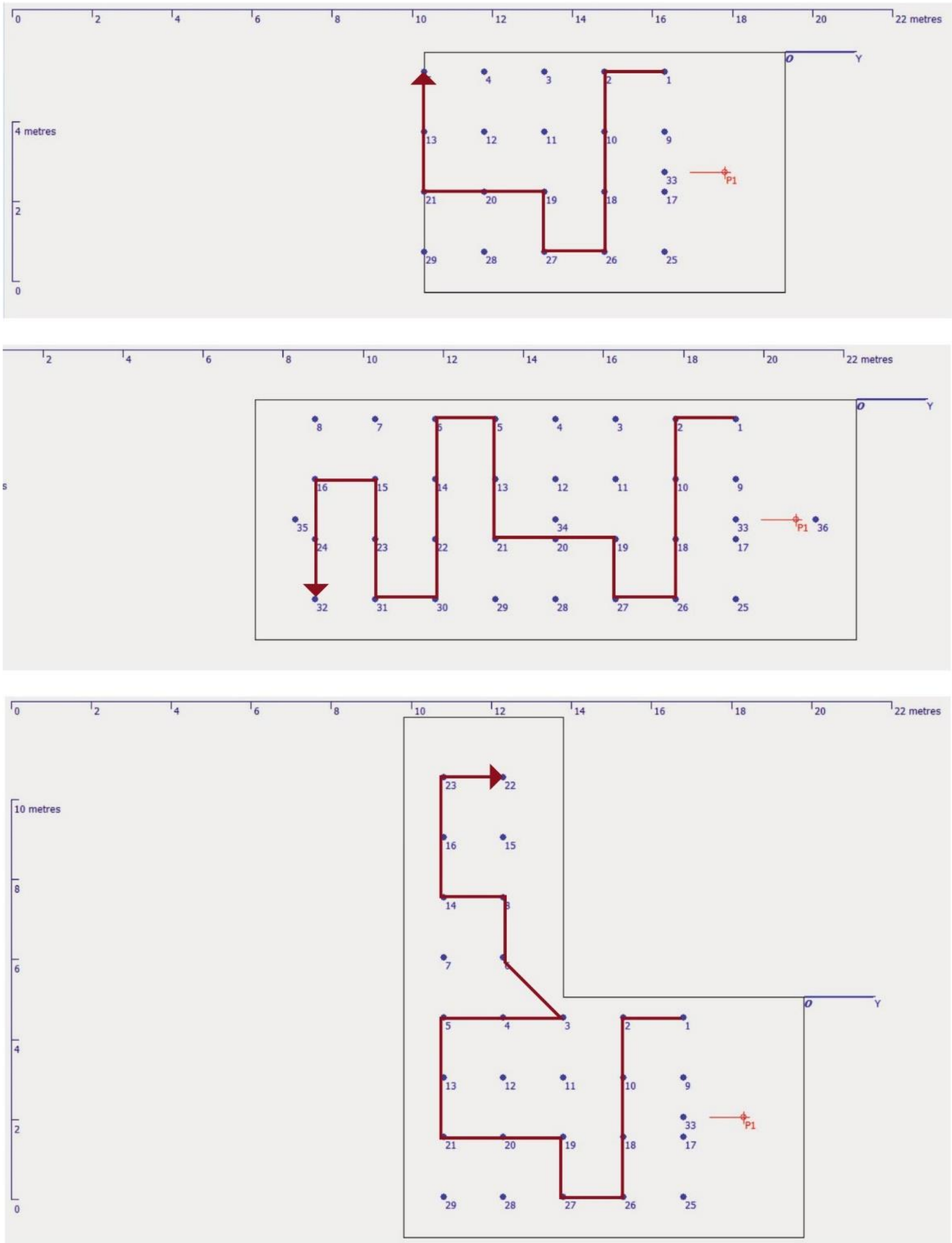


Figure 3-16 Routes of the Virtual Rooms in Odeon

The aim of the question is to understand if perceivers can understand the distance of a sound event with the help of their own movement in space. Another question is that the participant is asked to draw a mind map (plan diagram) of the space that visually represents the guessed form of the room envelope, sound source location, and the route. They also try to guess the room size in square meters. The aim of this question is to see if they can understand the room size and form of the envelope without any visual information. Later, the participants are given a plan diagram of the room with the correct room shape without any dimensions given and asked to locate the sound source and the route on it again. At this stage, they repeat the soundwalk. Lastly, the participant moves on with the listening test. This time the participants are expected to listen to the impulse sound from random points and expected to report the distance to the sound source of each point as well as localize themselves on the plan diagram. The aim of the listening test is to understand if perceivers can locate themselves and the sound event in a given space with the help of the information coming from the previous soundwalk movement and the form of the room envelope.

3.3.4.1.2.2 Soundwalk with Unity - VR

For the soundwalks of this session, participants experience both visual and auditory environments at the same time by making use of VR. The participants experience the soundwalk through VR headset in Unity, which provides a camera and an audio receiver following the decided route, and answer the same questions in the previous stage which are guessing: the direction of the sound, change of the distance from the sound source, a mind map drawing, the room size, source, and self-localization.

Figure 3-17 Virtual Soundwalk Session in Unity VR with Oculus DK2 Headset

The auralization for the furthest grid point in the virtual room is chosen to represent correct room size and the maximum distance within the space to the sound source by involving all reverberations the spatial qualities cause. The question of the direction of the sound gains importance since VR headset allows them to experience the perceptual change according to their head movement. They are asked to detect the direction of the sound the first moment they start the soundwalking before they move their head. Again, the participants are given a plan diagram of the room and asked to locate the sound source and the route on it. Later the participants move on to the listening test. This time the camera and the audio receiver on the route move randomly from point to point together and the participants are expected to report the guessed distance to the sound source of each point and localize themselves and the sound event on the plan diagram.

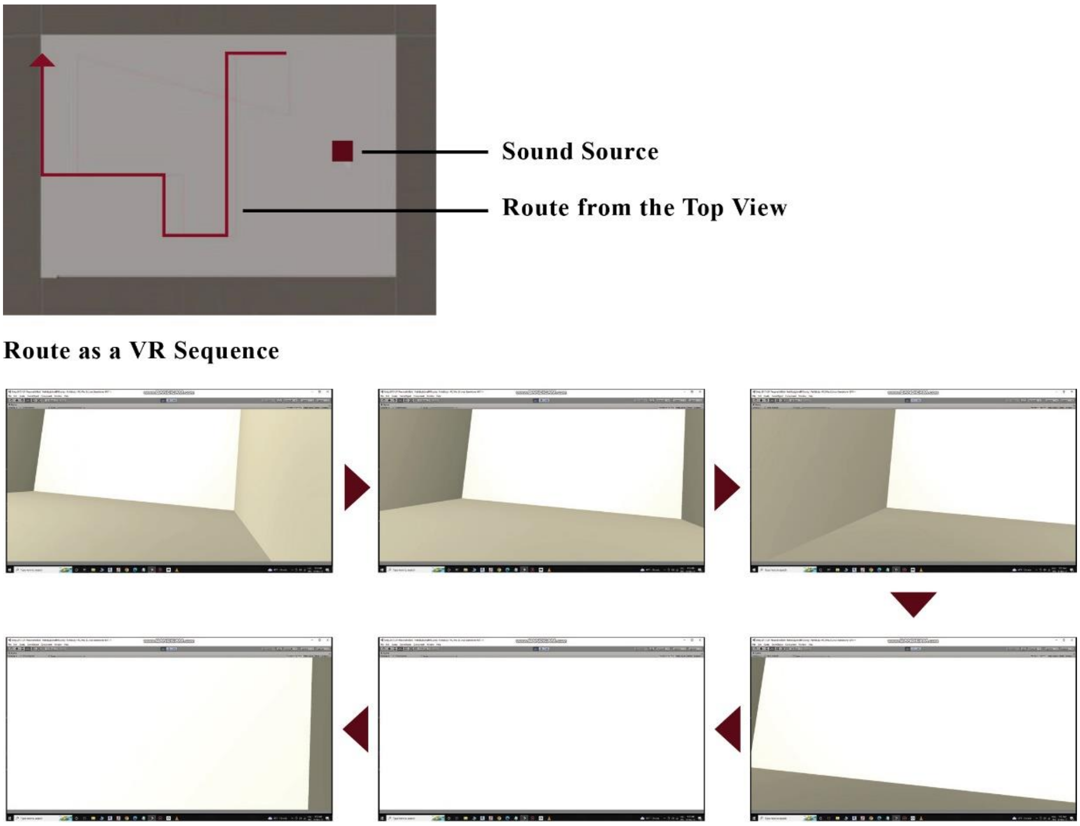


Figure 3-18 Route of the Small Rectangle Room in Unity VR Environment

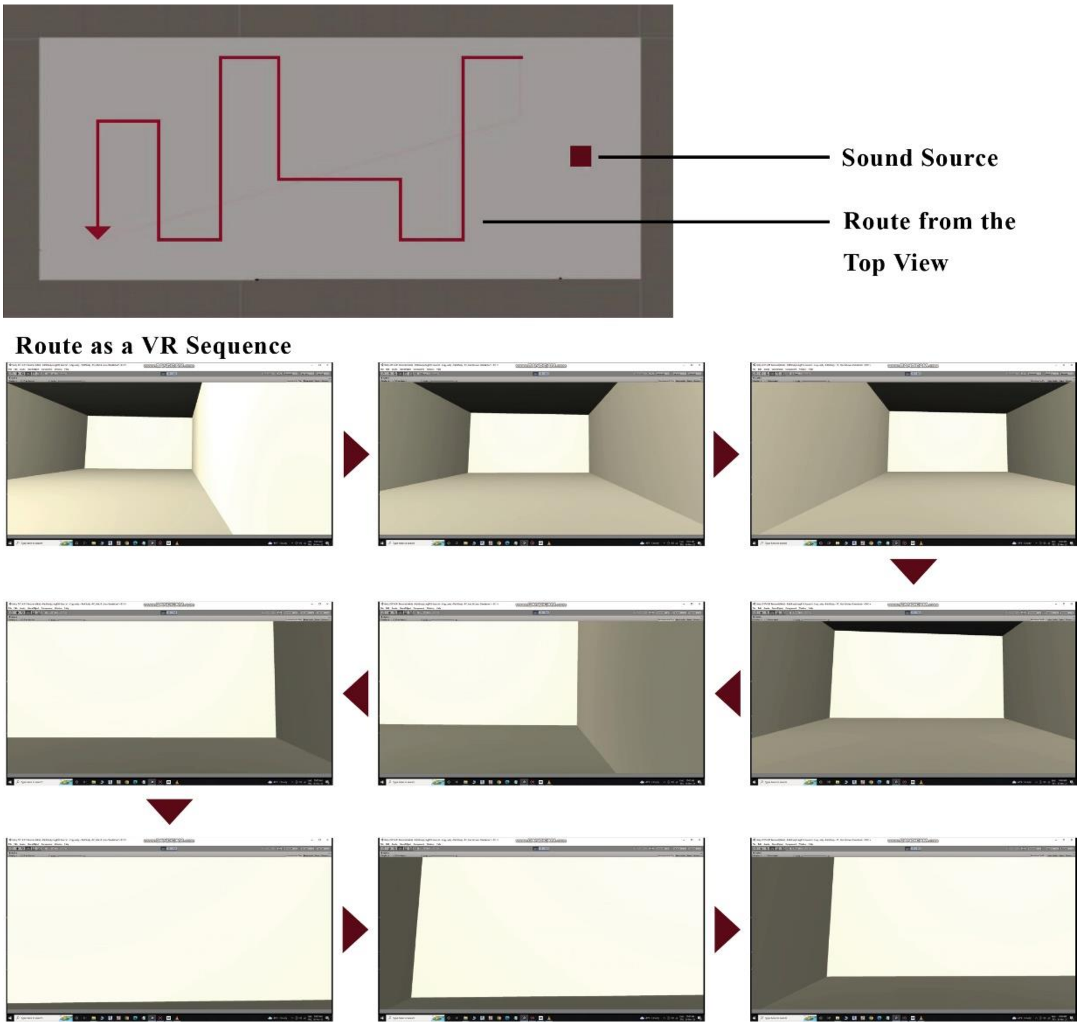


Figure 3-19 Route of the Long Rectangle Room in Unity VR Environment

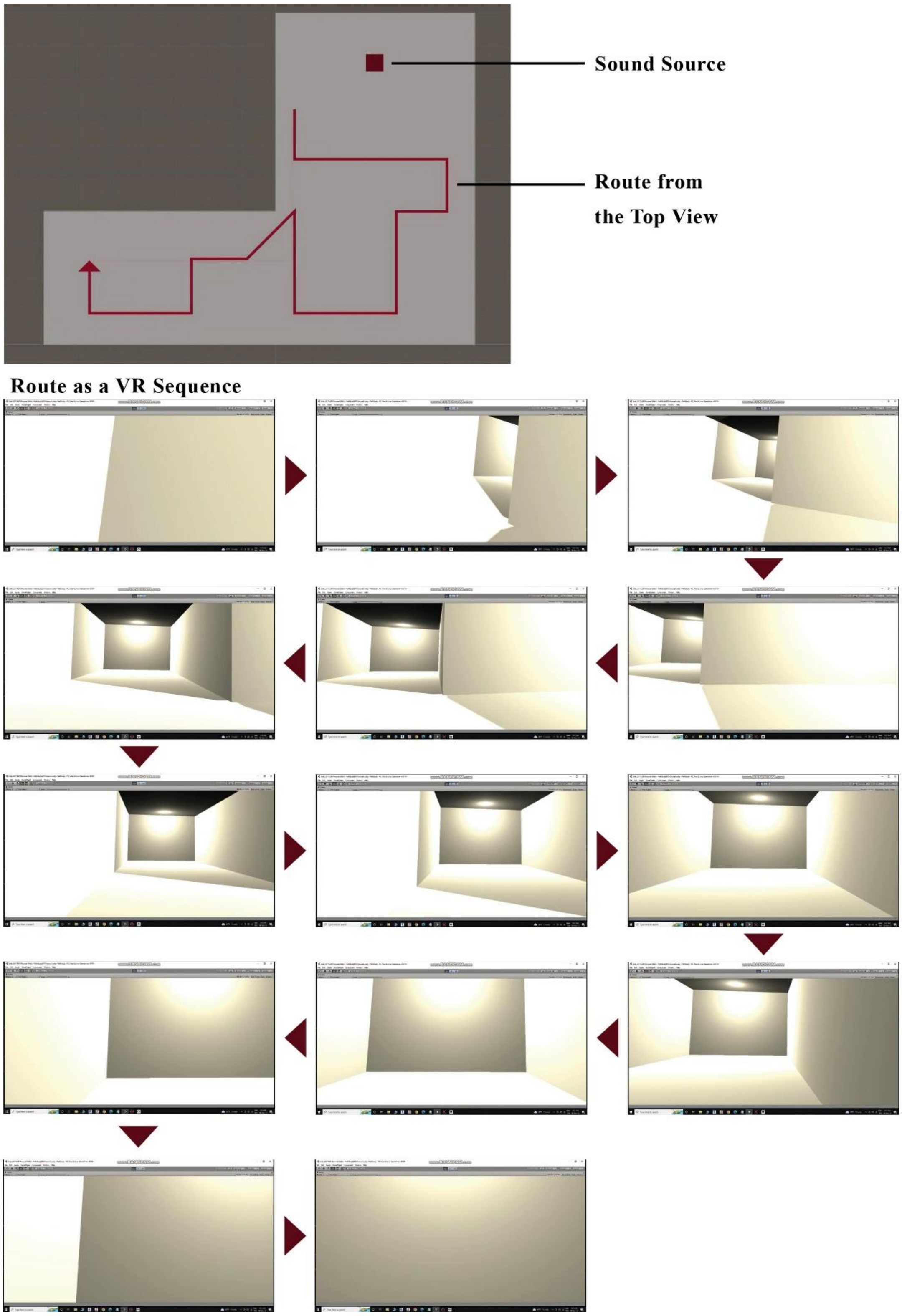


Figure 3-20 Route of the L-Shaped Room in Unity VR Environment

3.3.4.2 Questionnaire

The participants fill in a short questionnaire after the soundwalking sessions for the evaluation of the overall experience. The questionnaire is prepared according to Soundwalk Data Collection Method B, developed in the TUD COST Action TD0804, by ISO 12913-2018. Method B includes a questionnaire with two parts. In the first part, four adjectives are evaluated (loud, pleasent, appropriate and visiting again) with five-point unipolar continuous-category. The second part includes two open ended questions: listing the sound sources and describing thoughts and feelings. (ISO 12913-2018, 2018) Since this experiment includes one type of sound source, the question of listing the heard sources was replaced with describing the source they heard.

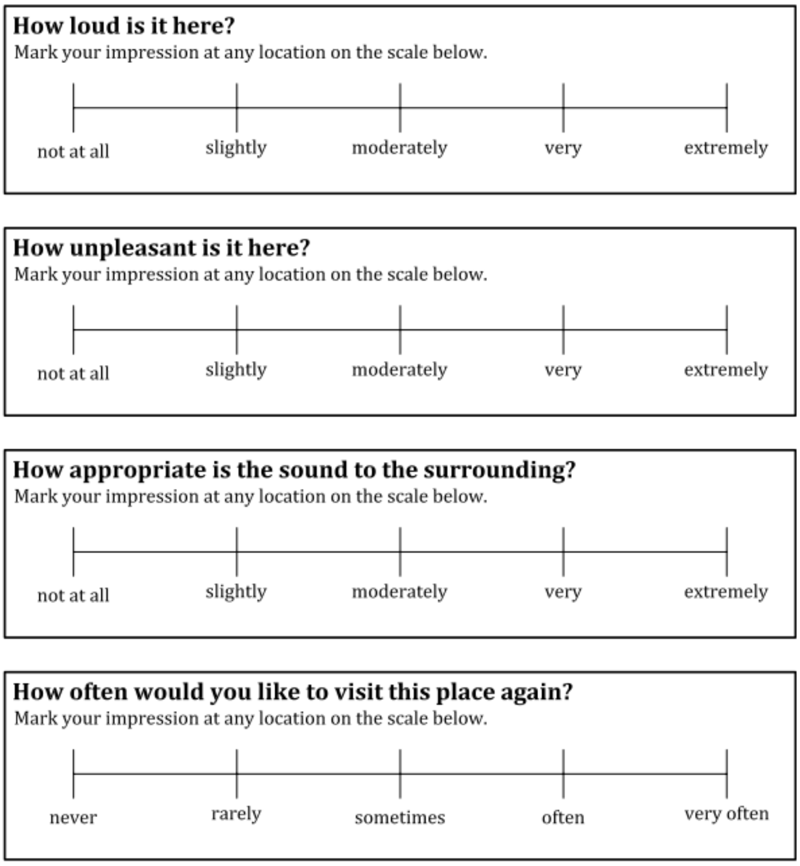


Figure 3-21 Soundwalk data collection part 1 related to the assessment of the sound environment (ISO/TS 12913-2018, 2018)

3.3.5 Case Study

The second experiments are in the form of a case study based on a physical space that the participants have different levels of familiarity. It is aiming to explore how the perception changes when the same sound event is tested in a detailed and familiar virtual space and check the reliability of the first experiments. The same experiment process is applied to a virtualized version of an existing studio in METU Architecture Faculty. Chosen studio is Digital Design Studio (DDS), where the experiments are physically conducted. Nine participants joined the case study experiments aged between 24-55 with an average of 29. Seven of the participants were volunteers from the previous trial experiments. Two of the participants (Participants 01, 04) had no experience with either the previous trials or the physical space they were in. Participant 01 also did not have any experience with VR. Participants 02 and 06 are people who regularly spent time in METU DDS. All of the participants experienced the virtual versions of METU DDS in both of the soundscape design methods. Four randomly selected participants experienced the simulation method first, then the immersive method; whereas the rest experienced the experiment in the opposite order. Total of 18 soundwalks are conducted in 2 soundscapes.

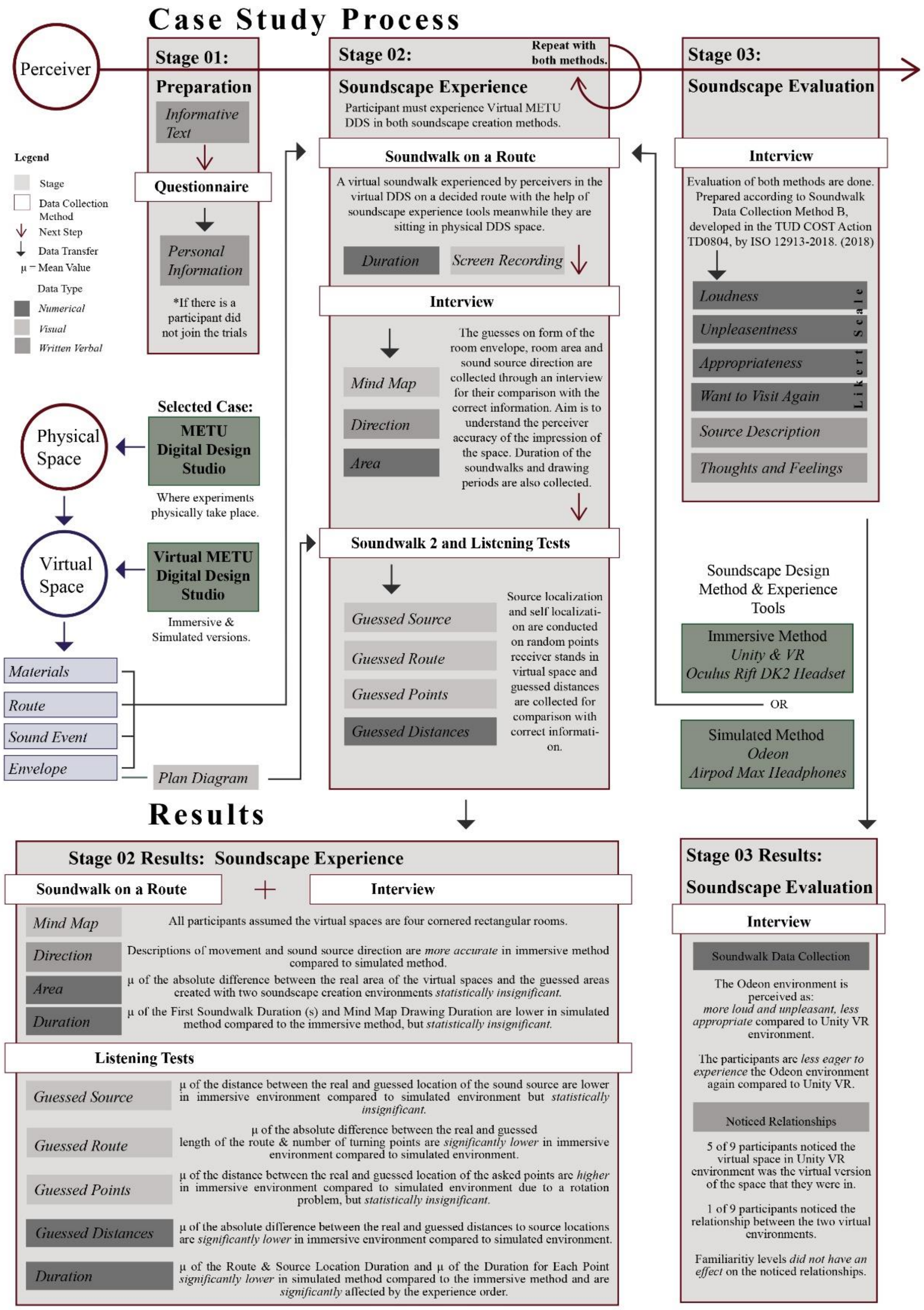


Figure 3-22 Pipeline Process of the Case Study Experiment (developed by the author)

Table 3-2 Case Study Groups

Group 01 (Order Type 1 = First Odeon, Second Unity VR)	**Group 02 (Order Type 2 = First Unity VR, Second Odeon)**
Participant 01	Participant 05
Participant 02	Participant 06
Participant 03	Participant 07
Participant 04	Participant 08
	Participant 09

The studio is modeled in Rhino 6 and transferred to Odeon and Unity environments with the same process as the trial experiments. Different than the previous trials, the 3D model of the classroom included surface openings such as windows and pieces of furniture. The model is created with layers specified according to the physical surface materials. In the Unity model, the physical materials of the classroom are integrated as visual textures whereas in Odeon model the materials are integrated as material choices from the Odeon Material Library.

Figure 3-23 Physical Space experiment took place and modeled virtually for the Case Study (METU Digital Design Studio)

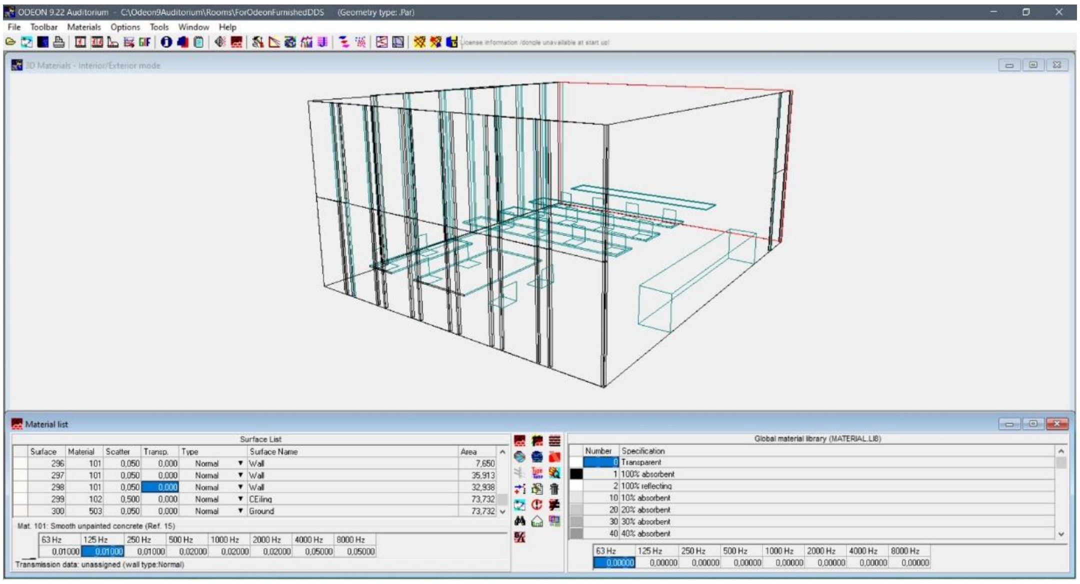


Figure 3-24 Case Study Soundscape in Odeon

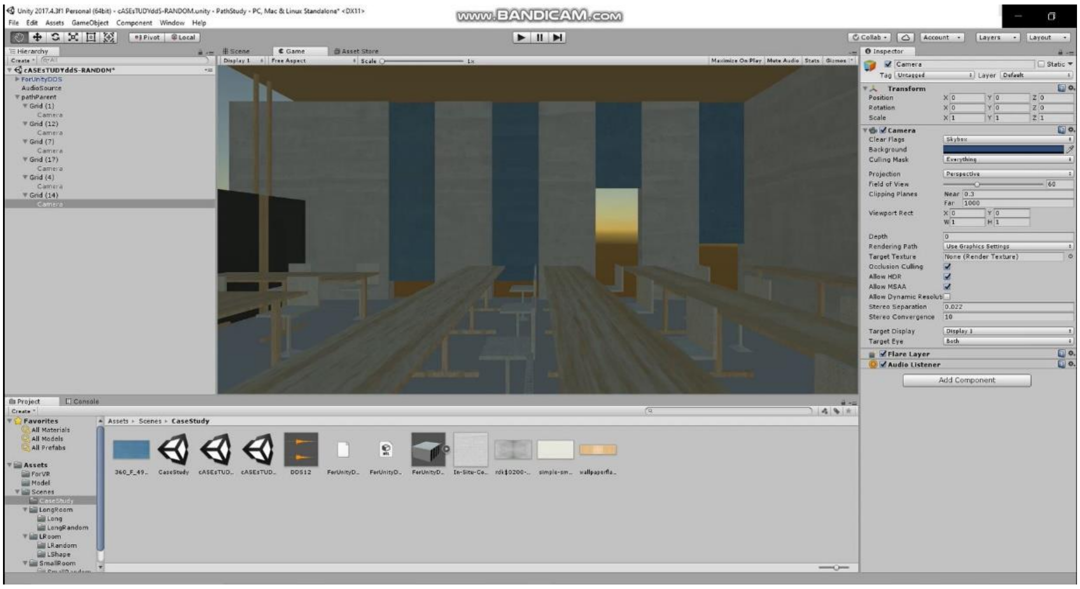


Figure 3-25 Case Study Soundscape in Unity - VR

Table 3-3 Materials used in Case Study in Odeon (According to Odeon Material Library, n.d.)

Materials	**Material Number**	**Scattering Coefficient**	**Absorption Coefficient for 1000 Hz**	**Total Surface Area (sqm)**
Empty Chairs, upholstered with cloth cover	906	0,050	0,89	5,76
Plywood Paneling, 1 cm thick	2033	0,050	0,09	60,001
Solid Wooden Door	603	0,050	0,08	2,125
Cotton Curtains (0,5kg/sqm)	1105	0,050	0,56	8,25
Carpet Heavy, with impermable latex backing on hairfelt foam rubber	2008	0,050	0,34	14,525
Double Glazing, 2-3 mm glass, > 30mm gap	602	0,050	0,03	56,177
Smooth Concrete, painted or glazed	102	0,500	0,02	73,732
Linoleum or Vinyl stuck to concrete	503	0,050	0,04	73,732
Smooth Unpainted Concrete	101	0,02	0,02	116,79

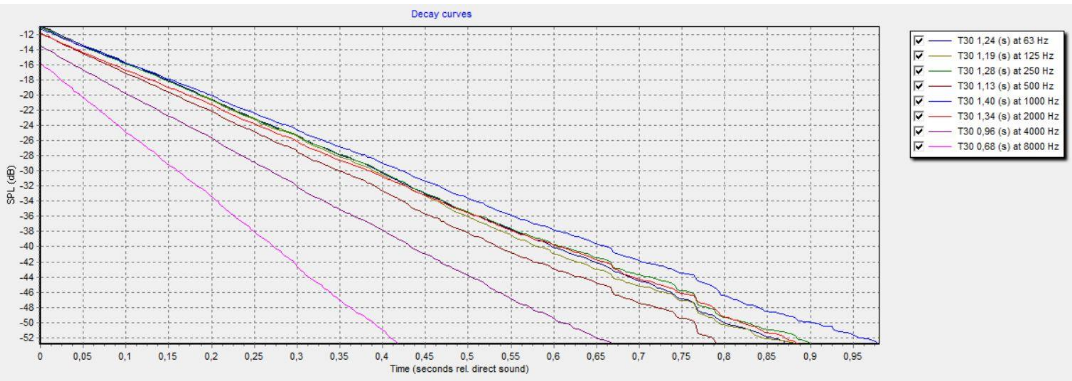


Figure 3-26 Decay Curves of Case Study Room - Digital Design Studio

Table 3-4 Room Acoustic Parameters of Case Study Room - Digital Design Studio (from the furthest point)

Receiver Number: 12 No description (x,y,z) = (-1,50, -1,50, 1,00)									
Band	(Hz)	63	125	250	500	1000	2000	4000	8000
EDT	(s)	1,26	1,25	1,24	1,12	1,39	1,32	0,93	0,65
T30	(s)	1,24	1,19	1,28	1,13	1,4	1,34	0,96	0,68
SPL	(dB)	-10,9	-11	-11,1	-11,8	-11,3	-11,9	-13,5	-15,8
C80	(dB)	1,6	1,7	1,6	2,2	1,1	1,6	3,4	6,4
D50	0,44	0,45	0,44	0,47	0,41	0,43	0,52	0,65	
Ts	(ms)	89	88	89	81	96	90	69	47
LF80	0,25	0,251	0,249	0,25	0,26	0,255	0,244	0,232	
SPL(A) = -5,5(dB)									
LG80* = -21,0(dB)									
STI = 0,57 (Theoretical based on T30, STI = 0,56)									

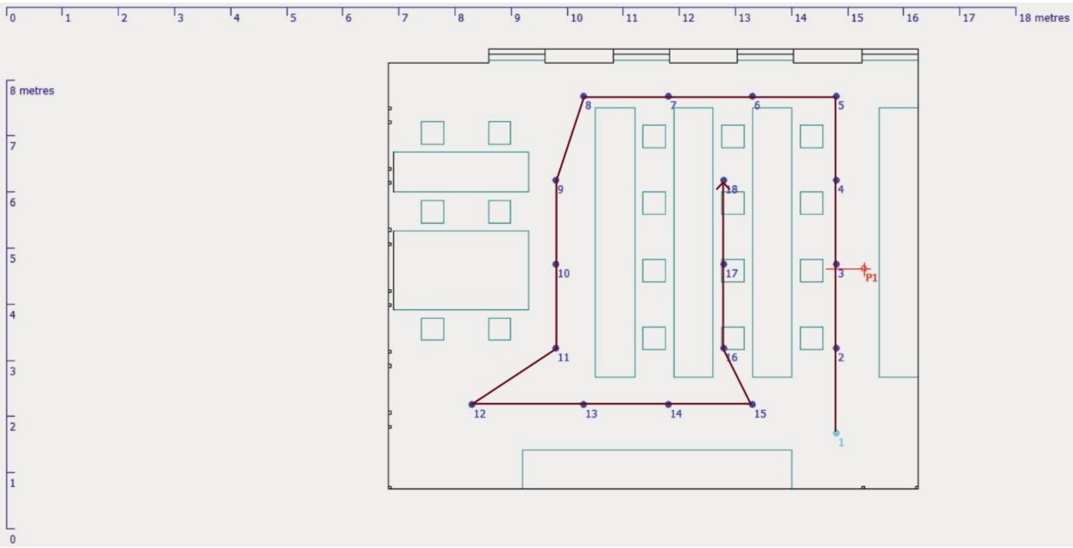


Figure 3-27 Sound Source Location and Route of the Case Study in Odeon Environment (P1= Sound Source, 1 meter height, audio only)

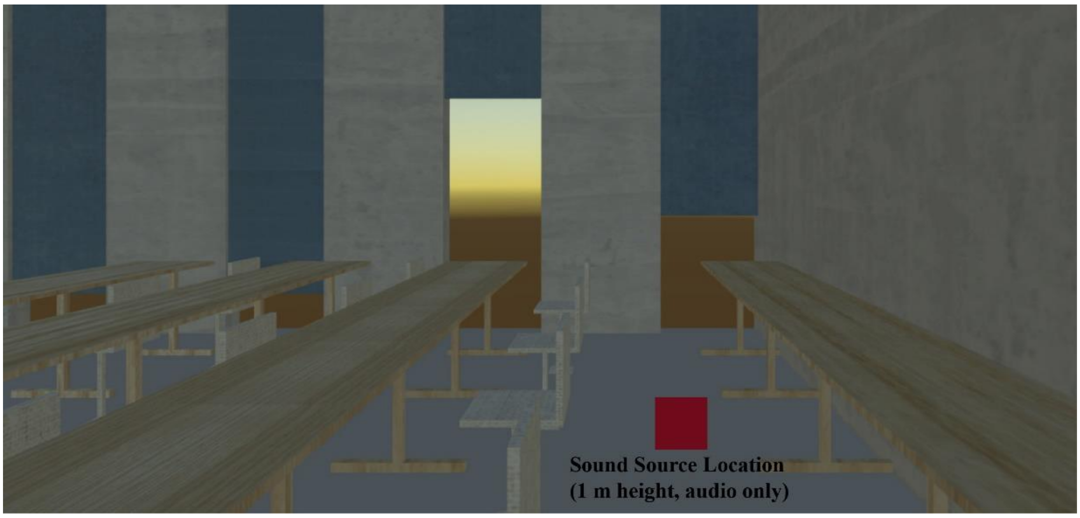


Figure 3-28 Sound Source Location of the Case Study in Unity VR Environment

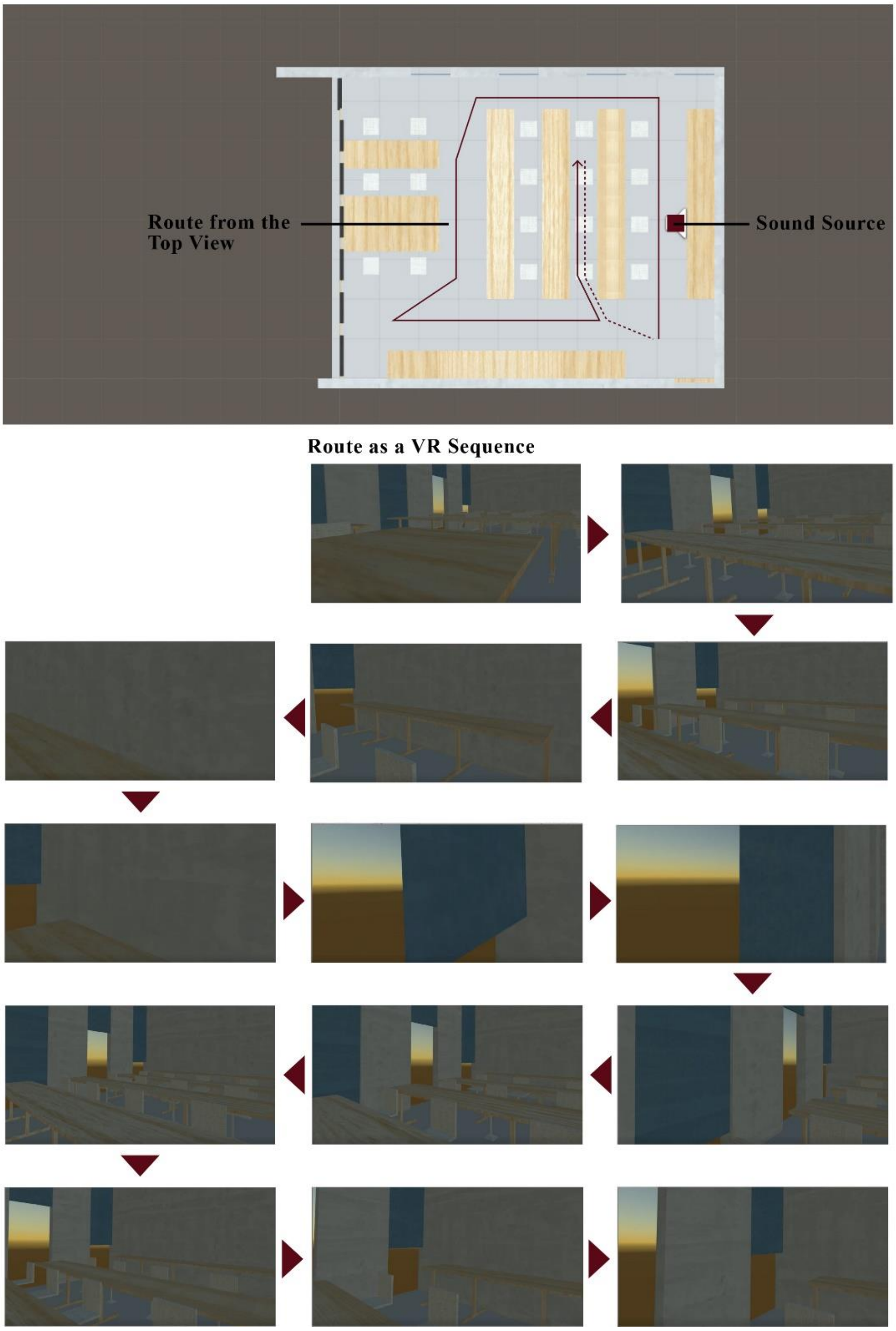


Figure 3-29 Route of the Case Study in Unity Environment

CHAPTER 4

RESULTS

In the first experiments, 20 participants voluntarily took part. All of the participants experienced the preparation, three soundwalks and matched listening tests and evaluation except Participant 4. Participant 4 requested to finish the experiment early and took part in two soundwalks instead of three. A total of 59 soundwalks are conducted, 33 of them were in Odeon environment and 26 of them in VR environment. Each soundscape is experienced by 3 to 5 different participants.

Case Study process is conducted with 09 participants and 18 soundwalks are conducted in 2 soundscapes.

4.1 Data Analysis

The soundwalking process includes written verbal data from the interview questions for sound source direction and movement, numerical data from the guessed room size, and visual data from the mind map drawing stage. The drawn mind maps are analyzed visually and used for revealing the accuracy of the perceived room envelope. The listening tests provide numerical and visual data. The numerical data is the guessed distances to the sound source. The visual data includes the points and the pathway located by the participants on the given plan diagram. The diagrams are scanned and juxtapositioned onto the correct plan diagrams of the virtual rooms on a reference coordinate system. This process allows both visual comparison and the transformation of the visual data to numerical data. The points are transformed into coordinate locations. The guessed path is analyzed through its length and the number of turning points and compared to the correct one. The location information of the random points and the guessed distance data are analyzed with four dimensions based on finding out the difference between the participants' answers and the correct answers for each asked point. The closest differences get to the zero, accepted as a more accurate perception of self-location and distance. The first dimension is self-localization, which requires participants to find out where they are on the given plan diagram. Since the participants do not have any information on the dimensions of the virtual space other than their spatial perception, they had to be tested in terms of self-consistency as well. Self-consistency dimension compares the distance between the guessed sound source location (independent from the correct sound source location) and the guessed self-location point with the guessed distance. The accuracy of the self-consistency dimension shows that the participant is able to relate a location to an appropriate change of distance, whether or not it matches the information of the given virtual space. Guessed distance dimension searches for the difference between the real distance and the guessed distance directly. Localized distance searches for the difference between the real distance and the distance of the guessed location to the real sound source location. The reason for analyzing the distance in two dimensions is to avoid losing information from the possibility of participants having a big error with source localization, but finding out the correct distance with a big error with self-localization. (see table) For the comparison of two methods all the results are analyzed with a multivariate ANOVA conducted with IBM SPSS software with significance level as $\sigma < 0{,}05$.

Table 4-1 Formula Table of the Dimensions of Soundscape Experiment

Dimensions of Soundwalk
Description of Direction (descriptive) (accurate, close, wrong)
Description of Movement (descriptive) (accurate, close, wrong)
Route Length Error (m) = |(Real route length) – (Guessed route length)|
Route Shape Error = |(Real route turning point number) – (Guessed route turning point number)|
Envelope Form Error = |(Real corner number) – (Guessed corner number)|
Room Size Error (sqm) = |(Real area) – (Guessed area)|
Dimensions of Listening Test
Source Localization Error (m) = (Real source location) – (Guessed source location)
Self Localization Error (m) = (Real location) – (Guessed location)

(Table 4-1 continued)

Self Consistency Error (m) = |(Guessed distance to guessed source by location) - (Guessed distance)|
Guessed Distance Error (m) = |(Real distance) – (Guessed distance)|
Localized Distance Error (m) = |(Real distance) – (Guessed distance by location)|

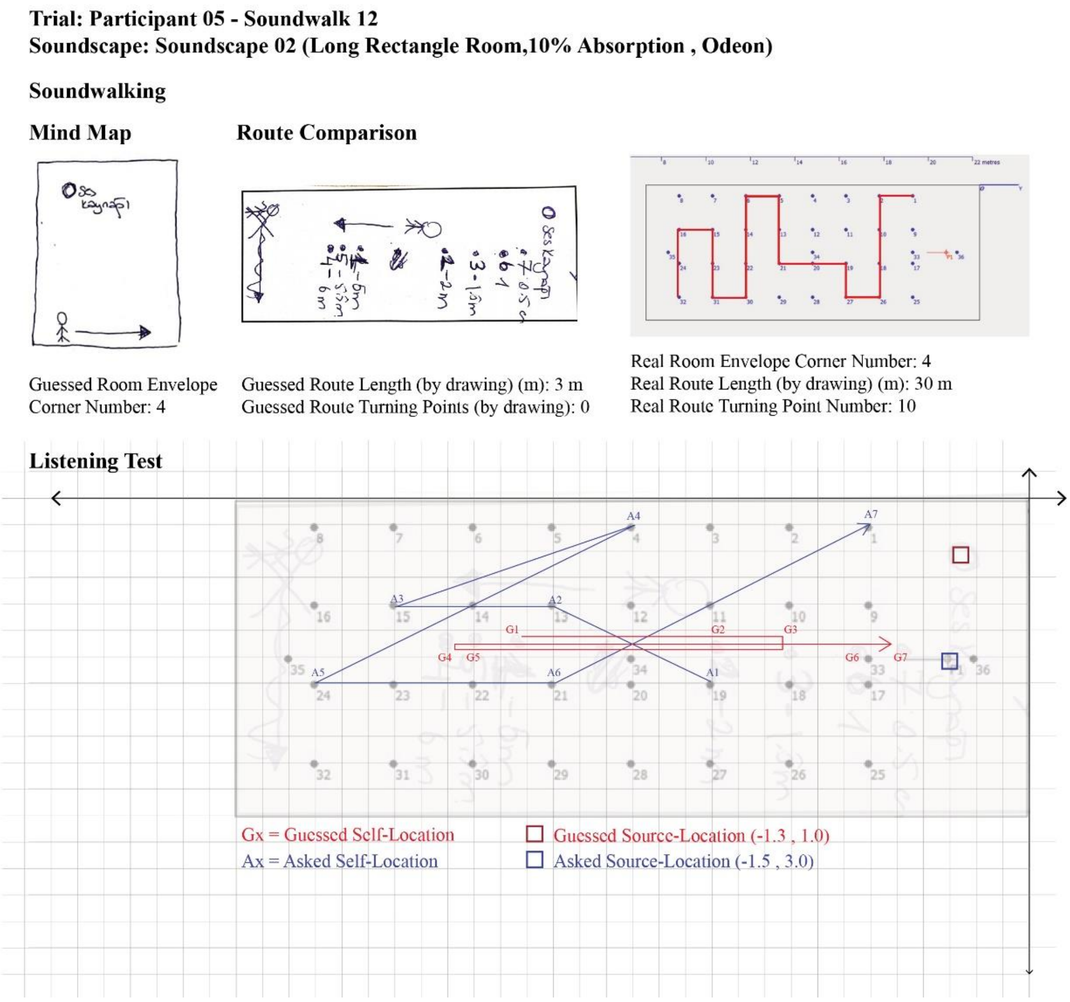


Figure 4-1 Example of the Visual Analysis Process (Soundwalk 12)

Table 4-2 Example of the Numerical Analysis Process (Listening Test 12)

Asked Point DATA					Guessed DATA					Values				Absolute Values			
Asked Point Number	Asked Grid Number	Asked Points X Location	Asked Points Y Location	Real Distance to Real Source from Asked Points	Guessed Point X Location	Guessed Point Y Location	Guessed Distance to Guessed Source by Location	Guessed Distance to Real Source	Guessed Distance to Real Source by Location	Self Localization Error (m)	Self Consistency Error (m)	Guessed Distance Error (m)	Localized Distance Error (m)	|Self Localization Error| (m)	|Self Consistency Error| (m)	|Guessed Distance Error| (m)	|Localized Distance Error| (m)
1	19	-6	3,50	4,53	-9,60	2,60	8,45	5,00	8,11	3,71	3,45	-0,47	-3,58	3,71	3,45	0,47	3,58
2	13	-9	2,00	7,57	-5,80	2,60	4,78	2,00	4,32	3,26	2,78	5,57	3,25	3,26	2,78	5,57	3,25
3	15	-12	2,00	10,55	-4,60	2,60	3,67	1,50	3,13	7,42	2,17	9,05	7,42	7,42	2,17	9,05	7,42
4	1	-3	0,50	2,92	-10,80	2,60	9,63	6,00	9,31	8,08	3,63	-3,08	-6,39	8,08	3,63	3,08	6,39
5	24	-13,5	3,50	12,01	-10,40	2,60	9,24	5,50	8,91	3,23	3,74	6,51	3,10	3,23	3,74	6,51	3,10
6	21	-9	3,50	7,52	-3,20	2,60	2,48	1,00	1,75	5,87	1,48	6,52	5,77	5,87	1,48	6,52	5,77
7	1	-3	0,50	2,92	2,60	2,60	4,22	0,50	4,12	5,98	3,72	2,42	-1,20	5,98	3,72	2,42	1,20
									Mean	1,85	0,82	4,02	4,69	1,85	0,82	2,72	2,03
									Standard Deviation	5,36	3,00	3,79	1,19	5,36	3,00	4,80	4,39

4.2 Results of the First Experiments

The soundscapes with the same form of room envelope and material selection, but created with different design methods are compared with each other. The matching soundscapes are shown next to each other in the table below. Soundscape 15 is created only in Odeon and not subjected to a comparison with Unity VR because it is a later addition just to observe if any difference occurs according to the chosen surfaces of the L-Shaped room while designing with mixed material options.

Table 4-3 Matching Soundscapes For Soundscape Design Method Comparison

Soundscapes created with Odeon	**Number of Trials**	**Soundscapes created with Unity VR**	**Number of Trials**
Soundscape 01	3	Soundscape 11	3
Soundscape 02	4	Soundscape 12	3

(Table 4-3 continued)

Soundscape 03	5	Soundscape 13	4
Soundscape 04	4	Soundscape 14	5
Soundscape 08	5	Soundscape 05	4
Soundscape 09	4	Soundscape 06	3
Soundscape 10	4	Soundscape 07	4
Soundscape 15	4		
Total Odeon	33	Total Unity VR	26
Total			59

4.2.1 Soundwalk & Interview

Total of 59 soundwalks are examined for analyzing the perception of room envelope form, sound source direction and room size.

4.2.1.1 Perception of Form of the Room Envelope

The perception of the form of room envelope is analyzed by the absolute difference between the corner number between the real form and the guessed form by making use of the drawn mind maps. Mean value of the absolute difference between the corner number between real form and guessed form is lower in immersive method compared to simulated method. Results of the three soundwalks were not usable for the analysis because the mind maps were either not drawn (04), or they do not provide clear information on the room envelope due to the participant's claim on virtual space being open space (07, 21).

Table 4-4 Results of the Envelope Form Errors

Soundwalk Number	Soundscape Information				
	Environment	Soundscape Number	Envelope Form	Material Choice	Envelope Form Error
Soundwalk 01	Odeon	Soundscape 02	Long Rectangle	%10 Abs	0

(Table 4-4 continued)

Soundwalk 02	Odeon	Soundscape 08	L-Shaped	%10 Abs	0
Soundwalk 03	Odeon	Soundscape 03	Long Rectangle	%90 Abs	0
Soundwalk 04	Odeon	Soundscape 03	Long Rectangle	%90 Abs	NA
Soundwalk 05	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	4
Soundwalk 06	VR	Soundscape 06	L-Shaped	%90 Abs	2
Soundwalk 07	Odeon	Soundscape 02	Long Rectangle	%10 Abs	NA
Soundwalk 08	Odeon	Soundscape 03	Long Rectangle	%90 Abs	0
Soundwalk 09	VR	Soundscape 05	L-Shaped	%10 Abs	-1
Soundwalk 10	Odeon	Soundscape 10	L-Shaped	Mixed Abs	0
Soundwalk 11	VR	Soundscape 14	Long Rectangle	Mixed Abs	0
Soundwalk 12	Odeon	Soundscape 02	Long Rectangle	%10 Abs	0
Soundwalk 13	Odeon	Soundscape 03	Long Rectangle	%90 Abs	0
Soundwalk 14	VR	Soundscape 05	L-Shaped	%10 Abs	0
Soundwalk 15	Odeon	Soundscape 03	Long Rectangle	%90 Abs	0
Soundwalk 16	VR	Soundscape 06	L-Shaped	%90 Abs	0
Soundwalk 17	VR	Soundscape 07	L-Shaped	Mixed Abs	0
Soundwalk 18	Odeon	Soundscape 09	L-Shaped	%90 Abs	2
Soundwalk 19	VR	Soundscape 12	Long Rectangle	%10 Abs	0
Soundwalk 20	VR	Soundscape 13	Long Rectangle	%90 Abs	0
Soundwalk 21	Odeon	Soundscape 10	L-Shaped	Mixed Abs	NA
Soundwalk 22	VR	Soundscape 11	Small Rectangle	%10 Abs	0
Soundwalk 23	VR	Soundscape 14	Long Rectangle	Mixed Abs	0
Soundwalk 24	Odeon	Soundscape 08	L-Shaped	%10 Abs	2
Soundwalk 25	Odeon	Soundscape 09	L-Shaped	%90 Abs	-1
Soundwalk 26	VR	Soundscape 12	Long Rectangle	%10 Abs	-2
Soundwalk 27	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	0
Soundwalk 28	VR	Soundscape 06	L-Shaped	%90 Abs	0
Soundwalk 29	VR	Soundscape 07	L-Shaped	Mixed Abs	0
Soundwalk 30	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	0
Soundwalk 31	VR	Soundscape 05	L-Shaped	%10 Abs	0
Soundwalk 32	VR	Soundscape 07	L-Shaped	Mixed Abs	0
Soundwalk 33	Odeon	Soundscape 08	L-Shaped	%10 Abs	2
Soundwalk 34	Odeon	Soundscape 09	L-Shaped	%90 Abs	-2
Soundwalk 35	VR	Soundscape 12	Long Rectangle	%10 Abs	0
Soundwalk 36	Odeon	Soundscape 10	L-Shaped	Mixed Abs	2
Soundwalk 37	VR	Soundscape 11	Small Rectangle	%10 Abs	0
Soundwalk 38	VR	Soundscape 14	Long Rectangle	Mixed Abs	0
Soundwalk 39	Odeon	Soundscape 08	L-Shaped	%10 Abs	2
Soundwalk 40	Odeon	Soundscape 09	L-Shaped	%90 Abs	2
Soundwalk 41	VR	Soundscape 13	Long Rectangle	%90 Abs	0
Soundwalk 42	Odeon	Soundscape 02	Long Rectangle	%10 Abs	0
Soundwalk 43	Odeon	Soundscape 08	L-Shaped	%10 Abs	2
Soundwalk 44	VR	Soundscape 05	L-Shaped	Mixed Abs	0
Soundwalk 45	Odeon	Soundscape 10	L-Shaped	Mixed Abs	2
Soundwalk 46	VR	Soundscape 11	Small Rectangle	%10 Abs	0
Soundwalk 47	VR	Soundscape 14	Long Rectangle	Mixed Abs	0
Soundwalk 48	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	0
Soundwalk 49	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	2
Soundwalk 50	VR	Soundscape 07	L-Shaped	Mixed Abs	-1
Soundwalk 51	Odeon	Soundscape 01	Small Rectangle	%10 Abs	0
Soundwalk 52	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	2
Soundwalk 53	VR	Soundscape 14	Long Rectangle	Mixed Abs	0
Soundwalk 54	Odeon	Soundscape 01	Small Rectangle	%10 Abs	0
Soundwalk 55	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	2
Soundwalk 56	VR	Soundscape 13	Long Rectangle	%90 Abs	0

(Table 4-4 continued)

Soundwalk 57	Odeon	Soundscape 01	Small Rectangle	%10 Abs	0
Soundwalk 58	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	2
Soundwalk 59	VR	Soundscape 13	Long Rectangle	%90 Abs	0

4.2.1.2 Perception of Sound Source Direction

The DATA collected on Sound Source Direction and Movement was not reliable enough to reach sufficient results. The participants expressed confusion and gave unclear results. Therefore, the direction and movement description are not converted into numerical data useful for a Likert Scale. The results are classified as Accurate, Close and Wrong, which is visible in the Table. The results revealed that there are higher numbers of accurate descriptions of movement and sound source in the immersive method compared to the simulated method.

Table 4-5 Direction and Movement Description Results

Soundwalk Number	Soundscape Information					
	Environment	Soundscape Number	Envelope Form	Material Choice	Direction Description	Movement Description
Soundwalk 01	Odeon	Soundscape 02	Long Rectangle	%10 Abs	Close	Accurate
Soundwalk 02	Odeon	Soundscape 08	L-Shaped	%10 Abs	Close	Accurate
Soundwalk 03	Odeon	Soundscape 03	Long Rectangle	%90 Abs	Close	Accurate
Soundwalk 04	Odeon	Soundscape 03	Long Rectangle	%90 Abs	Close	Accurate
Soundwalk 05	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	Close	Accurate
Soundwalk 06	VR	Soundscape 06	L-Shaped	%90 Abs	Accurate	Accurate
Soundwalk 07	Odeon	Soundscape 02	Long Rectangle	%10 Abs	Accurate	Close
Soundwalk 08	Odeon	Soundscape 03	Long Rectangle	%90 Abs	Wrong	Accurate
Soundwalk 09	VR	Soundscape 05	L-Shaped	%10 Abs	Accurate	Accurate
Soundwalk 10	Odeon	Soundscape 10	L-Shaped	Mixed Abs	Close	Close
Soundwalk 11	VR	Soundscape 14	Long Rectangle	Mixed Abs	Wrong	Wrong
Soundwalk 12	Odeon	Soundscape 02	Long Rectangle	%10 Abs	Accurate	Accurate
Soundwalk 13	Odeon	Soundscape 03	Long Rectangle	%90 Abs	Wrong	Wrong
Soundwalk 14	VR	Soundscape 05	L-Shaped	%10 Abs	Accurate	Accurate
Soundwalk 15	Odeon	Soundscape 03	Long Rectangle	%90 Abs	Wrong	Wrong

(Table 4-5 continued)

Soundwalk 16	VR	Soundscape 06	L-Shaped	%90 Abs	Wrong	Accurate
Soundwalk 17	VR	Soundscape 07	L-Shaped	Mixed Abs	Accurate	Accurate
Soundwalk 18	Odeon	Soundscape 09	L-Shaped	%90 Abs	Accurate	Close
Soundwalk 19	VR	Soundscape 12	Long Rectangle	%10 Abs	Accurate	Accurate
Soundwalk 20	VR	Soundscape 13	Long Rectangle	%90 Abs	Accurate	Accurate
Soundwalk 21	Odeon	Soundscape 10	L-Shaped	Mixed Abs	Wrong	Wrong
Soundwalk 22	VR	Soundscape 11	Small Rectangle	%10 Abs	Accurate	Accurate
Soundwalk 23	VR	Soundscape 14	Long Rectangle	Mixed Abs	Close	Accurate
Soundwalk 24	Odeon	Soundscape 08	L-Shaped	%10 Abs	Accurate	Close
Soundwalk 25	Odeon	Soundscape 09	L-Shaped	%90 Abs	Wrong	Close
Soundwalk 26	VR	Soundscape 12	Long Rectangle	%10 Abs	Close	Accurate
Soundwalk 27	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	Close	Close
Soundwalk 28	VR	Soundscape 06	L-Shaped	%90 Abs	Close	Accurate
Soundwalk 29	VR	Soundscape 07	L-Shaped	Mixed Abs	Accurate	Accurate
Soundwalk 30	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	Wrong	Accurate
Soundwalk 31	VR	Soundscape 05	L-Shaped	%10 Abs	Accurate	Accurate
Soundwalk 32	VR	Soundscape 07	L-Shaped	Mixed Abs	Accurate	Close
Soundwalk 33	Odeon	Soundscape 08	L-Shaped	%10 Abs	Wrong	Wrong
Soundwalk 34	Odeon	Soundscape 09	L-Shaped	%90 Abs	Wrong	Close
Soundwalk 35	VR	Soundscape 12	Long Rectangle	%10 Abs	Close	Accurate
Soundwalk 36	Odeon	Soundscape 10	L-Shaped	Mixed Abs	Accurate	Close
Soundwalk 37	VR	Soundscape 11	Small Rectangle	%10 Abs	Accurate	Wrong
Soundwalk 38	VR	Soundscape 14	Long Rectangle	Mixed Abs	Wrong	Wrong
Soundwalk 39	Odeon	Soundscape 08	L-Shaped	%10 Abs	Wrong	Wrong
Soundwalk 40	Odeon	Soundscape 09	L-Shaped	%90 Abs	Wrong	Wrong
Soundwalk 41	VR	Soundscape 13	Long Rectangle	%90 Abs	Wrong	Accurate
Soundwalk 42	Odeon	Soundscape 02	Long Rectangle	%10 Abs	Wrong	Accurate
Soundwalk 43	Odeon	Soundscape 08	L-Shaped	%10 Abs	Wrong	Accurate
Soundwalk 44	VR	Soundscape 05	L-Shaped	Mixed Abs	Close	Wrong
Soundwalk 45	Odeon	Soundscape 10	L-Shaped	Mixed Abs	Wrong	Accurate
Soundwalk 46	VR	Soundscape 11	Small Rectangle	%10 Abs	Wrong	Accurate
Soundwalk 47	VR	Soundscape 14	Long Rectangle	Mixed Abs	Accurate	Accurate
Soundwalk 48	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	Accurate	Wrong
Soundwalk 49	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	Close	Accurate

(Table 4-5 continued)

Soundwalk 50	VR	Soundscape 07	L-Shaped	Mixed Abs	Accurate	Accurate
Soundwalk 51	Odeon	Soundscape 01	Small Rectangle	%10 Abs	Accurate	Wrong
Soundwalk 52	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	Accurate	Accurate
Soundwalk 53	VR	Soundscape 14	Long Rectangle	Mixed Abs	Accurate	Accurate
Soundwalk 54	Odeon	Soundscape 01	Small Rectangle	%10 Abs	Wrong	Wrong
Soundwalk 55	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	Close	Close
Soundwalk 56	VR	Soundscape 13	Long Rectangle	%90 Abs	Close	Accurate
Soundwalk 57	Odeon	Soundscape 01	Small Rectangle	%10 Abs	Close	Accurate
Soundwalk 58	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	Wrong	Wrong
Soundwalk 59	VR	Soundscape 13	Long Rectangle	%90 Abs	Accurate	Close

4.2.1.3 Perception of Room Size

The mean value of the absolute difference between the real area of the virtual spaces and the guessed areas created with two soundscape design environments statistically showed no difference. In % 28 of the soundwalks the area of the virtual space is overestimated and % 52 of the overestimated areas were in Odeon environment which is almost equal to the number of overestimated areas in VR. In one soundwalk (Trial 8 -1) the virtual space is described as an open space and is not included in the statistics. The smallest absolute difference mean between the real areas of the virtual spaces and the guessed areas belongs to the soundscapes design with materials with %10 absorption in total of the soundscapes. However, this result is not relevant for both soundscape design environments. In Odeon environment the smallest mean belongs to the soundscapes designed with mixed material choice which includes surface materials with both %10 and %90 absorption.

Table 4-6 Results of the Room Size Error

Soundwalk Number	Soundscape Information						
	Environment	Soundscape Number	Envelope Form	Material Choice	Real Area	Guessed Area	Room Size Difference
Soundwalk 01	Odeon	Soundscape 02	Long Rectangle	%10 Abs	90,00	225,00	-135,00
Soundwalk 02	Odeon	Soundscape 08	L-Shaped	%10 Abs	88,00	144,00	-56,00
Soundwalk 03	Odeon	Soundscape 03	Long Rectangle	%90 Abs	90,00	16,00	74,00
Soundwalk 04	Odeon	Soundscape 03	Long Rectangle	%90 Abs	90,00	25,00	65,00
Soundwalk 05	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	90,00	65,00	25,00
Soundwalk 06	VR	Soundscape 06	L-Shaped	%90 Abs	88,00	50,00	38,00
Soundwalk 07	Odeon	Soundscape 02	Long Rectangle	%10 Abs	90,00	9,00	81,00
Soundwalk 08	Odeon	Soundscape 03	Long Rectangle	%90 Abs	90,00	15,00	75,00
Soundwalk 09	VR	Soundscape 05	L-Shaped	%10 Abs	88,00	15,00	73,00
Soundwalk 10	Odeon	Soundscape 10	L-Shaped	Mixed Abs	88,00	30,00	58,00
Soundwalk 11	VR	Soundscape 14	Long Rectangle	Mixed Abs	90,00	30,00	60,00
Soundwalk 12	Odeon	Soundscape 02	Long Rectangle	%10 Abs	90,00	30,00	60,00
Soundwalk 13	Odeon	Soundscape 03	Long Rectangle	%90 Abs	90,00	10,00	80,00
Soundwalk 14	VR	Soundscape 05	L-Shaped	%10 Abs	88,00	20,00	68,00
Soundwalk 15	Odeon	Soundscape 03	Long Rectangle	%90 Abs	90,00	90,00	0,00
Soundwalk 16	VR	Soundscape 06	L-Shaped	%90 Abs	88,00	75,00	13,00
Soundwalk 17	VR	Soundscape 07	L-Shaped	Mixed Abs	88,00	200,00	-112,00
Soundwalk 18	Odeon	Soundscape 09	L-Shaped	%90 Abs	88,00	675,00	-587,00
Soundwalk 19	VR	Soundscape 12	Long Rectangle	%10 Abs	90,00	250,00	-160,00
Soundwalk 20	VR	Soundscape 13	Long Rectangle	%90 Abs	90,00	675,00	-585,00
Soundwalk 21	Odeon	Soundscape 10	L-Shaped	Mixed Abs	88,00	88,00	NA
Soundwalk 22	VR	Soundscape 11	Small Rectangle	%10 Abs	60,00	20,00	40,00
Soundwalk 23	VR	Soundscape 14	Long Rectangle	Mixed Abs	90,00	1000,00	-910,00
Soundwalk 24	Odeon	Soundscape 08	L-Shaped	%10 Abs	88,00	40,00	48,00
Soundwalk 25	Odeon	Soundscape 09	L-Shaped	%90 Abs	88,00	25,00	63,00
Soundwalk 26	VR	Soundscape 12	Long Rectangle	%10 Abs	90,00	30,00	60,00
Soundwalk 27	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	90,00	20,00	70,00
Soundwalk 28	VR	Soundscape 06	L-Shaped	%90 Abs	88,00	25,00	63,00

(Table 4-6 continued)

Soundwalk 29	VR	Soundscape 07	L-Shaped	Mixed Abs	88,00	30,00	58,00
Soundwalk 30	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	90,00	25,00	65,00
Soundwalk 31	VR	Soundscape 05	L-Shaped	%10 Abs	88,00	100,00	-12,00
Soundwalk 32	VR	Soundscape 07	L-Shaped	Mixed Abs	88,00	220,00	-132,00
Soundwalk 33	Odeon	Soundscape 08	L-Shaped	%10 Abs	88,00	15,00	73,00
Soundwalk 34	Odeon	Soundscape 09	L-Shaped	%90 Abs	88,00	30,00	58,00
Soundwalk 35	VR	Soundscape 12	Long Rectangle	%10 Abs	90,00	24,00	66,00
Soundwalk 36	Odeon	Soundscape 10	L-Shaped	Mixed Abs	88,00	25,00	63,00
Soundwalk 37	VR	Soundscape 11	Small Rectangle	%10 Abs	60,00	30,00	30,00
Soundwalk 38	VR	Soundscape 14	Long Rectangle	Mixed Abs	90,00	30,00	60,00
Soundwalk 39	Odeon	Soundscape 08	L-Shaped	%10 Abs	88,00	30,00	58,00
Soundwalk 40	Odeon	Soundscape 09	L-Shaped	%90 Abs	88,00	10,00	78,00
Soundwalk 41	VR	Soundscape 13	Long Rectangle	%90 Abs	90,00	12,00	78,00
Soundwalk 42	Odeon	Soundscape 02	Long Rectangle	%10 Abs	90,00	100,00	-10,00
Soundwalk 43	Odeon	Soundscape 08	L-Shaped	%10 Abs	88,00	50,00	38,00
Soundwalk 44	VR	Soundscape 05	L-Shaped	Mixed Abs	88,00	75,00	13,00
Soundwalk 45	Odeon	Soundscape 10	L-Shaped	Mixed Abs	88,00	50,00	38,00
Soundwalk 46	VR	Soundscape 11	Small Rectangle	%10 Abs	60,00	12,00	48,00
Soundwalk 47	VR	Soundscape 14	Long Rectangle	Mixed Abs	90,00	15,00	75,00
Soundwalk 48	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	90,00	100,00	-10,00
Soundwalk 49	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	88,00	30,00	58,00
Soundwalk 50	VR	Soundscape 07	L-Shaped	Mixed Abs	88,00	50,00	38,00
Soundwalk 51	Odeon	Soundscape 01	Small Rectangle	%10 Abs	60,00	80,00	-20,00
Soundwalk 52	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	88,00	750,00	-662,00
Soundwalk 53	VR	Soundscape 14	Long Rectangle	Mixed Abs	90,00	120,00	-30,00
Soundwalk 54	Odeon	Soundscape 01	Small Rectangle	%10 Abs	60,00	630,00	-570,00
Soundwalk 55	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	88,00	300,00	-212,00
Soundwalk 56	VR	Soundscape 13	Long Rectangle	%90 Abs	90,00	120,00	-30,00
Soundwalk 57	Odeon	Soundscape 01	Small Rectangle	%10 Abs	60,00	20,00	40,00
Soundwalk 58	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	88,00	35,00	53,00
Soundwalk 59	VR	Soundscape 13	Long Rectangle	%90 Abs	90,00	15,00	75,00

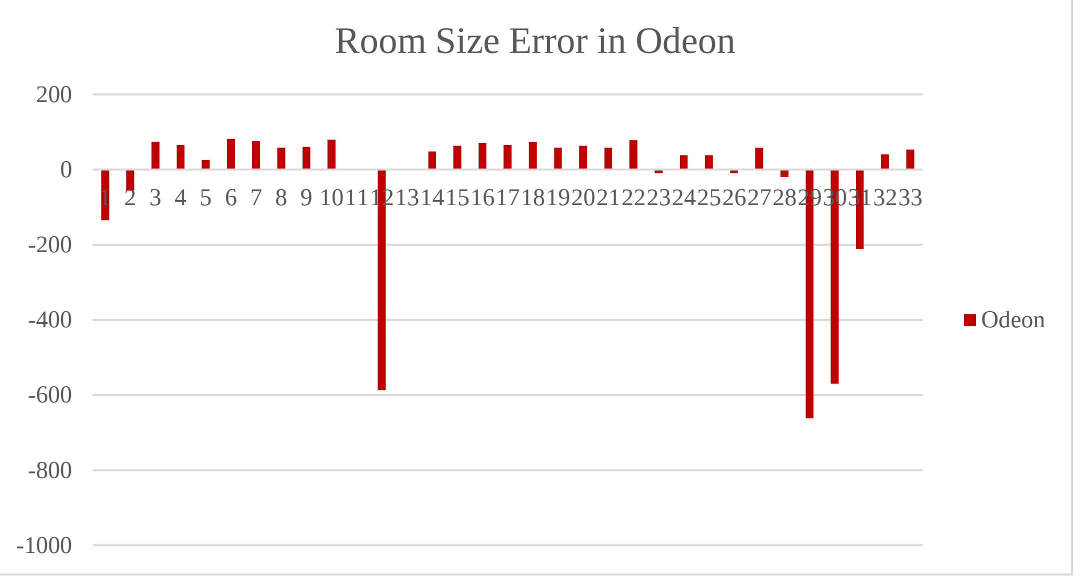


Figure 4-2 Room Size Errors of Soundwalks in Odeon

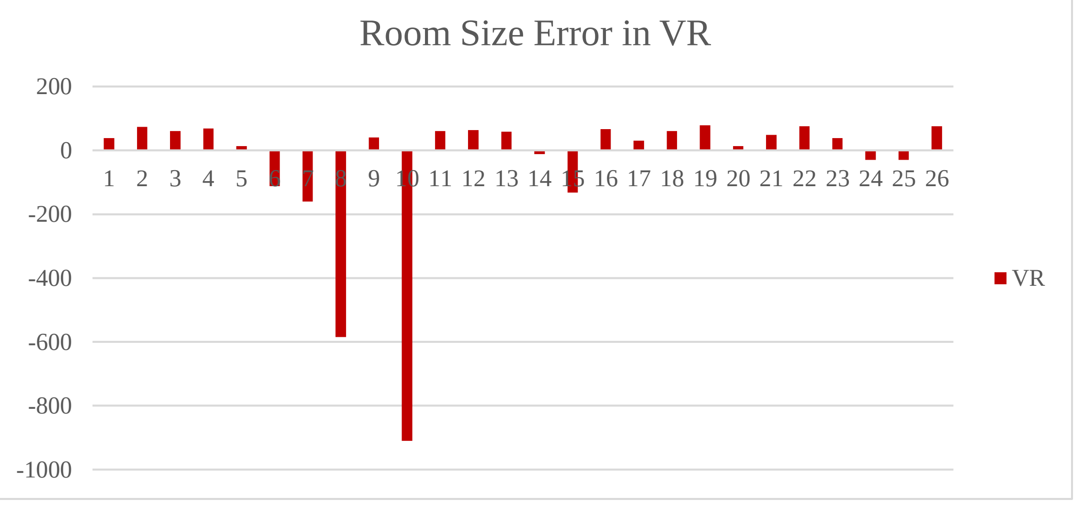


Figure 4-3 Room Size Errors of Unity - VR

4.2.2 Listening Test

Listening Test results include the errors of source localization and self localization.

4.2.2.1 Source Localization

Mean value of the distance between the real and guessed location of the sound source are lower in immersive environment compared to simulated environment but statistically insignificant. The overall sound localization errors differ between 0,70 and 11,01 meters.

Table 4-7 Results of the Source Localization Error

Soundwalk Number	Soundscape Information				
	Environment	Soundscape Number	Envelope Form	Material Choice	Source Localization Error (m)
Soundwalk 01	Odeon	Soundscape 02	Long Rectangle	%10 Abs	1,66
Soundwalk 02	Odeon	Soundscape 08	L-Shaped	%10 Abs	6,18
Soundwalk 03	Odeon	Soundscape 03	Long Rectangle	%90 Abs	1,50
Soundwalk 04	Odeon	Soundscape 03	Long Rectangle	%90 Abs	1,55
Soundwalk 05	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	0,85
Soundwalk 06	VR	Soundscape 06	L-Shaped	%90 Abs	3,35
Soundwalk 07	Odeon	Soundscape 02	Long Rectangle	%10 Abs	0,80
Soundwalk 08	Odeon	Soundscape 03	Long Rectangle	%90 Abs	0,82
Soundwalk 09	VR	Soundscape 05	L-Shaped	%10 Abs	1,00
Soundwalk 10	Odeon	Soundscape 10	L-Shaped	Mixed Abs	5,63
Soundwalk 11	VR	Soundscape 14	Long Rectangle	Mixed Abs	1,75
Soundwalk 12	Odeon	Soundscape 02	Long Rectangle	%10 Abs	2,01
Soundwalk 13	Odeon	Soundscape 03	Long Rectangle	%90 Abs	5,70
Soundwalk 14	VR	Soundscape 05	L-Shaped	%10 Abs	2,04
Soundwalk 15	Odeon	Soundscape 03	Long Rectangle	%90 Abs	6,40
Soundwalk 16	VR	Soundscape 06	L-Shaped	%90 Abs	1,90
Soundwalk 17	VR	Soundscape 07	L-Shaped	Mixed Abs	1,61
Soundwalk 18	Odeon	Soundscape 09	L-Shaped	%90 Abs	5,15
Soundwalk 19	VR	Soundscape 12	Long Rectangle	%10 Abs	0,80
Soundwalk 20	VR	Soundscape 13	Long Rectangle	%90 Abs	1,00
Soundwalk 21	Odeon	Soundscape 10	L-Shaped	Mixed Abs	2,12
Soundwalk 22	VR	Soundscape 11	Small Rectangle	%10 Abs	2,55
Soundwalk 23	VR	Soundscape 14	Long Rectangle	Mixed Abs	1,12
Soundwalk 24	Odeon	Soundscape 08	L-Shaped	%10 Abs	2,06
Soundwalk 25	Odeon	Soundscape 09	L-Shaped	%90 Abs	1,58
Soundwalk 26	VR	Soundscape 12	Long Rectangle	%10 Abs	5,61

(Table 4-7 continued)

Soundwalk 27	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	3,72
Soundwalk 28	VR	Soundscape 06	L-Shaped	%90 Abs	1,02
Soundwalk 29	VR	Soundscape 07	L-Shaped	Mixed Abs	2,51
Soundwalk 30	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	9,22
Soundwalk 31	VR	Soundscape 05	L-Shaped	%10 Abs	1,42
Soundwalk 32	VR	Soundscape 07	L-Shaped	Mixed Abs	1,10
Soundwalk 33	Odeon	Soundscape 08	L-Shaped	%10 Abs	8,46
Soundwalk 34	Odeon	Soundscape 09	L-Shaped	%90 Abs	4,30
Soundwalk 35	VR	Soundscape 12	Long Rectangle	%10 Abs	1,50
Soundwalk 36	Odeon	Soundscape 10	L-Shaped	Mixed Abs	0,70
Soundwalk 37	VR	Soundscape 11	Small Rectangle	%10 Abs	2,24
Soundwalk 38	VR	Soundscape 14	Long Rectangle	Mixed Abs	2,41
Soundwalk 39	Odeon	Soundscape 08	L-Shaped	%10 Abs	7,76
Soundwalk 40	Odeon	Soundscape 09	L-Shaped	%90 Abs	5,47
Soundwalk 41	VR	Soundscape 13	Long Rectangle	%90 Abs	2,77
Soundwalk 42	Odeon	Soundscape 02	Long Rectangle	%10 Abs	3,67
Soundwalk 43	Odeon	Soundscape 08	L-Shaped	%10 Abs	5,12
Soundwalk 44	VR	Soundscape 05	L-Shaped	Mixed Abs	1,21
Soundwalk 45	Odeon	Soundscape 10	L-Shaped	Mixed Abs	11,01
Soundwalk 46	VR	Soundscape 11	Small Rectangle	%10 Abs	3,69
Soundwalk 47	VR	Soundscape 14	Long Rectangle	Mixed Abs	1,58
Soundwalk 48	Odeon	Soundscape 04	Long Rectangle	Mixed Abs	3,54
Soundwalk 49	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	4,39
Soundwalk 50	VR	Soundscape 07	L-Shaped	Mixed Abs	2,00
Soundwalk 51	Odeon	Soundscape 01	Small Rectangle	%10 Abs	1,75
Soundwalk 52	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	1,75
Soundwalk 53	VR	Soundscape 14	Long Rectangle	Mixed Abs	0,70
Soundwalk 54	Odeon	Soundscape 01	Small Rectangle	%10 Abs	4,19
Soundwalk 55	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	0,90
Soundwalk 56	VR	Soundscape 13	Long Rectangle	%90 Abs	2,18
Soundwalk 57	Odeon	Soundscape 01	Small Rectangle	%10 Abs	3,61
Soundwalk 58	Odeon	Soundscape 15	L-Shaped	Mixed2 Abs	0,91
Soundwalk 59	VR	Soundscape 13	Long Rectangle	%90 Abs	0,73

4.2.2.2 Self Localization : Route

The overall movement in all soundwalks is getting away from the sound event, however, the route traversed which means that at some points the perceivers get closer to the room envelope surfaces as shown before in the previous chapter. Self-localization differences on the route are analyzed according to two dimensions. The first dimension is the difference between guessed and real turning point numbers. The second one is the absolute difference between guessed and real total route length. For both dimensions, the differences are significantly lower in VR environment compared to Odeon. From 59 soundwalks 12 of the soundwalks overestimated the route length whereas the rest underestimated. All of the overestimated guesses are soundwalks conducted in VR environment. All of the route length guesses in Odeon environment were underestimated. The number of turning points was also underestimated in Odeon environment by all participants. From 33 soundwalks in Odeon, 7 of the soundwalks resulted in a perception of the route as a movement in one direction and some of them only drew a small arrow showing the direction of movement without indicating any details which prevented them to guess the correct distance as well.

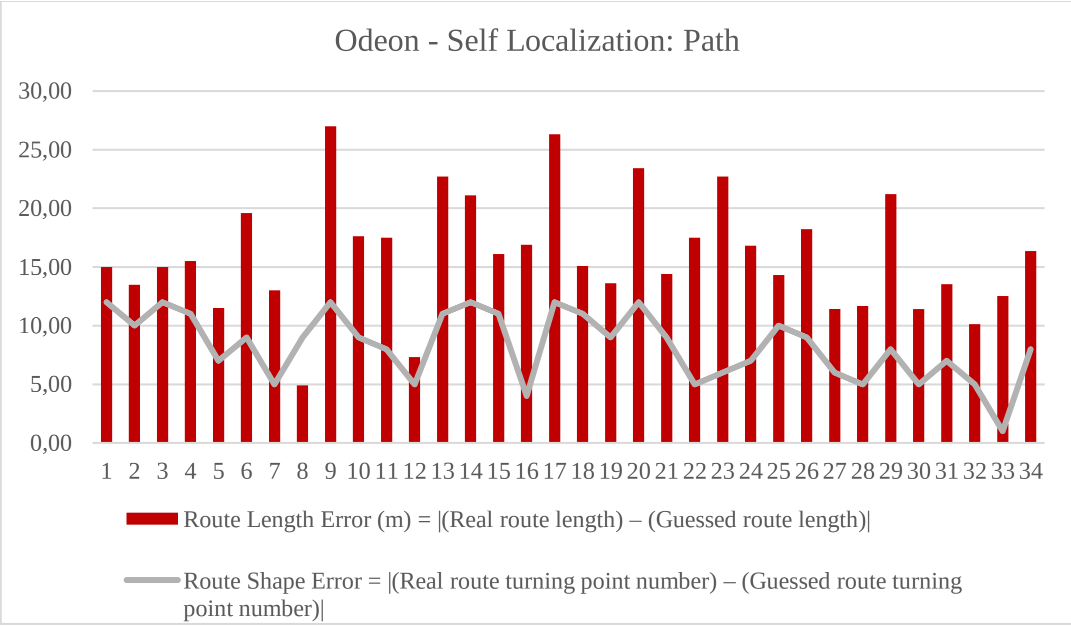


Figure 4-4 Diagrams of Self Localization Results by Route in Odeon - Headphones

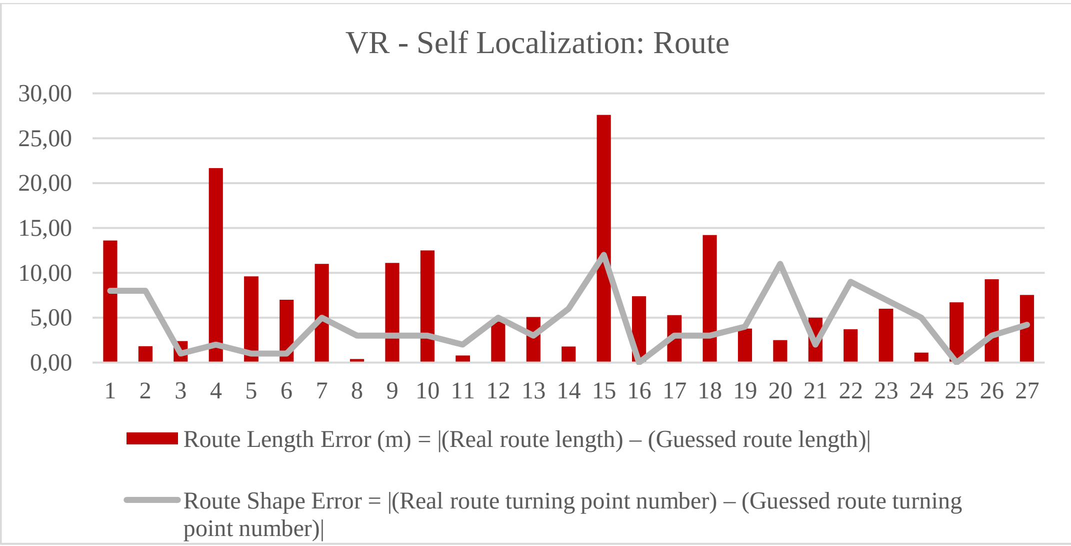
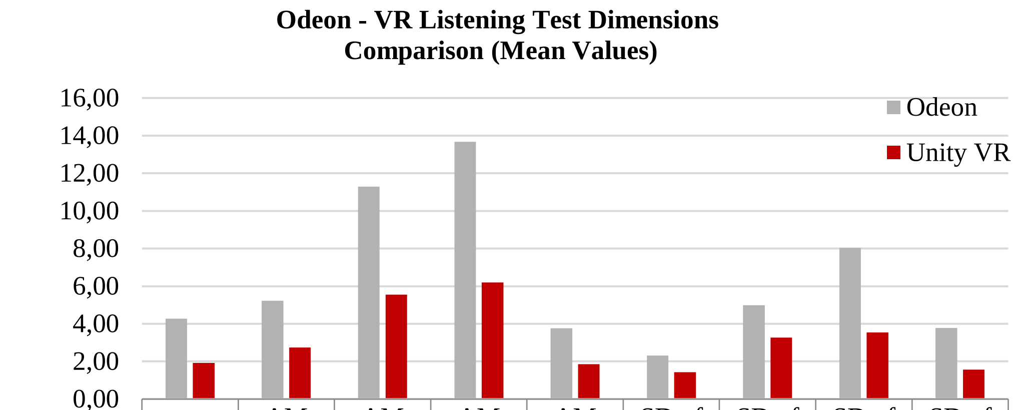


Figure 4-5 Diagrams of Self Localization Results by Route in Unity VR

In Odeon environment, the participants usually interpreted all the perceived loudness changes as getting away or getting closer to the sound source on a line they drew. Therefore, it can be said that they were able to perceive the change between getting closer or further away from the room envelope surfaces but were not able to interpret it correctly. Compared to their drawings, their descriptions of the movement relative to the sound source indicate more details about the soundwalk route.

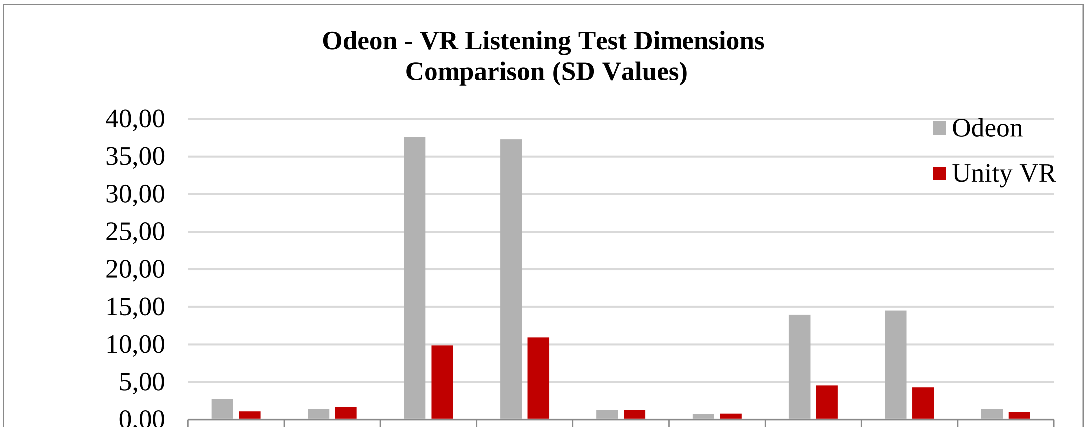
4.2.2.3 Self Localization : Random Points & Distance

The mean values of the differences between the participant guesses and the correct numbers are lower for all four analysis dimensions of the listening tests (self-localization, self-consistency, source distance by guess, and source distance by location) in soundscapes created with VR compared to Odeon. Nevertheless, only self-localization and source disance by location are statistically significant with σ < 0,01.



	Source Localization Error (m)	AM Self Localization Error (m)	AM Self Consistency Error (m)	AM Guessed Distance Error (m)	AM Localized Distance Error (m)	SD of Self Localization Error (m)	SD of Self Consistency Error (m)	SD of Guessed Distance Error (m)	SD of Localized Distance Error (m)
Odeon	4,27	5,23	11,30	13,68	3,76	2,31	4,99	8,03	3,78
Unity VR	1,92	2,74	5,55	6,19	1,85	1,43	3,27	3,54	1,57

Figure 4-6 Mean Values of Dimensions of Listening Tests in Odeon and Unity - VR Environment (AM = Absolute Mean, SD = Standard Deviation)



	Source Localization Error (m)	AM Self Localization Error (m)	AM Self Consistency Error (m)	AM Guessed Distance Error (m)	AM Localized Distance Error (m)	SD of Self Localization Error (m)	SD of Self Consistency Error (m)	SD of Guessed Distance Error (m)	SD of Localized Distance Error (m)
Odeon	2,71	1,44	37,61	37,29	1,25	0,76	13,98	14,53	1,40
Unity VR	1,09	1,71	9,89	10,95	1,29	0,82	4,57	4,27	1,02

Figure 4-7 Standard Deviation Values of Dimensions of Listening Tests in Odeon and Unity - VR Environment (AM = Absolute Mean, SD = Standard Deviation)

4.2.3 Results of the Soundscape Evaluation

Total of 19 participants evaluated their experience. According to Soundwalk Data Collection Method B, developed in the TUD COST Action TD0804, by ISO 12913-2018, the evaluation criteria included loudness, unpleasentness, appropriateness, and the desire to experience the soundscape again. (2018) None of the participants evaluated their virtual soundwalks as extremely loud or unpleasent. For four evaluation criteria: Distribution of answers to each level (1-2-3-4-5) according to Likert scale is shown below.

Table 4-8 Overall Soundwalk Experience Distribution Results based on ISO 12913-2018 Method B

	Levels According to Likert Scale					
	1	**2**	**3**	**4**	**5**	**Mean µ**
Loudness	6	7	6	0	0	2,00
Unpleasentness	9	7	0	3	0	1,84
Appropriateness	1	3	8	6	1	3,16
Visiting Again	3	3	6	4	3	3,05

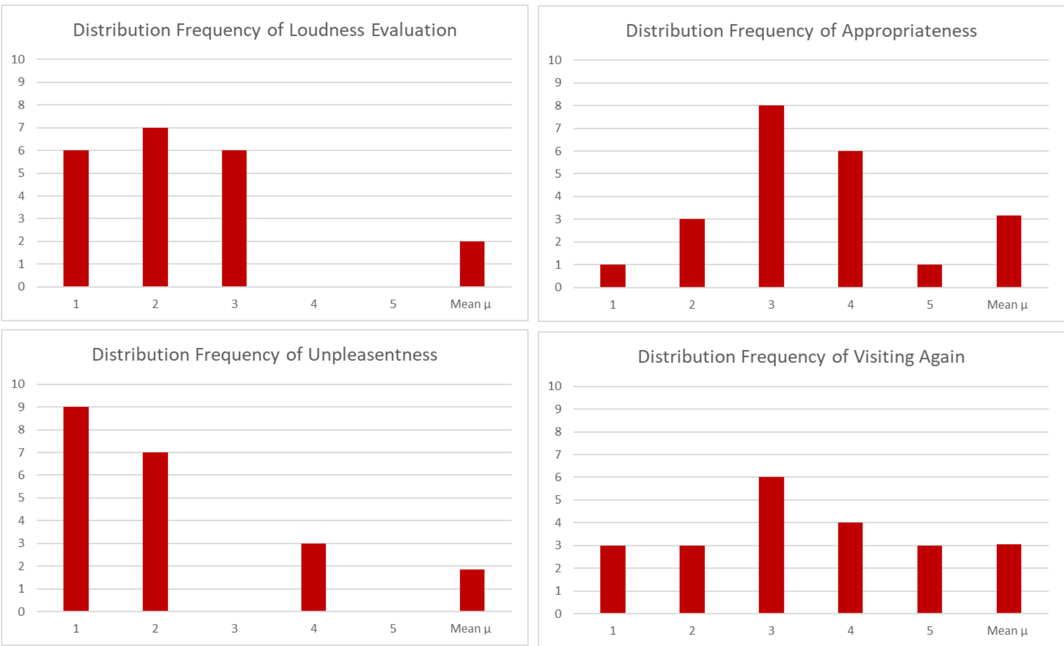


Figure 4-8 Overall Soundwalk Experience Distribution Results based on ISO 12913-2018 Method B - Likert Scale

In open ended questions part for source description, thoughts and feelings 6 participants mentioned the word rhythm (or periodical or repetitiveness or tık tık etc.) Whereas 7 participants commented on space or spatial qualities. 7 participants commented on experiment settings. 7 participants commented on movement (or route, walking, steps).

4.3 Results of the Case Study

Different than the Trial Experiments, Case Studies include extra DATA collection dimensions which are shown in the table below.

Table 4-9 Extra DATA Collection Dimensions for the Case Study

First Soundwalk Duration (minutes, second)	The time each participant needed in the first soundwalk in a virtual space for answering the first four questions of the interview.
Mind Map Drawing Duration (minutes, second)	The time each participant took for drawing the mind map. (Question 04)
Second Soundwalk Duration (minutes, second)	The time each participant needed in the second soundwalk in the same virtual space for locating the sound source and the movement route on the given plan diagram.
Route & Source Location Duration (minutes, second)	The time each participant took for visually locating the sound source and the movement route on the given plan diagram. (Question 05)
Mean Duration for Each Point (minutes, second)	The mean time each participant took for locating each asked random points and guessing their distance to the source.
Loudness of Asked Points (Likert Scale)	The perceived loudness of each asked points according to participants.
Head Movement	The head movement of the participants through the soundwalk in Unity VR environment, obtained by regular screen shots.
Separate Soundscape Evaluations (Likert Scale)	Instead of an overall evaluation, participants evaluated both soundscape design methods separately.

The DATA Analysis of the case study experiments also starts with a visual analysis and continues with a numerical analysis.

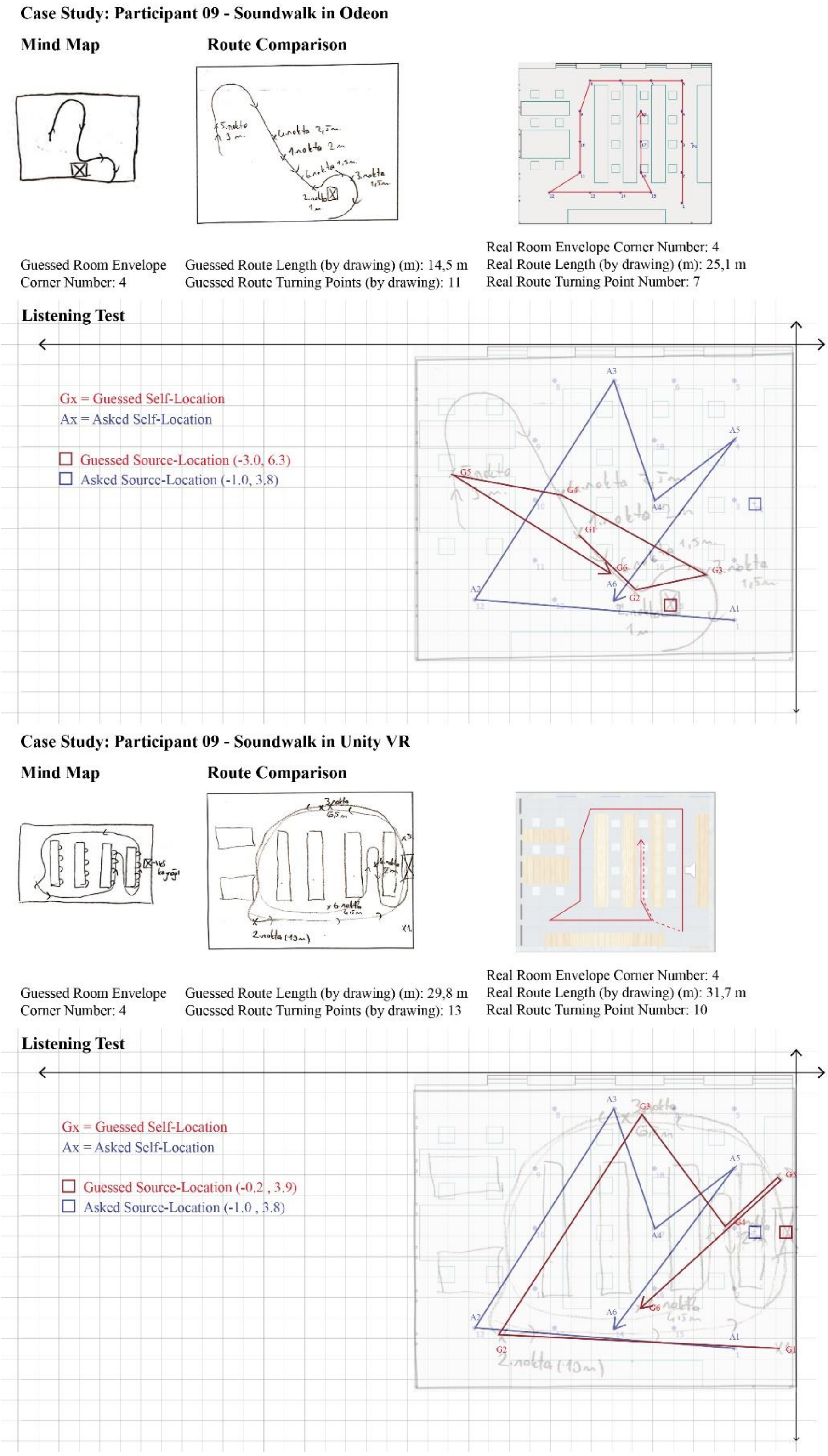


Figure 4-9 Example of the Visual Analysis Process (Case Study Participant 09)

4.3.1 Case Study Method 01: Odeon and Headphones

The time spans of the sessions are collected to understand if the environment or the experience order affects the duration participants need. The results showed that the participants experiencing Odeon environment needed an average of 65 seconds of soundwalking and 49 seconds of drawing for creating their mind maps without having any visual information. There were no errors in any of the participants' guesses on the room envelope form since all of them assumed the virtual space was a rectangular room. After seeing the plan diagram showing the room envelope, the participants needed an average of 54 seconds for soundwalking again and 35 seconds for drawing the route and localizing the sound source. The participants spent an average of 13 seconds for self-localization according to a randomly asked point.

Table 4-10 Durations of the Case Study Experiments in Odeon Environment

Participant Number	Order	First Soundwalk Duration	Mind Map Drawing Duration	Second Soundwalk Duration	Route & Source Location Duration	Mean Duration for Each Point
P 01	1	01:00,3	00:26,9	00:40,7	00:30,2	00:14,3
P 02	1	00:47,8	00:23,9	00:45,3	00:35,3	00:13,9
P 03	1	00:47,8	00:17,7	00:22,3	00:39,6	00:12,9
P 04	1	01:19,7	02:03,0	01:29,3	00:38,3	00:28,0
P 05	2	01:58,2	01:06,9	01:48,0	00:30,3	00:09,8
P 06	2	01:33,4	00:42,2	01:07,0	00:49,6	00:14,7
P 07	2	00:45,8	00:36,1	00:42,9	00:44,7	00:09,6
P 08	2	00:45,9	01:03,9	00:40,8	00:30,6	00:05,8
P 09	2	00:45,3	00:38,0	00:24,4	00:18,2	00:07,3
Mean		**01:04,9**	**00:48,7**	**00:53,4**	**00:35,2**	**00:12,9**

Similar to the previous trials, the description of sound source direction and movement in case studies lacks the reliability, therefore they are not transformed into numerical DATA. The experience order did not have a difference for the number of accurate descriptions for both direction and movement in Odeon environment.

Table 4-11 Direction and Movement Description Results of Case Studies in Odeon Environment

Participant Number	Environment	Order	Description of Direction	Description of Movement
P 01	Odeon	1	NA	Close
P 02	Odeon	1	Wrong	Accurate
P 03	Odeon	1	Wrong	Close
P 04	Odeon	1	Close	Accurate
P 05	Odeon	2	Close	Accurate
P 06	Odeon	2	Close	Accurate
P 07	Odeon	2	Wrong	Wrong
P 08	Odeon	2	Wrong	Close
P 09	Odeon	2	Wrong	Close

Table 4-12 Results of the Case Study Experiment - Soundwalks in Odeon Environment

Participant Number	Order	|Room Size Error (sqm)|	Route Length Error (m)	Route Shape Error
P 01	1	61,44	14,00	4,00
P 02	1	128,56	10,50	2,00
P 03	1	61,44	7,90	2,00
P 04	1	21,44	18,10	4,00
P 05	2	41,44	12,90	16,00
P 06	2	153,56	15,80	5,00
P 07	2	1,44	9,80	3,00
P 08	2	56,44	8,80	7,00
P 09	2	46,44	10,60	4,00
Mean		**63,58**	**12,04**	**5,22**

Table 4-13 Results of the Case Study Experiment - Listening Tests in Odeon Environment

Participant Number	Order	Source Localization Error (m)	AM Self Localization Error (m)	AM Self Consistency Error (m)	AM Guessed Distance Error (m)	AM Localized Distance Error (m)	SD of Self Localization Error (m)	SD of Self Consistency Error (m)	SD of Guessed Distance Error (m)	SD of Localized Distance Error (m)
P 01	1	2,10	3,42	0,79	1,87	1,31	0,78	0,05	1,94	1,64
P 02	1	4,27	2,93	0,34	3,00	1,93	1,61	0,17	2,41	2,33
P 03	1	3,80	2,90	2,12	4,02	2,38	1,41	2,04	1,74	2,73

(Table 4-13 continued)

P 04	1	2,69	3,22	6,83	4,88	2,14	2,00	2,96	4,40	2,30
P 05	2	3,36	2,73	1,21	2,35	1,41	1,04	0,73	2,32	1,80
P 06	2	4,90	3,74	3,29	2,95	1,65	1,44	2,31	3,19	1,91
P 07	2	3,10	3,46	0,50	3,12	2,27	2,60	0,53	2,43	2,89
P 08	2	5,10	2,98	1,15	2,60	1,81	1,67	1,01	1,36	1,89
P 09	2	3,20	3,04	0,99	2,60	1,93	1,58	1,18	1,95	2,18
Mean		**3,61**	**3,16**	**1,91**	**3,05**	**1,87**	**1,57**	**1,22**	**2,42**	**2,18**

The distribution of soundscape evaluation perceptions to each level (1-2-3-4-5) according to Likert scale in Odeon environment is shown below.

Table 4-14 Soundwalk Experience Distribution Results in Odeon Environment based on ISO 12913-2018

Odeon	**Levels According to Likert Scale**					
	1	**2**	**3**	**4**	**5**	**Mean μ**
Loudness	2	1	3	2	1	**2,88889**
Unpleasentness	2	2	3	1	1	**2,66667**
Appropriateness	3	1	2	3	0	**2,55556**
Visiting Again	4	1	2	0	2	**2,44444**

4.3.2 Case Study Method 02: Unity and Virtual Reality

The results showed that the participants experiencing Unity VR environment needed an average of 101 seconds of soundwalking and 69 seconds of drawing for creating their mind maps. There were no errors in any of the participants' guesses on the room envelope form since all of them assumed the virtual space was a rectangular room. After seeing the plan diagram showing the room envelope, the participants needed an average of 59 seconds for soundwalking again and 78 seconds for drawing the route and localizing the sound source. The participants spent an average of 18 seconds for self-localization according to a randomly asked point.

Table 4-15 Durations of the Case Study Experiments in Unity VR Environment

	Order	First Soundwalk Duration	Mind Map Drawing	Second Soundwalk Duration	Route & Source Location Duration	Mean Duration for Each Point
P 01	1	02:04,5	00:57,3	01:04,2	01:53,1	00:22,9
P 02	1	02:06,5	01:35,7	00:46,3	01:43,9	00:27,4
P 03	1	01:35,1	00:21,0	00:32,4	01:06,8	00:26,8
P 04	1	02:25,0	00:54,8	02:14,0	02:25,0	00:29,7
P 05	2	03:19,5	03:02,5	01:53,8	00:41,3	00:09,2
P 06	2	01:06,7	00:34,1	00:38,9	01:16,2	00:15,3
P 07	2	00:39,6	01:49,8	00:36,8	00:41,4	00:11,9
P 08	2	00:55,5	00:35,0	00:33,4	00:25,5	00:11,9
P 09	2	00:56,6	00:34,2	00:38,8	01:31,1	00:11,7
Mean		**01:41,0**	**01:09,4**	**00:59,8**	**01:18,3**	**00:18,5**

Five of the nine participants (Participants 01, 02, 04, 06, 09) included the furniture of the virtual space in their mind maps and plan diagrams for Unity VR method. However, only three of the nine participants (Participants 01, 02, 03) mentioned the furniture of the virtual space when they are describing the sound source, its location, or as in a general comment.

Unlike Odeon environment, there is a higher number of accurate descriptions for both sound source direction and movement in Group 02, who experienced the Unity VR environment before Odeon environment. However, due to the lack of reliability of the descriptive DATA, it is not possible to prove if the difference is emerged due to the experience order.

Table 4-16 Direction and Movement Description Results of Case Studies in Unity VR Environment

Participant Number	Environment	Order	Description of Direction	Description of Movement
P 01	Unity VR	1	NA	Accurate
P 02	Unity VR	1	Close	Accurate
P 03	Unity VR	1	Wrong	Wrong
P 04	Unity VR	1	Accurate	Accurate
P 05	Unity VR	2	Close	Accurate
P 06	Unity VR	2	Accurate	Accurate

(Table 4-16 continued)

P 07	Unity VR	2	Accurate	Close
P 08	Unity VR	2	Wrong	Accurate
P 09	Unity VR	2	Accurate	Accurate

Aiming to explore the movements of the head in Unity VR environment, the screen is recorded through the experiment. The Head movements of Participant 01 are unavailable due to a technical error in the recording process. Eight Participants' head movements are analyzed through their soundwalks and listening tests. The results revealed that five (Participants 02, 04, 05, 07, 08) of eight participants showed no significant head movement through their first soundwalks. Whereas Participants 06 and 09 repeatedly rotated their heads in all directions, including up and down motion, aiming to explore the space. Only Participant 03 tried to match the looking direction with the movement direction. Head movements in the second soundwalk were also the same for all participants.

Table 4-17 Results of the Case Study Experiment - Soundwalks in Unity VR Environment

	Environment	**Order**	**|Room Size Error (sqm)|**	**Route Length Error (m)**	**Route Shape Error**
P 01	Unity VR	1	55,44	9,50	2,00
P 02	Unity VR	1	28,56	3,00	3,00
P 03	Unity VR	1	46,44	3,30	3,00
P 04	Unity VR	1	22,44	7,70	0,00
P 05	Unity VR	2	78,56	20,90	1,00
P 06	Unity VR	2	22,44	11,40	2,00
P 07	Unity VR	2	21,44	3,00	3,00
P 08	Unity VR	2	31,44	1,30	2,00
P 09	Unity VR	2	78,56	1,90	3,00
Mean			**42,81**	**6,89**	**2,11**

Through the listening tests Participants 05 and 08 showed no significant head movements while self-locating, similar to the soundwalk sessions. Four (Participants 03, 04, 06, 09) of eight participants showed significant head movements while self-locating each asked point. Two (Participants 02, 07) of eight participants did not show significant head movements for all locations. Participant 02 did not move while locating Point 2 and Point 6, while Participant 07 did not move while locating Point 3.

Table 4-18 Results of the Case Study Experiment - Listening Tests in Unity VR Environment

Participant Number	**Order**	**Source Localization Error (m)**	**AM Self Localization Error (m)**	**AM Self Consistency Error (m)**	**AM Guessed Distance Error (m)**	**AM Localized Distance Error (m)**	**SD of Self Localization Error (m)**	**SD of Self Consistency Error (m)**	**SD of Guessed Distance Error (m)**	**SD of Localized Distance Error (m)**
P 01	1	5,40	4,80	3,03	3,35	2,63	1,73	1,02	1,38	2,92
P 02	1	1,70	2,34	0,66	2,29	1,75	1,70	0,68	1,19	1,35
P 03	1	4,27	3,69	0,89	1,54	2,25	1,63	0,88	1,08	2,53
P 04	1	4,63	4,82	0,75	2,02	3,75	1,55	0,81	2,21	3,80
P 05	2	4,27	2,67	1,66	1,69	1,16	0,85	1,05	0,94	1,32
P 06	2	4,82	4,58	0,48	1,62	2,13	1,84	0,36	2,23	2,61
P 07	2	1,00	2,10	1,16	0,73	1,37	1,81	1,31	0,80	1,22
P 08	2	4,46	4,17	2,16	3,17	2,16	2,05	1,91	2,07	2,62
P 09	2	0,81	1,87	0,97	1,62	1,35	1,93	0,92	2,21	1,45
Mean		**3,48**	**3,45**	**1,31**	**2,00**	**2,06**	**1,68**	**0,99**	**1,57**	**2,20**

The distribution of soundscape evaluation perceptions to each level (1-2-3-4-5) according to Likert scale in Unity VR environment is shown below.

Table 4-19 Soundwalk Experience Distribution Results in Unity VR Environment based on ISO 12913-2018

Unity VR	**Levels According to Likert Scale**					
	1	**2**	**3**	**4**	**5**	**Mean µ**
Loudness	3	3	2	1	0	2,11111
Unpleasentness	4	2	1	2	0	2,11111
Appropriateness	1	1	2	3	2	3,44444
Visiting Again	3	1	2	2	1	2,66667

The answers to the open ended questions include enjoyment from the virtual reality experience, complaints about the irrelevant background noise coming from the devices in physical space, disturbance due to optimization problems.

CHAPTER 5

DISCUSSION OF THE RESULTS

5.1 Discussion of First Experiments

The results of the first experiments revealed that the soundscape design method significantly affected the perceptual accuracy of the form of the envelope, movement route, sound source localization, self-localization, and estimated source distance derived from source and self-localization ($\sigma < 0{,}01$). However, no statistically significant changes were found for the perceptual accuracy of room size ($\sigma = 0{,}552 > 0{,}05$), guessed sound source distances ($\sigma = 0{,}47 > 0{,}05$), and the self-consistency ($\sigma = 0{,}554 > 0{,}05$) of the participants. The perceptual accuracy of self-localization is higher for 90% absorption material choice compared to 10% and Mixed material absorptions in both environments. These results match the expectation of having larger errors in more reverberant spaces. (Blauert, 1997) The overall results suggested that the participants perceived their location more accurately in the Unity VR environment than Odeon environment. This is in line with the observations of Calcagno, Abregú, Eguía, and Vergara, which suggest that visual cues are more beneficial compared to auditory cues by means of perceiving spatial qualities like size, shape, or materials. (2012) The visual cues gain a lot more importance in an immersive environment since the participants can see the room from the first-person perspective even though they do not see the sound source itself. There are also unexpected results like a huge spread in self-consistency and guessed distance dimensions in the immersive environment for the Small Room. This could be related to the observation of Zahorik, Brungart, and Bronkhorst which suggests that source distances smaller than 1.9 m are usually overestimated. (2005) Most of the participants overestimated the soundwalk routes in the immersive environment, in contrast to the simulated environment. Therefore more detailed comparisons of the two environments are required in future studies. An important issue that affected the guessed room size is the physical environment in which the experiment took place. Most of the participants tried to understand the size of the physical room they were in and tried to guess a logical size for the virtual experiment rooms by comparison. The perceived realism of the virtual spaces was questionable since the participants were still under the effect of the physical space.

In a simulated environment, participants usually tend to accept the room as a rectangular space while drawing the mind maps in their first soundwalk, however, when they see the plan diagram of an L-shaped room once, they started to notice if an L-shaped room presented in later soundwalks. These results are in line with the findings of Viaud-Delmon and Warusfel who suggest that training has a positive effect on spatial cognition. (2014) However, three soundwalks presented to the participants in this study are conducted in separate virtual spaces and cannot be accepted as a training process and only provides them with a slight familiarity with the geometry options.

Comparison of the matching soundscape results are presented in the diagrams below. Three soundwalks are conducted for both Soundscape 01 and 11.

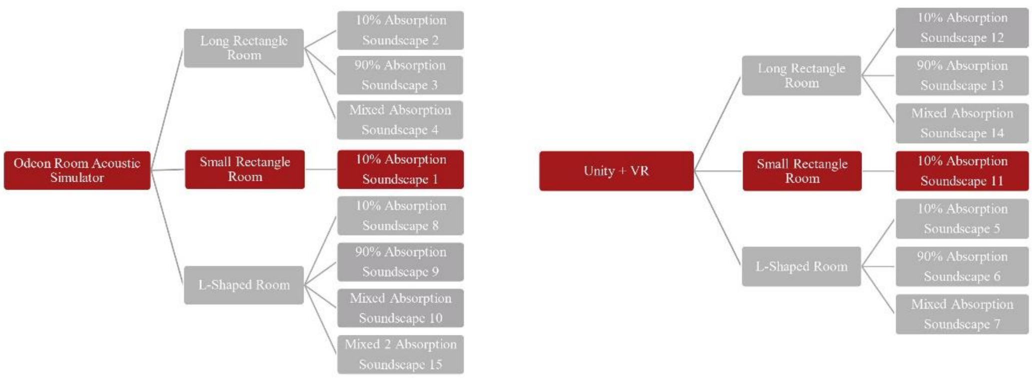


Figure 5-1 Compared Soundscapes 01 – 11

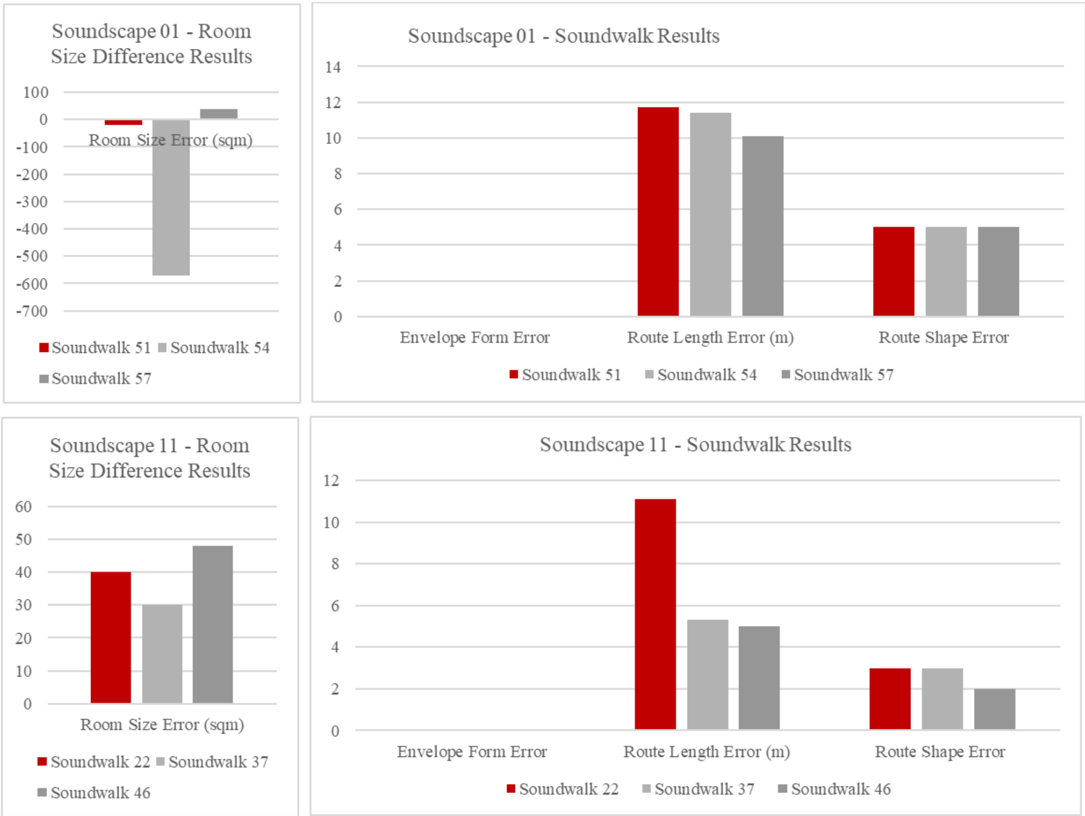


Figure 5-2 Diagrams of Soundwalks of Soundscape 01 (Odeon) - 11 (Unity VR)

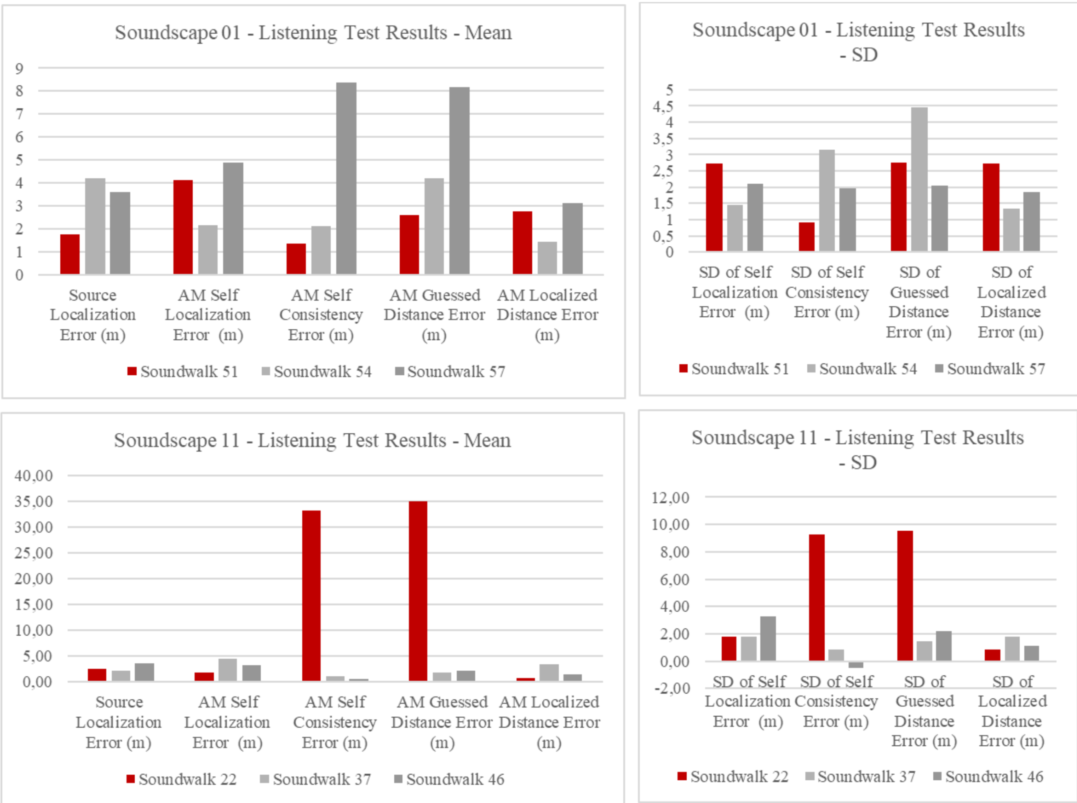


Figure 5-3 Diagrams of Listening Tests of Soundscape 01 (Odeon) - 11 (Unity VR)

Four soundwalks are conducted for Soundscape 02, three soundwalks are conducted for Soundscape for 12.

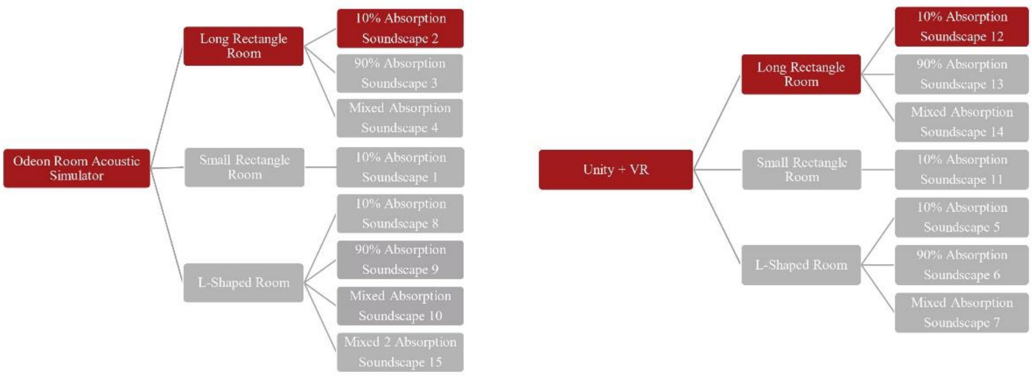


Figure 5-4 Compared Soundscapes 02 – 12

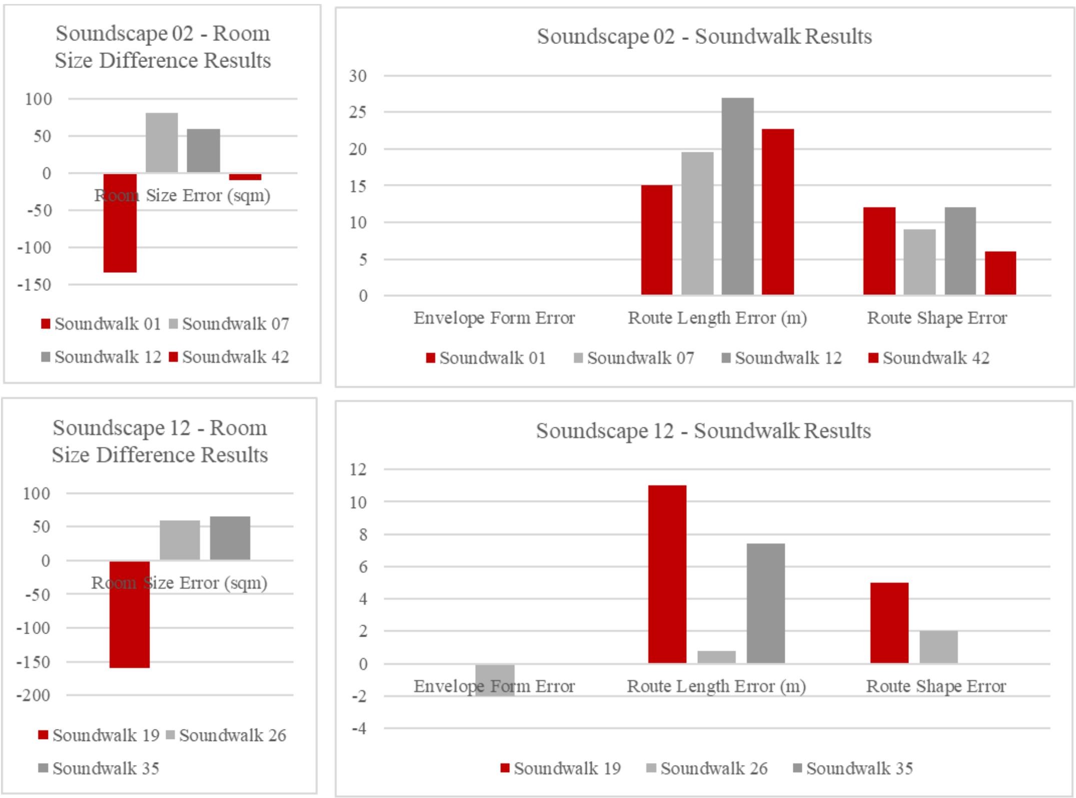


Figure 5-5 Diagrams of Soundwalks of Soundscape 02 (Odeon) - 12 (Unity VR)

Figure 5-6 Diagrams of Listening Tests of Soundscape 02 (Odeon) - 12 (Unity VR)

Five soundwalks are conducted for Soundscape 03, four soundwalks are conducted for Soundscape for 13.

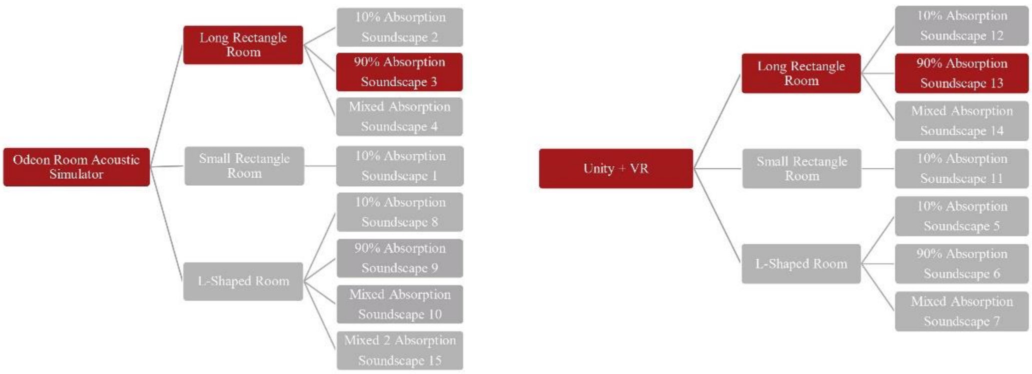


Figure 5-7 Compared Soundscapes 03 – 13

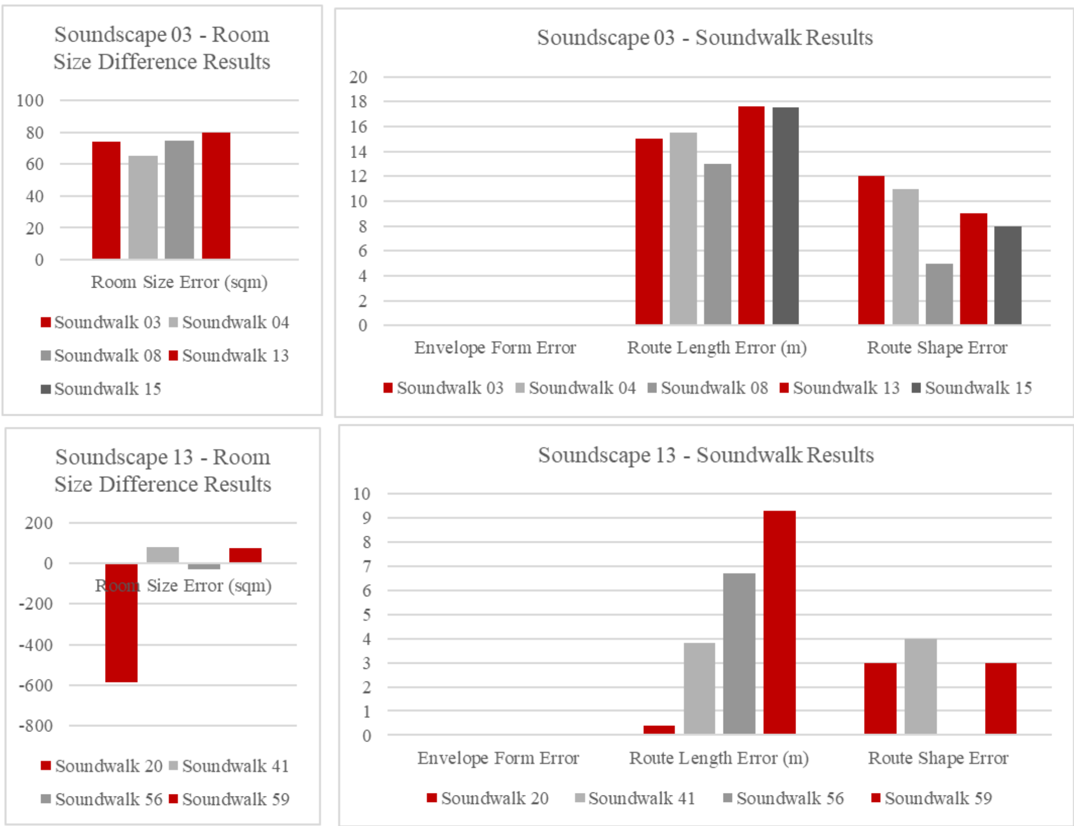


Figure 5-8 Diagrams of Soundwalks of Soundscape 03 (Odeon) - 13 (Unity VR)

Figure 5-9 Diagrams of Listening Tests of Soundscape 03 (Odeon) - 13 (Unity VR)

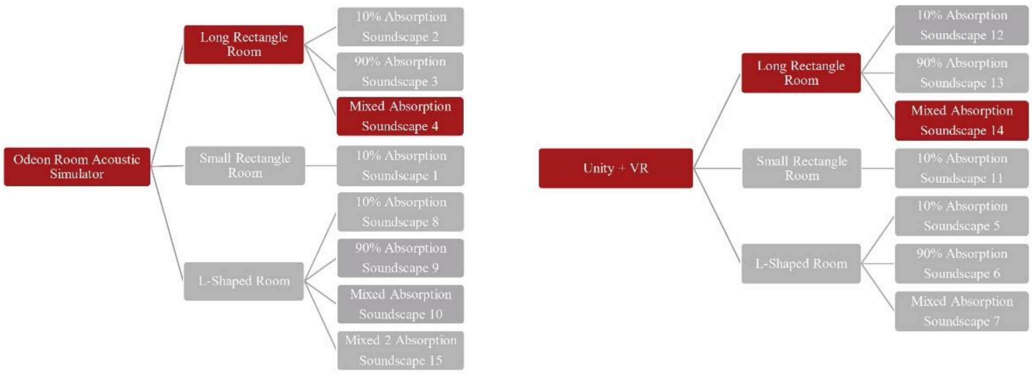


Figure 5-10 Compared Soundscapes 04 – 14

Four soundwalks are conducted for Soundscape 04, five soundwalks are conducted for Soundscape for 14.

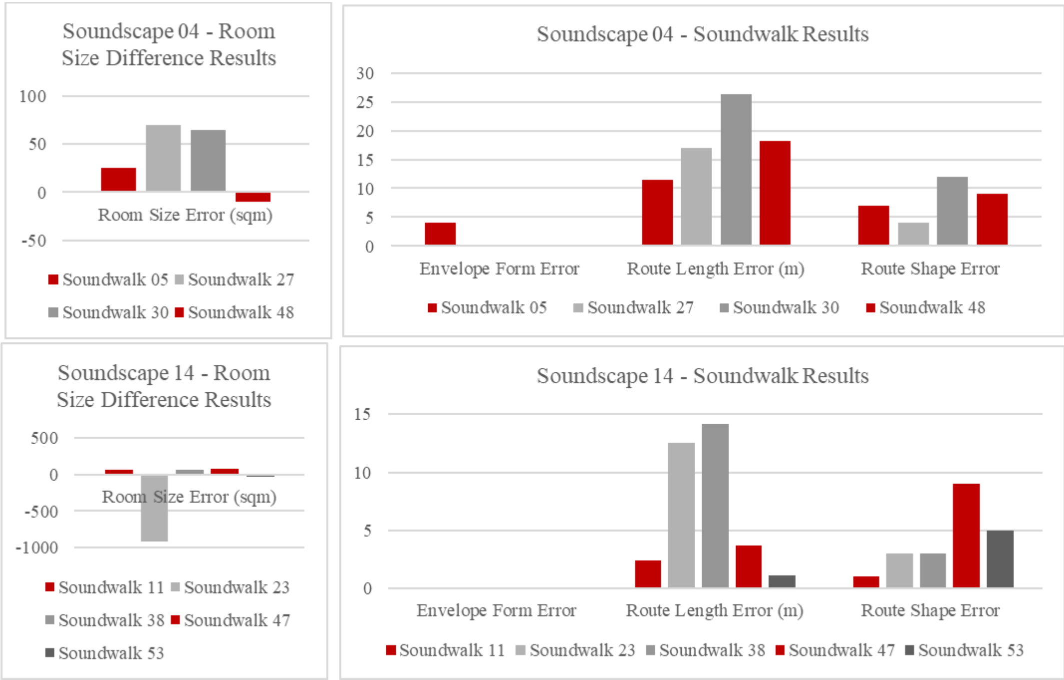


Figure 5-11 Diagrams of Soundwalks of Soundscape 04 (Odeon) - 14 (Unity VR)

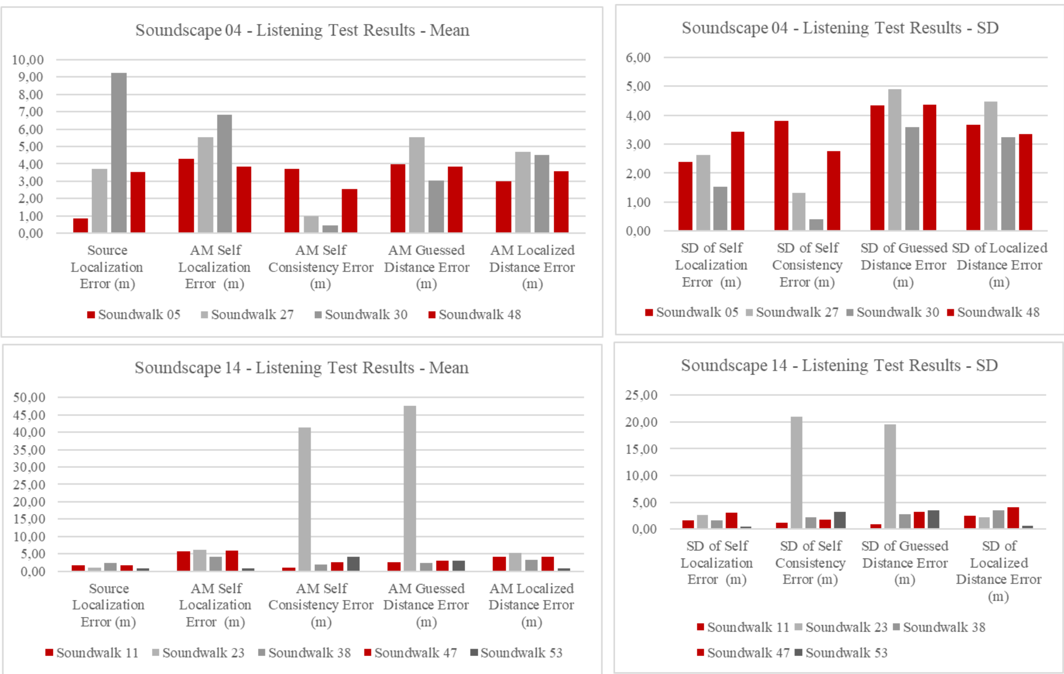


Figure 5-12 Diagrams of Listening Tests of Soundscape 04 (Odeon) - 14 (Unity VR)

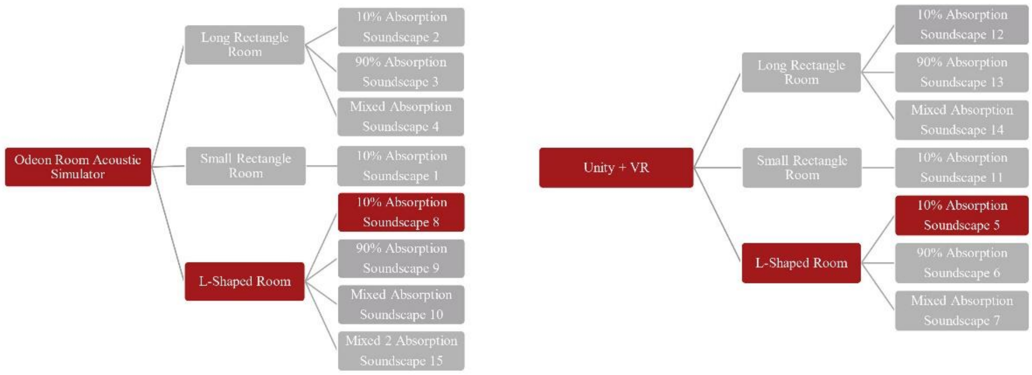


Figure 5-13 Compared Soundscapes 08 – 05

Five soundwalks are conducted for Soundscape 05, four soundwalks are conducted for Soundscape for 08.

Figure 5-14 22 Diagrams of Soundwalks of Soundscape 08 (Odeon) - 05 (Unity VR)

Figure 5-15 Diagrams of Listening Tests of Soundscape 08 (Odeon) - 05 (Unity VR)

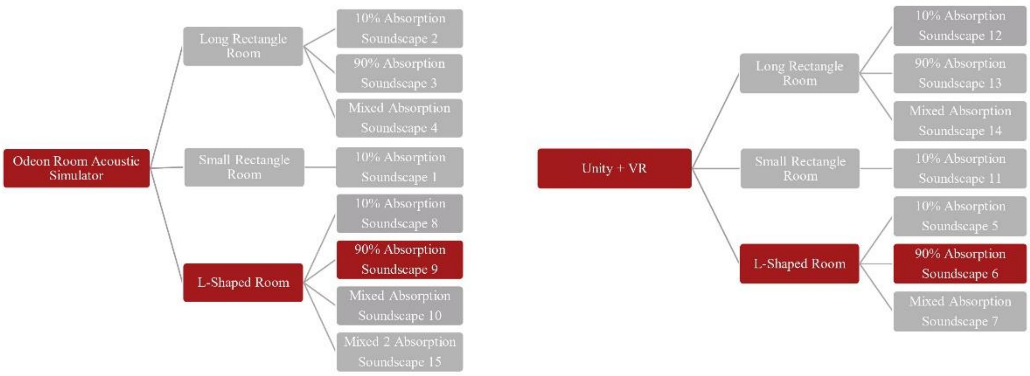


Figure 5-16 Compared Soundscapes 09 – 06

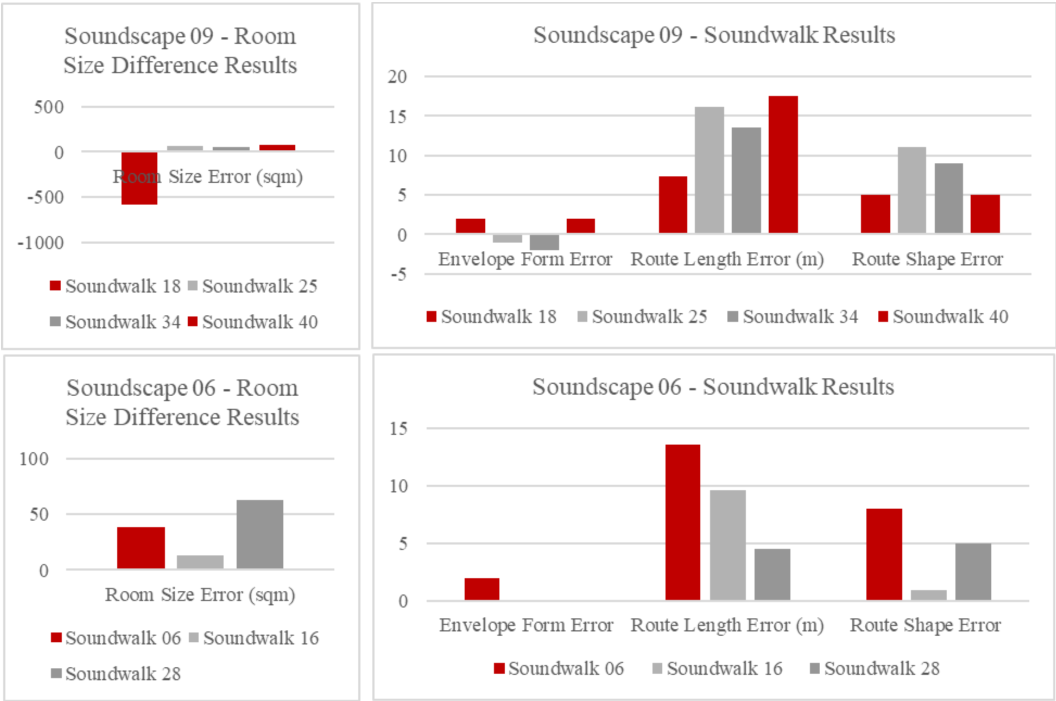


Figure 5-17 Diagrams of Soundwalks of Soundscape 09 (Odeon) - 06 (Unity VR)

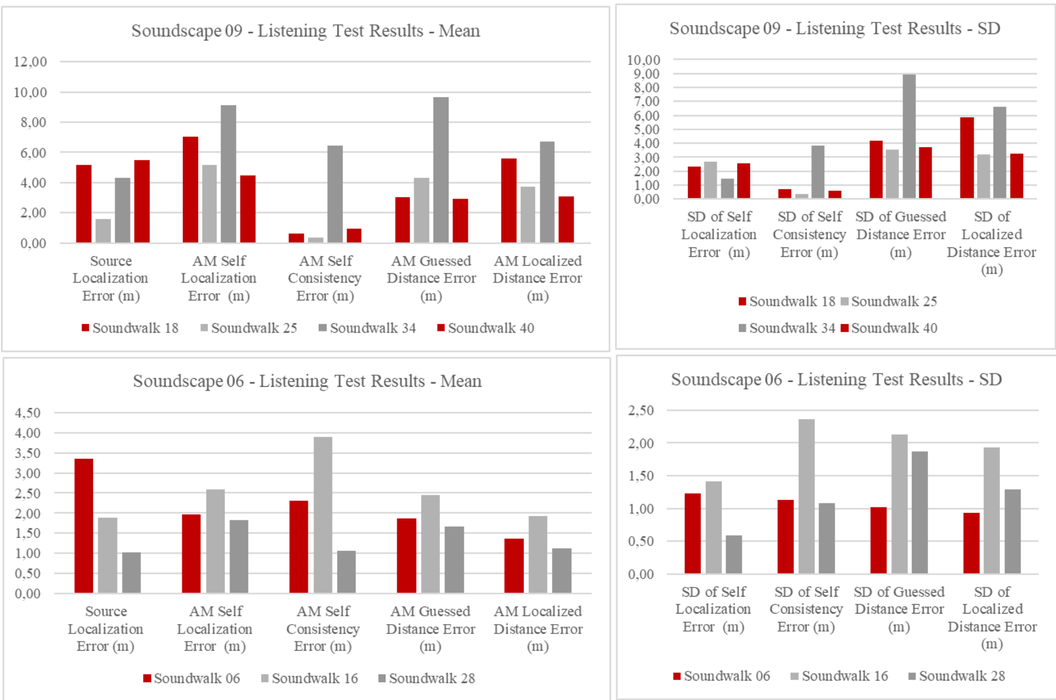


Figure 5-18 Diagrams of Listening Tests of Soundscape 09 (Odeon) - 06 (Unity VR)

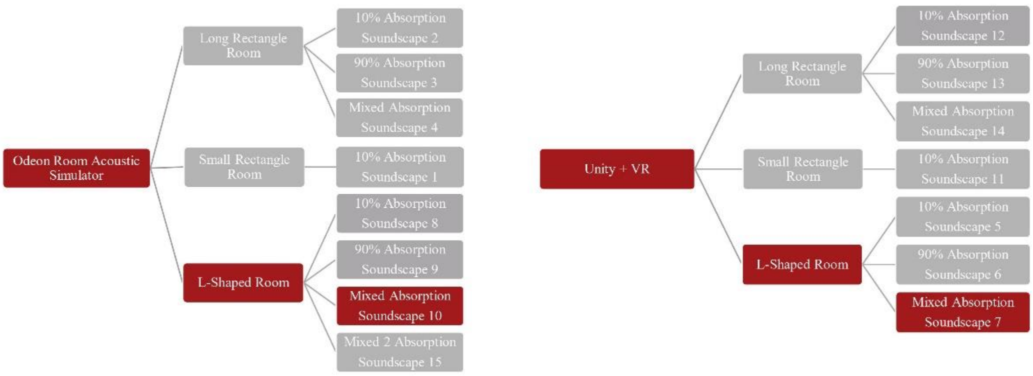


Figure 5-19 Compared Soundscapes 10 – 07

Figure 5-20 Diagrams of Soundwalks of Soundscape 10 (Odeon) - 07 (Unity VR)

Figure 5-21 Diagrams of Listening Tests of Soundscape 10 (Odeon) - 07 (Unity VR)

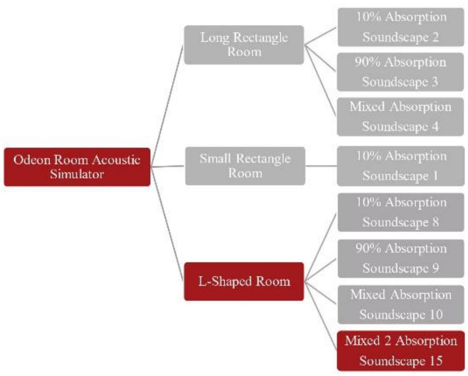


Figure 5-22Soundscape 15

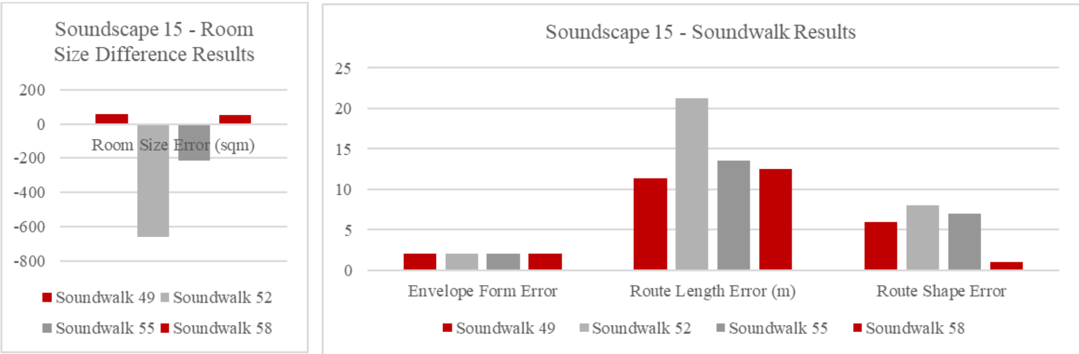


Figure 5-23 Diagrams of Soundwalks of Soundscape 15 (Odeon)

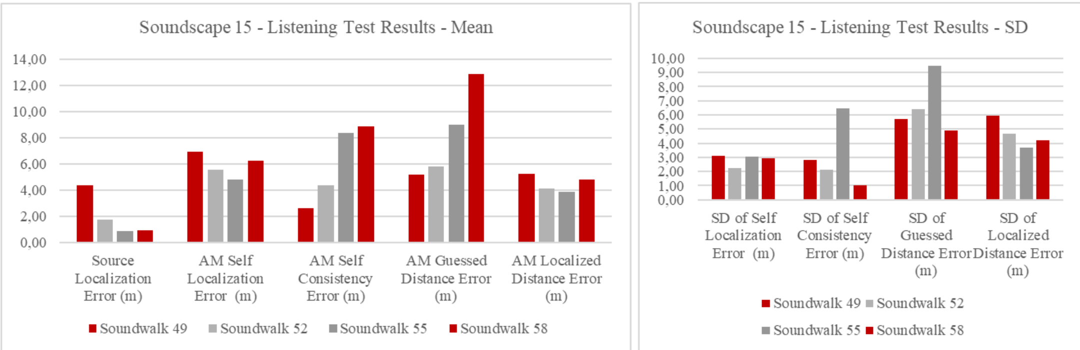


Figure 5-24 Diagrams of Listening Tests of Soundscape 15 (Odeon)

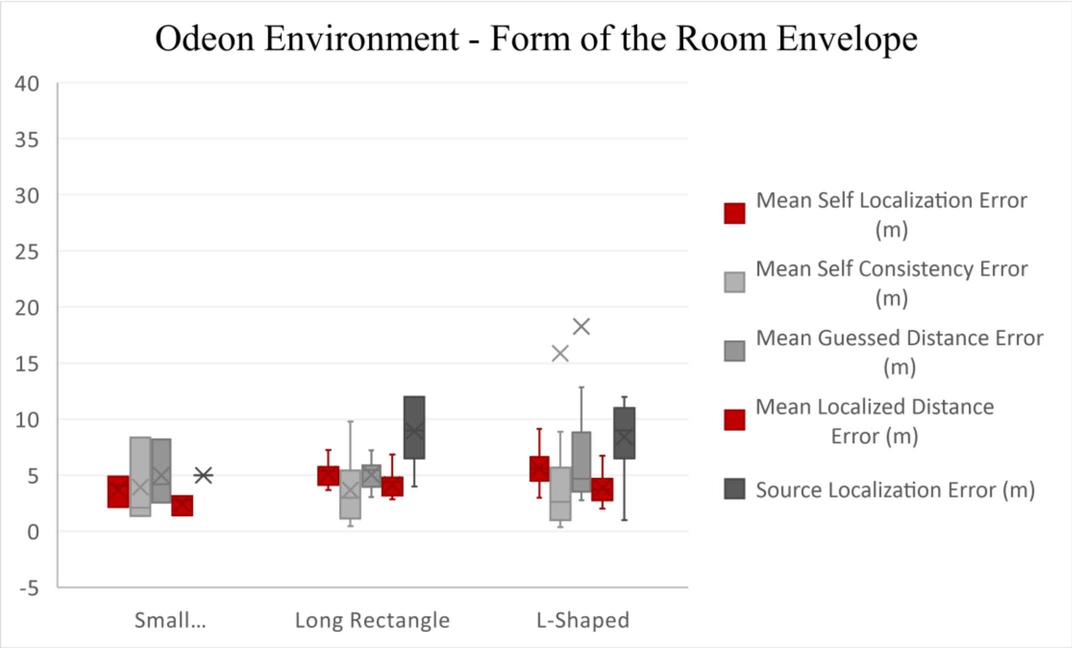


Figure 5-25 Box Plots of Listening Test Dimensions in Odeon Environment According to Form of the Room Envelope

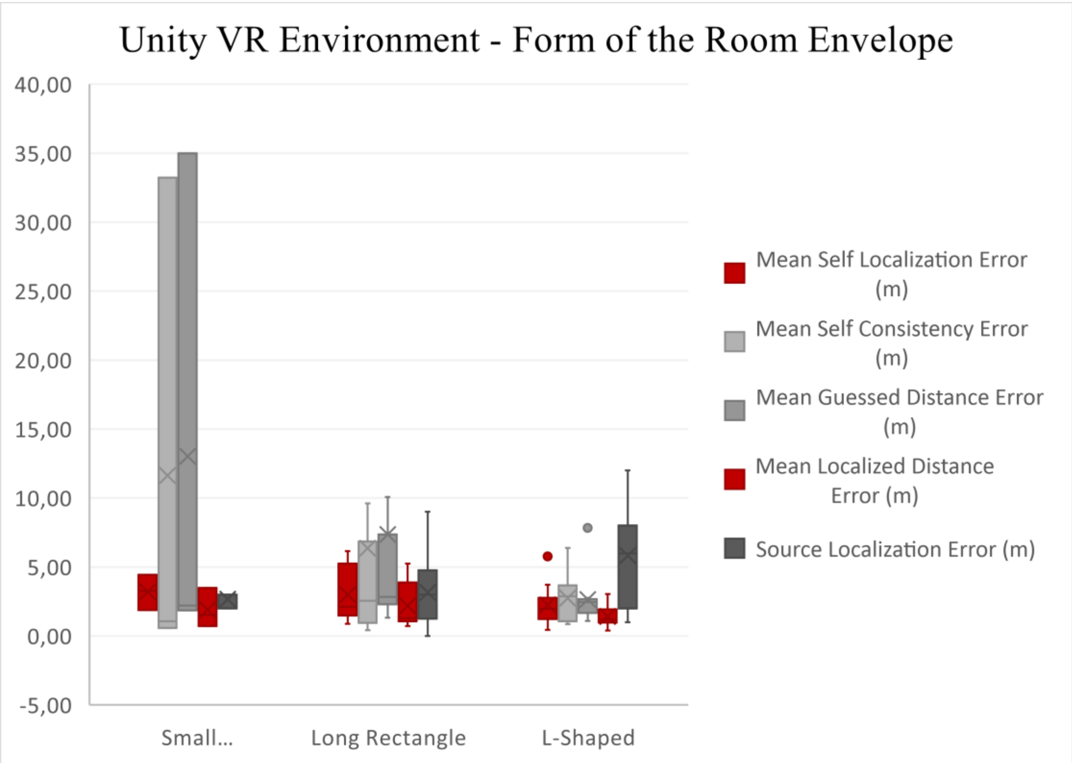


Figure 5-26 Box Plots of Listening Test Dimensions in Unity VR Environment According to Form of the Room Envelope

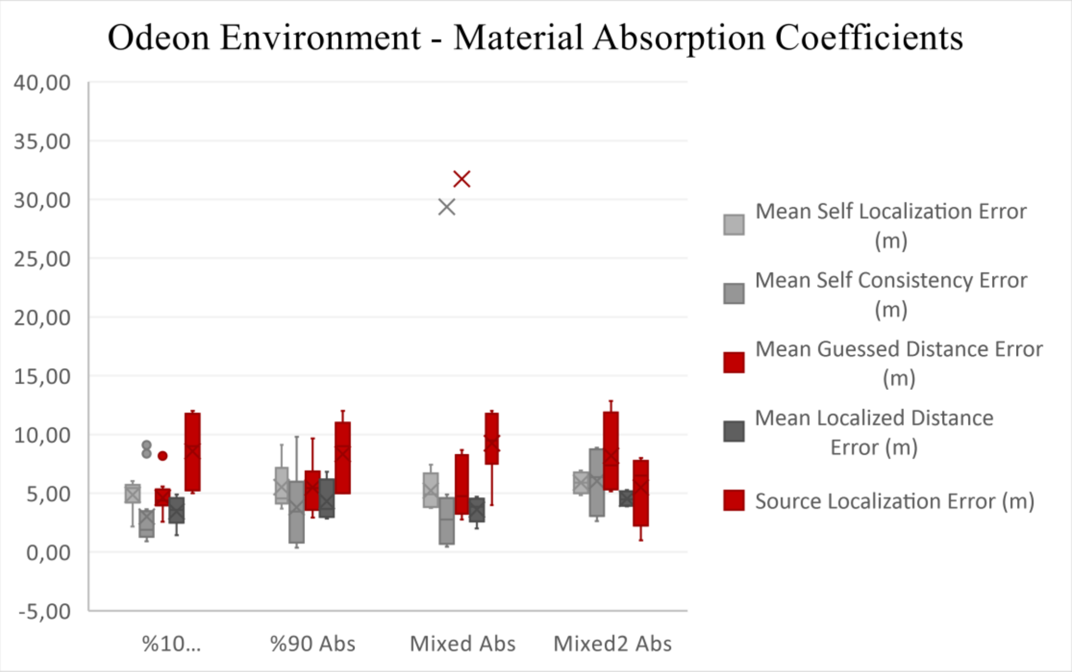


Figure 5-27 Box Plots of Listening Test Dimensions in Odeon Environment According to Absorption Coefficient of Surface Envelope Materials

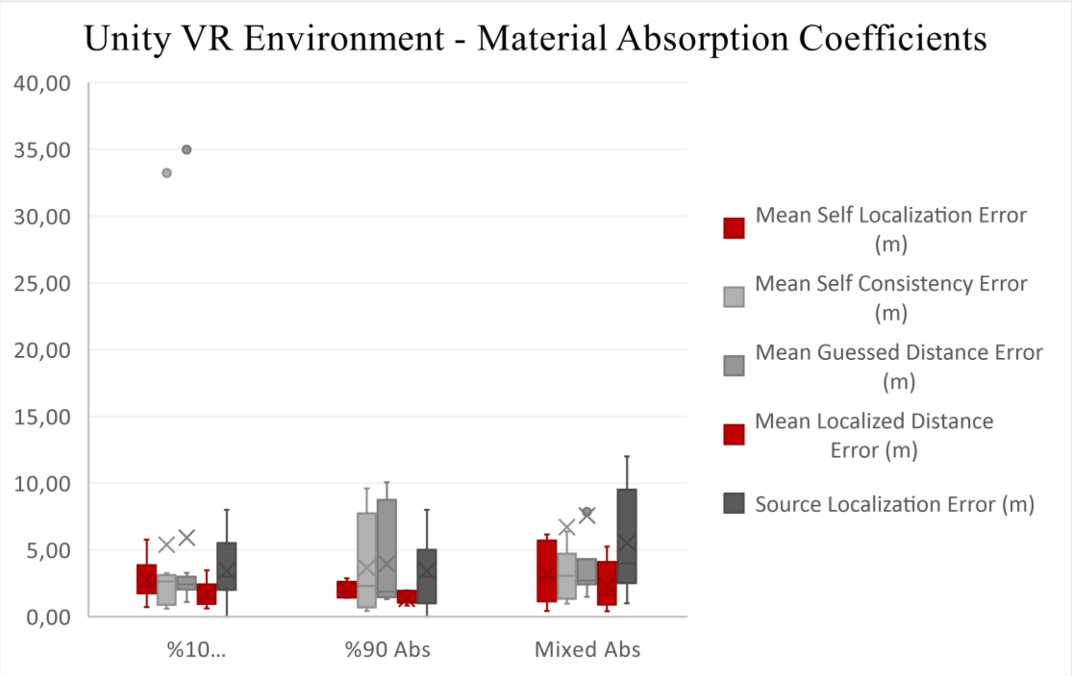


Figure 5-28 Box Plots of Listening Test Dimensions in Unity VR Environment According to Absorption Coefficient of Surface Envelope Materials

The absorption coefficient of the chosen materials directly affects Early Decay Time (EDT), Reverberation Time (T30), Clarity (C80), Lateral Energy Fraction (LF80), and Late Arriving Lateral Energy (LG80). The soundscapes designed with materials with 10% absorption had higher EDT, RT (T30), SPL, and LG80 values than those designed with Mixed or Mixed 2 material choice and materials with 90% absorption. For the mentioned parameters, the lowest values are achieved by 90% absorbent material selection, whereas the highest values for C80, D50, and STI are achieved by soundscapes designed with materials with 90% absorption.

Table 5-1 Room Acoustic Parameters of Matching Soundscapes at 1000 Hz (Calculated by Odeon)

Soundscape Numbers in Odeon – Unity VR	**01 - 11**	**02 -12**	**03 - 13**	**04 - 14**	**08 - 05**	**09 - 06**	**10 - 07**	**15**
EDT (s)	1,45	1,32	0,04	0,16	1,22	0,11	0,53	0,48
T30 (s)	1,43	1,23	0,07	0,47	1,06	0,06	0,78	0,85
SPL (dB)	89,7	90,9	78,1	82,6	90,3	60,5	82,2	70,7
C80 (dB)	2,1	1,8	52,9	17,4	1,4	56,3	8,7	7,5
D50	0,51	0,49	1	0,96	0,34	1	0,81	0,65
Ts (ms)	83	85	2	11	97	12	44	48
LF80	0,246	0,266	0,02	0,094	0,375	0,142	0,399	0,285
SPL(A) (dB)	96,2	97,7	85,8	90,4	96,7	66,5	88,8	78,5
LG80* (dB)	81,0	82,4	18,1	61,2	81,8	4,5	68,4	56,8
STI	0,58	0,60	1,00	0,86	0,60	0,95	0,76	0,72

A dimension change in one direction of the form envelope is compared by Soundscape 01 and Soundscape 02. Nevertheless, it did not show a significant difference in the acoustic parameters. Reverberation time (T30) was slightly longer in Soundscape 03 (Long Rectangle Room, 10% Absorption) compared to Soundscape 01 (Small Rectangle Room, 10% Absorption). The difference caused by changing the room envelope form to an L-Shape is more significant for all parameters except SPL and LG80, which affects the Listener Envelopment (LEV). (Beranek, 2010) Reverberation Time was significantly lower in L-shaped soundscapes compared to long rectangle rooms with the same material selection.

LF80 is affected by the room envelope form and the reverberation time. L-shaped rooms have significantly higher LF80 values than long rectangle rooms with the same material selection. Since LF80 is related to Apparent Source Width (ASW) (Beranek, 2010), it is expected to cause more significant errors in source localization due to the blurring of the sound source location and the overestimation of the distances.

The virtual spaces that have lower LF80 and LG80 values are expected to be perceived as less reverberant and spacious. Therefore, it is expected that the guessed room sizes would be overestimated for higher LF80 and LG80 values. Six participants (Participants 01, 03, 05, 09, 12, 14) experienced the same room geometry for both 10% absorbent and %90 absorbent material selections in Odeon environment. % 66,66 of these participants' guessed sqm of the room size for 90% absorbent material was lower than their guesses for 10% absorbent material. The results align with the expectations. However, the percentage is not enough to prove a direct relation.

The values for room acoustic parameters for each soundscape are compared with the mean results of the listening tests with correlation analysis. The soundscapes that are designed with the same form envelope and material selection but different design methods are compared, aiming to understand the perception of acoustic parameters in the two soundscape design methods.

Table 5-2 Pearson Correlation Analysis Between the Listening Test Results and Room Acoustic Parameters

	EDT (s)	T30 (s)	SPL (dB)	C80 (dB)	D50	Ts (ms)	LF80	SPL(A) (dB)	LG80* (dB)	STI
AM Source Localization Error Odeon (m)	-0,07	-0,15	0,12	0,02	0,00	0,02	0,26	0,09	0,05	0,06
AM Source Localization Error Unity VR (m)	0,60	0,55	0,19	-0,25	-0,37	0,44	0,08	0,17	0,24	-0,48
AM Self Localization Error (m) Odeon	-0,47	-0,47	-0,70	0,35	0,33	-0,34	0,01	-0,71	-0,46	0,36
AM Self Localization Error (m) Unity VR	0,04	0,16	0,26	-0,31	-0,06	0,01	-0,16	0,28	0,32	-0,15
AM Self Consistency Error (m) Odeon	-0,10	0,03	0,05	-0,17	0,14	-0,05	0,51	0,04	0,15	0,00
AM Self Consistency Error (m) Unity Unity VR	0,08	0,22	0,25	#NA	0,08	-0,08	-0,32	0,27	0,22	-0,09
AM Guessed Distance Error (m) Odeon	-0,11	0,02	0,03	-0,17	0,15	-0,05	0,52	0,02	0,14	0,01
AM Guessed Distance Error (m) Unity VR	0,07	0,22	0,28	-0,21	0,08	-0,09	-0,34	0,30	0,24	-0,09
AM Localized Distance Error (m) Odeon	-0,48	-0,49	-0,60	0,43	#NA	-0,43	-0,35	-0,59	-0,51	0,43
AM Localized Distance Error (m) Unity VR	-0,16	-0,03	0,12	-0,16	0,15	-0,19	-0,30	0,15	0,17	#NA

The results showed that, in Odeon environment, Absolute Mean Source Localization Error (m) did not show a significant correlation with any of the acoustic parameters studied. The highest correlation is with LF80 (R = 0,26), which could indicate the effect of ASW in Odeon environment. Unlike Odeon, the Absolute Mean Source Localization Error (m) showed a positive correlation with EDT (R = 0,60), T30 (R = 0,55), and Ts (R = 0,44). Source Localization Error in Unity VR also showed a slight positive correlation with LG80 (R = 0,24). An increase in reverberation time is perceivable in Unity VR environment and it increases the source localization error. Therefore, the effect of LEV is present in source localization errors in Unity VR environment.

Absolute Mean Self localization Error (m) in Odeon environment showed a negative correlation to EDT (R = -0,47), T30 (R = -0,47), SPL (R = -0,70), LG80 (R = -0,46). An increase in reverberation time is perceivable in Odeon and it decreases the self-localization error. Therefore, the effect of LEV is present in self-localization in Odeon environment. In contrast, in Unity VR environment these correlations do not exist for self-localization errors. There are slightly positive correlations to SPL (R = 0,28) and LG80 (R = 0,32), which shows an opposite relation with Odeon Environment. Therefore, the perception of listener envelopment LEV is significantly different in the two soundscape environments. The source localization and self-localization are also differently affected by LEV.

Absolute Mean Self Consistency (m) in Odeon environment showed a correlation with only one parameter LF80 (R= 0,51), similar to the Absolute Mean Source Localization, which could indicate the effect of ASW in Odeon. In Unity VR environment, there is a slight positive correlation between Absolute Mean Self Consistency (m) with T30 (R= 0,22), SPL (R = 0,25), and LG80 (R = 0,22) and a negative correlation with LF80 (R = -0,32). These results suggest an opposite relation with Odeon Environment. Therefore, the perception of ASW is significantly different in the two soundscape environments.

Absolute Mean Guessed Distance (m) in Odeon environment showed a correlation with only one parameter LF80 (R= 0,52), similar to the results of the source localization and self-consistency dimensions. These results strengthen the effect of ASW in Odeon environment. Unlike Odeon, In Unity VR environment, there is a slight positive correlation between Absolute Mean Guessed Distance (m) with T30 (R= 0,22), SPL (R = 0,28), LG80 (R = 0,24) and a negative correlation with LF80 (R = -0,34), which shows an opposite relation with Odeon Environment. Therefore, the perception of ASW is significantly different in the two soundscape environments.

AM Localized Distance Error (m) in Odeon environment showed negative correlations to EDT (R = -0,48), T30 (R = -0,49), SPL (R = -0,60), Ts (R= -0,43), LF80 (R= -0,35), and LG80 (R = -0,51). Whereas in Unity VR the only existing relation between the AM Localized Distance Error (m) and acoustic parameters is with LF80 (R=-0,30).

ASW in Odeon environment showed positive correlations with error rates in source localization, self-consistency, and guessed distance and no relation with self-localization. In Unity VR, it showed negative correlations with errors in self-consistency and guessed distance. ASW did not show any correlation with source localization and self-localization in Unity VR environment. Lastly, ASW showed negative correlations with errors in the localized distances in both environments.

LEV in Odeon environment did not show any relation with errors of source localization, self-consistency, and guessed distance and showed negative correlations with errors of self-localization and localized distance. However, in Unity VR, LEV showed positive correlations with the errors of source localization, self-localization, self-consistency, and guessed distance and no relation to errors of localized distance.

In conclusion, ASW are perceivable in both soundscape design methods. However, they are perceived differently and have opposite effects on error rates of the listening test. The errors are expected to correlate positively with ASW values. The perception of ASW in Odeon environment is in line with the expectations but not in Unity VR, therefore, the perception of ASW in immersive environment is not accurate. LEV also have opposite correlations in two environment for self-localization dimension. As a result, the reliability of accurate perception of LEV is questionable in Unity VR.

5.2 Discussion of Case Study Results

The Case Study experiment collected the durations of each session in addition to the previous experiment dimensions. Mean First Soundwalk Duration and Mean Mind Map Drawing Duration are lower in the Odeon environment compared to the Unity VR environment in both groups. However, the effect of the soundscape design method was statistically not significant. ($\sigma = 0{,}067 > 0{,}05$ and $\sigma = 0{,}381 > 0{,}05$) Mean Second Soundwalk Duration is higher in the Unity VR environment compared to the Odeon environment for Group 01, whereas it is opposite for the Group 2. There is no significant statistical relation found for this dimension with both the environment and the experience order. Mean Route & Source Location Duration is higher in the Unity VR environment compared to Odeon for both of the groups. In addition, the Mean Route & Source Location Duration of Group 01 is higher than Group 02. The results are backed by the statistical analysis which shows that this dimension is statistically related to both the soundscape design method ($\sigma < 0{,}01$) and the experience order ($\sigma = 0{,}023 < 0{,}05$). Viaud-Delmon and Warusfel showed that the mean time of localization of a target sound source decreases with the increased trial numbers. (2014) In the current study, the participants have lower mean time spent in both environments if they experienced the immersive environment first. As a result, it can be said that using an immersive environment is more efficient compared to a simulated environment for source localization training. The results also showed that Mean Duration for Each Point in the Unity VR environment is also higher compared to Odeon for both of the groups. The relationship between Mean Duration for Each Point and the soundscape design method is proved by the statistical analysis as well ($\sigma = 0{,}009 < 0{,}05$). Therefore, it can be said that participants tend to spend more time transferring DATA from their experience in an immersive virtual soundscape to a plan diagram, compared to an experience in a simulated virtual soundscape.

However, there is no evidence that the duration of the soundwalks or mind map drawings is related to the soundscape design method or experience order. The reason could be that there are more DATA to process in an immersive soundscape environment since both visual and auditory senses are involved in the soundwalk process. The results showed that the mean time participants take for locating randomly asked points in both soundscape design methods was higher in Group 1, which experienced the simulated method first. The order of experiencing the methods affects the mean time participants took for each point. ($\sigma < 0{,}01$) This result is in contrast with the time spent on the source and route localization. The reason could be that the participants become biased when the movement is not on a route but asked randomly. However, the experience order only affected the time spent, not the accuracy of the location or distance guess.

The results of the Description of Direction and Movement revealed that there are higher numbers of accurate descriptions of movement and sound source direction in the immersive method compared to the simulated method.

The mean room size error is lower in the Unity VR environment compared to the Odeon environment in both of the groups. Nevertheless, no statistical relations were found between the perceived room size with both the design method and experience order. In both of the groups, the participants' mean route length error and mean route shape error is lower in the Unity VR environment compared to the Odeon environment in both groups. The relationship between the soundscape design method with the route length error ($\sigma = 0{,}056 \sim 0{,}005$) and route shape error ($\sigma = 0{,}058 \sim 0{,}005$) is also proved by statistical analysis. These results can be indicated as the success of the participants in understanding the movement route in an immersive virtual space is higher compared to a simulated environment.

There is a common problem in case study experiments that is not observed in the first experiments. The visual analysis showed that three of the nine participants (Participant 01, 04, 06) plan drawings included a ninety-degree rotated version of the nearly accurate source localization and soundwalk route for the Unity VR method, the accuracy is strengthened by the placement of furniture as well. Therefore the numerical data analysis gave poor results for understanding the accuracy of listening tests in case study experiments, unlike the previous trials. The reason for these results could be about the boundaries of the virtual space since the ratio of the short edge of the room to the long edge (0,82) is not as significant as the previous rectangle spaces (0,6 for Small Rectangle Room, 0,4 for Long Rectangle Room).

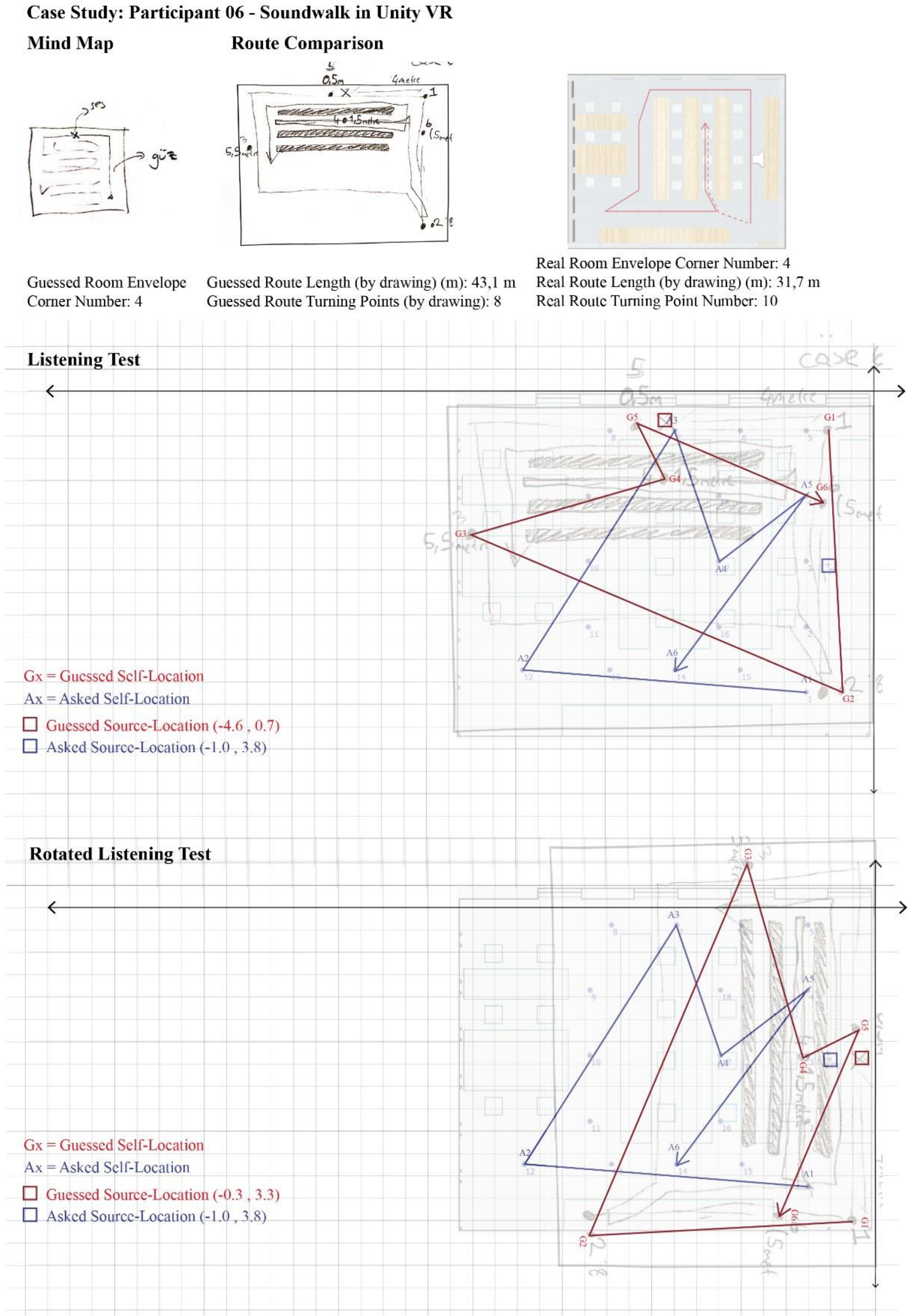


Figure 5-29 Visual Analysis of the Listening Test showing the rotation problem (Case Study Participant 06)

The relationship between the physical space and the virtual space was not one of the subjects mentioned in the questionnaire or interview aiming to prevent biasing the participants. However, if the participants mentioned their discovery orally they were encouraged to write it in their soundscape evaluation forms. Five of the participants (Participants 02, 04, 06, 08, 09) noticed that the virtual space in Unity VR environment was the virtual version of the space that they were in. Participants 02 and 06 are people who regularly spent time in METU DDS, which could be the reason for making it easier for them to recognize the relationship. Participants 06, 08, and 09 are people who visited the physical space only once before for the previous comparison trial experiment. Participant 04 recognized the relationship even though it was the first time she visited the physical space. None of the participants noticed that the space they experienced in Odeon environment is the virtual version of the physical space they experienced. Four of the nine participants (Participants 01, 03, 05, 07) did not notice the relationship between the physical and the virtual spaces in none of the environments. Only one of the participants (Participant 05) noticed the relationship between the two virtual environments.

Table 5-3 Noticed Relationships between Physical and Virtual Spaces

		Noticed Relationships		
Participants	**Familiarity with Physical Space**	**Physical Space - Odeon**	**Physical Space – Unity VR**	**Odeon – Unity VR**
P 01	*First Time*			
P 02	*Regular User*		**x**	
P 03	*Second Time*			
P 04	*First Time*		**x**	
P 05	*Second Time*			**x**
P 06	*Regular User*		**x**	
P 07	*Second Time*			
P 08	*Second Time*		**x**	
P 09	*Second Time*		**x**	
Total		**0**	**5**	**1**

Results of the soundscape evaluation questionnaires show that Odeon environment is perceived as more loud and unpleasant compared to Unity VR environment. The perceived appropriateness is higher in Unity VR environment than Odeon environment, and participants are more eager to experience the Unity VR environment. In open-ended questions part for source description, thoughts and feelings, four (Participants 02, 03, 07, 08) of the nine participants mentioned spatial qualities of the virtual spaces. Four (Participants 01, 03, 06, 09) of them talked about their movement or route. Five (Participants 01, 04, 05, 06, 09) of them mentioned experiment settings.

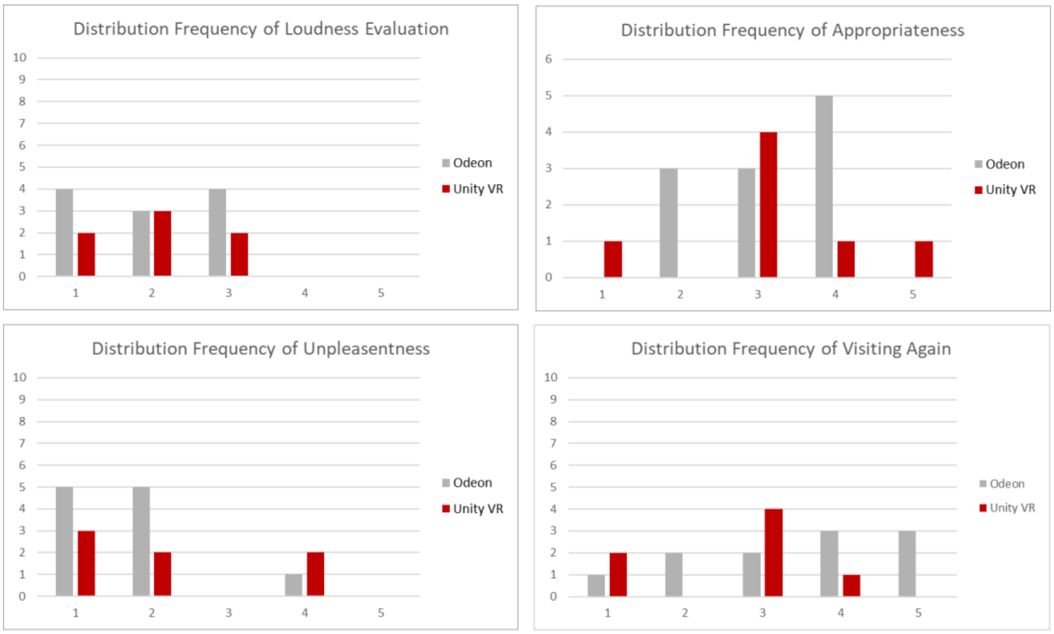


Figure 5-30 Soundwalk Experience Distribution Results in Odeon Environment and Unity VR Environment based on ISO 12913-2018 Method B – Likert Scale

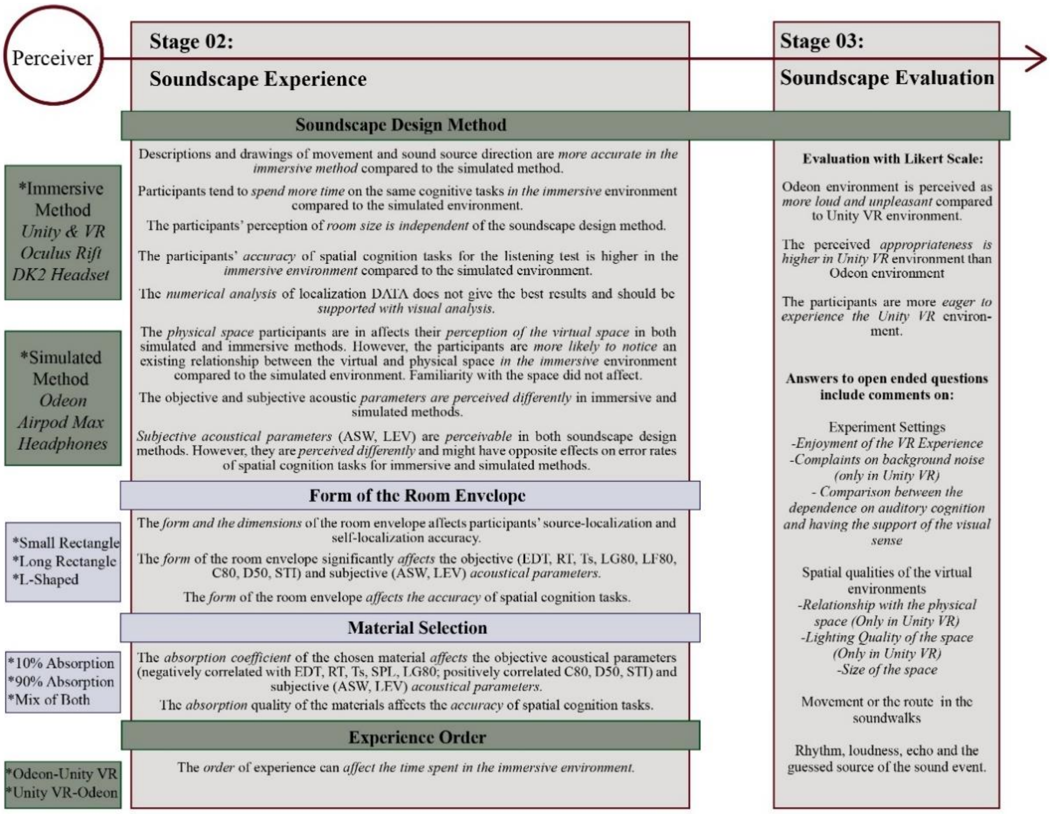


Figure 5-31 Overall Observations

CHAPTER 6

CONCLUSION

6.1 Summary

The study emerged to make a contribution to the literature on the improvement of the auditory perception of virtual spaces by integrating acoustical simulations with the immersive environment and questioning the user experience in auditory simulation environments. The author proposes to combine the design, cognition, and perception of virtual environments with Shafer's soundscape idea and compare the effects of acoustically simulated and immersive virtual soundscape design methods on auditory perception through changing forms and materials.

A literature review is conducted for exploring both virtual environments and their experienced qualities as well as the research on soundscapes aiming to understand how two concepts are related to each other in previous research. It has been revealed that there is an increasing interest in auditory spatial cognition in virtual environments however these studies were not studied from the perspective of soundscape and the reliability of the used methods for auditory experience was questionable. According to existing studies, two types of possible virtual soundscape design methods are detected, which are acoustic simulators and gaming engines combined with virtual reality. One of the main lacking points in the studies that used one or both of the methods was the undeniable difference between the perception of these two methods. Acoustic simulators provide an accurate soundscape simulation backed with calculations of objective and subjective parameters of the room, whereas the gaming engines with VR provide an immersive first-person view experience. There is a research gap in the reliable integration of both methods in soundscape studies. From this standing point, an experiment process is designed to compare two different methods of virtual soundscape design, the simulation method, and the immersive method, by means of spatial cognition and relations with the indoor acoustic parameters.

The experiment process included two series of experiments designed to compare and understand the effects of acoustically simulated and immersive virtual soundscape design methods on auditory perception. A soundwalk combined with an interview, followed by a listening test and a soundscape evaluation questionnaire. Two soundscape design methods are tested with 20 participants including 59 soundwalks in total. For the experiment, fifteen different soundscapes are designed with the combinations of three parameters such as two soundscape design methods, three room envelope form options, and four material selection options according to different absorption coefficients.

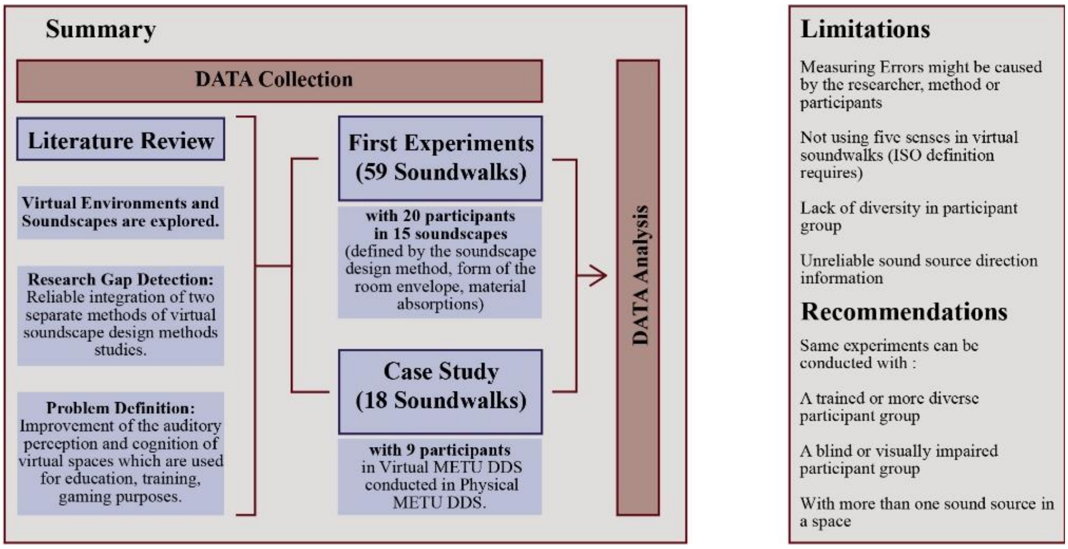


Figure 6-1 Summary

Aiming to test the reliability of the first experiments a case study experiment is also conducted. The physical space where experiments take place is virtually recreated with both soundscape design methods and compared similarly to the previous experiments to provide a familiar virtual space to the participants. The overall experiment results suggested that the participants achieve more accurate results of source localization, self-localization, and distance guessing in an immersive environment than in the simulated environment. In addition, they were more aware of the soundwalk route, spent more time on tasks, and evaluated the soundscape experience more positively in an immersive environment compared to simulations. Even though Odeon provides a realistic auralization of the soundscape, it is not perceived by the participants accurately without having visual information except the plan diagram. The reason could be that the participants are used to combining information provided by different senses together for spatial cognition, and lack of visual sense for the first time affected their perception negatively. The physical space participants are in also affected their perception of the virtual space in both simulated and immersive methods. However, the participants are more likely to notice an existing relationship between the virtual and physical space in the immersive environment compared to the simulated environment. Despite the placement of the furthest point auralizations by the simulation software as sound sources in tested immersive environments and resulting in more accurate answers for the cognitive tasks, there is still a lack of auditory representation of spatial qualities compared to the accurate calculation of acoustical parameters in a simulated environment. Due to accurate auralizations, an acoustic simulator could still be a great tool for professional use in designing and navigating blind or visually impaired people. Nevertheless, it does not offer a preferable context for collecting user input about the design spaces. Providing a first-person viewpoint of the space, an immersive environment is revealed to be a better environment for source-localization and self-localization even though the participants do not see the sound source itself. Supporting the positive effect of visual sense on spatial cognition, some of the participants reported that they have a hard time imagining their movement in space when they have no visual information and perceived the sound source as the moving object instead of themselves. Another factor that might add to the result could be the advantage of using head movements thanks to the VR headset, which is not caused by the relation of the two senses, but by the perception of the direction of a sound source from all angles.

Therefore, immersive environments have the potential to provide a better environment for virtual soundscapes by means of user experience and cognitive accuracy compared to simulated environments. However, there is still room for development in terms of realistic auditory spatial representation and requiring a less computational cost.

6.2 Limitations and Future Recommendatitons

The main limitation of the study is the possibility of measurement errors due to researcher or participant mistakes. Since the study includes experiments that collect different types of DATA and strongly rely on the subjective perception of the individuals, there is a risk of losing or misrepresenting the results through the transformation of DATA types into each other. For instance, it is revealed that the geometry of the virtual space affects the precision of the DATA analysis. The numerical analysis of localization DATA does not give the best results for all virtual spaces and should be supported with visual analysis. Another example is, the unreliable results for the sound source direction due to participants' confusion while answering. Another example could be technical errors while screen recording, which resulted in missing information on the head movements in Unity VR.

The second limitation is the lack of diversity in the participant group. The group included a wide range of ages. However, it was not diverse enough for testing the effects of training. Since the previous literature showed that (Battal et al., 2020) auditory cognition could be developed by practice, it would be beneficial to observe the results of regularly trained individuals on auditory perception, professionally experienced people on acoustics, as well as a blind or visually impaired group of participants with both soundscape design methods. The inclusion of people who do not rely on visual sense would be beneficial for the development of more inclusive immersive virtual environments. Therefore, more reliable results can be achieved by increasing the number of soundwalks and gathering data from a larger group of participants.

The last limitation is due to the definition of the measuring method. According to ISO 12913-2-2018, a soundwalk must include the use of all senses. (2018) However, the virtual soundwalks conducted for this study only make use of auditory and visual senses partially due to the nature of the experiment aim and the equipment used. Also, all the soundscapes designed for this study include one sound event only. Therefore the effect of the background sounds or the relationship between separate sound events is not in the scope of this study. For future research, it would be beneficial to include different numbers and types of sound sources in one soundscape. In addition, more geometrical forms and material combinations should be tested with immersive and simulated design methods for reaching a trusted soundscape design method for a variety of spaces.

In conclusion, immersive environments have the potential to provide realistic virtual soundscapes utilizing user experience compared to simulated environments. To achieve a successful experience, virtual environments must represent spatial qualities accurately and offer a clear, real-time auditory experience to users. The representation of spatial sound and auditory qualities of virtual spaces should be studied in more detail, for providing a reliable solution for future research and applications in fields like gaming, cognitive training, education purposes, user perception-based spatial design, and universal design.

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APPENDICES

A. Room Acoustic Parameters and Decay Curves of the Soundscapes created in Odeon

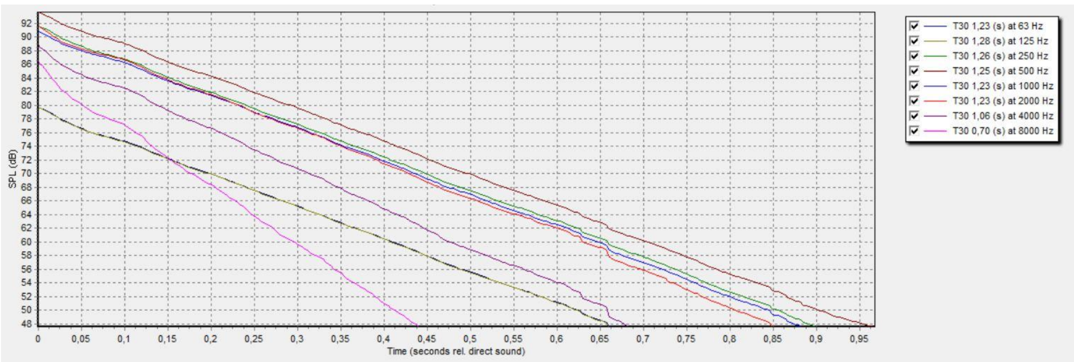


Figure 7-1 Soundscape 02 Decay Curves (Long Rectangle Room - 10% Absorption)

Table 7-1 Soundscape 02 Room Acoustic Parameters (from the grid in the furthest row) (Long Rectangle Room %10 Absorption)

Soundscape 02 -Long Rectangle Room %10 Absorption								
Receiver Number: 24 Receiver1		(x,y,z) = (3,50, ,13,50, 1,00)						
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	1,22	1,31	1,29	1,27	1,32	1,23	1,12	0,71
T30 (s)	1,23	1,28	1,26	1,25	1,23	1,23	1,06	0,7
SPL (dB)	79,6	79,6	91,6	93,7	90,9	91,8	88,9	86,5
C80 (dB)	2,2	2,3	2,1	1,7	1,8	2,6	4,3	7,8
D50	0,51	0,51	0,5	0,48	0,49	0,56	0,64	0,78
Ts (ms)	84	84	84	87	85	75	59	36
LF80	0,278	0,277	0,272	0,276	0,266	0,244	0,224	0,212
SPL(A) = 97,7(dB)								
LG80* = 82,4(dB)								
STI = 0,60 (Theoretical based on T30, STI = 0,56)								

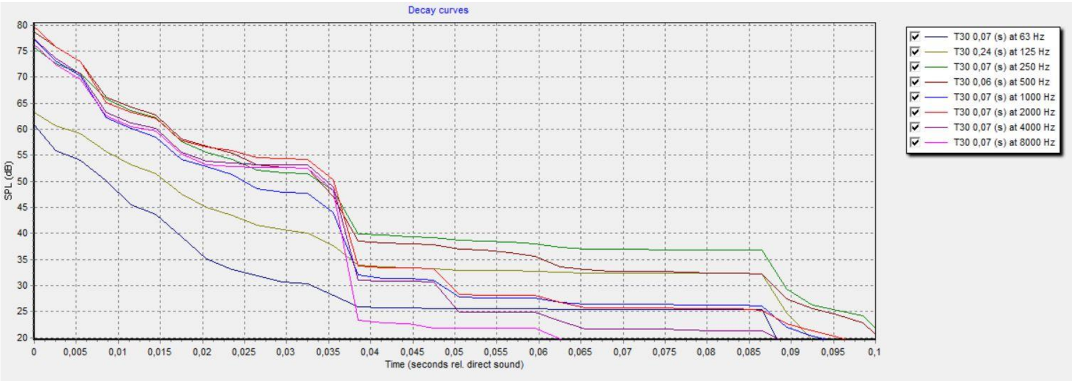


Figure 7-2 Soundscape 03 Decay Curves (Long Rectangle Room - 90% Absorption)

Table 7-2 Soundscape 03 Room Acoustic Parameters (from the grid in the furthest row) (Long Rectangle Room %90 Absorption)

Soundscape 03 -Long Rectangle Room %90 Absorption								
Receiver Number: 24 Receiver1 (x,y,z) = (3,50, -13,50, 1,00)								
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	0,05	0,07	0,05	0,05	0,04	0,04	0,04	0,04
T30 (s)	0,07	0,24	0,07	0,06	0,07	0,07	0,07	0,07
SPL (dB)	61,8	63,7	76,3	79,3	78,1	80,5	78,1	77
C80 (dB)	38	32,7	40,8	47,8	52,9	55,6	57,3	59,8
D50	1	1	1	1	1	1	1	1
Ts (ms)	2	3	3	2	2	2	2	2
LF80	0,031	0,065	0,049	0,033	0,02	0,024	0,028	0,03
SPL(A) = 85,8(dB)								
LG80* = 18,1(dB)								
STI = 1,00 (Theoretical based on T30, STI = 0,97)								

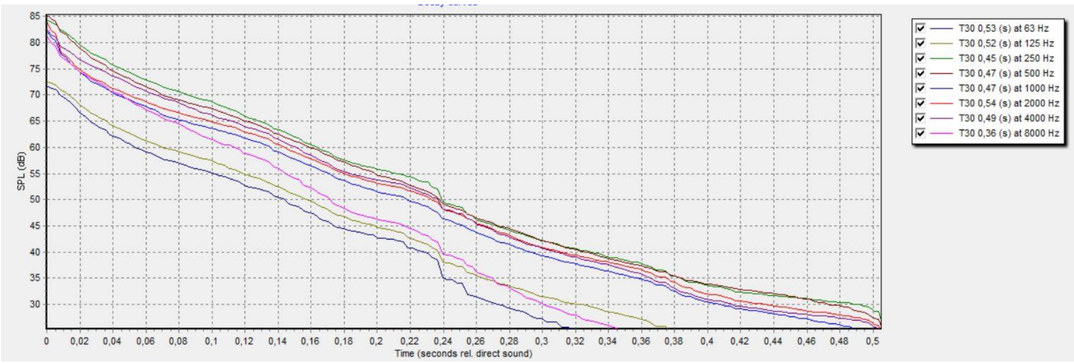


Figure 7-3 Soundscape 04 Decay Curves (Long Rectangle Room - Mixed Absorption)

Table 7-3 Soundscape 04 Room Acoustic Parameters (from the grid in the furthest row) (Long Rectangle Room Mixed Absorption)

Soundscape 04 -Long Rectangle Room Mixed Absorption								
Receiver Number: 24 Receiver1 (x,y,z) = (3,50, -13,50, 1,00)								
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	0,26	0,31	0,3	0,22	0,16	0,14	0,27	0,22
T30 (s)	0,53	0,52	0,45	0,47	0,47	0,54	0,49	0,36
SPL (dB)	71,7	72,5	84,3	85,4	82,6	84,2	83	81,5
C80 (dB)	14,7	13,3	13,7	16,4	17,4	17,7	14,5	17,2
D50	0,92	0,9	0,9	0,94	0,96	0,96	0,92	0,95
Ts (ms)	19	22	20	14	11	9	16	12
LF80	0,176	0,18	0,163	0,129	0,094	0,091	0,116	0,112
SPL(A) = 90,4(dB)								
LG80* = 61,2(dB)								
STI = 0,86 (Theoretical based on T30, STI = 0,75)								

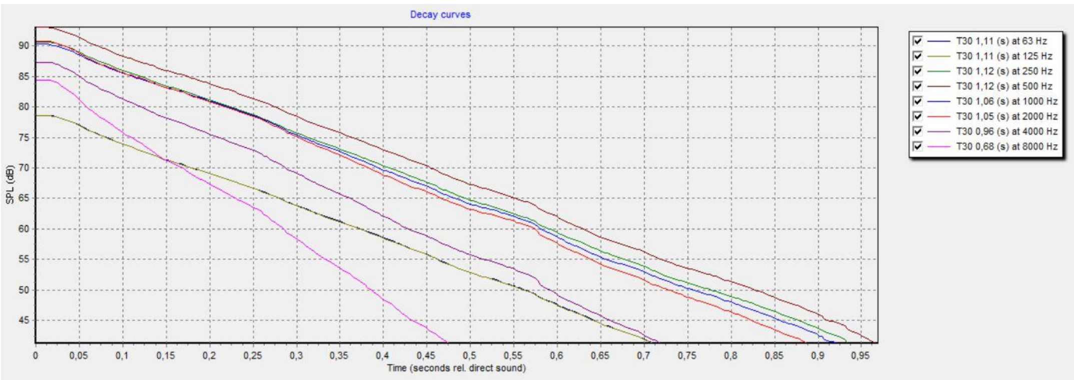


Figure 7-4 Soundscape 08 Decay Curves (L-Shaped Room - 10% Absorption)

Table 7-4 Soundscape 08 Room Acoustic Parameters (from the grid in the furthest row) (L-Shaped Room 10% Absorption)

Soundscape 08 - L-Shaped Room 10% Absorption								
Receiver Number: 23 L7	(x,y,z) = (-5,50, -9,00, 1,00)							
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	1,11	1,12	1,16	1,22	1,22	1,07	0,89	0,65
T30 (s)	1,11	1,11	1,12	1,12	1,06	1,05	0,96	0,68
SPL (dB)	78,6	78,6	90,6	93,1	90,3	90,8	87,3	84,4
C80 (dB)	1,2	1,2	1,2	1,3	1,4	2,1	3,1	5,8
D50	0,32	0,33	0,33	0,34	0,34	0,38	0,43	0,54
Ts (ms)	97	97	98	97	97	91	79	60
LF80	0,358	0,36	0,372	0,377	0,375	0,375	0,365	0,366
SPL(A) = 96,7(dB)								
LG80* = 81,8(dB)								
STI = 0,60 (Theoretical based on T30, STI = 0,59)								

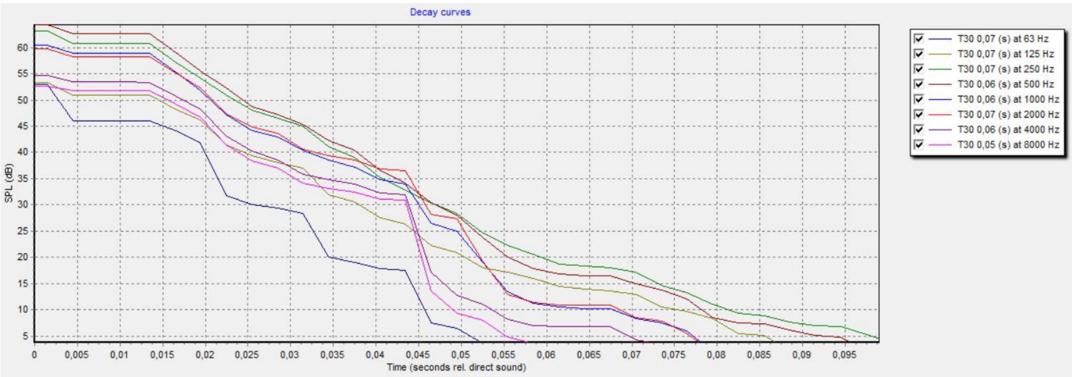


Figure 7-5 Soundscape 09 Decay Curves (L-Shaped Room - 90% Absorption)

Table 7-5 Soundscape 09 Room Acoustic Parameters (from the grid in the furthest row) (L-Shaped Room 90% Absorption)

Soundscape 09 - L-Shaped Room 90% Absorption								
Receiver Number: 23 L7	(x,y,z) = (-5,50, -9,00, 1,00)							
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	0,1	0,12	0,11	0,11	0,11	0,12	0,12	0,12
T30 (s)	0,07	0,07	0,07	0,06	0,06	0,07	0,06	0,05
SPL (dB)	52,9	53,3	63,2	64,4	60,5	59,8	54,7	52,7
C80 (dB)	56,9	45,2	51,4	53,9	56,3	55,4	54,8	57,2
D50	1	1	1	1	1	1	1	1
Ts (ms)	4	11	10	12	12	12	13	14
LF80	0,034	0,112	0,128	0,147	0,142	0,15	0,168	0,177
SPL(A) = 66,5(dB)								
LG80* = 4,5(dB)								
STI = 0,95 (Theoretical based on T30, STI = 0,99)								

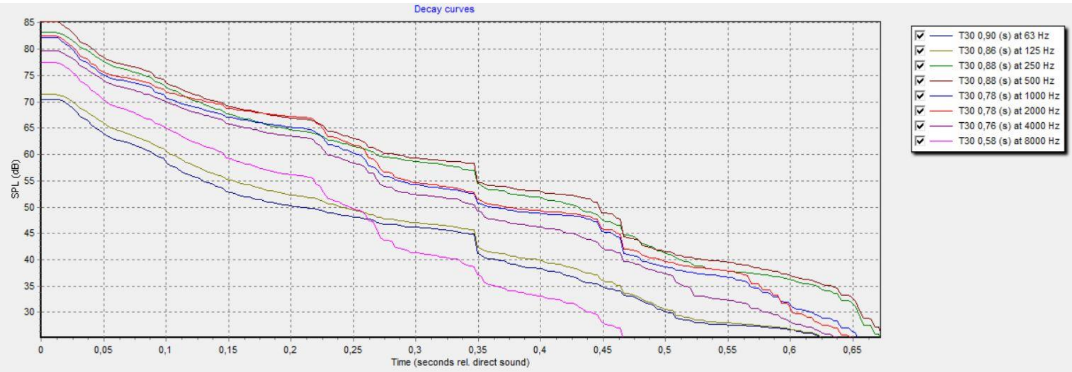


Figure 7-6 Soundscape 10 Decay Curves (L-Shaped Room - Mixed Absorption)

Table 7-6 Soundscape 10 Room Acoustic Parameters (from the grid in the furthest row) (L-Shaped Room Mixed Absorption)

Soundscape 10 - L-Shaped Room Mixed Absorption								
Receiver Number: 23 L7	(x,y,z) = (-5,50, -9,00, 1,00)							
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	0,39	0,49	0,56	0,5	0,53	0,51	0,52	0,39
T30 (s)	0,9	0,86	0,88	0,88	0,78	0,78	0,76	0,58
SPL (dB)	70,5	71,4	83,2	85,2	82,2	82,5	79,7	77,5
C80 (dB)	8,9	8	7,5	8,8	8,7	8,2	7,3	9,9
D50	0,79	0,73	0,73	0,8	0,81	0,8	0,74	0,81

(Table 7-6 continued)

Ts (ms)	41	46	46	41	41	44	48	39
LF80	0,354	0,36	0,382	0,389	0,387	0,399	0,371	0,375
SPL(A) = 88,8(dB)								
LG80* = 68,4(dB)								
STI = 0,76 (Theoretical based on T30, STI = 0,64)								

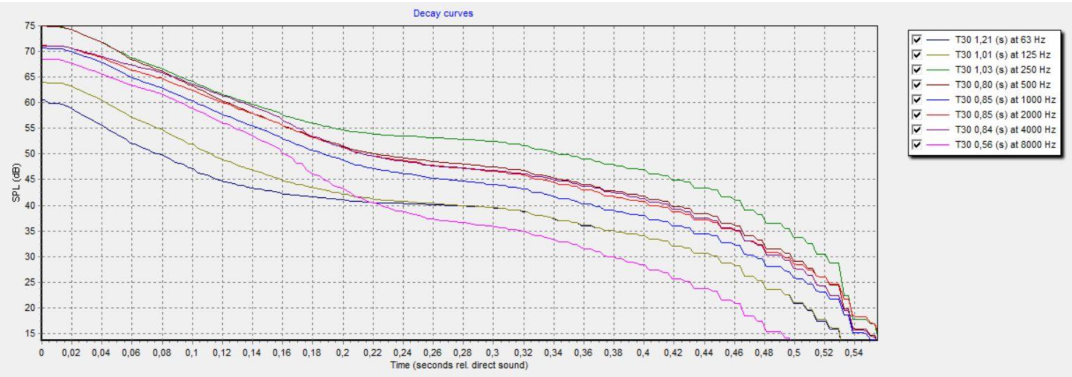
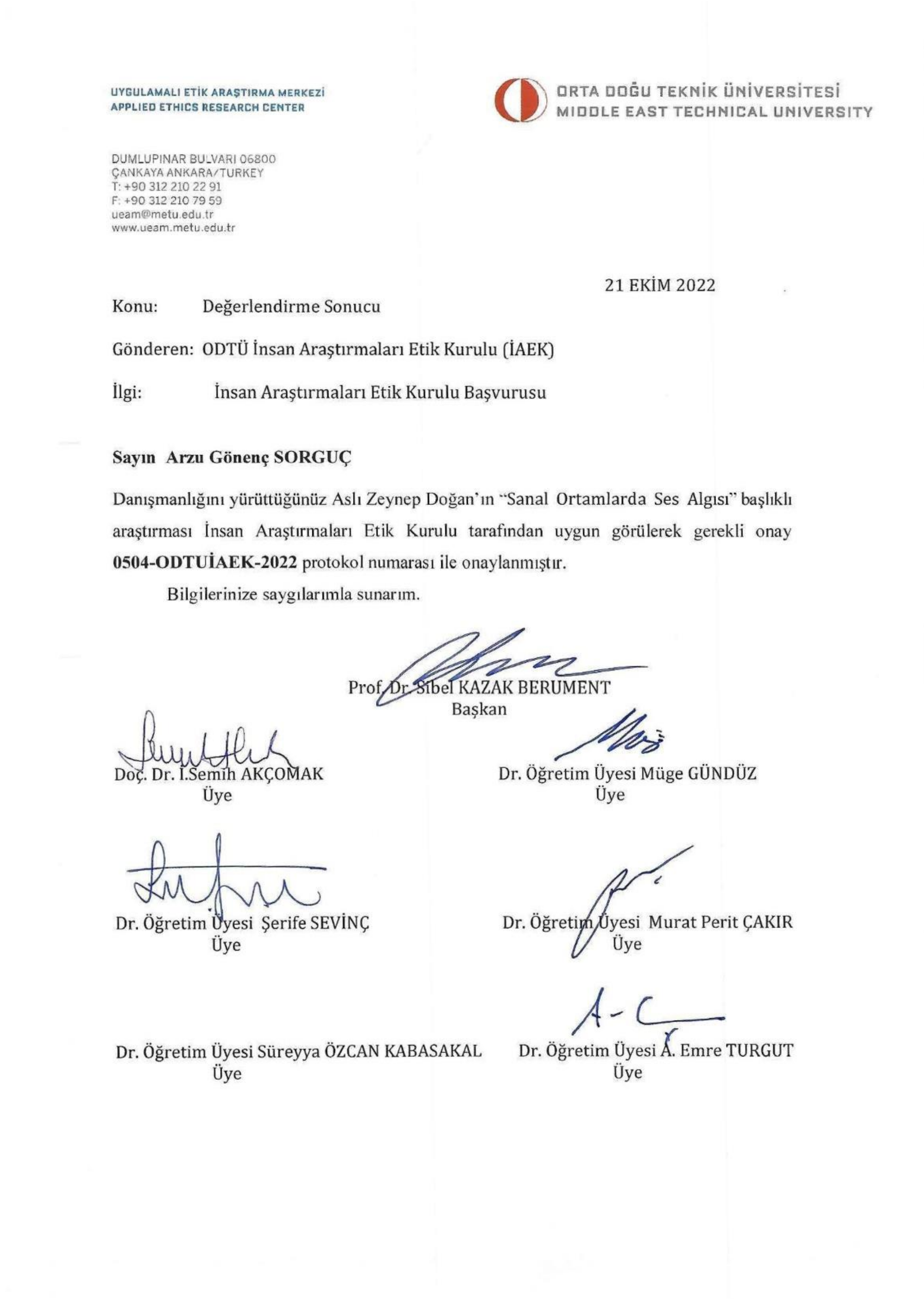


Figure 7-7 Soundscape 15 Decay Curves (L-Shaped Room - Mixed 2 Absorption)

Table 7-7 Soundscape 15 Room Acoustic Parameters (from the grid in the furthest row) (L-Shaped Room Mixed 2 Absorption)

Soundscape 10 - L-Shaped Room Mixed Absorption								
Receiver Number: 23 L7 (x,y,z) = (-5,50, -9,00, 1,00)								
Band (Hz)	63	125	250	500	1000	2000	4000	8000
EDT (s)	0,34	0,41	0,45	0,42	0,48	0,65	0,64	0,56
T30 (s)	1,21	1,01	1,03	0,8	0,85	0,85	0,84	0,56
SPL (dB)	60,5	64	75	75	70,7	71,2	71,1	68,4
C80 (dB)	10,8	9,2	8	8,7	7,5	5,8	4,1	6,1
D50	0,8	0,72	0,68	0,69	0,65	0,59	0,51	0,61
Ts (ms)	36	43	47	44	48	55	62	51
LF80	0,229	0,273	0,278	0,283	0,285	0,288	0,275	0,274
SPL(A) = 78,5(dB)								
LG80* = 56,8(dB)								
STI = 0,72 (Theoretical based on T30, STI = 0,63)								

B. Approval of METU Human Subjects Ethics Committee



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21 EKİM 2022

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Arzu Gönenç SORGUÇ

Danışmanlığını yürüttüğünüz Aslı Zeynep Doğan'ın "Sanal Ortamlarda Ses Algısı" başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek gerekli onay **0504-ODTUİAEK-2022** protokol numarası ile onaylanmıştır.

Bilgilerinize saygılarımla sunarım.

Prof. Dr. Sibel KAZAK BERUMENT
Başkan

Doç. Dr. I.Semih AKÇOMAK
Üye

Dr. Öğretim Üyesi Müge GÜNDÜZ
Üye

Dr. Öğretim Üyesi Şerife SEVİNÇ
Üye

Dr. Öğretim Üyesi Murat Perit ÇAKIR
Üye

Dr. Öğretim Üyesi Süreyya ÖZCAN KABASAKAL
Üye

Dr. Öğretim Üyesi A. Emre TURGUT
Üye

Figure 7-8 B. Approval of METU Human Subjects Ethics Committe

C. Visual Analysis Process of Each Soundwalk of First Experiments

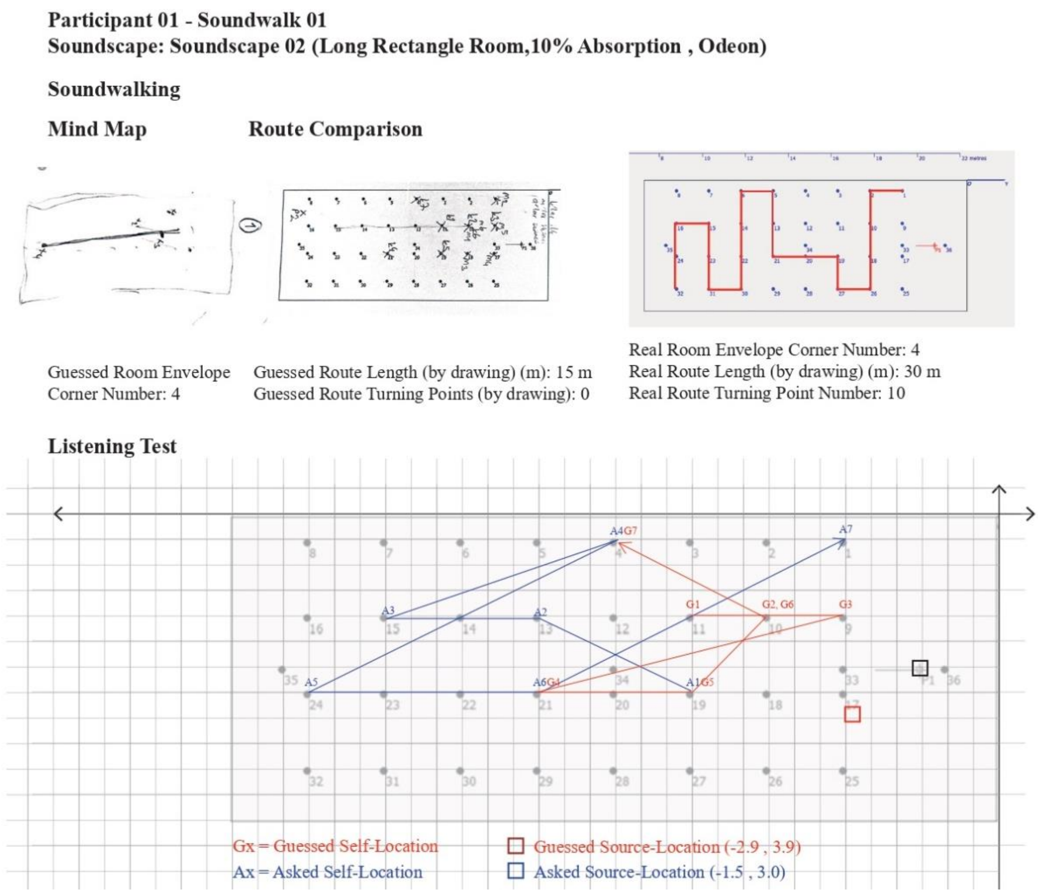
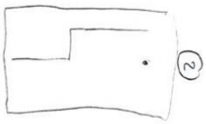


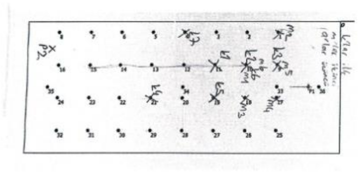
Figure 7-9 First Experiments - Visual Analysis of Soundwalk 01

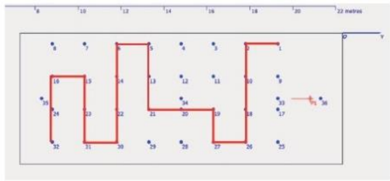
Participant 01 - Soundwalk 02
Soundscape: Soundscape 03 (Long Rectangle Room, 90% Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 15 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

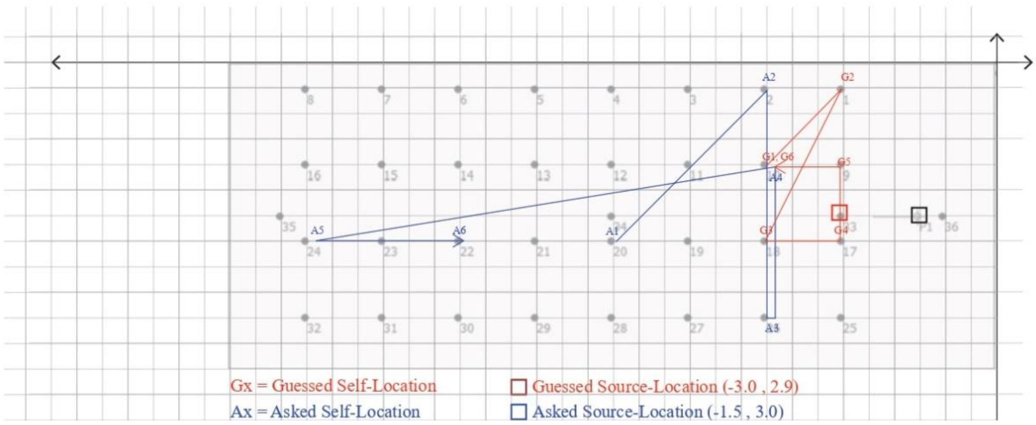
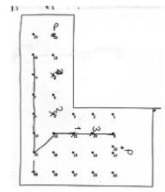


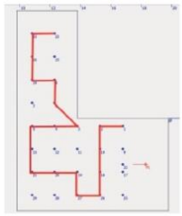
Figure 7-10 First Experiments - Visual Analysis of Soundwalk 02

Participant 01 - Soundwalk 03
Soundscape: Soundscape 05 (L-Shaped Room, 10% Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**





Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): 14,11 m
Guessed Route Turning Points (by drawing): 2

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

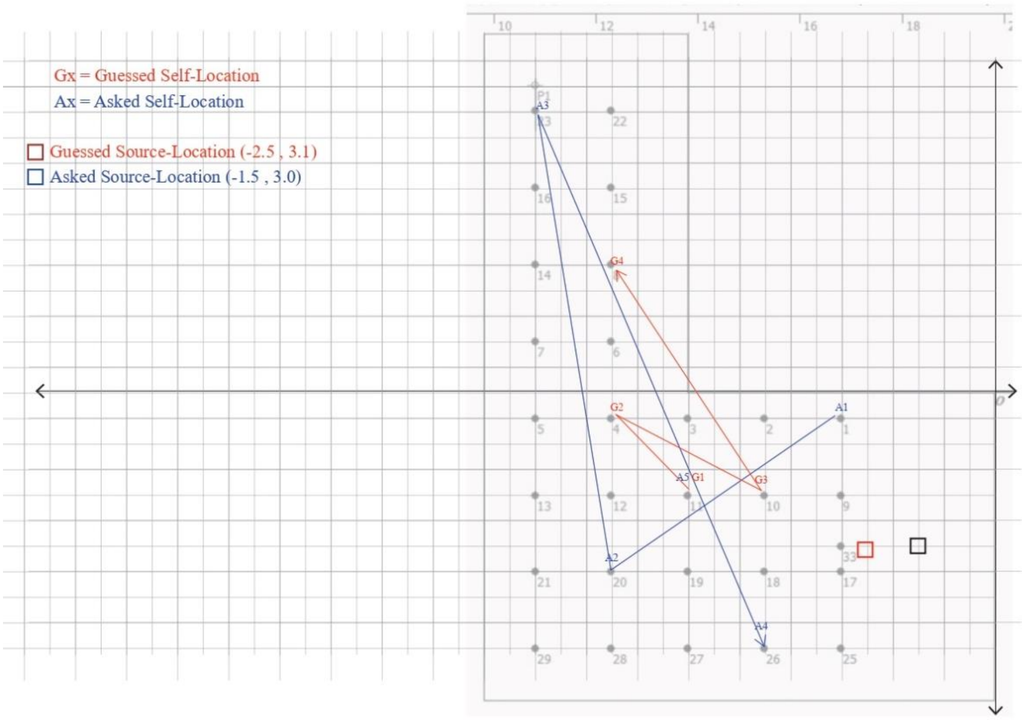
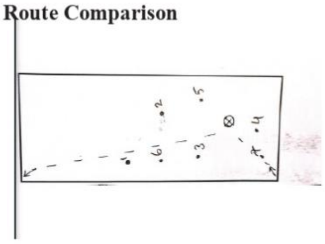


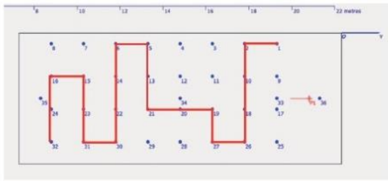
Figure 7-11 First Experiments - Visual Analysis of Soundwalk 03

Participant 02 - Soundwalk 04
Soundscape: Soundscape 03 (Long Rectangle Room, 90% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**





Guessed Room Envelope Corner Number: -

Guessed Route Length (by drawing) (m): 14,5 m
Guessed Route Turning Points (by drawing): 1

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

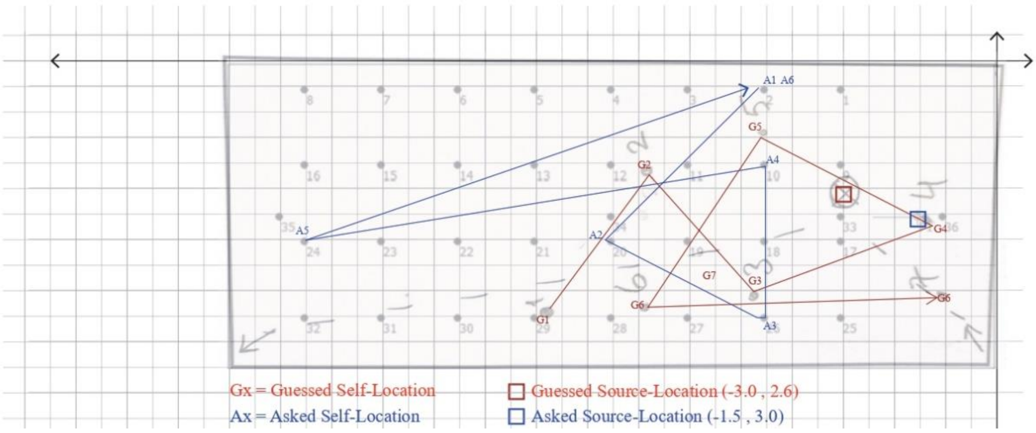
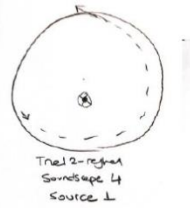
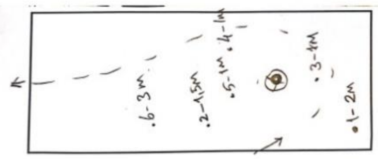
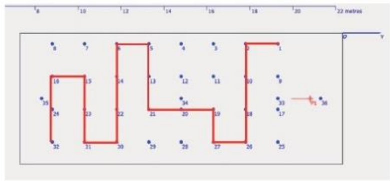


Figure 7-12 First Experiments - Visual Analysis of Soundwalk 04

Participant 02 - Soundwalk 05
Soundscape: Soundscape 04 (Long Rectangle Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map	**Route Comparison**	
		
Guessed Room Envelope Corner Number: -	Guessed Route Length (by drawing) (m): 18,5 m Guessed Route Turning Points (by drawing): 1	Real Room Envelope Corner Number: 4 Real Route Length (by drawing) (m): 30 m Real Route Turning Point Number: 10

Listening Test

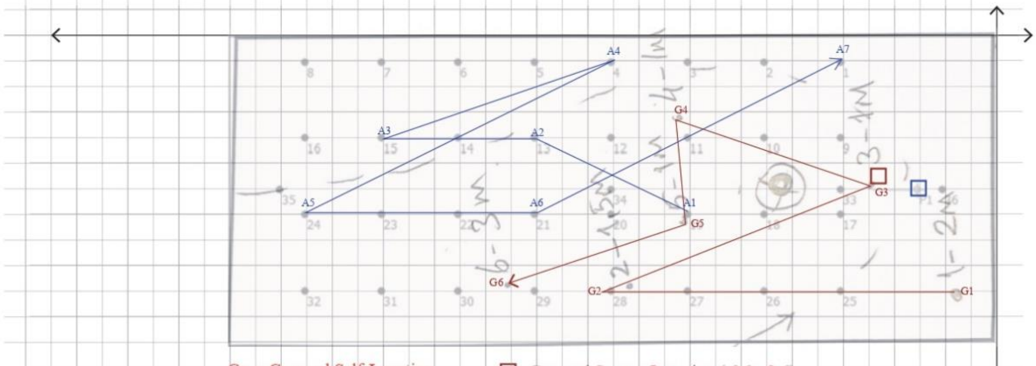
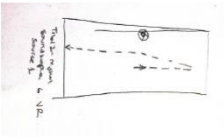


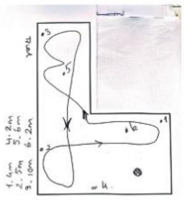
Figure 7-13 First Experiments - Visual Analysis of Soundwalk 05

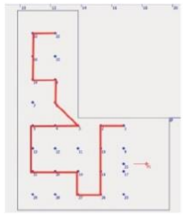
Participant 02 - Soundwalk 06
Soundscape: Soundscape 06 (L-Shaped Room, 90% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 41,2 m
Guessed Route Turning Points (by drawing): 20

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

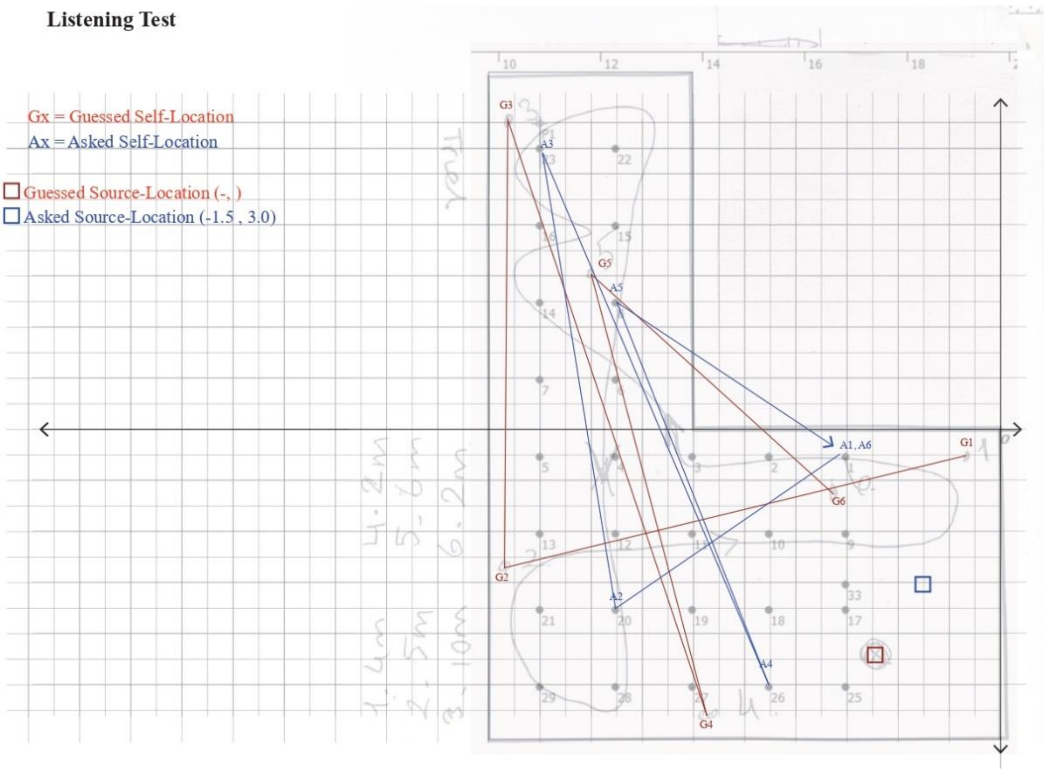
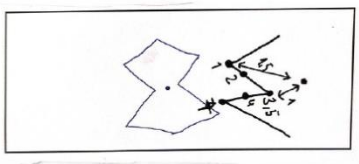


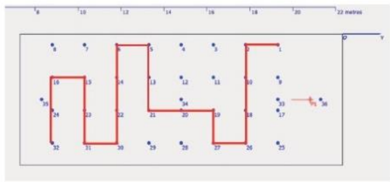
Figure 7-14 First Experiments - Visual Analysis of Soundwalk 06

Participant 03 - Soundwalk 07
Soundscape: Soundscape 02 (Long Rectangle Room, 10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**





Guessed Room Envelope Corner Number: -

Guessed Route Length (by drawing) (m): 10,4 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

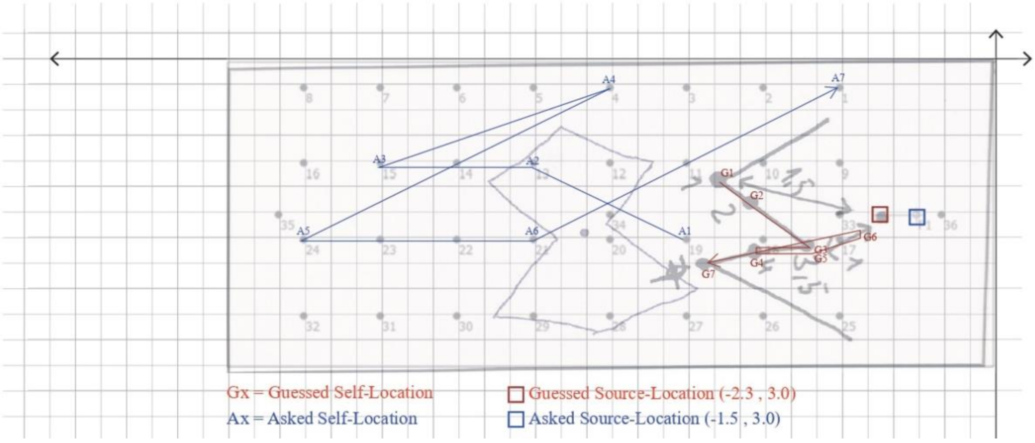
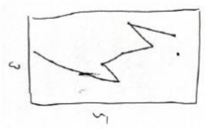


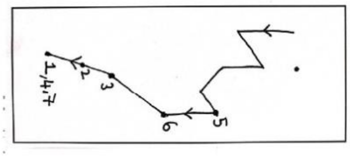
Figure 7-15 First Experiments - Visual Analysis of Soundwalk 07

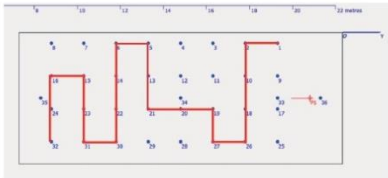
Participant 03 - Soundwalk 08
Soundscape: Soundscape 03 (Long Rectangle Room, 90% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 17 m
Guessed Route Turning Points (by drawing): 7

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

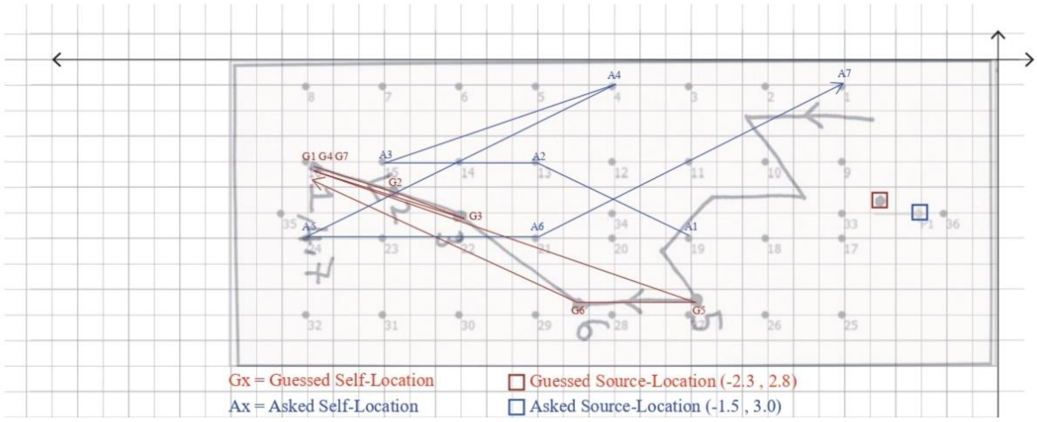
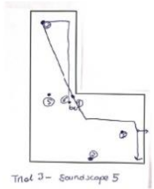


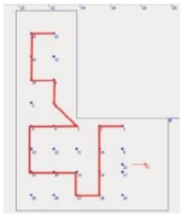
Figure 7-16 First Experiments - Visual Analysis of Soundwalk 08

Participant 03 - Soundwalk 09
Soundscape: Soundscape 05 (L-Shaped Room, 10% Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**





Guessed Room Envelope Corner Number: 7

Guessed Route Length (by drawing) (m): 25,8 m
Guessed Route Turning Points (by drawing): 4

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

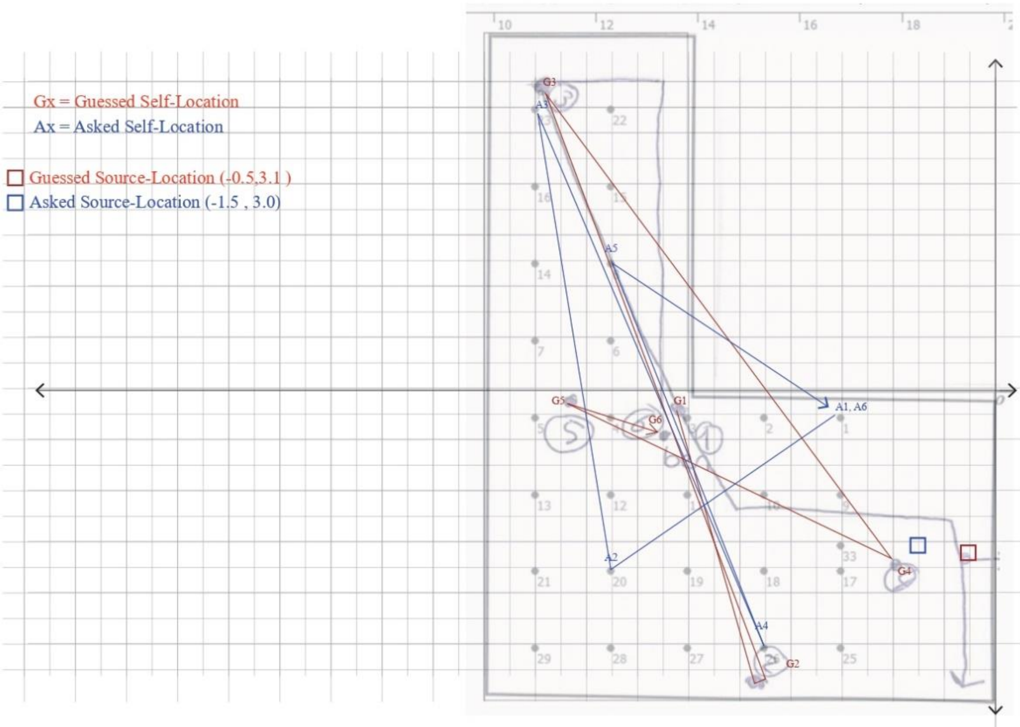
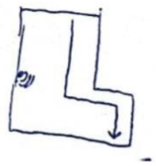


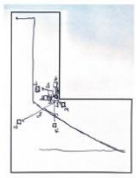
Figure 7-17 First Experiments - Visual Analysis of Soundwalk 09

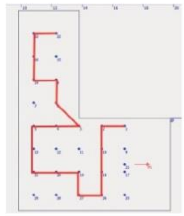
Participant 04 - Soundwalk 10
Soundscape: Soundscape 10 (L-Shaped Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): 22,7 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

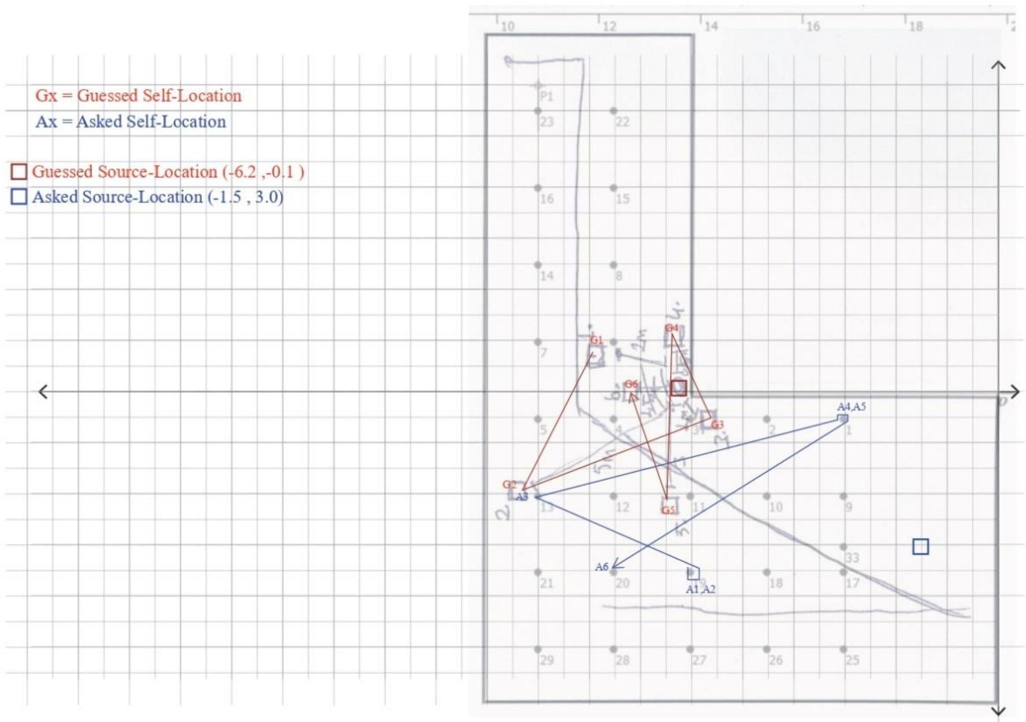
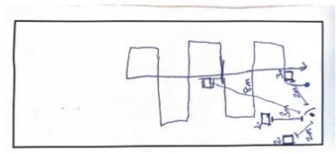


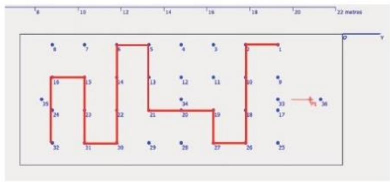
Figure 7-18 First Experiments - Visual Analysis of Soundwalk 10

Participant 04 - Soundwalk 11
Soundscape: Soundscape 14 (Long Rectangle Room, Mixed Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 32,4 m
Guessed Route Turning Points (by drawing): 11

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

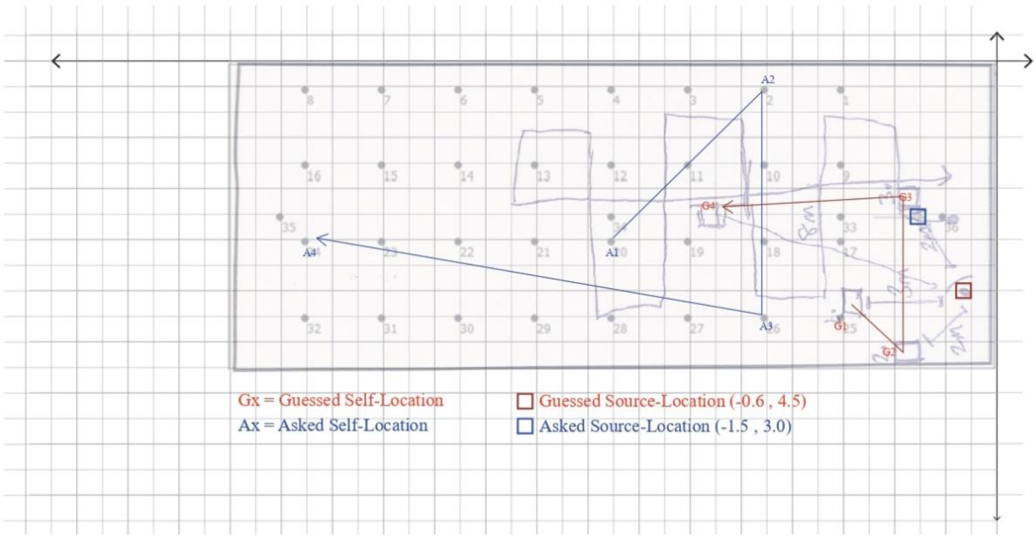
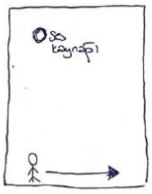


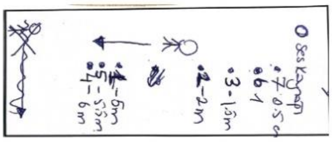
Figure 7-19 First Experiments - Visual Analysis of Soundwalk 11

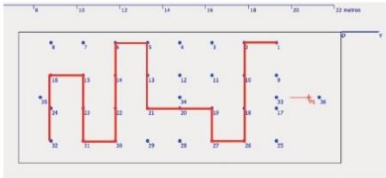
Participant 05 - Soundwalk 12
Soundscape: Soundscape 02 (Long Rectangle Room,10% Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 3 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

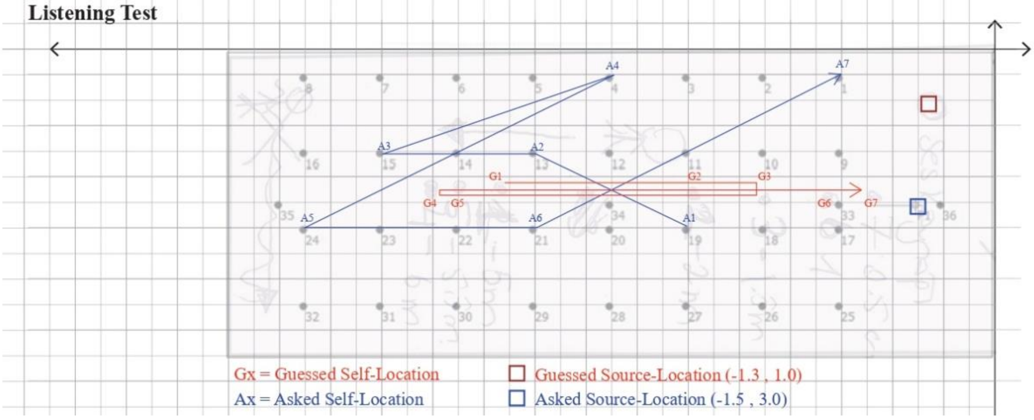
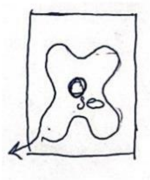


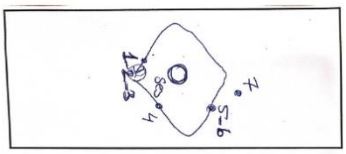
Figure 7-20 First Experiments - Visual Analysis of Soundwalk 12

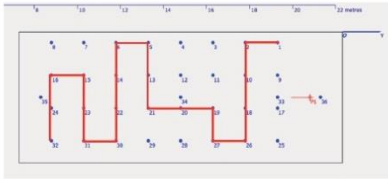
Participant 05 - Soundwalk 13
Soundscape: Soundscape 03 (Long Rectangle Room,90% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 12,4 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

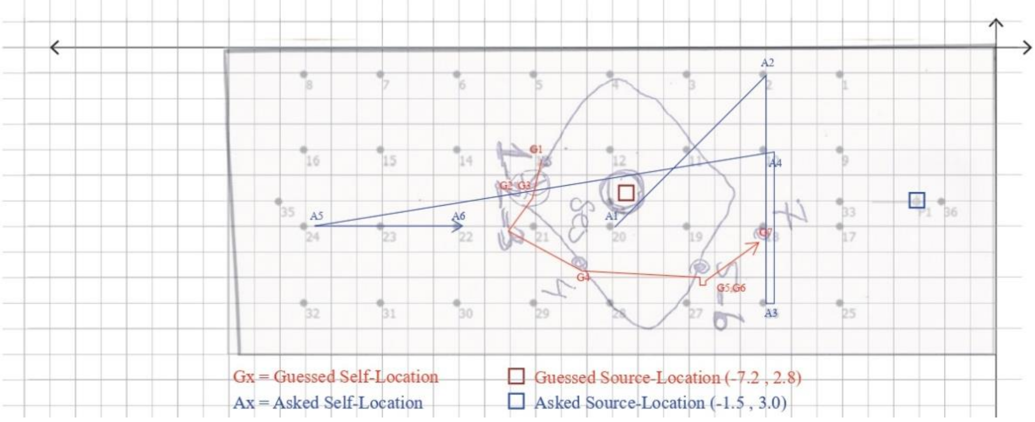
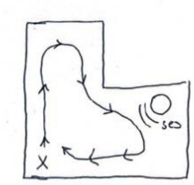


Figure 7-21 First Experiments - Visual Analysis of Soundwalk 13

Participant 05 - Soundwalk 14
Soundscape: Soundscape 05 (L-Shaped Room, 10% Absorption , VR)

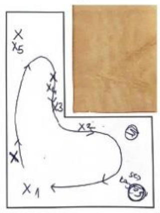
Soundwalking

Mind Map

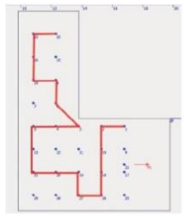


Guessed Room Envelope Corner Number: 6

Route Comparison



Guessed Route Length (by drawing) (m): 49,3 m
Guessed Route Turning Points (by drawing): 10



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

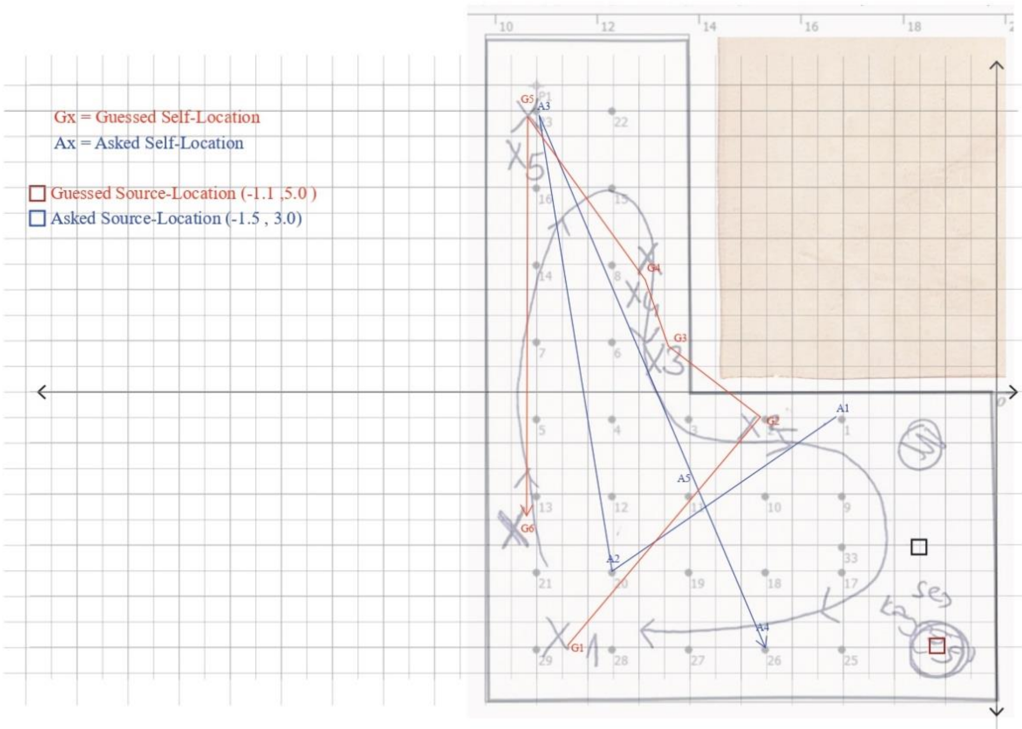
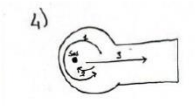


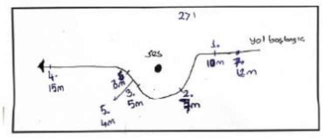
Figure 7-22 First Experiments - Visual Analysis of Soundwalk 14

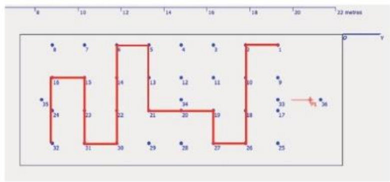
Participant 06 - Soundwalk 15
Soundscape: Soundscape 04 (Long Rectangle Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 12.5 m
Guessed Route Turning Points (by drawing): 4

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

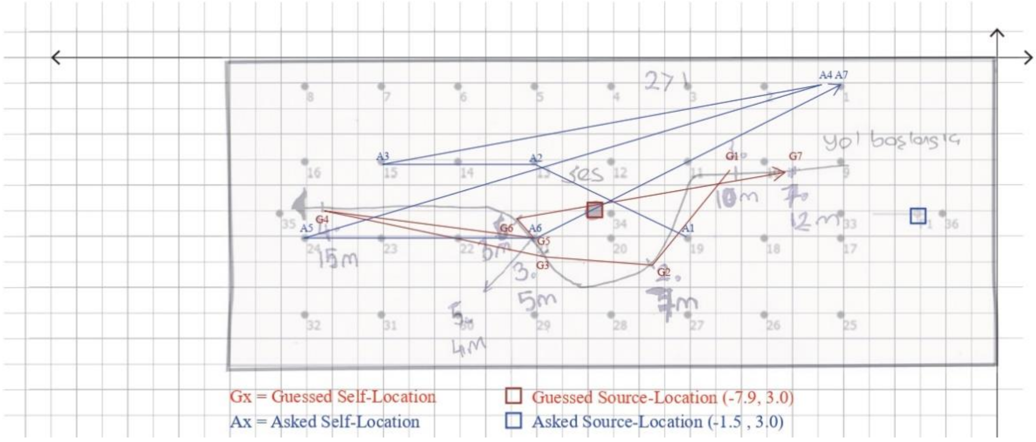


Figure 7-23 First Experiments - Visual Analysis of Soundwalk 15

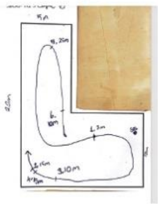
Participant 06 - Soundwalk 16
Soundscape: Soundscape 07 (L-Shaped Room, Mixed Absorption , VR)

Soundwalking

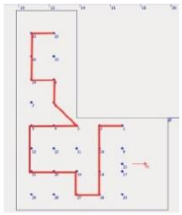
Mind Map

Guessed Room Envelope Corner Number: 6

Route Comparison



Guessed Route Length (by drawing) (m): 34,6 m
Guessed Route Turning Points (by drawing): 13



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

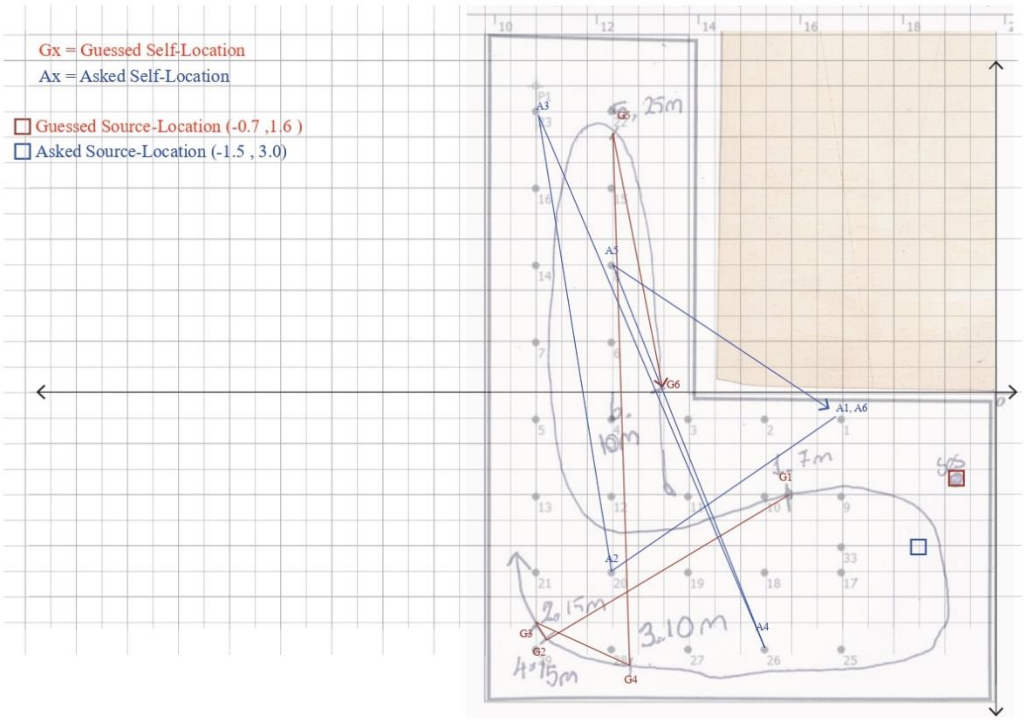
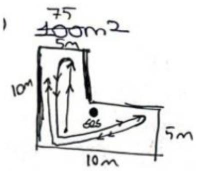


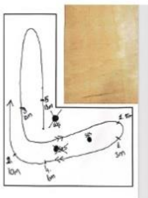
Figure 7-24 First Experiments - Visual Analysis of Soundwalk 16

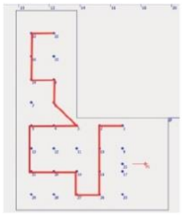
Participant 06 - Soundwalk 17
Soundscape: Soundscape 06 (L-Shaped Room, 90% Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): 37,2 m
Guessed Route Turning Points (by drawing): 13

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

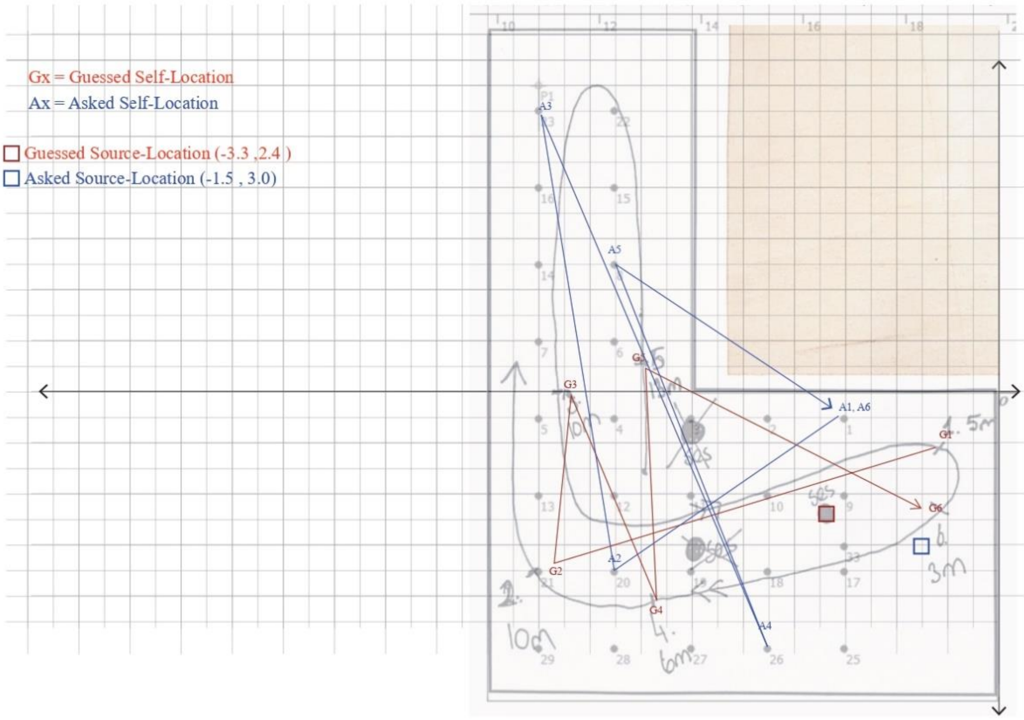
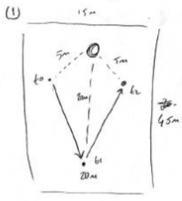


Figure 7-25 First Experiments - Visual Analysis of Soundwalk 17

Participant 07 - Soundwalk 18
Soundscape: Soundscape 09 (L-Shaped Room, 90% Absorption , Odeon)

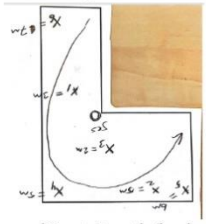
Soundwalking

Mind Map

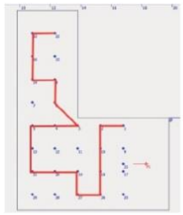


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 20,3 m
Guessed Route Turning Points (by drawing): 7



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

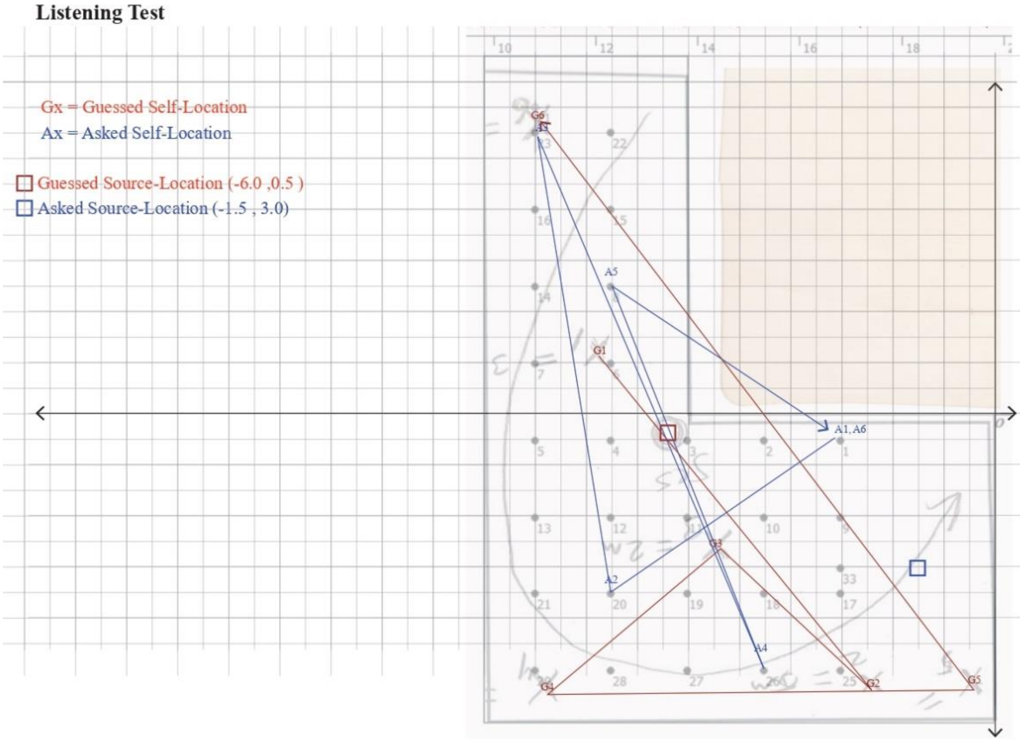
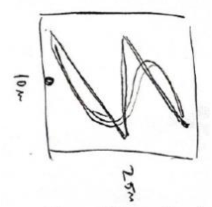


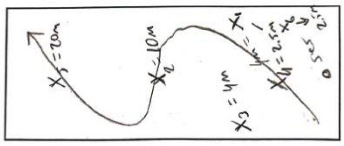
Figure 7-26 First Experiments - Visual Analysis of Soundwalk 18

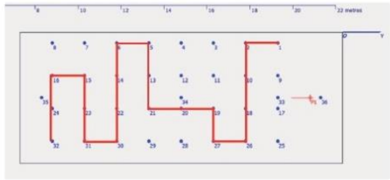
Participant 07 - Soundwalk 19
Soundscape: Soundscape 12 (Long Rectangle Room, 10% Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 19 m
Guessed Route Turning Points (by drawing): 7

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

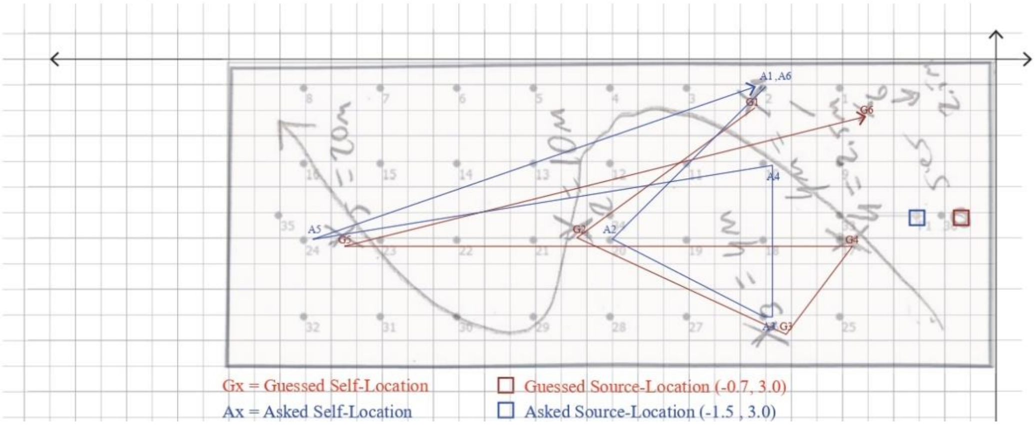
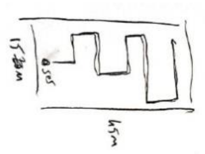


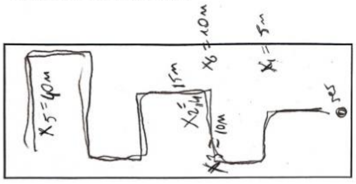
Figure 7-27 First Experiments - Visual Analysis of Soundwalk 19

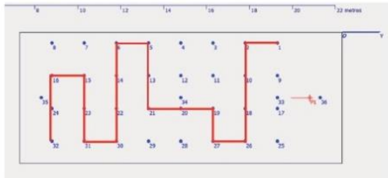
Participant 07 - Soundwalk 20
Soundscape: Soundscape 13 (Long Rectangle Room,90% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 29,6 m
Guessed Route Turning Points (by drawing): 7

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

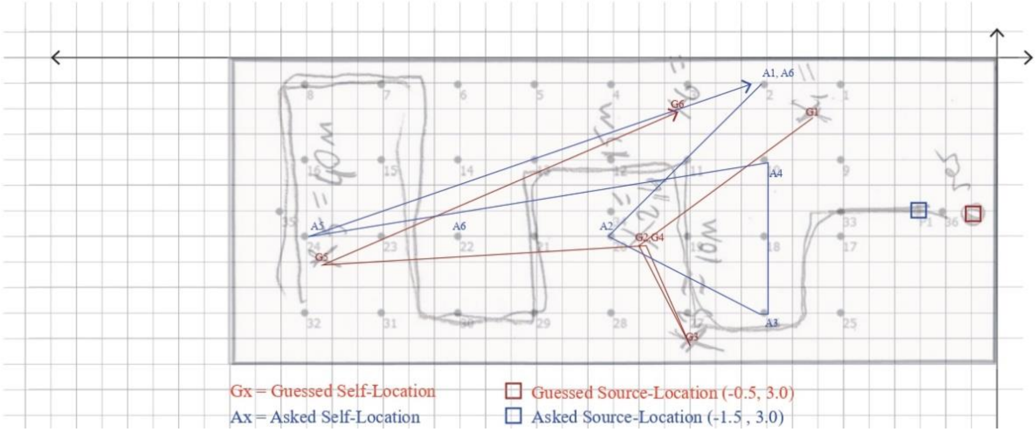
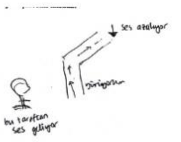


Figure 7-28 First Experiments - Visual Analysis of Soundwalk 20

Participant 08 - Soundwalk 21
Soundscape: Soundscape 10 (L-Shaped Room, Mixed Absorption , Odeon)

Soundwalking

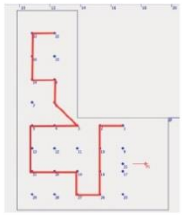
Mind Map



Guessed Room Envelope Corner Number: 6

Route Comparison

Guessed Route Length (by drawing) (m): 4,9 m
Guessed Route Turning Points (by drawing): 1



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

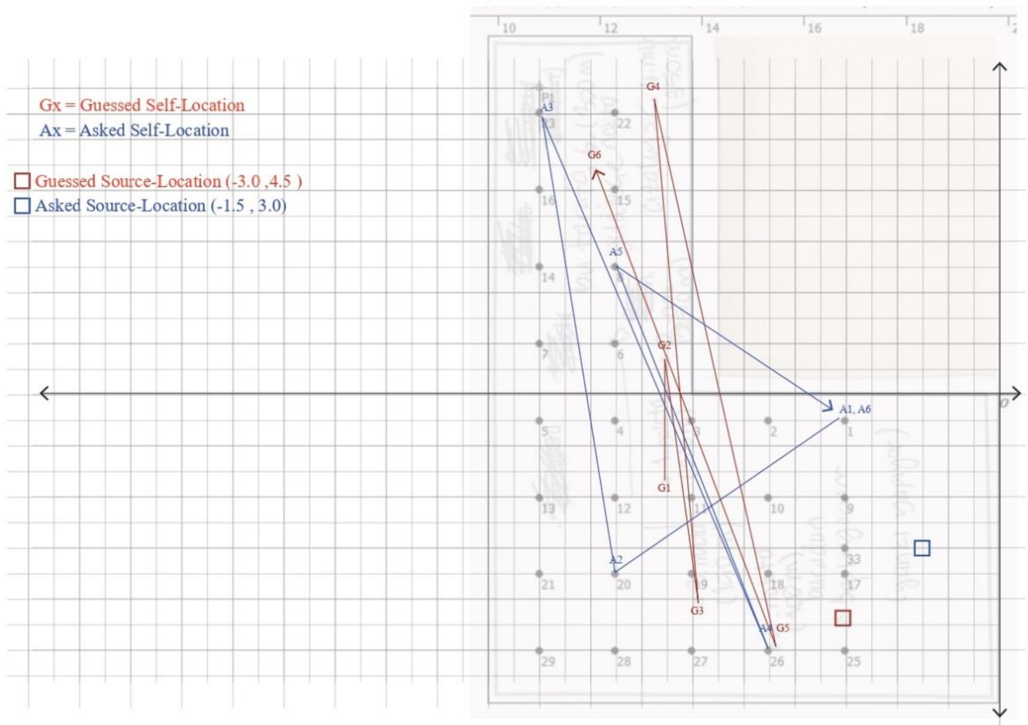
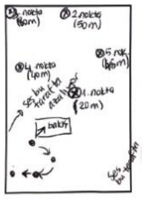


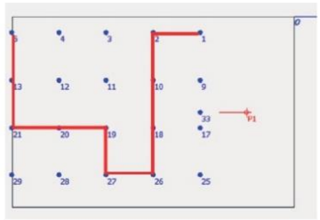
Figure 7-29 First Experiments - Visual Analysis of Soundwalk 21

Participant 08 - Soundwalk 22
Soundscape: Soundscape 11 (Small Rectangle Room,10% Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 3,9 m
Guessed Route Turning Points (by drawing): 2

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

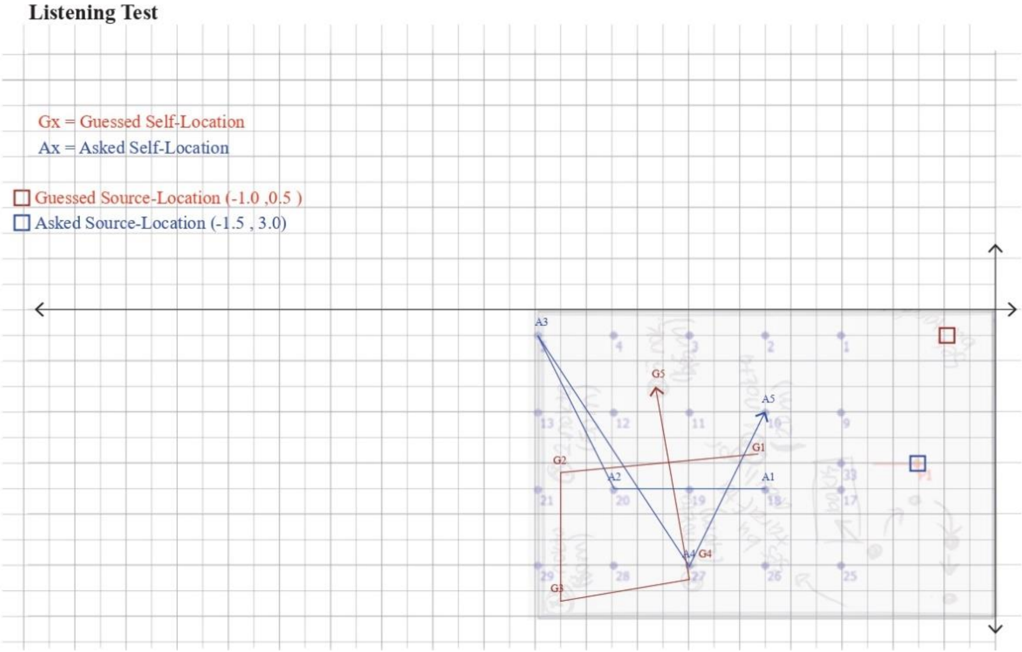
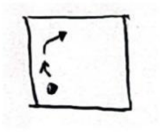


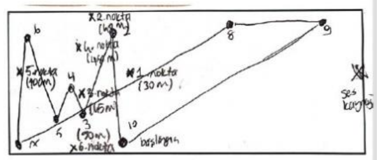
Figure 7-30 First Experiments - Visual Analysis of Soundwalk 22

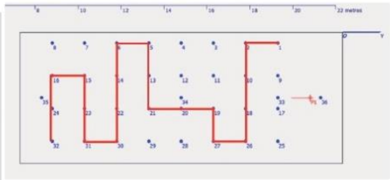
Participant 08 - Soundwalk 23
Soundscape: Soundscape 14 (Long Rectangle Room, Mixed Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 42,5 m
Guessed Route Turning Points (by drawing): 9

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

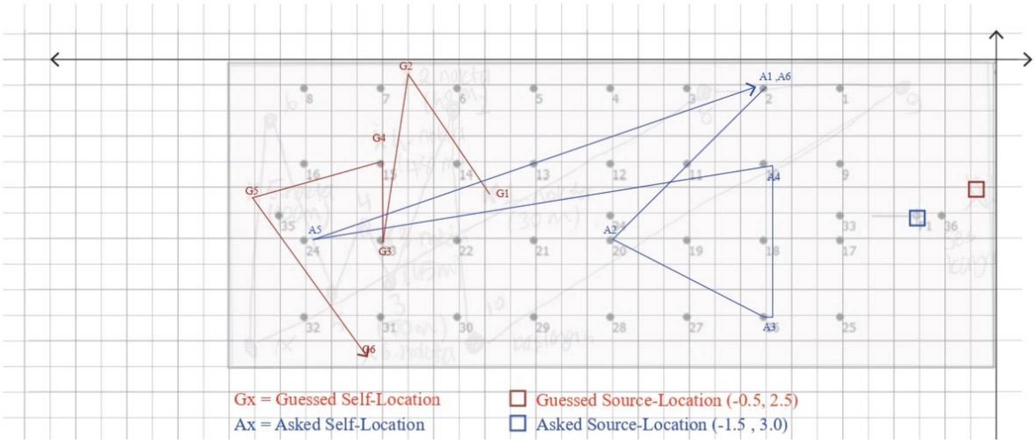
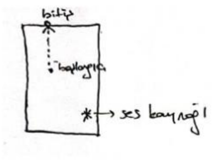


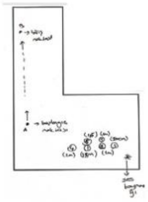
Figure 7-31 First Experiments - Visual Analysis of Soundwalk 23

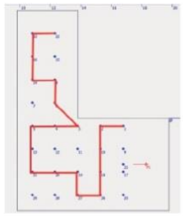
Participant 09 - Soundwalk 24
Soundscape: Soundscape 08 (L-Shaped Room, 10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 6,5 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

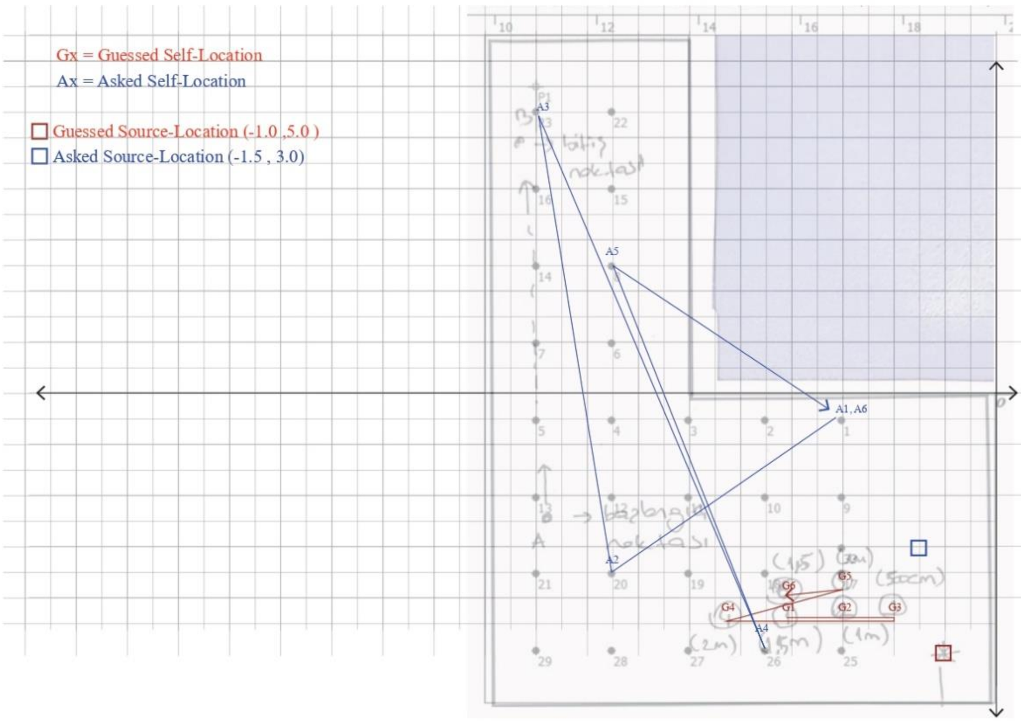
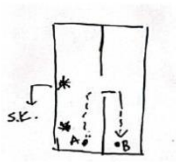


Figure 7-32 First Experiments - Visual Analysis of Soundwalk 24

Participant 09 - Soundwalk 25
Soundscape: Soundscape 09 (L-Shaped Room, 90% Absorption , Odeon)

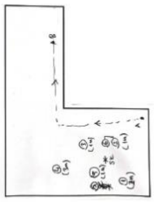
Soundwalking

Mind Map

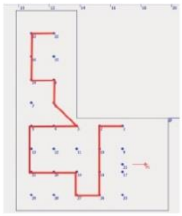


Guessed Room Envelope Corner Number: 6

Route Comparison



Guessed Route Length (by drawing) (m): 11,5 m
Guessed Route Turning Points (by drawing): 1



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

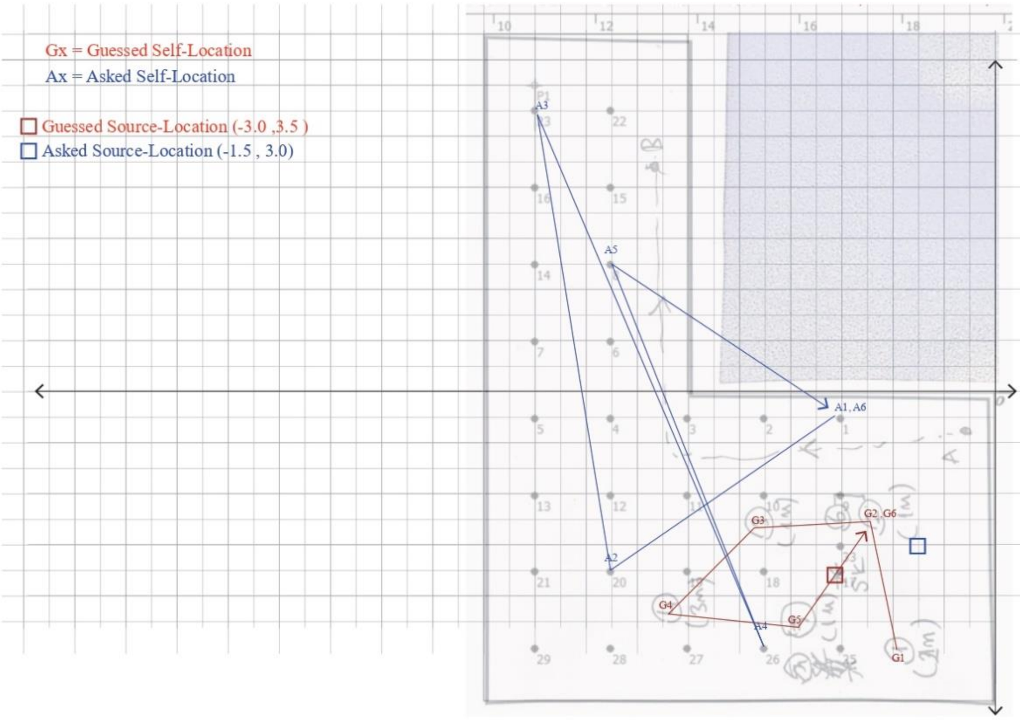
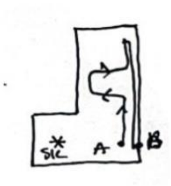


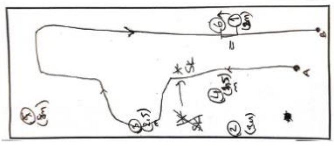
Figure 7-33 First Experiments - Visual Analysis of Soundwalk 25

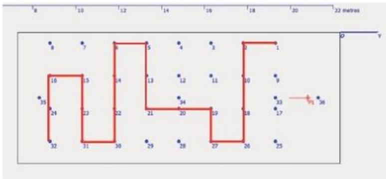
Participant 09 - Soundwalk 26
Soundscape: Soundscape 12 (Long Rectangle Room, 10% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): 29,2 m
Guessed Route Turning Points (by drawing): 10

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

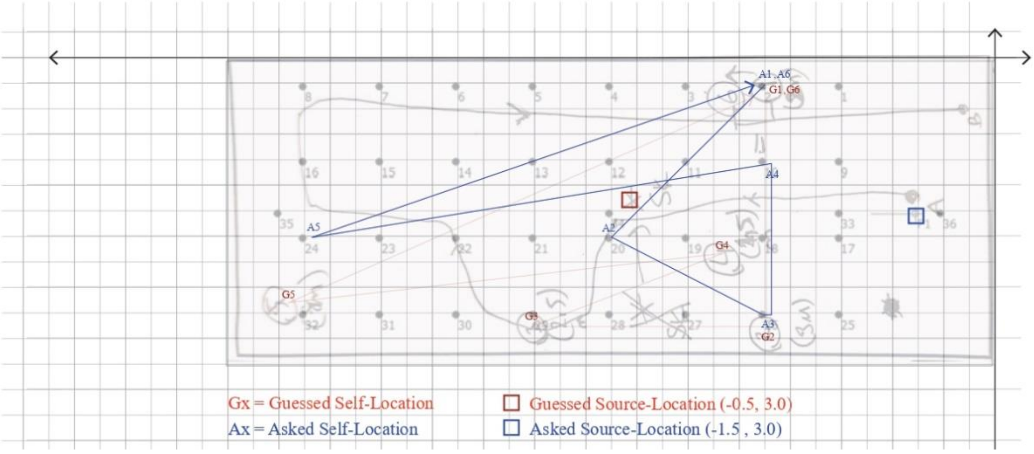
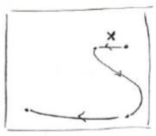


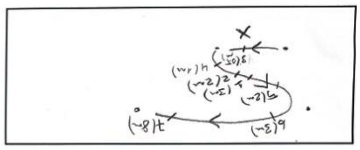
Figure 7-34 First Experiments - Visual Analysis of Soundwalk 26

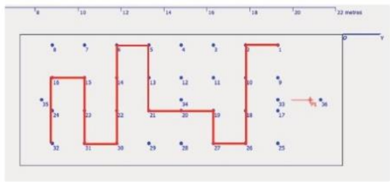
Participant 10 - Soundwalk 27
Soundscape: Soundscape 04 (Long Rectangle Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 13,1 m
Guessed Route Turning Points (by drawing): 8

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

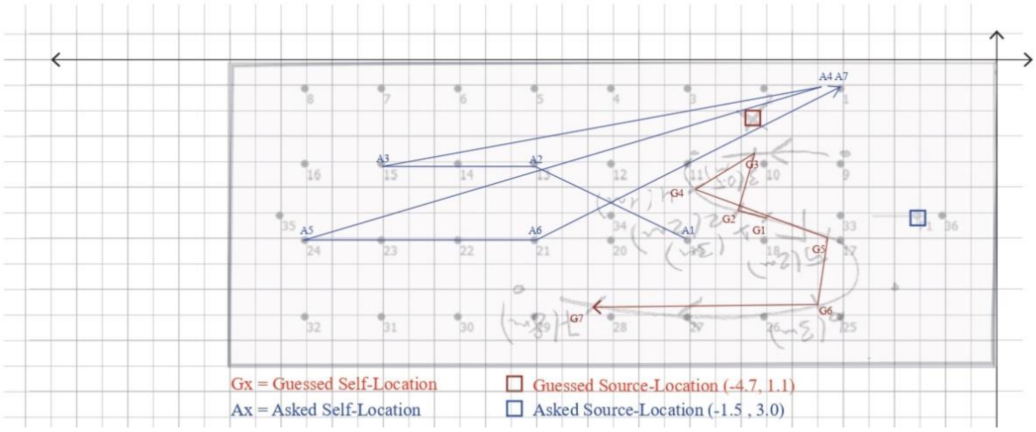
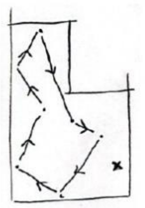


Figure 7-35 First Experiments - Visual Analysis of Soundwalk 27

Participant 10 - Soundwalk 28
Soundscape: Soundscape 06 (L-Shaped Room, 90% Absorption , VR)

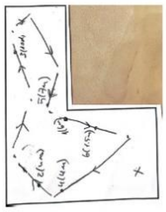
Soundwalking

Mind Map

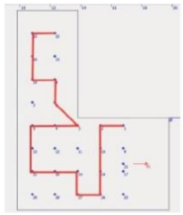


Guessed Room Envelope Corner Number: 6

Route Comparison



Guessed Route Length (by drawing) (m): 32,2 m
Guessed Route Turning Points (by drawing): 7



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

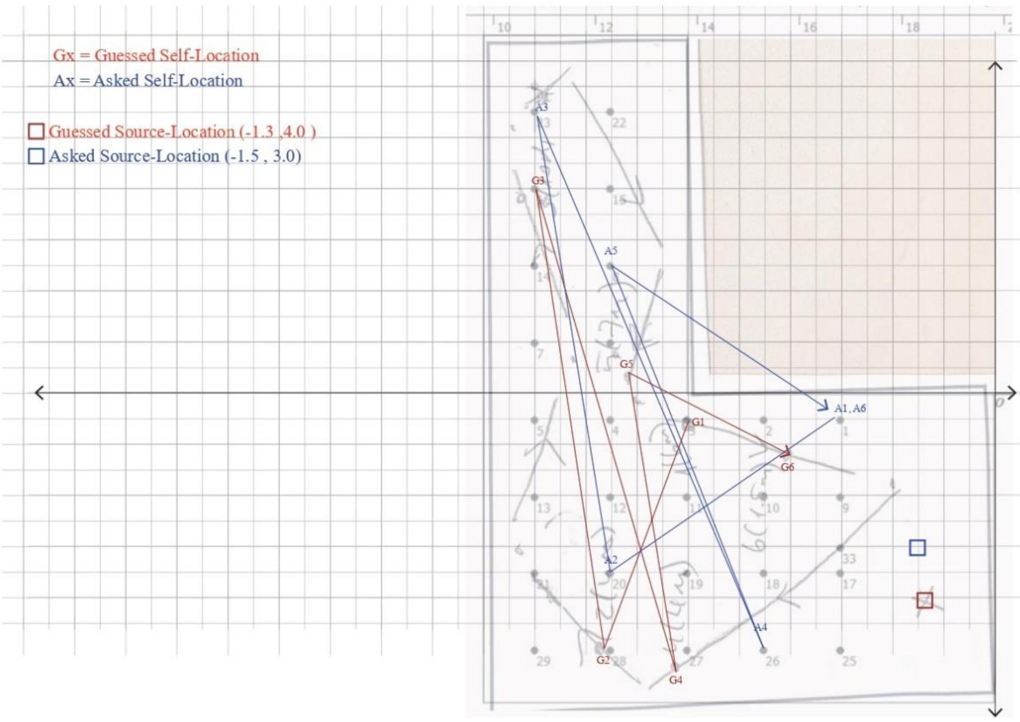
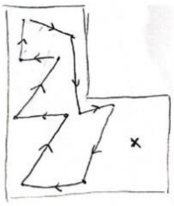
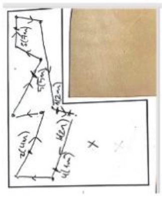
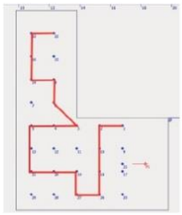


Figure 7-36 First Experiments - Visual Analysis of Soundwalk 28

Participant 10 - Soundwalk 29
Soundscape: Soundscape 07 (L-Shaped Room, Mixed Absorption , VR)

Soundwalking

Mind Map	**Route Comparison**	
		
Guessed Room Envelope Corner Number: 6	Guessed Route Length (by drawing) (m): 32,7 m Guessed Route Turning Points (by drawing): 9	Real Room Envelope Corner Number: 6 Real Route Length (by drawing) (m): 27,61 m Real Route Turning Point Number: 12

Listening Test

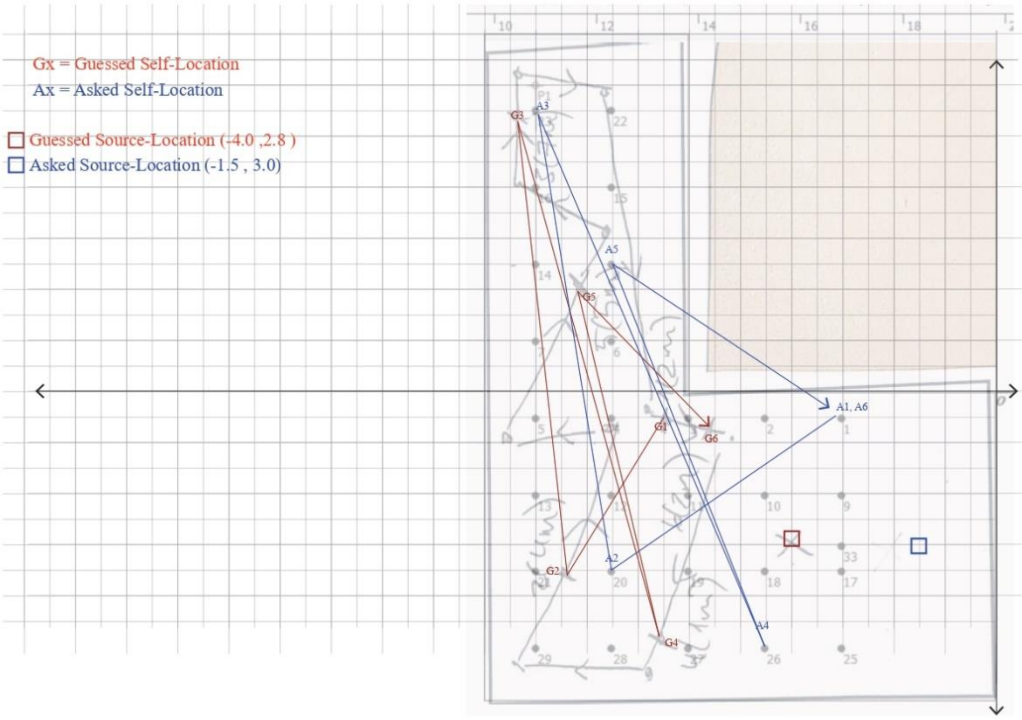
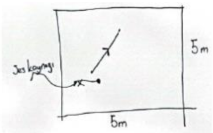


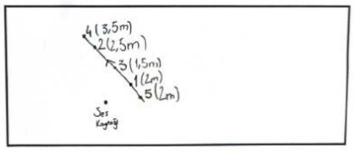
Figure 7-37 First Experiments - Visual Analysis of Soundwalk 29

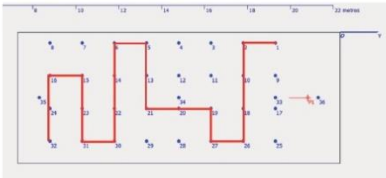
Participant 11 - Soundwalk 30
Soundscape: Soundscape 04 (Long Rectangle Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 3,7 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

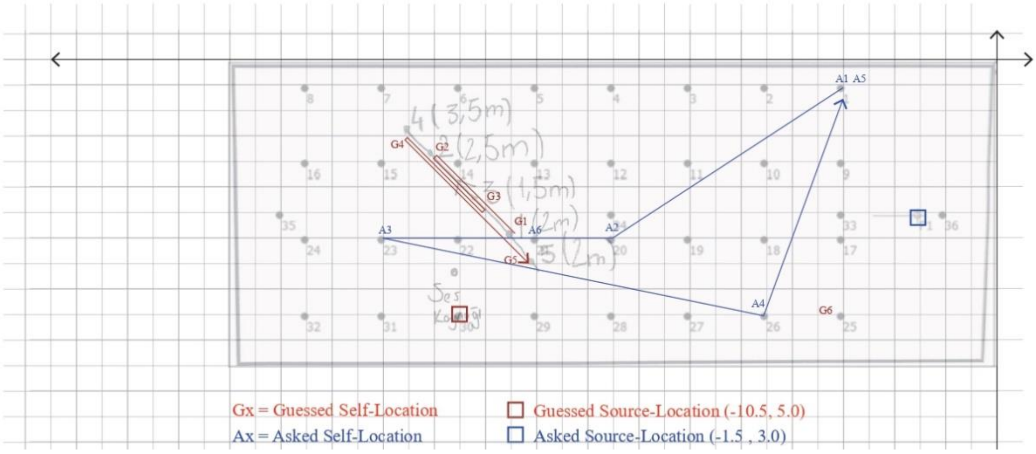
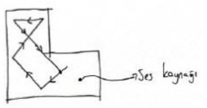


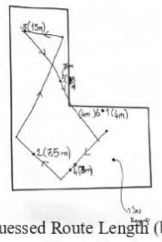
Figure 7-38 First Experiments - Visual Analysis of Soundwalk 30

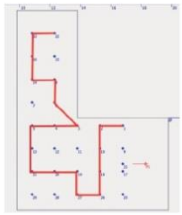
Participant 11 - Soundwalk 31
Soundscape: Soundscape 05 (L-Shaped Room, 10% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): 29,4 m
Guessed Route Turning Points (by drawing): 6

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

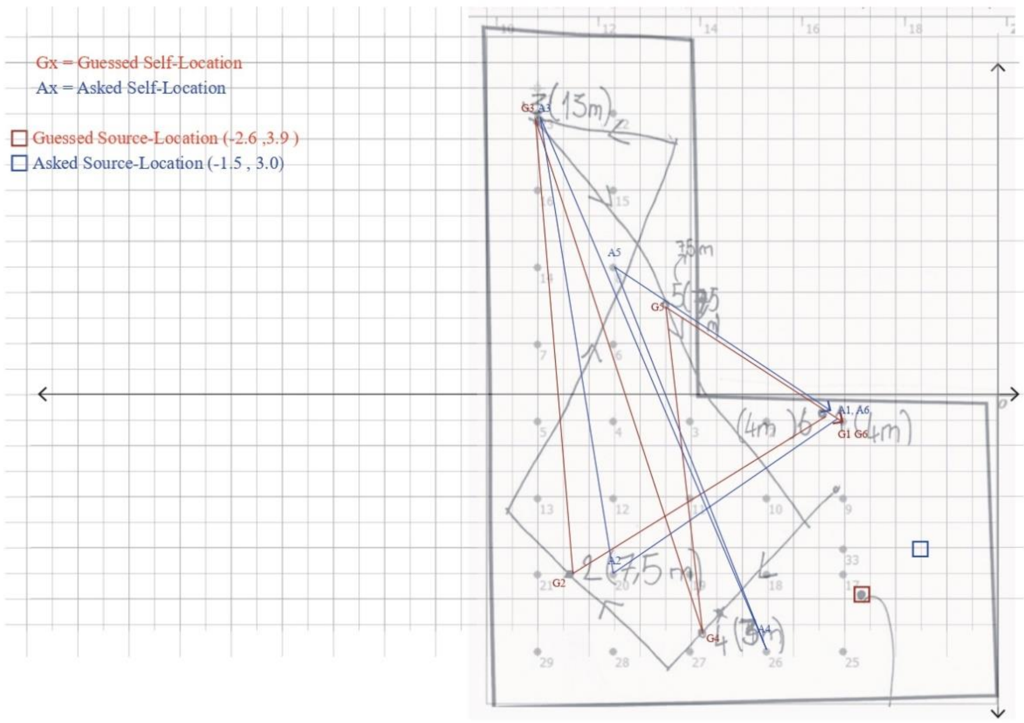
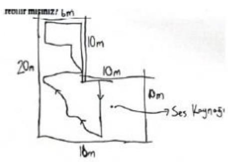


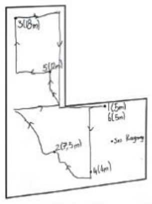
Figure 7-39 First Experiments - Visual Analysis of Soundwalk 31

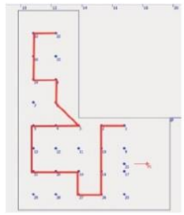
Participant 11 - Soundwalk 32
Soundscape: Soundscape 07 (L-Shaped Room, Mixed Absorption , VR)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 6

Guessed Route Length (by drawing) (m): - m
Guessed Route Turning Points (by drawing): -

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

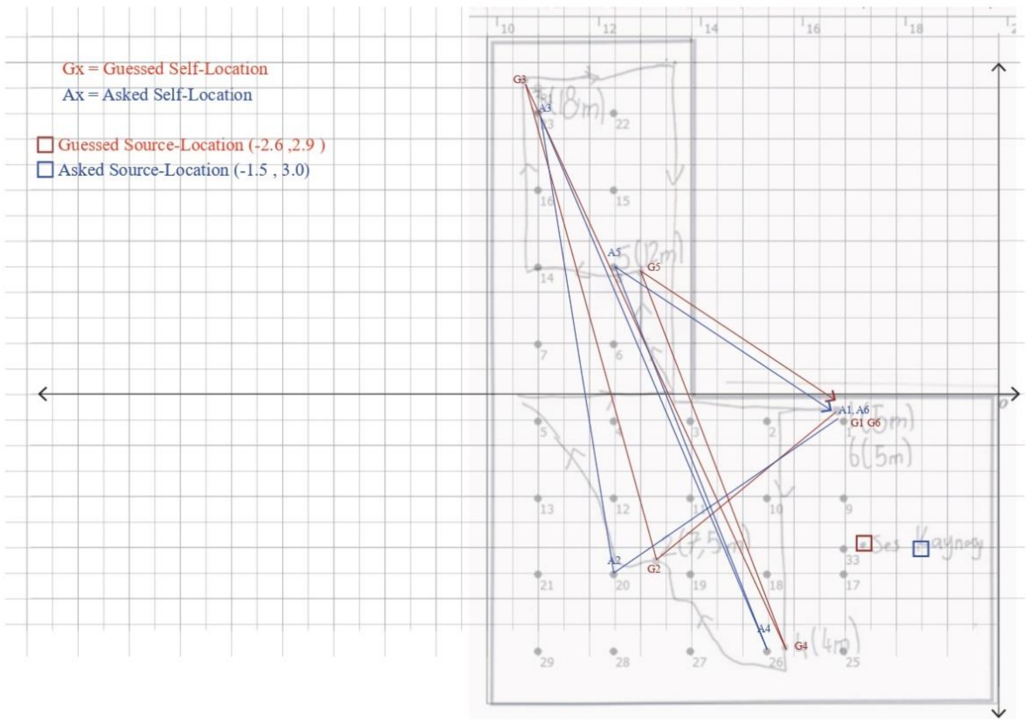
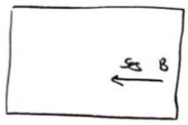


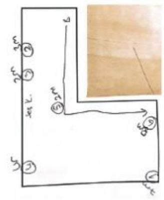
Figure 7-40 First Experiments - Visual Analysis of Soundwalk 32

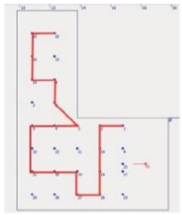
Participant 12 - Soundwalk 33
Soundscape: Soundscape 08 (L-Shaped Room, 10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 12,5 m
Guessed Route Turning Points (by drawing): 1

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

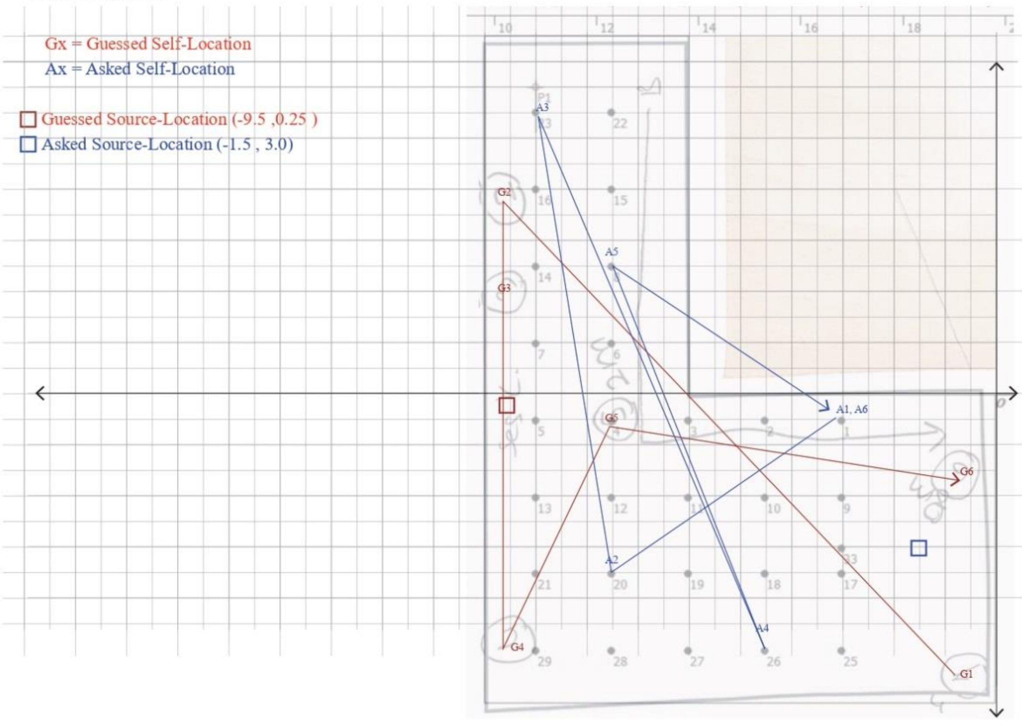
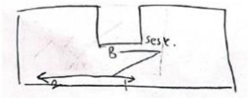


Figure 7-41 First Experiments - Visual Analysis of Soundwalk 33

Participant 12 - Soundwalk 34
Soundscape: Soundscape 09 (L-Shaped Room, 90% Absorption , Odeon)

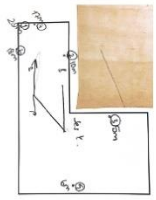
Soundwalking

Mind Map

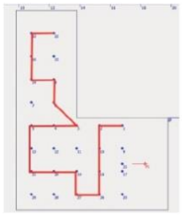


Guessed Room Envelope Corner Number: 8

Route Comparison



Guessed Route Length (by drawing) (m): 14 m
Guessed Route Turning Points (by drawing): 3



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

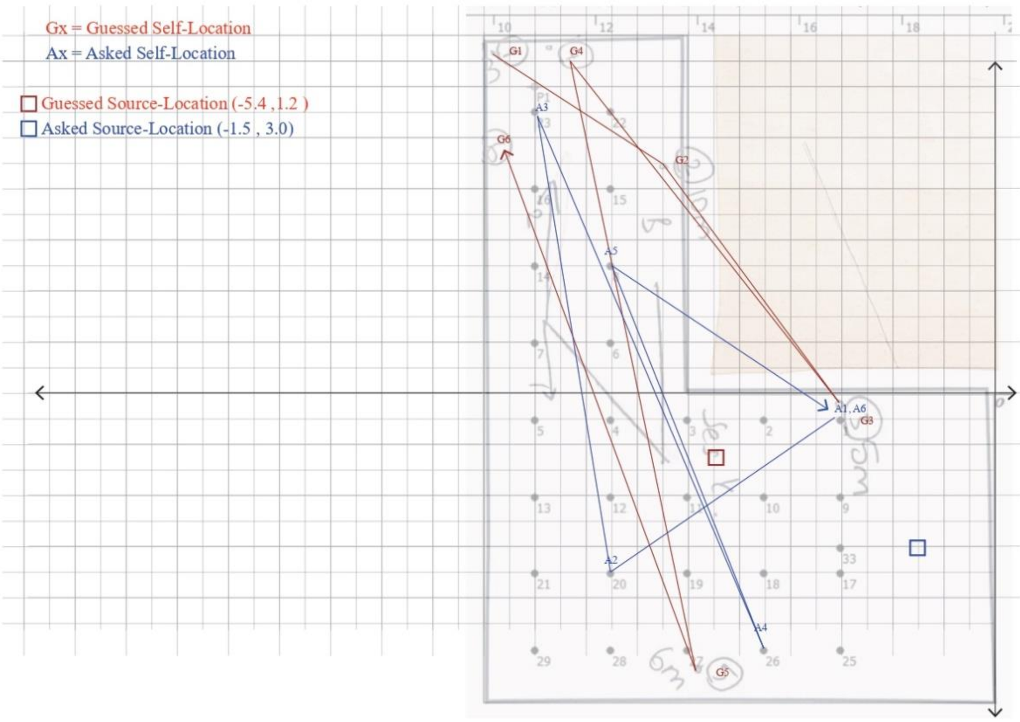
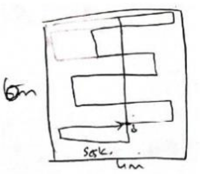


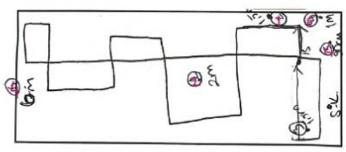
Figure 7-42 First Experiments - Visual Analysis of Soundwalk 34

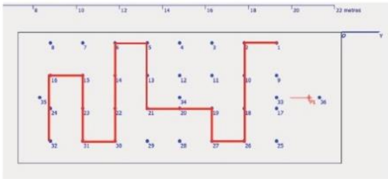
Participant 12 - Soundwalk 35
Soundscape: Soundscape 04 (Long Rectangle Room, 10% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 37,4 m
Guessed Route Turning Points (by drawing): 12

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

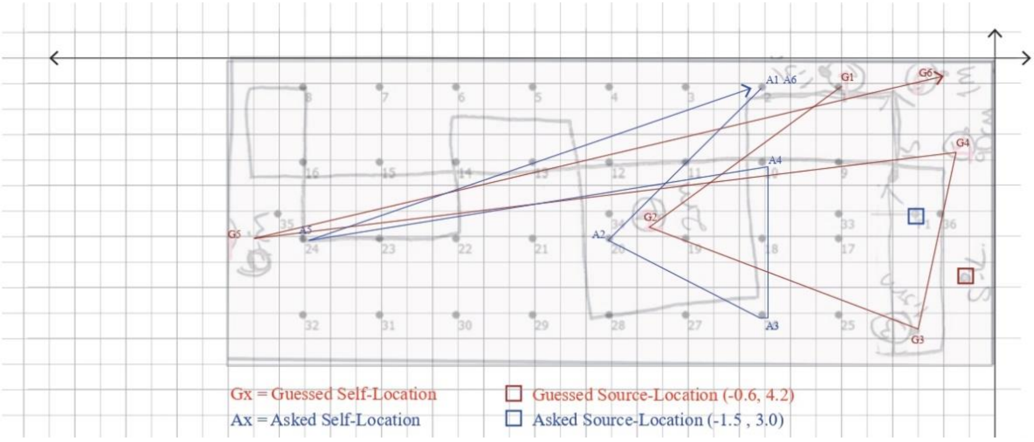
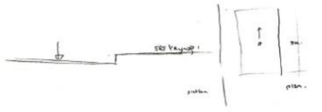


Figure 7-43 First Experiments - Visual Analysis of Soundwalk 35

Participant 13 - Soundwalk 36
Soundscape: Soundscape 10 (L-Shaped Room, Mixed Absorption , Odeon)

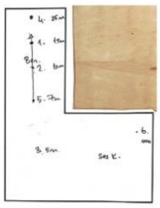
Soundwalking

Mind Map

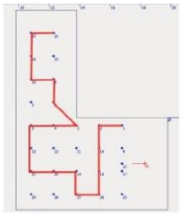


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 4,2 m
Guessed Route Turning Points (by drawing): 0



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

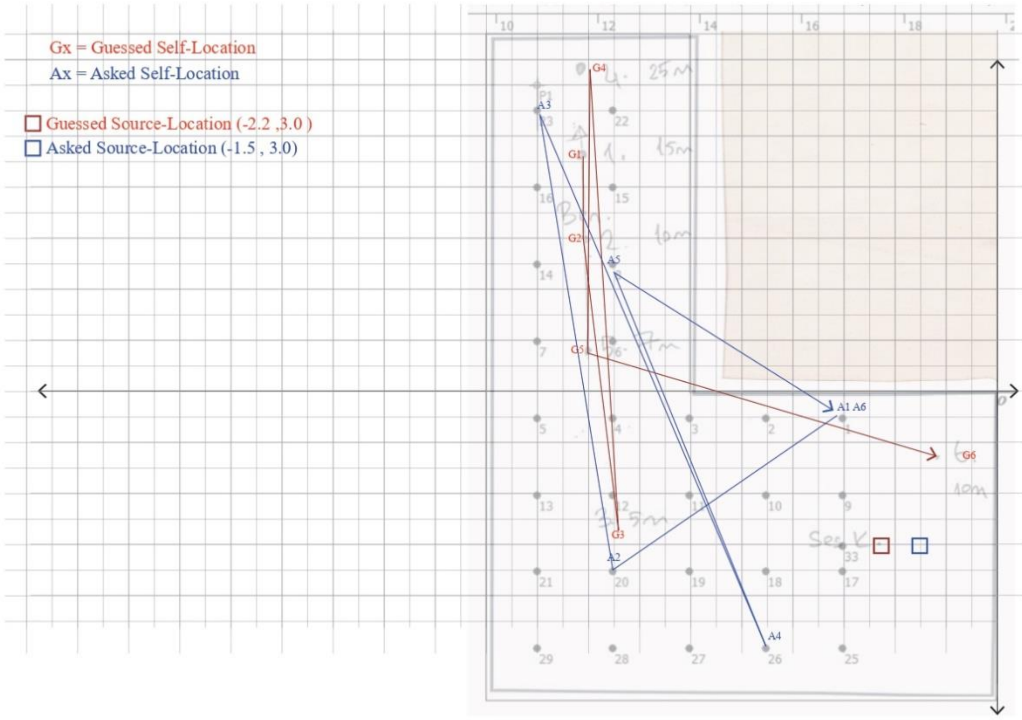
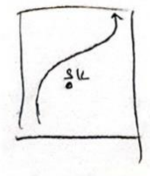


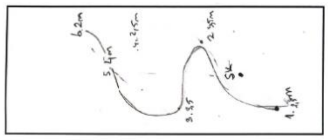
Figure 7-44 First Experiments - Visual Analysis of Soundwalk 36

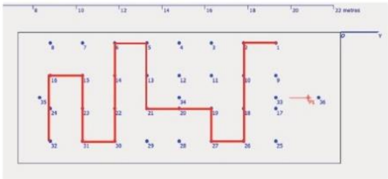
Participant 13 - Soundwalk 37
Soundscape: Soundscape 14 (Long Rectangle Room, Mixed Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 15,8 m
Guessed Route Turning Points (by drawing): 12

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

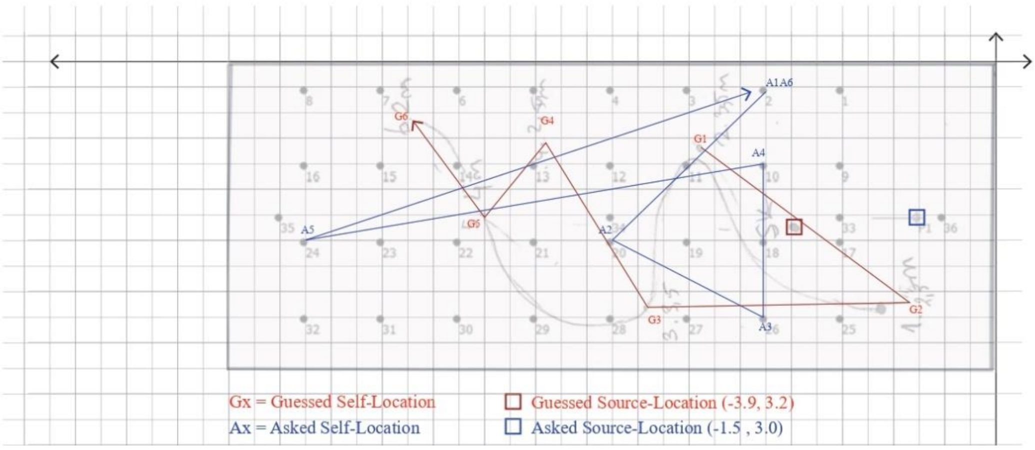
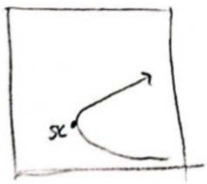


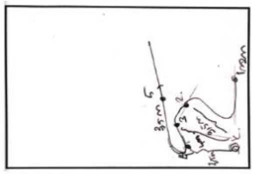
Figure 7-45 First Experiments - Visual Analysis of Soundwalk 37

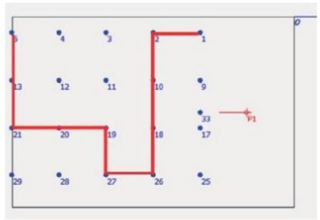
Participant 13 - Soundwalk 38
Soundscape: Soundscape 11 (Small Rectangle Room,10% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 9,7 m
Guessed Route Turning Points (by drawing): 8

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

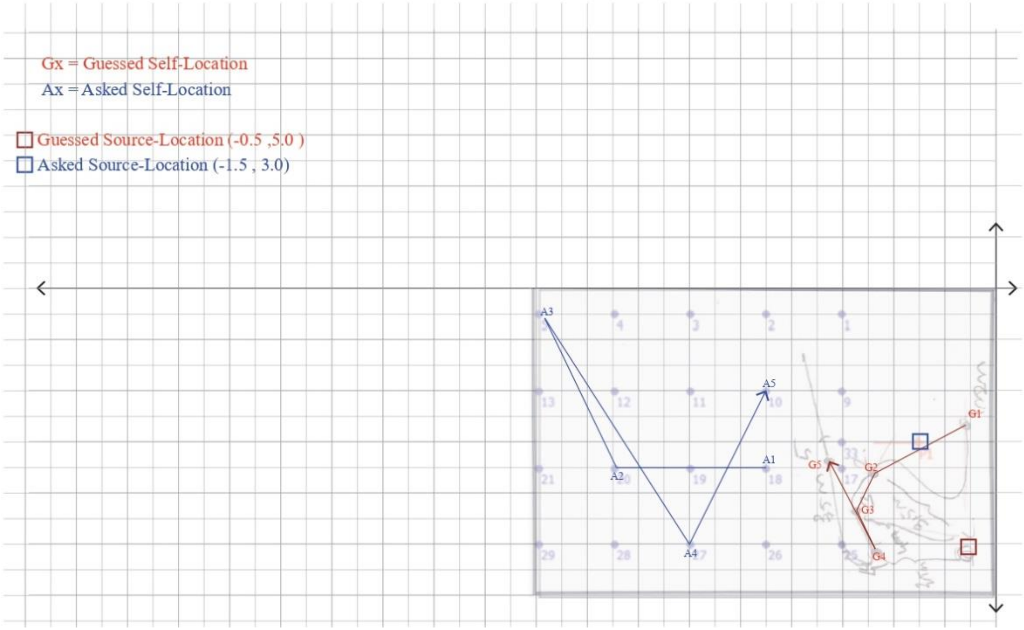
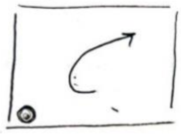


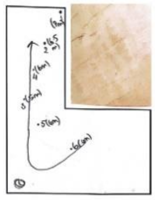
Figure 7-46 First Experiments - Visual Analysis of Soundwalk 38

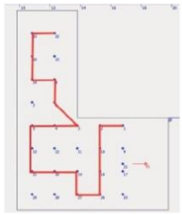
Participant 14 - Soundwalk 39
Soundscape: Soundscape 08 (L-Shaped Room, 10% Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 13,2 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

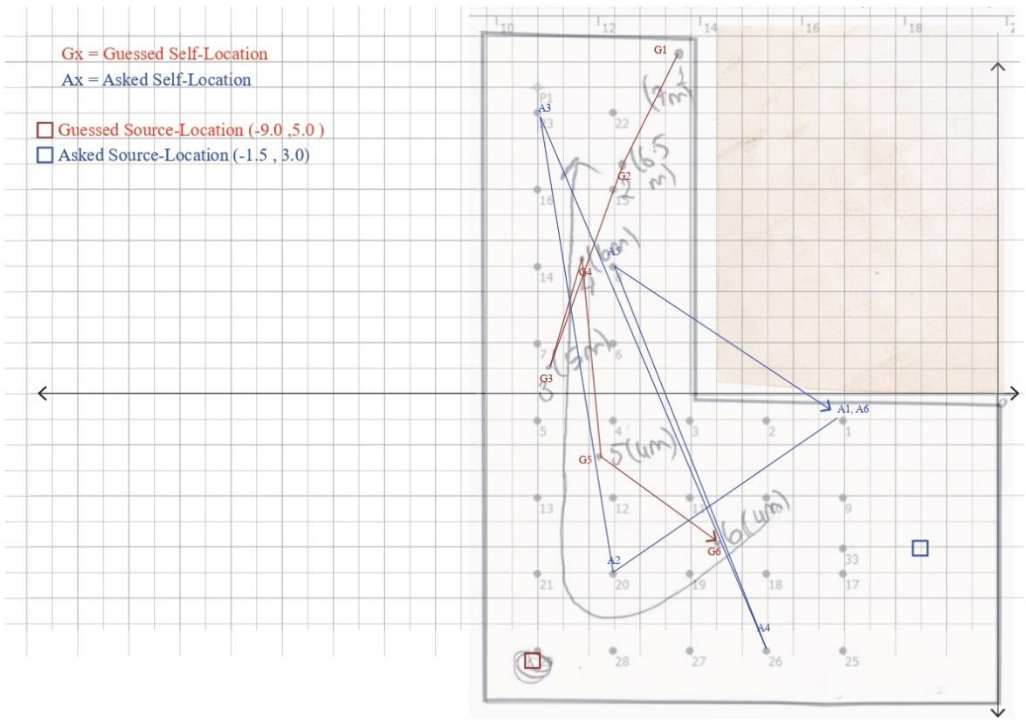


Figure 7-47 First Experiments - Visual Analysis of Soundwalk 39

Participant 14 - Soundwalk 40
Soundscape: Soundscape 09 (L-Shaped Room, 90% Absorption , Odeon)

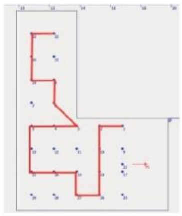
Soundwalking

Mind Map

Guessed Room Envelope Corner Number: 4

Route Comparison

Guessed Route Length (by drawing) (m): 10,1 m
Guessed Route Turning Points (by drawing): 7



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

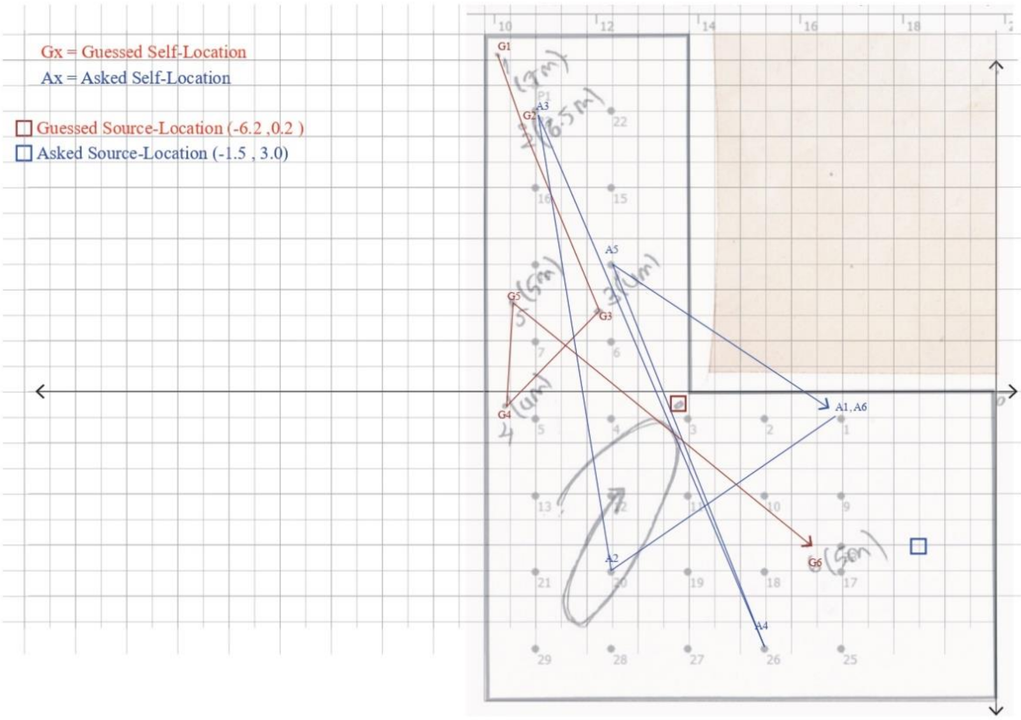
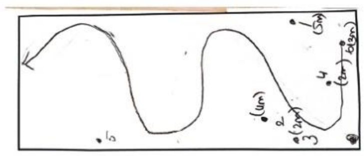


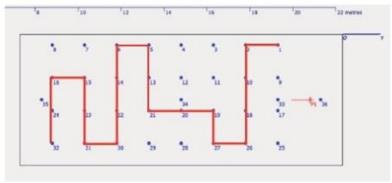
Figure 7-48 First Experiments - Visual Analysis of Soundwalk 40

Participant 14 - Soundwalk 41
Soundscape: Soundscape 13 (Long Rectangle Room, 90% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 26,2 m
Guessed Route Turning Points (by drawing): 16

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

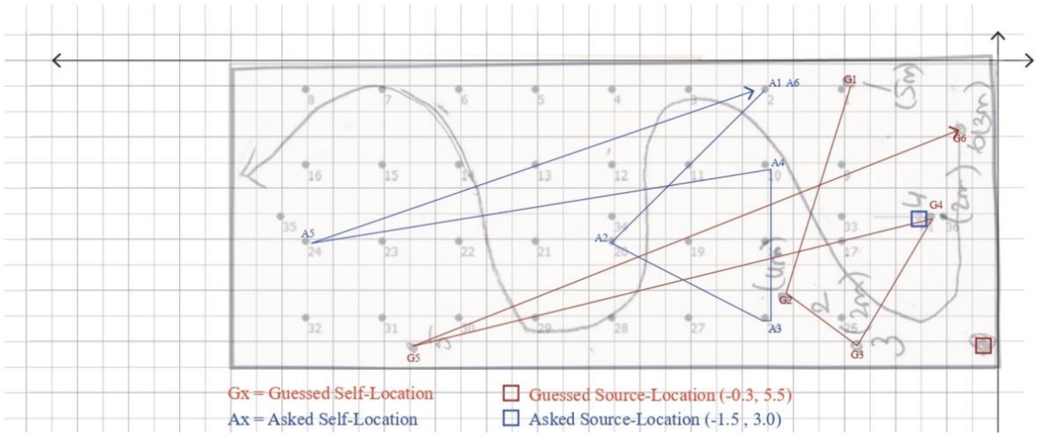
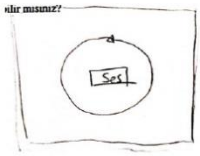


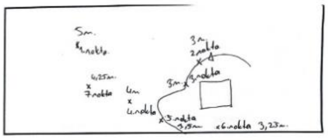
Figure 7-49 First Experiments - Visual Analysis of Soundwalk 41

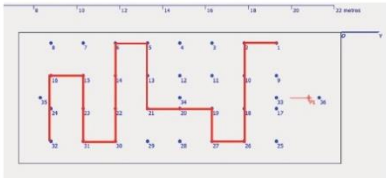
Participant 15 - Soundwalk 42
Soundscape: Soundscape 02 (Long Rectangle Room, 10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 7,3 m
Guessed Route Turning Points (by drawing): 6

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

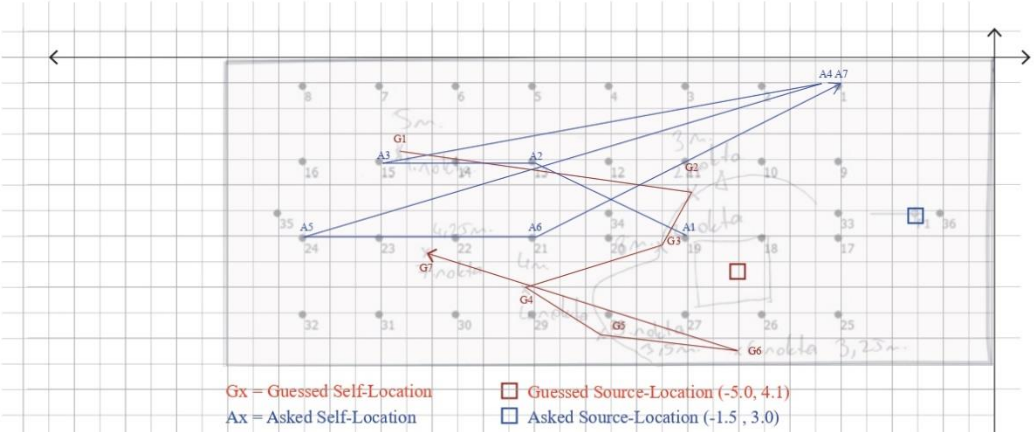
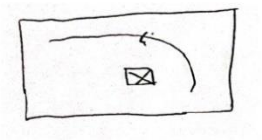


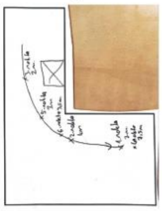
Figure 7-50 First Experiments - Visual Analysis of Soundwalk 42

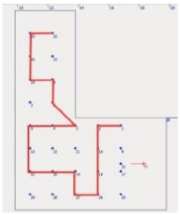
Participant 15 - Soundwalk 43
Soundscape: Soundscape 08 (L-Shaped Room, 10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 10,8 m
Guessed Route Turning Points (by drawing): 5

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

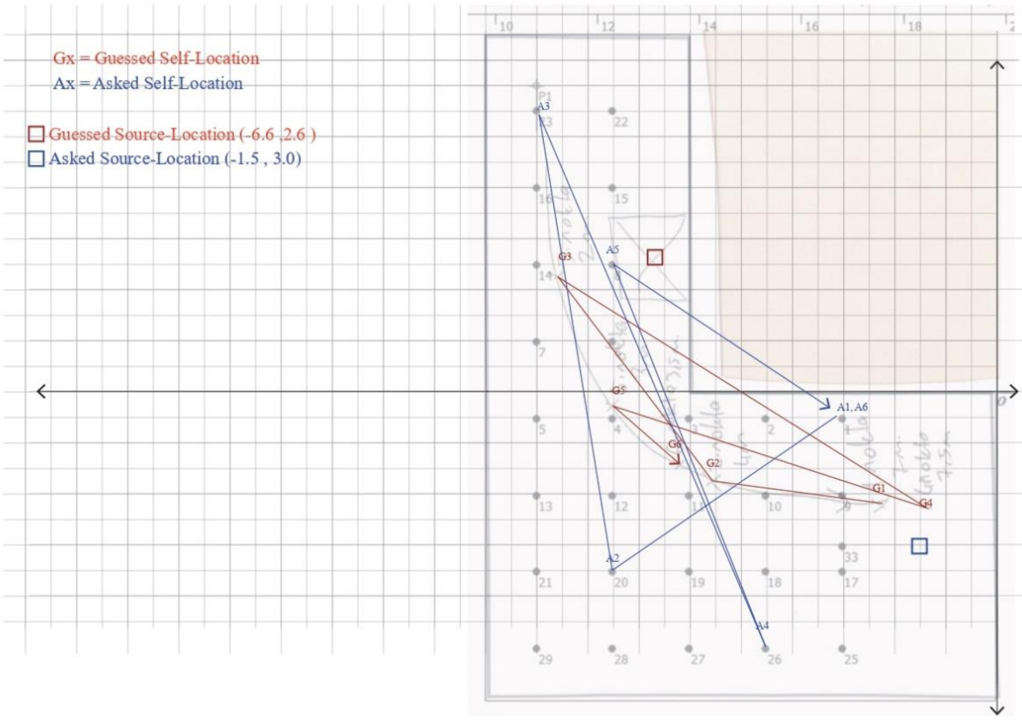
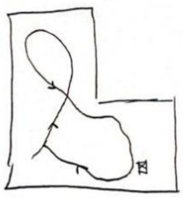


Figure 7-51 First Experiments - Visual Analysis of Soundwalk 43

Participant 15 - Soundwalk 44
Soundscape: Soundscape 05 (L-Shaped Room, 10% Absorption , VR)

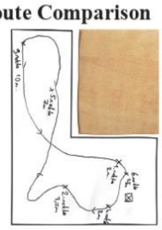
Soundwalking

Mind Map

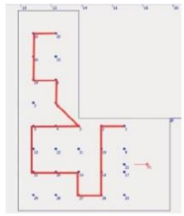


Guessed Room Envelope Corner Number: 6

Route Comparison



Guessed Route Length (by drawing) (m): 25,1 m
Guessed Route Turning Points (by drawing): 23



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

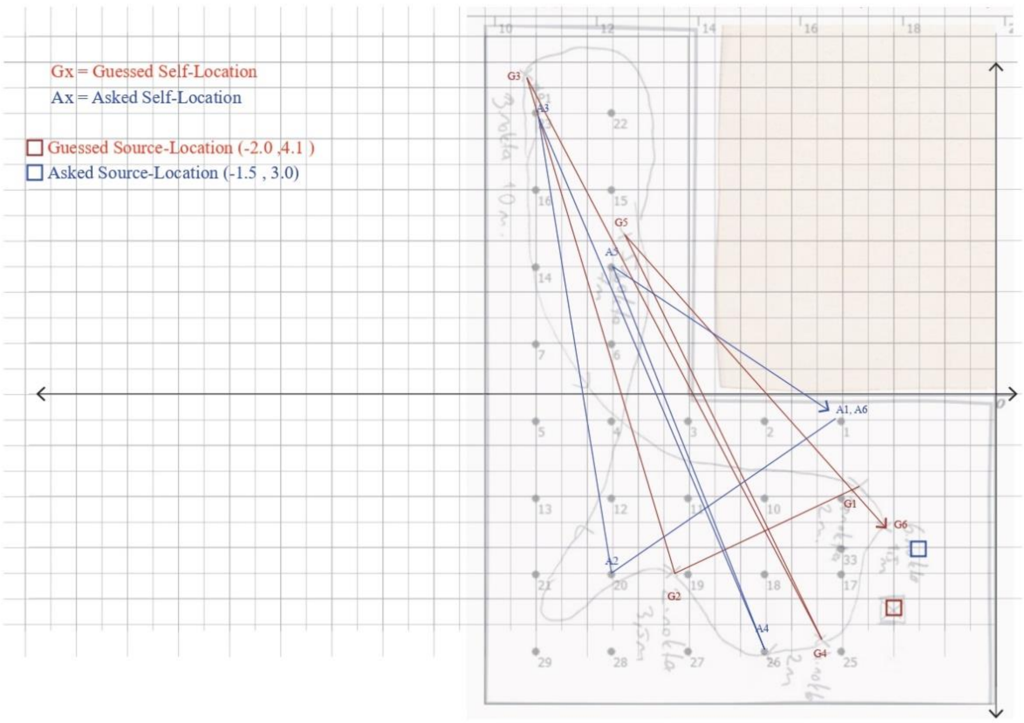
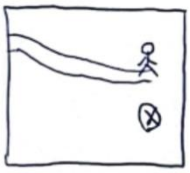


Figure 7-52 First Experiments - Visual Analysis of Soundwalk 44

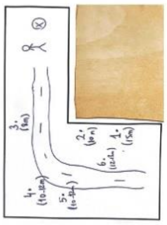
Participant 16 - Soundwalk 45
Soundscape: Soundscape 10 (L-Shaped Room, Mixed Absorption , Odeon)

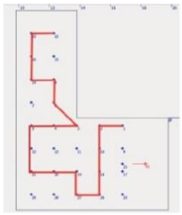
Soundwalking

Mind Map



Route Comparison





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 13,3 m
Guessed Route Turning Points (by drawing): 2

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

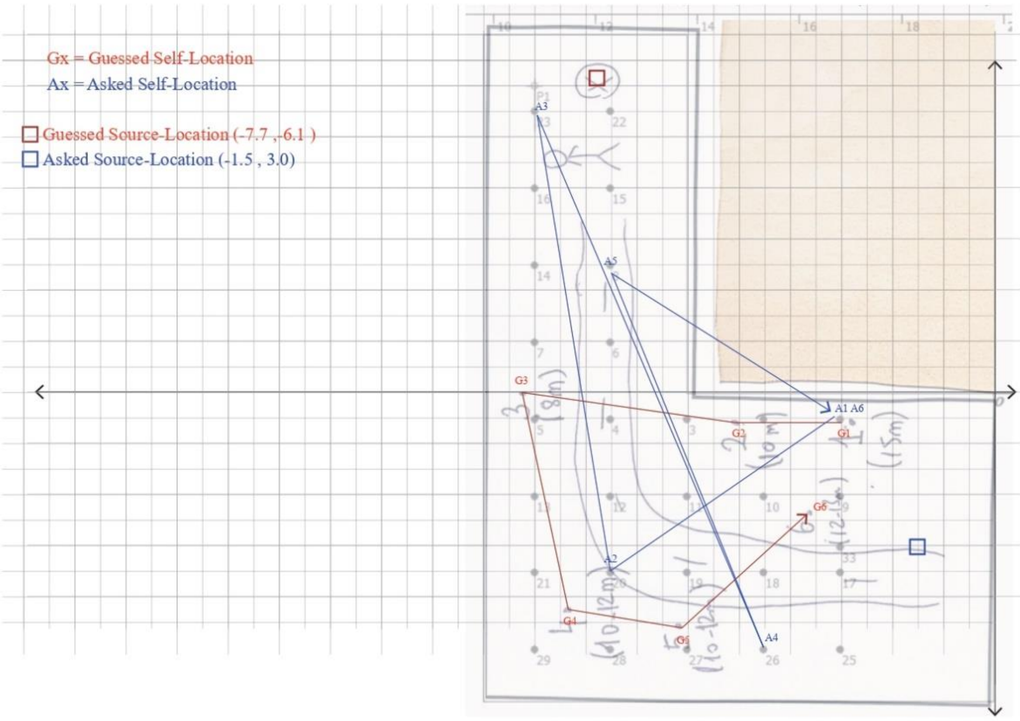
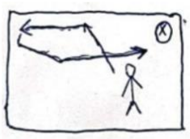


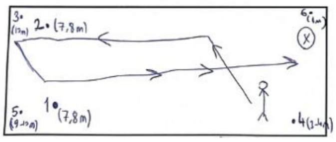
Figure 7-53 First Experiments - Visual Analysis of Soundwalk 45

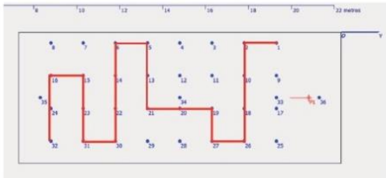
Participant 16 - Soundwalk 46
Soundscape: Soundscape 14 (Long Rectangle Room, Mixed Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 26,3 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

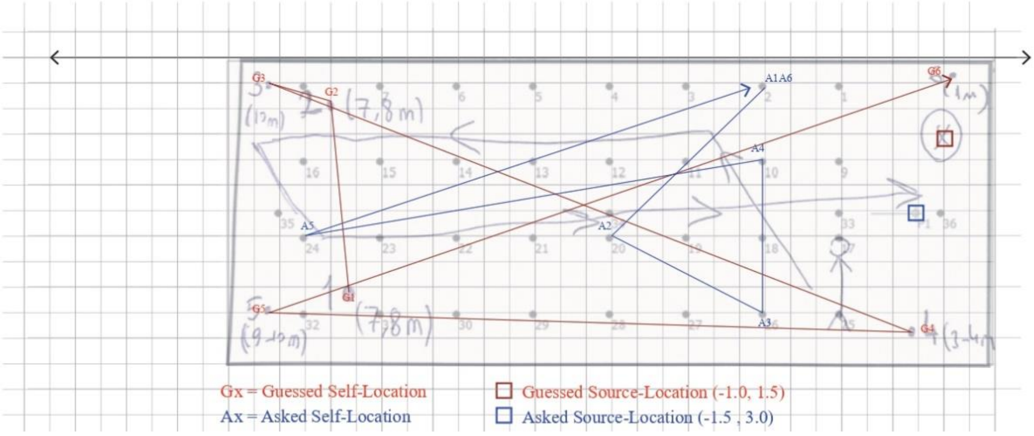
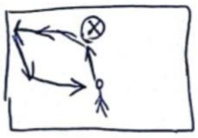


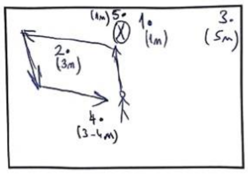
Figure 7-54 First Experiments - Visual Analysis of Soundwalk 46

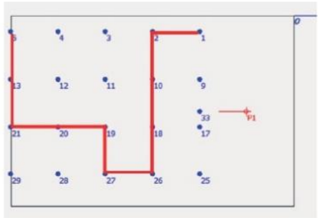
Participant 16 - Soundwalk 47
Soundscape: Soundscape 11 (Small Rectangle Room,10% Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 10 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

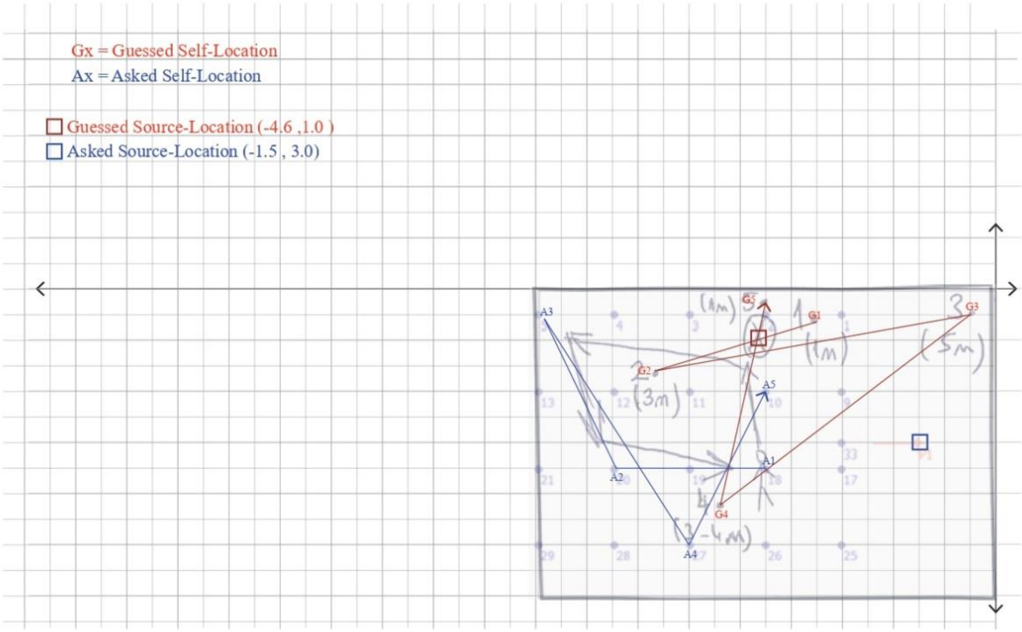
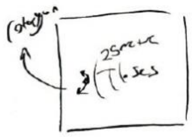


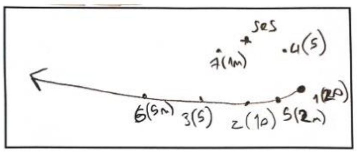
Figure 7-55 First Experiments - Visual Analysis of Soundwalk 47

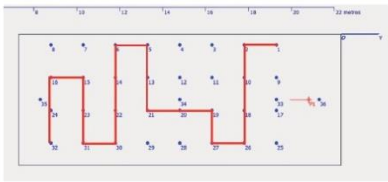
Participant 17 - Soundwalk 48
Soundscape: Soundscape 04 (Long Rectangle Room, Mixed Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 11,8 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

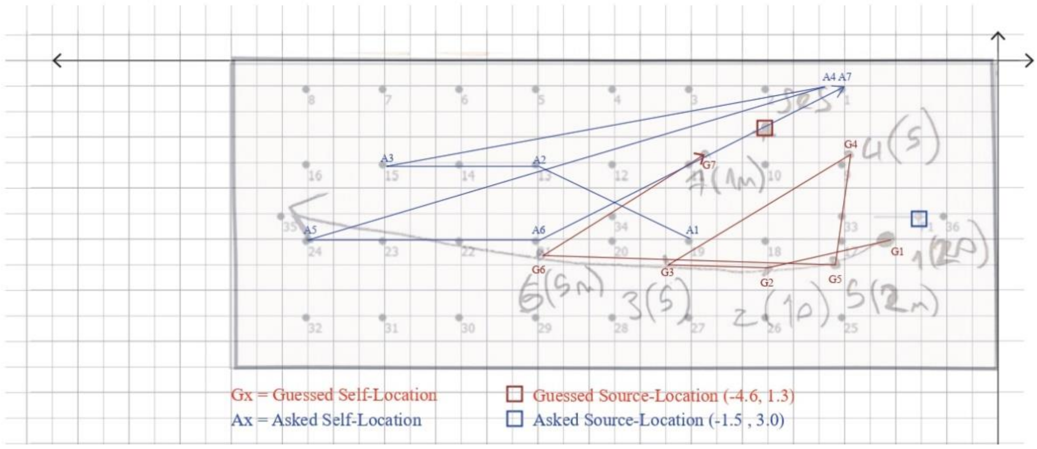
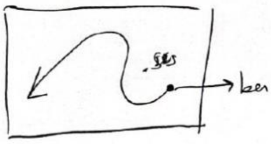


Figure 7-56 First Experiments - Visual Analysis of Soundwalk 48

Participant 17 - Soundwalk 49
Soundscape: Soundscape 15 (L-Shaped Room, Mixed Absorption , Odeon)

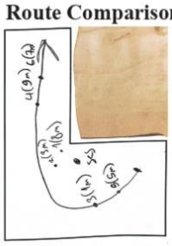
Soundwalking

Mind Map

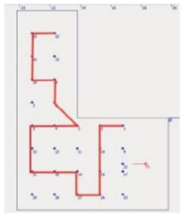


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 16,2 m
Guessed Route Turning Points (by drawing): 6



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

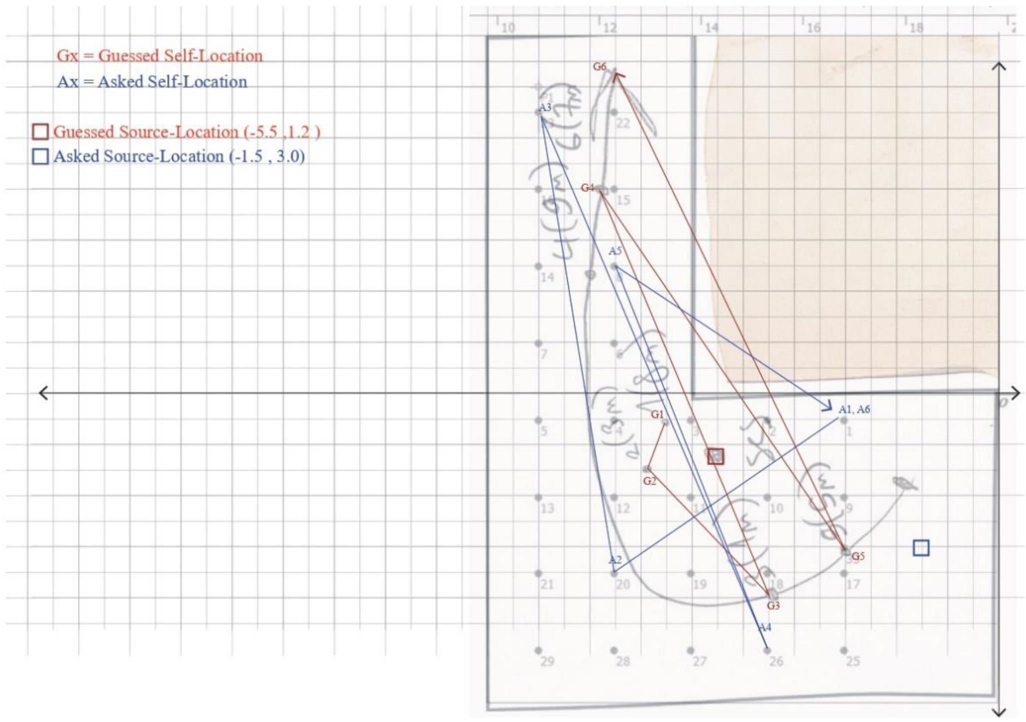
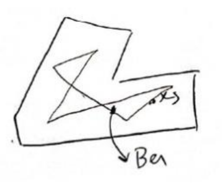


Figure 7-57 First Experiments - Visual Analysis of Soundwalk 49

Participant 17 - Soundwalk 50
Soundscape: Soundscape 07 (L-Shaped Room, Mixed Absorption , VR)

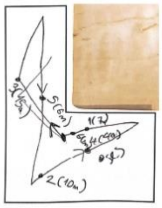
Soundwalking

Mind Map

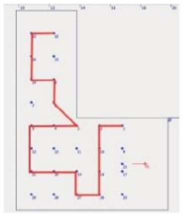


Guessed Room Envelope Corner Number: 7

Route Comparison



Guessed Route Length (by drawing) (m): 33,6 m
Guessed Route Turning Points (by drawing): 5



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

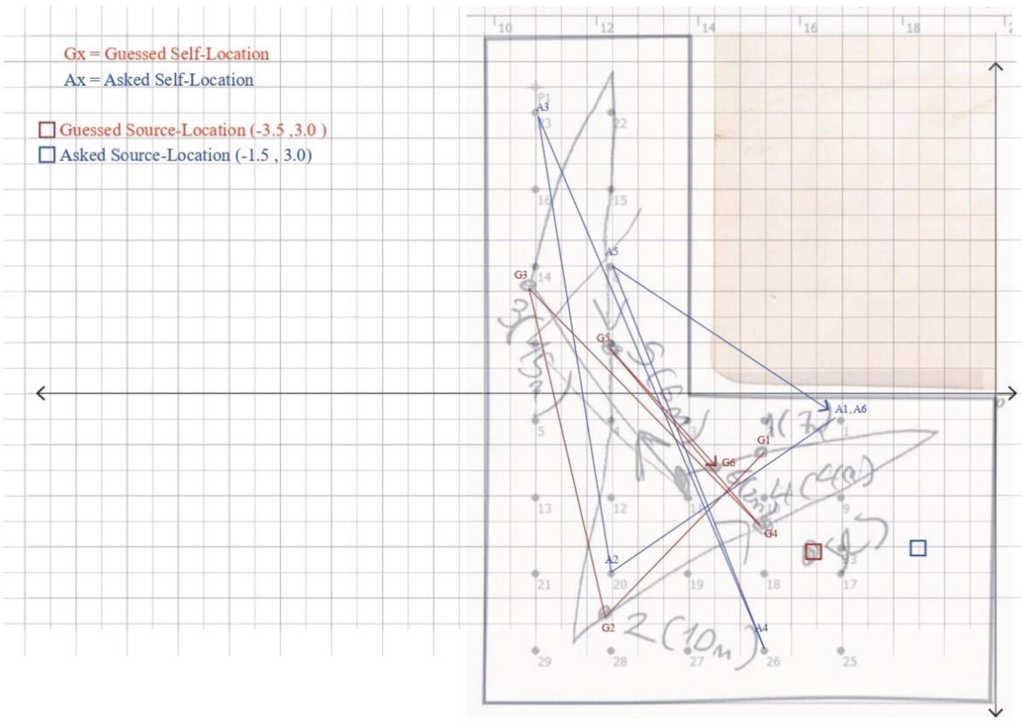
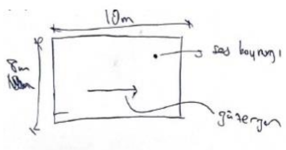


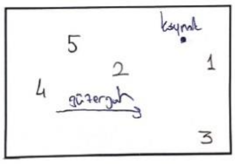
Figure 7-58 First Experiments - Visual Analysis of Soundwalk 50

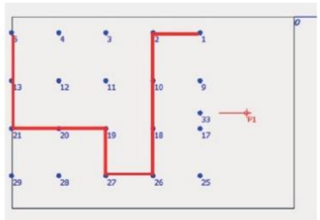
Participant 18 - Soundwalk 51
Soundscape: Soundscape 01 (Small Rectangle Room,10% Absorption , Odeon)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 3,3 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

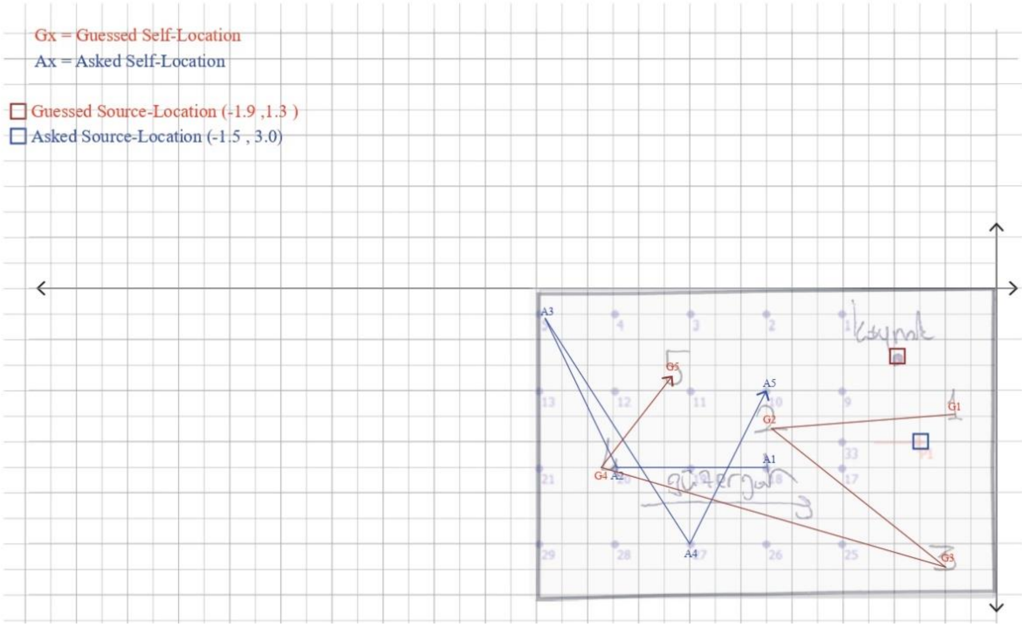
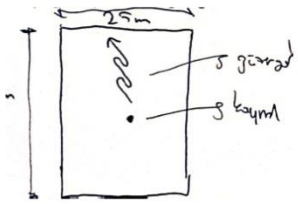


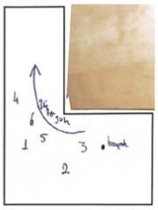
Figure 7-59 First Experiments - Visual Analysis of Soundwalk 51

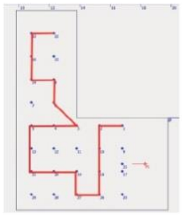
Participant 18 - Soundwalk 52
Soundscape: Soundscape 15 (L-Shaped Room, Mixed2 Absorption , Odeon)

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 6,4 m
Guessed Route Turning Points (by drawing): 4

Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

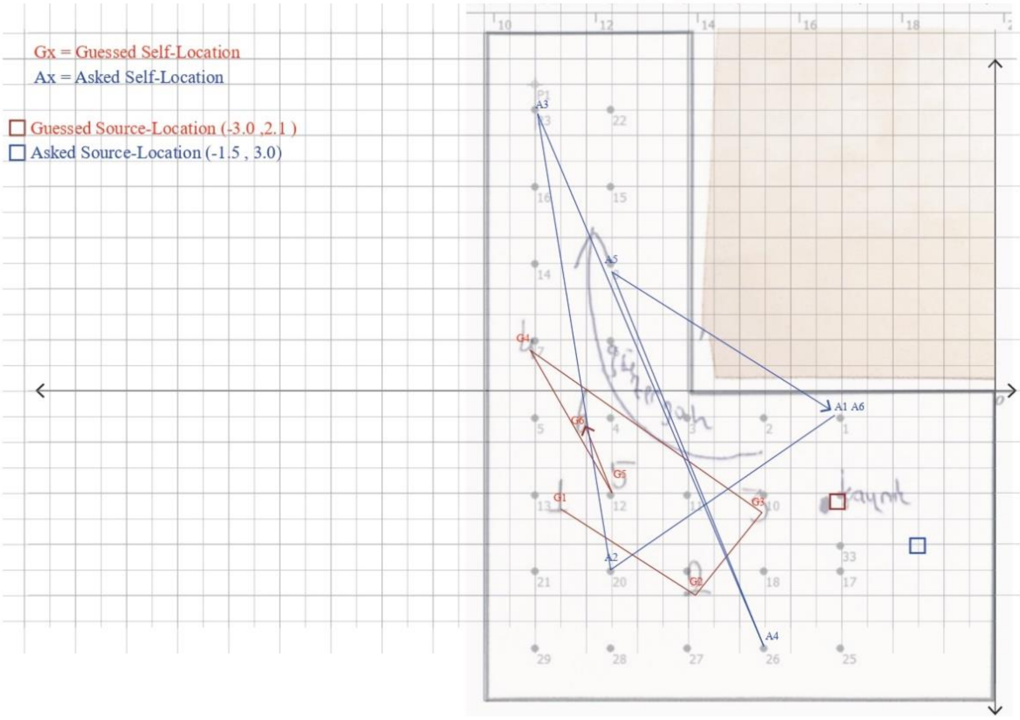
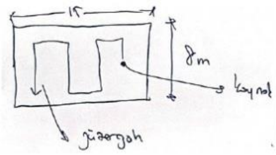


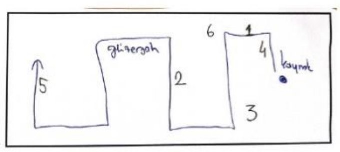
Figure 7-60 First Experiments - Visual Analysis of Soundwalk 52

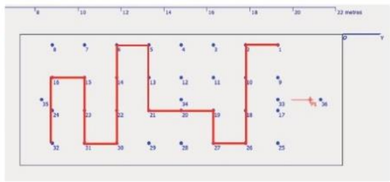
Participant 18 - Soundwalk 53
Soundscape: Soundscape 14 (Long Rectangle Room, Mixed Absorption , VR)

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 28,9 m
Guessed Route Turning Points (by drawing): 7

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

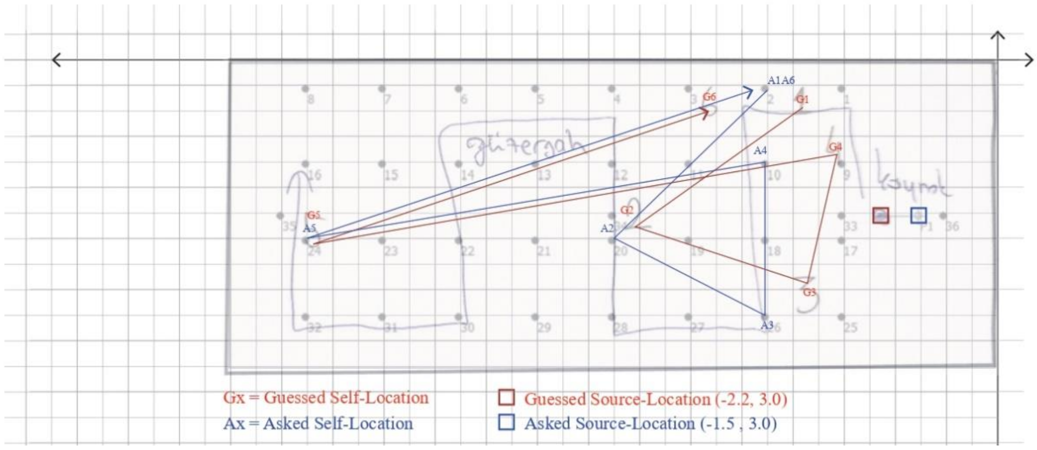
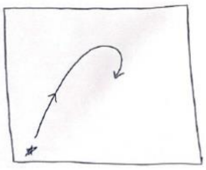


Figure 7-61 First Experiments - Visual Analysis of Soundwalk 53

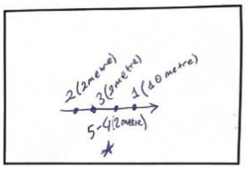
Participant 19 - Soundwalk 54
Soundscape: Soundscape 01 (Small Rectangle Room,10% Absorption , Odeon)

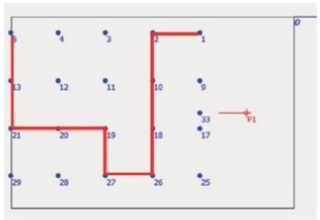
Soundwalking

Mind Map



Route Comparison





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 3,6 m
Guessed Route Turning Points (by drawing): 0

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

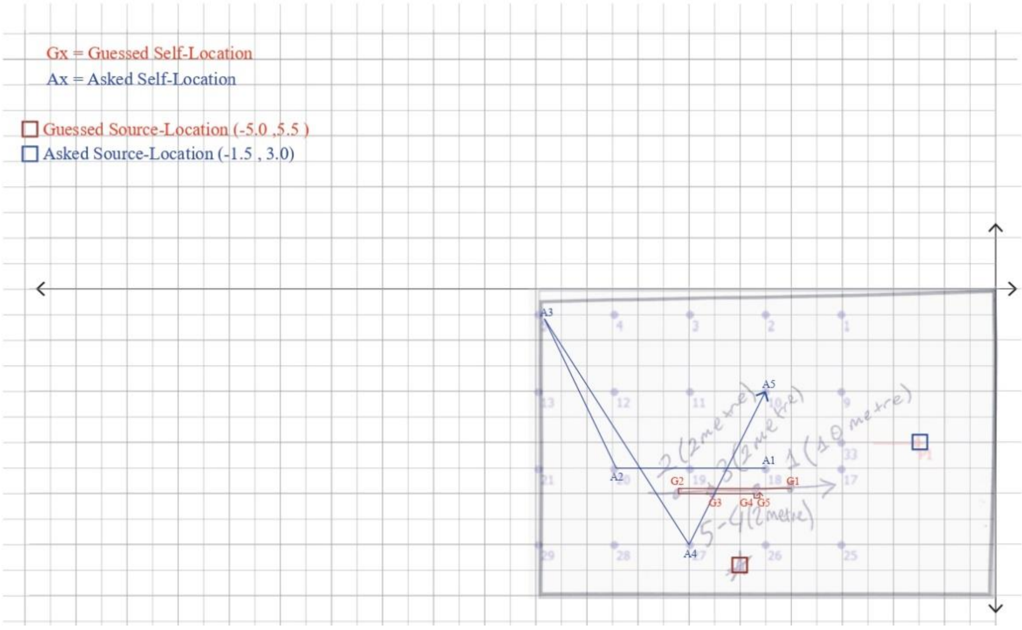
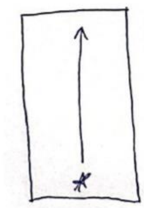


Figure 7-62 First Experiments - Visual Analysis of Soundwalk 54

Participant 19 - Soundwalk 55
Soundscape: Soundscape 15 (L-Shaped Room, Mixed2 Absorption , Odeon)

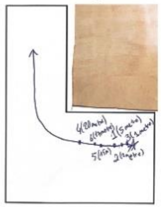
Soundwalking

Mind Map

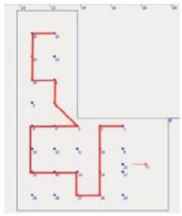


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 14,1 m
Guessed Route Turning Points (by drawing): 5



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

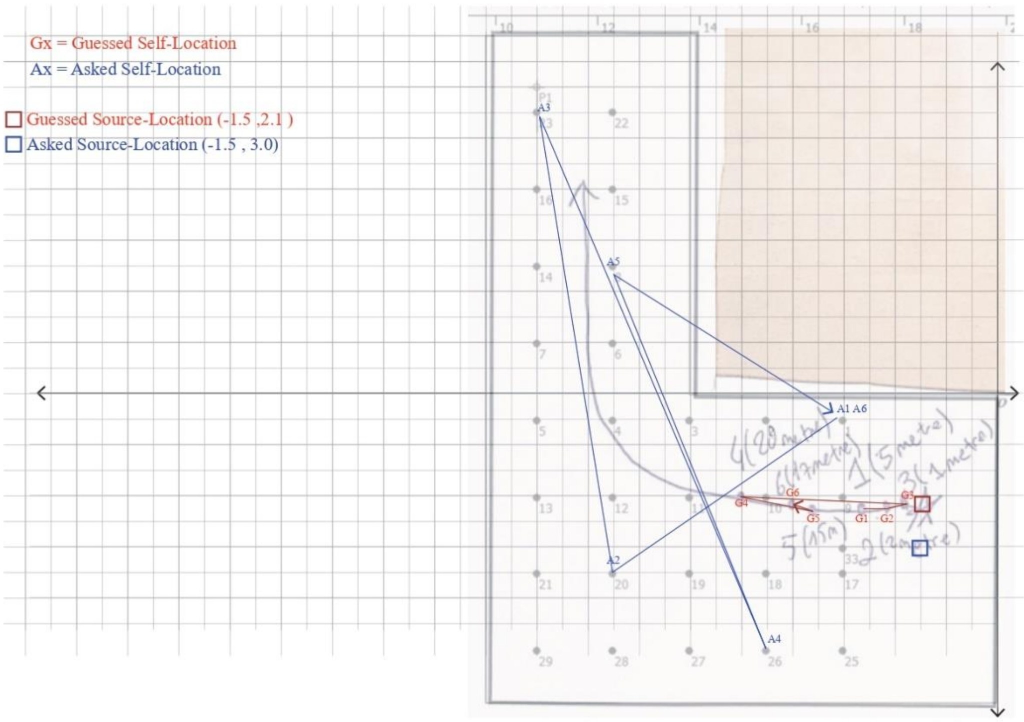
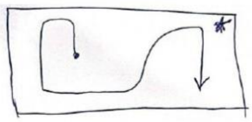


Figure 7-63 First Experiments - Visual Analysis of Soundwalk 55

Participant 19 - Soundwalk 56
Soundscape: Soundscape 13 (Long Rectangle Room, 90% Absorption , VR)

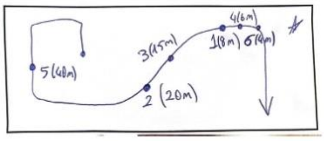
Soundwalking

Mind Map

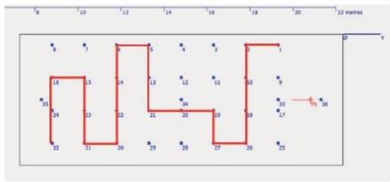


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 23,3 m
Guessed Route Turning Points (by drawing): 12



Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

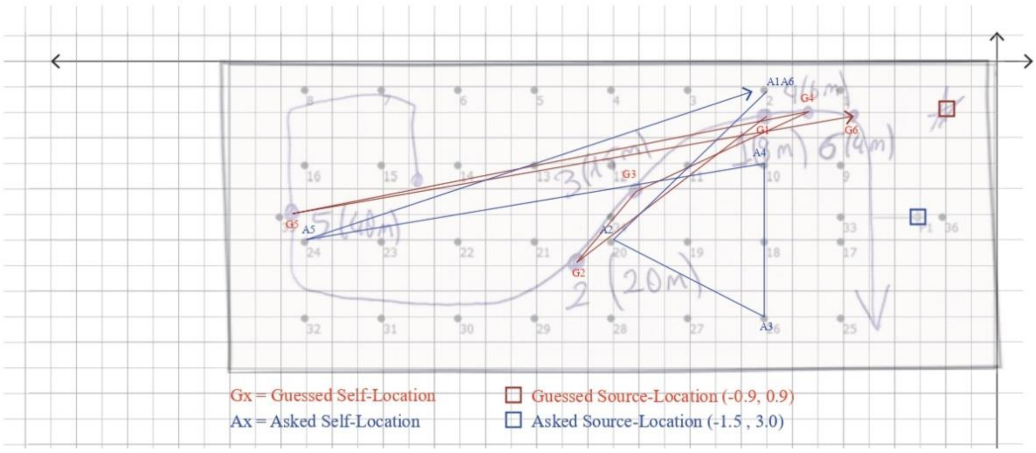
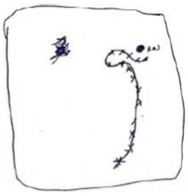


Figure 7-64 First Experiments - Visual Analysis of Soundwalk 56

Participant 20 - Soundwalk 57
Soundscape: Soundscape 01 (Small Rectangle Room,10% Absorption , Odeon)

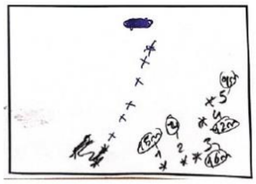
Soundwalking

Mind Map

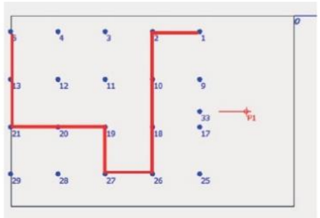


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 4,9 m
Guessed Route Turning Points (by drawing): 0



Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 15 m
Real Route Turning Point Number: 5

Listening Test

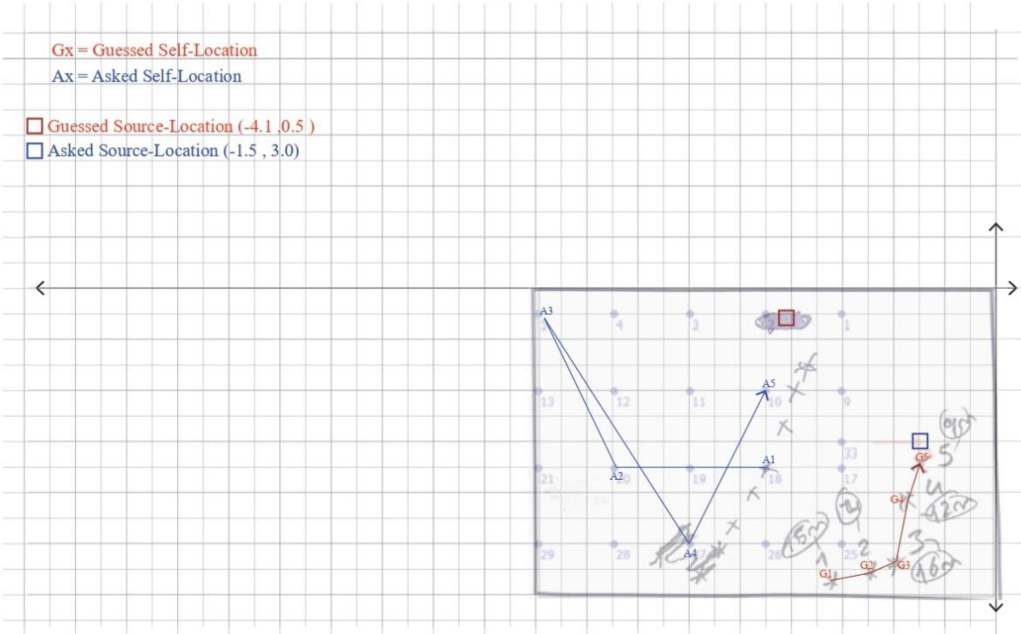


Figure 7-65 First Experiments - Visual Analysis of Soundwalk 57

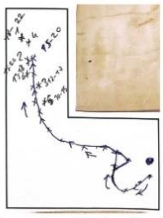
Participant 20 - Soundwalk 58
Soundscape: Soundscape 15 (L-Shaped Room, Mixed2 Absorption , Odeon)

Soundwalking

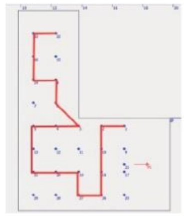
Mind Map

Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 15,1 m
Guessed Route Turning Points (by drawing): 11



Real Room Envelope Corner Number: 6
Real Route Length (by drawing) (m): 27,61 m
Real Route Turning Point Number: 12

Listening Test

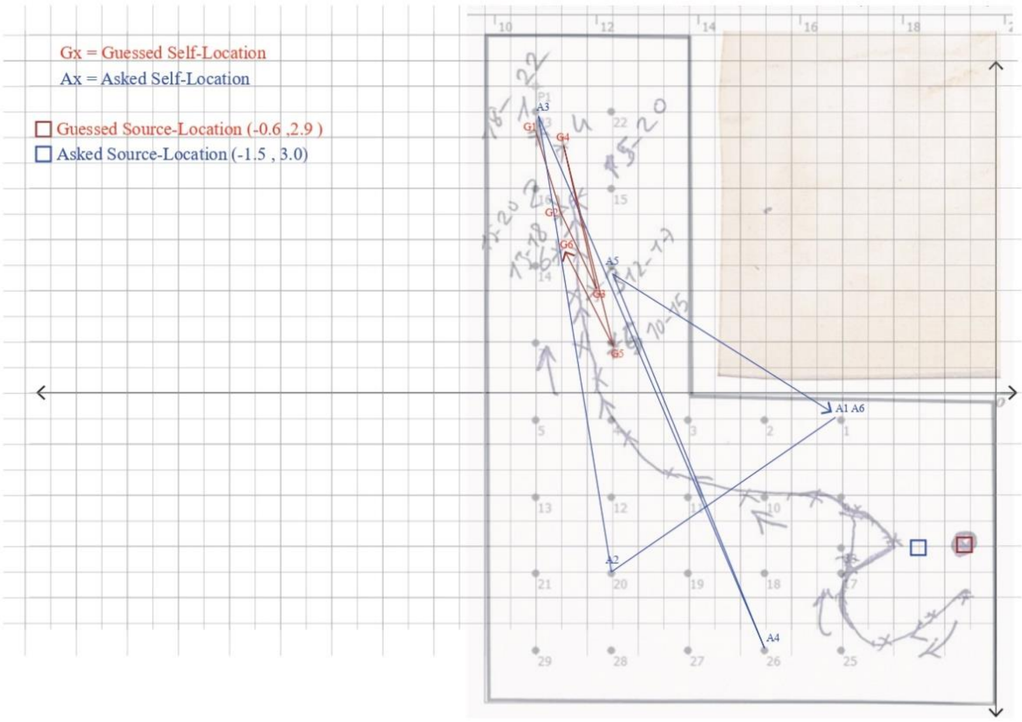
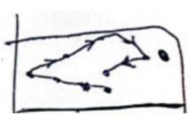


Figure 7-66 First Experiments - Visual Analysis of Soundwalk 58

Participant 20 - Soundwalk 59
Soundscape: Soundscape 13 (Long Rectangle Room, 90% Absorption , VR)

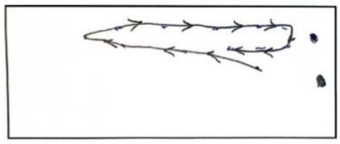
Soundwalking

Mind Map

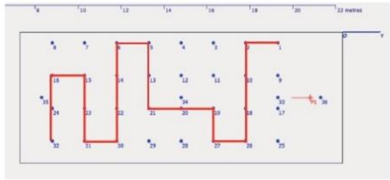


Guessed Room Envelope Corner Number: 4

Route Comparison



Guessed Route Length (by drawing) (m): 20,7 m
Guessed Route Turning Points (by drawing): 9



Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 30 m
Real Route Turning Point Number: 10

Listening Test

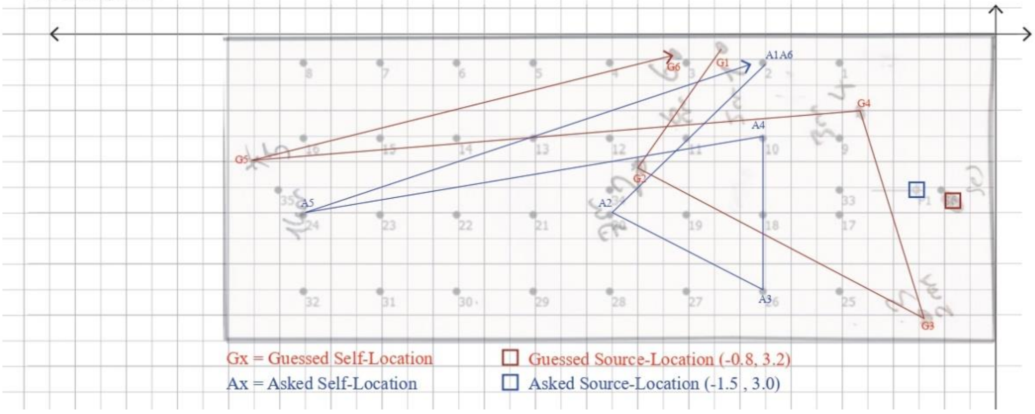


Figure 7-67 First Experiments - Visual Analysis of Soundwalk 59

D. Visual Analysis Process of Each Soundwalk of Case Study Experiments

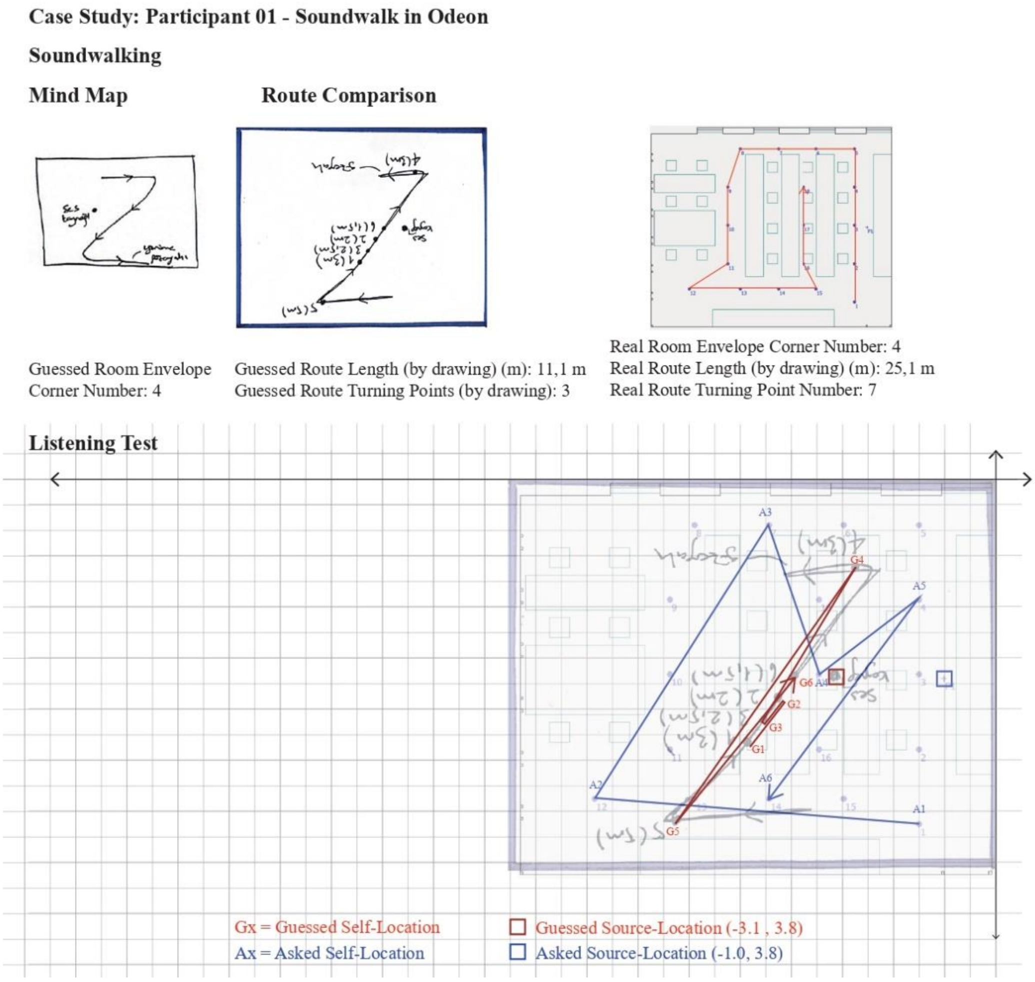
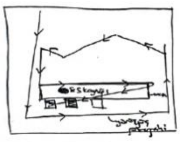


Figure 7-68 Case Study Experiments - Visual Analysis of Participant 01 in Simulated Environment

Case Study: Participant 01 - Soundwalk in Unity VR

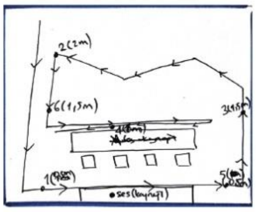
Soundwalking

Mind Map

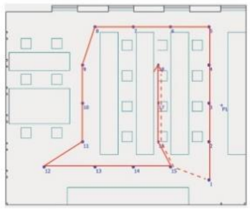


Guessed Room Envelope Corner Number: 4

Route Comparison

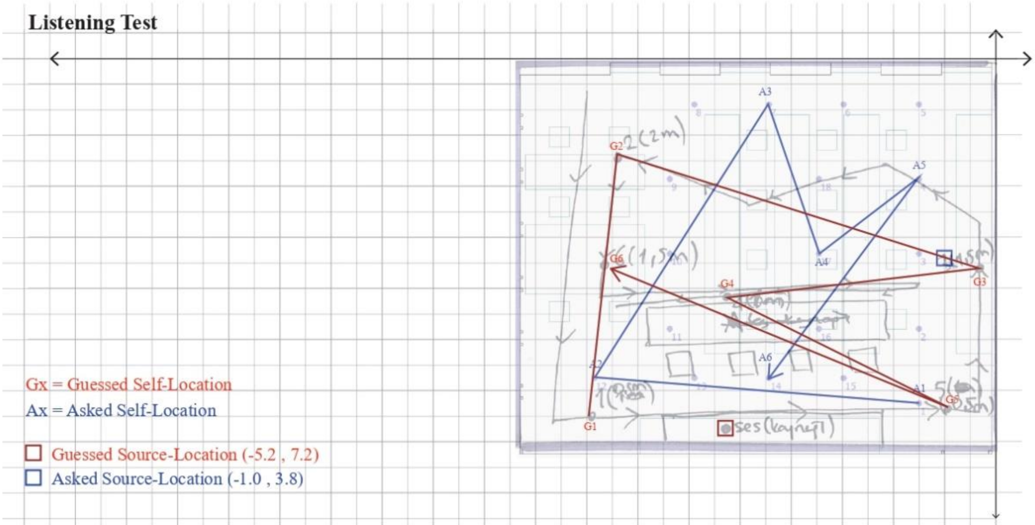


Guessed Route Length (by drawing) (m): 41,2 m
Guessed Route Turning Points (by drawing): 8



Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 31,7 m
Real Route Turning Point Number: 10

Listening Test



Rotated Listening Test

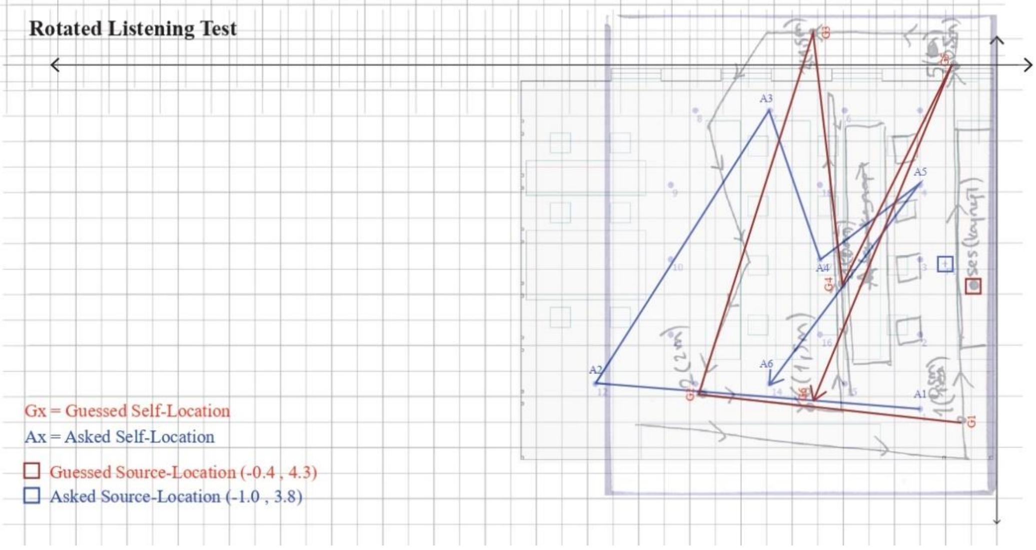


Figure 7-69 Case Study Experiments - Visual Analysis of Participant 01 in Immersive Environment

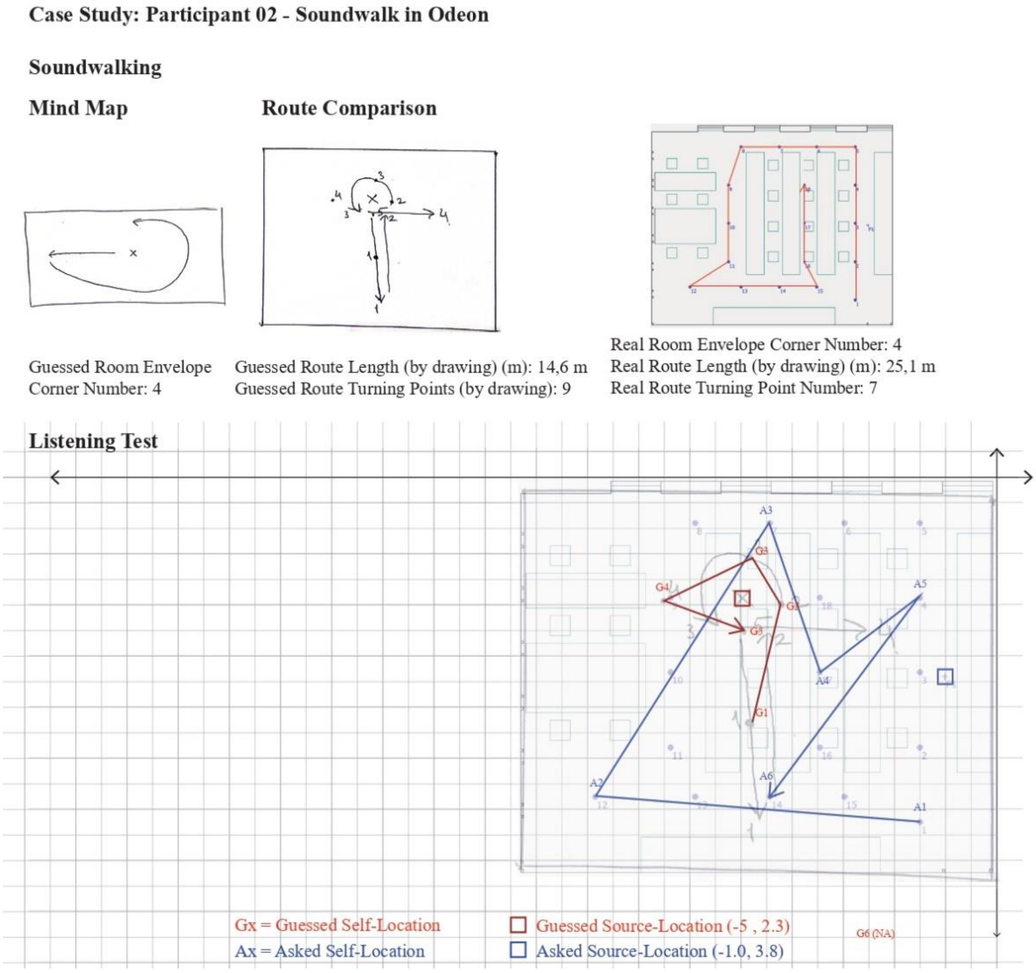


Figure 7-70 Case Study Experiments - Visual Analysis of Participant 02 in Simulated Environment

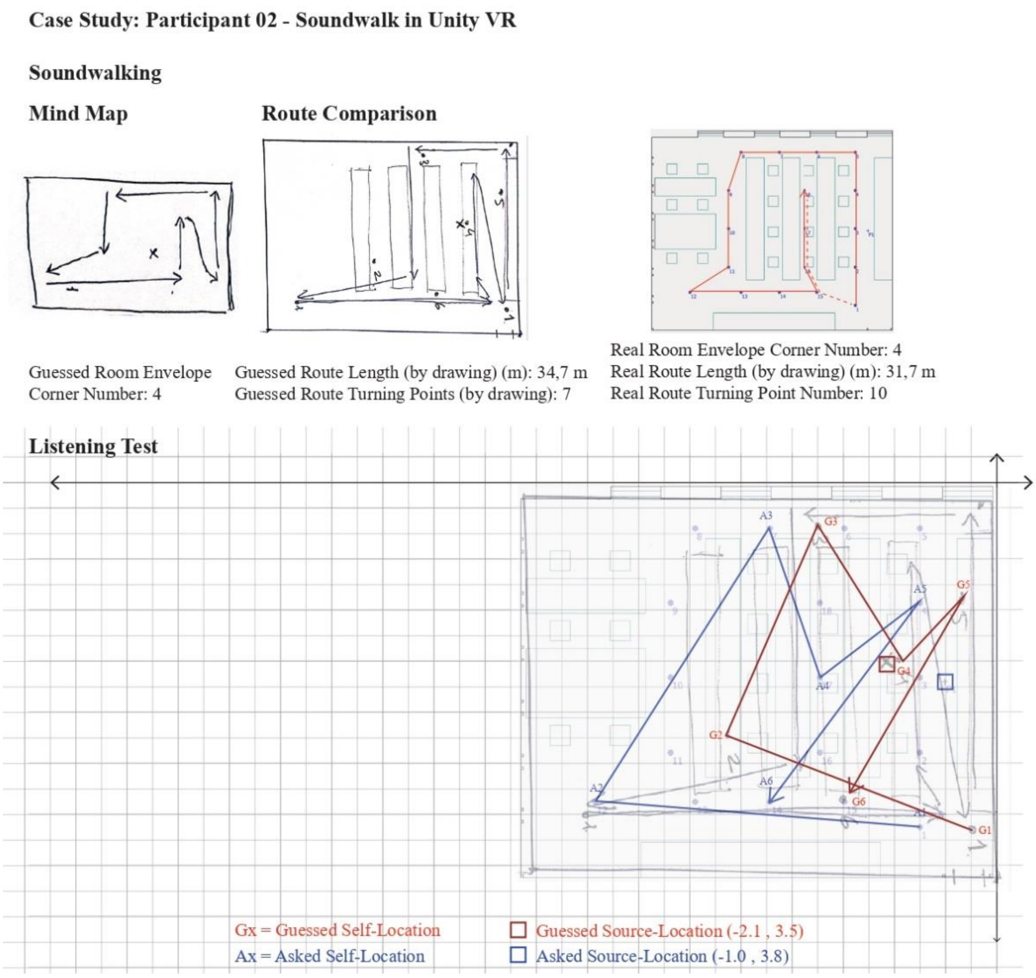


Figure 7-71 Case Study Experiments - Visual Analysis of Participant 02 in Immersive Environment

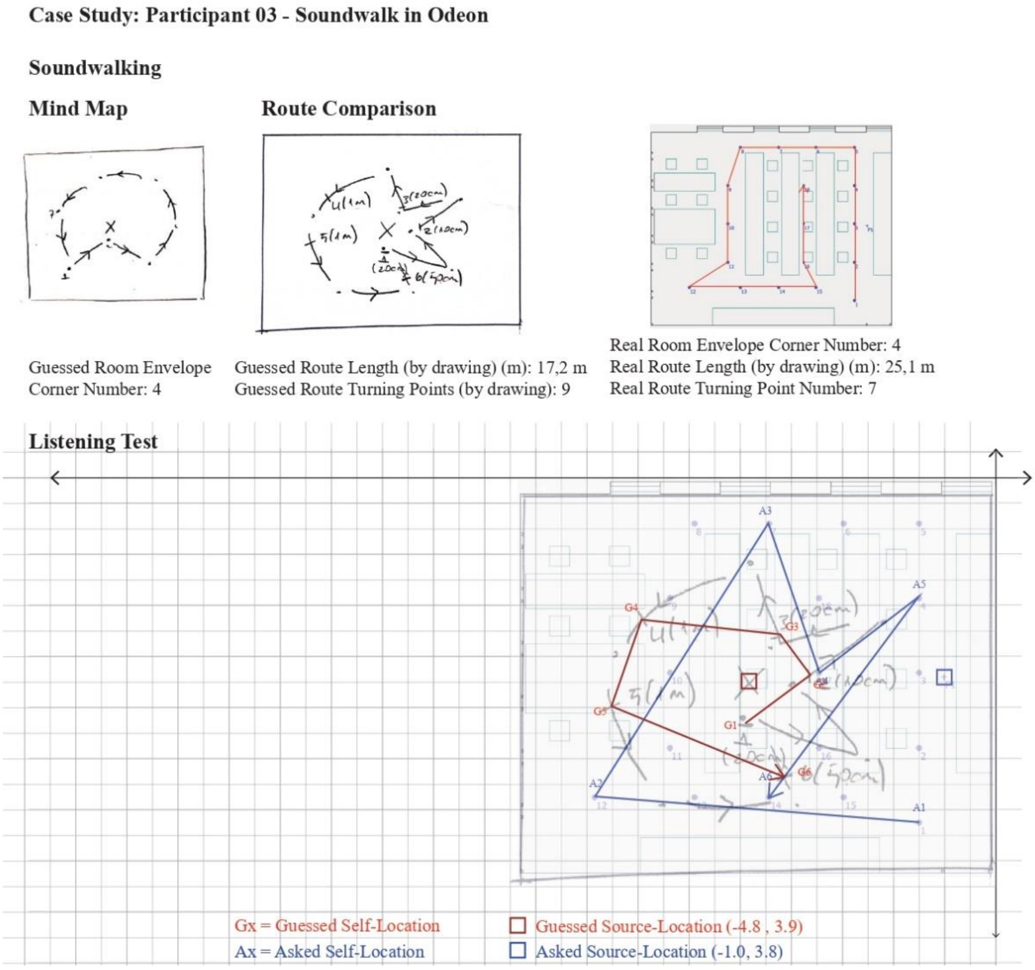
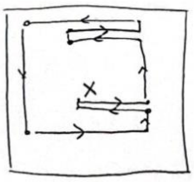


Figure 7-72 Case Study Experiments - Visual Analysis of Participant 03 in Simulated Environment

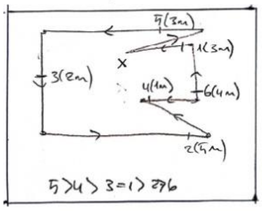
Case Study: Participant 03 - Soundwalk in Unity VR

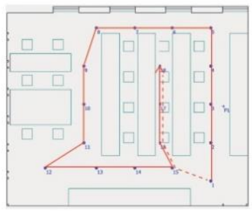
Soundwalking

Mind Map



Route Comparison





Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 28,4 m
Guessed Route Turning Points (by drawing): 7

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 31,7 m
Real Route Turning Point Number: 10

Listening Test

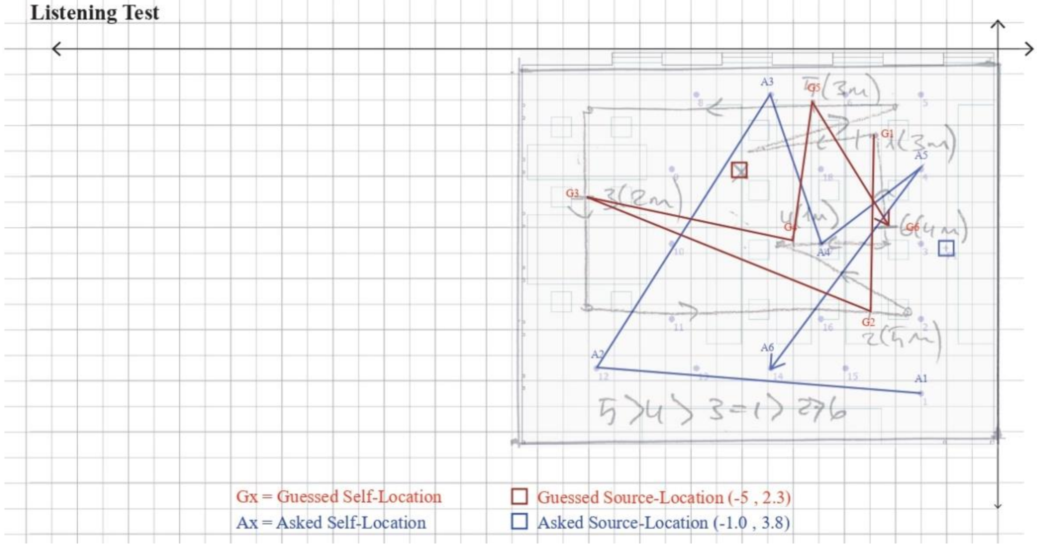
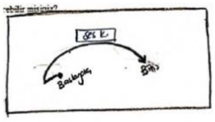


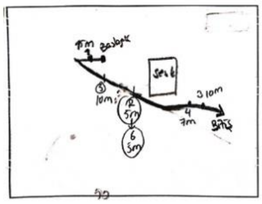
Figure 7-73 Case Study Experiments - Visual Analysis of Participant 03 in Immersive Environment

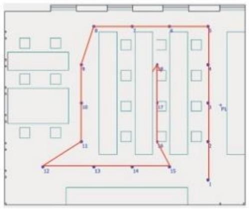
Case Study: Participant 04 - Soundwalk in Odeon

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 7 m
Guessed Route Turning Points (by drawing): 3

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 25,1 m
Real Route Turning Point Number: 7

Listening Test

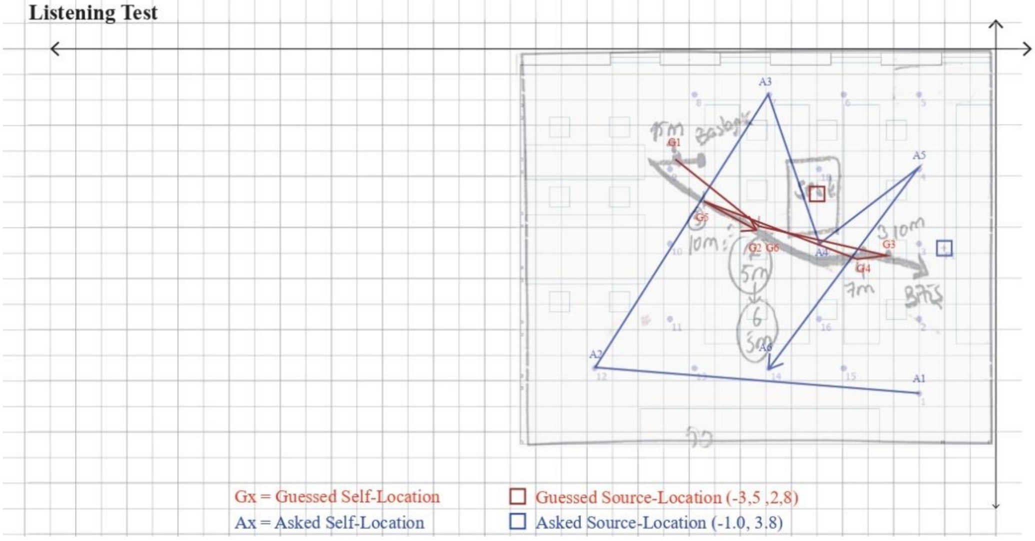
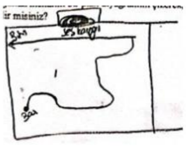


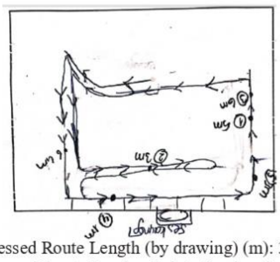
Figure 7-74 Case Study Experiments - Visual Analysis of Participant 04 in Simulated Environment

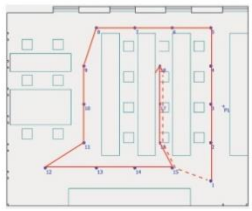
Case Study: Participant 04 - Soundwalk in Unity VR

Soundwalking

Mind Map | **Route Comparison**





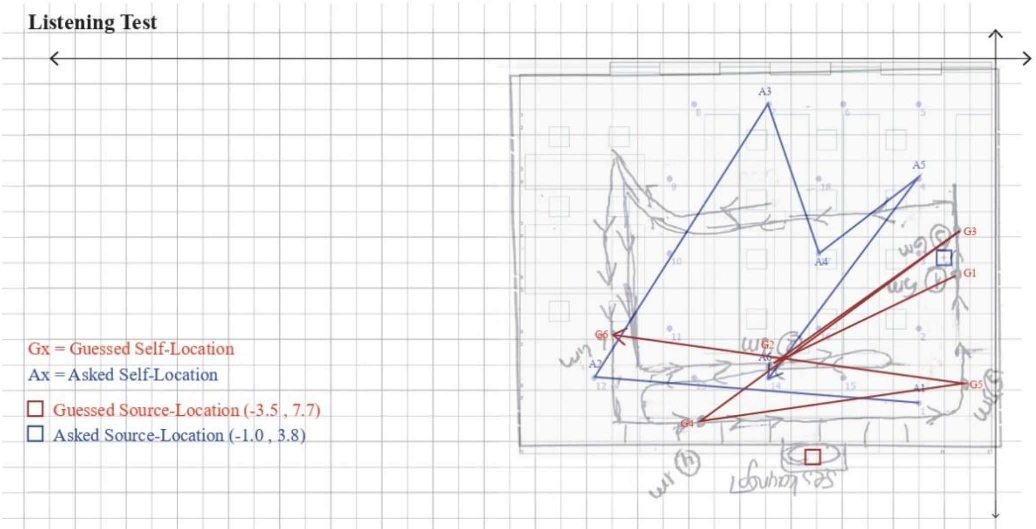


Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 39,4 m
Guessed Route Turning Points (by drawing): 10

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 31,7 m
Real Route Turning Point Number: 10

Listening Test



Rotated Listening Test

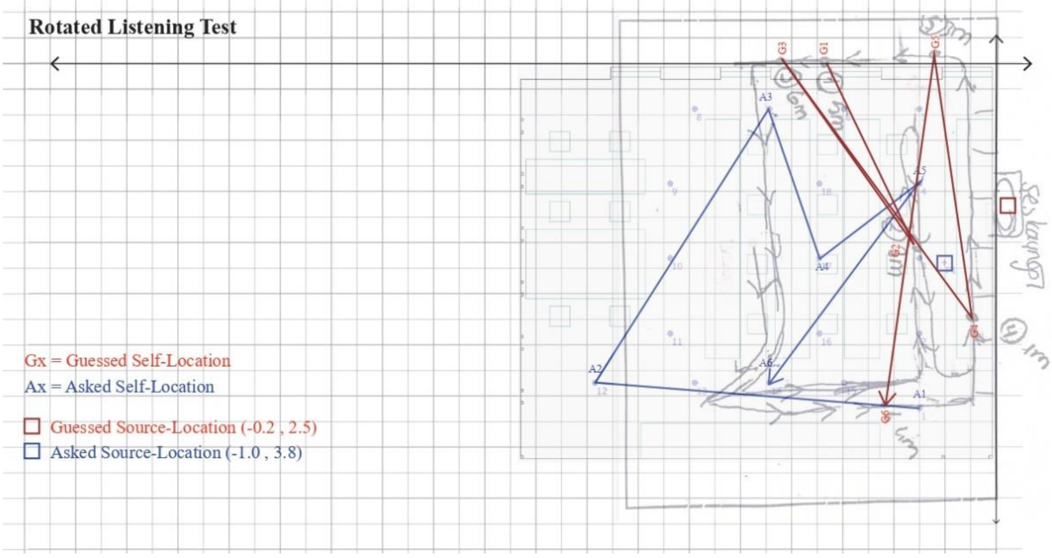


Figure 7-75 Case Study Experiments - Visual Analysis of Participant 04 in Immersive Environment

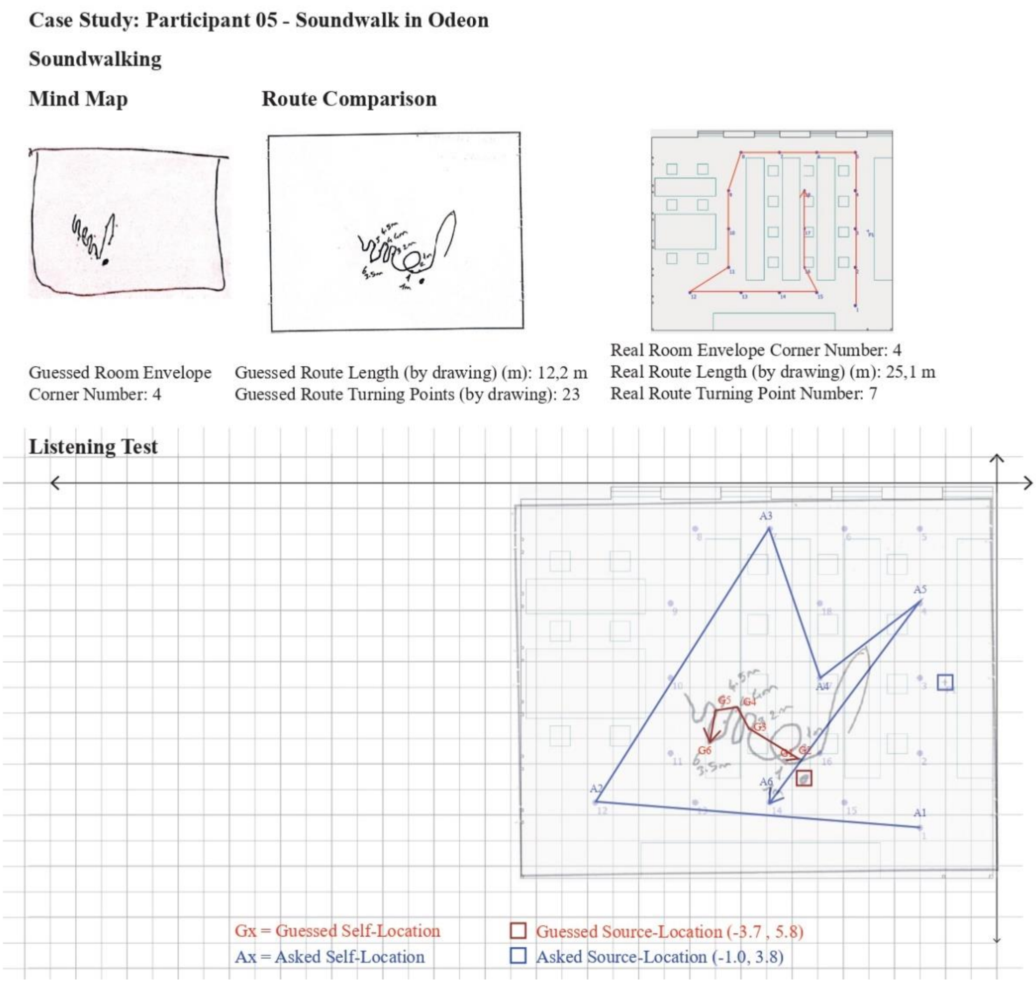


Figure 7-76 Case Study Experiments - Visual Analysis of Participant 05 in Simulated Environment

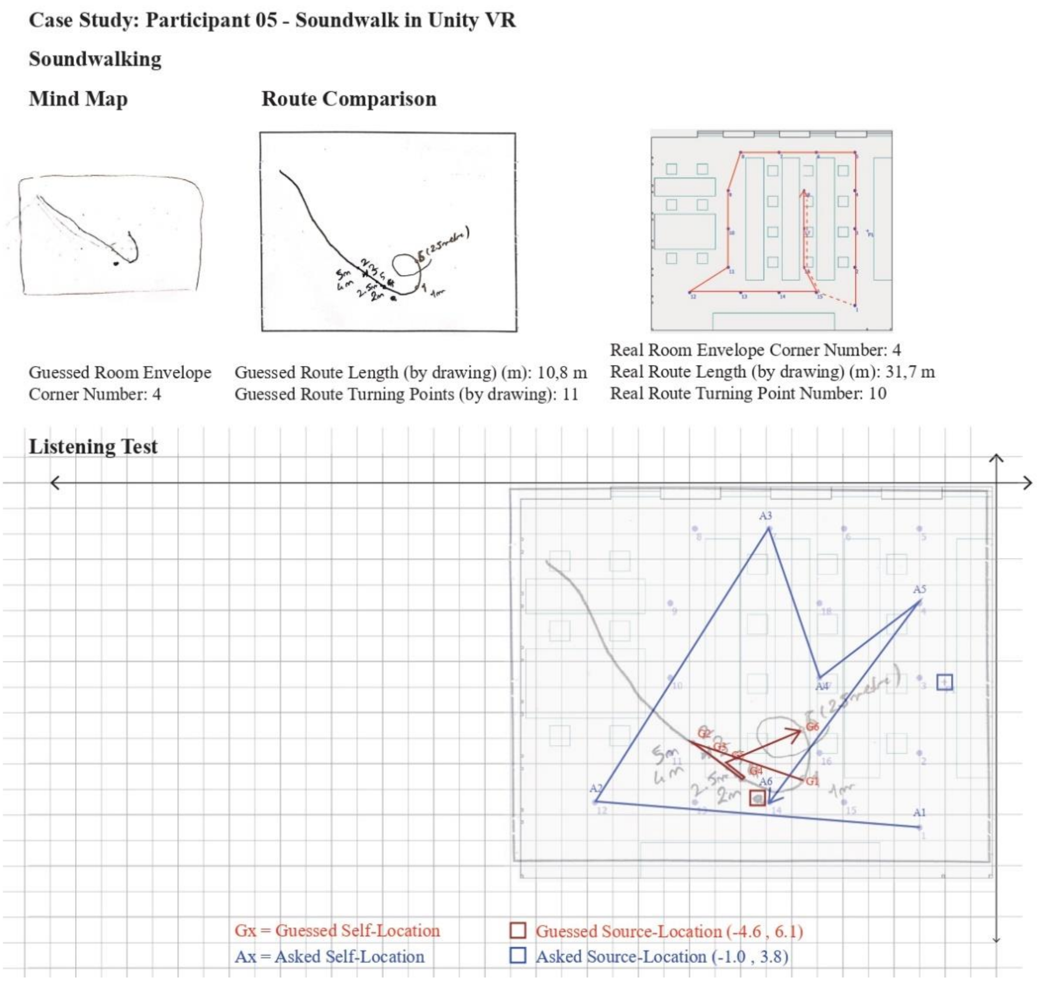


Figure 7-77 Case Study Experiments - Visual Analysis of Participant 05 in Immersive Environment

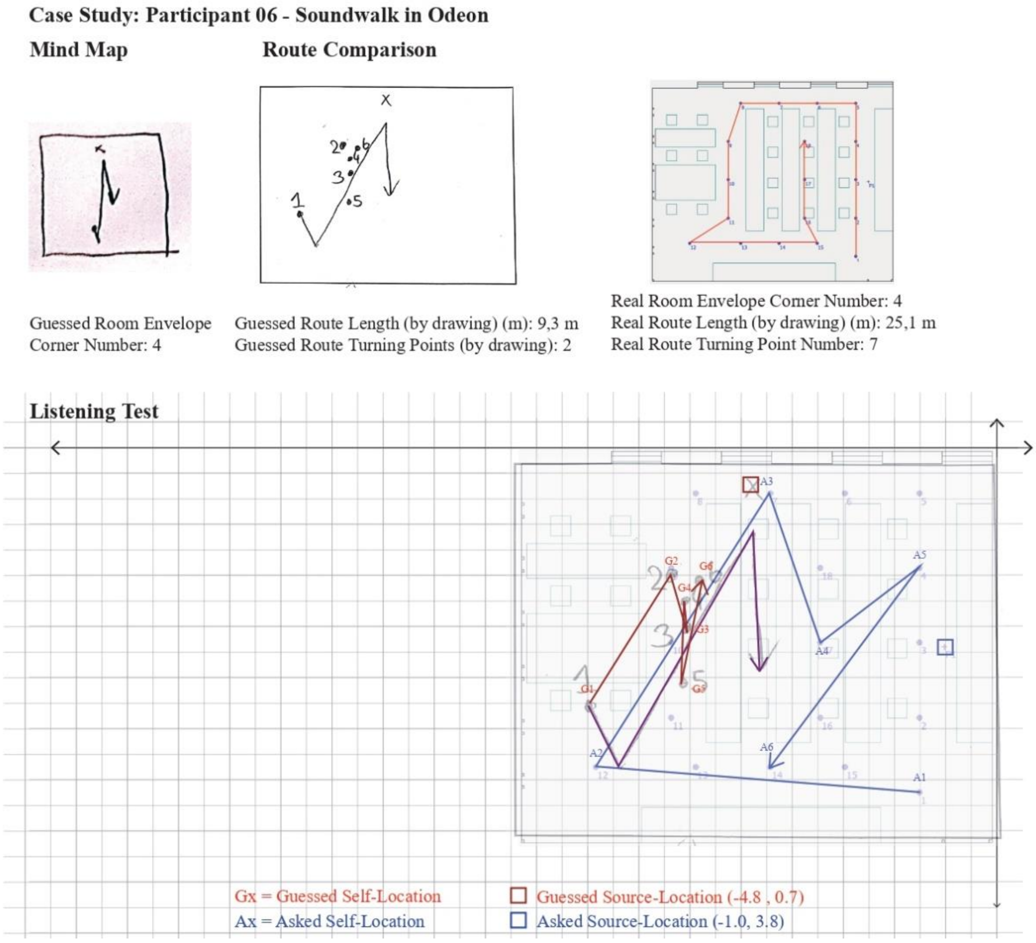
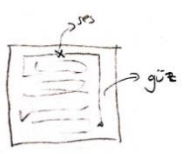
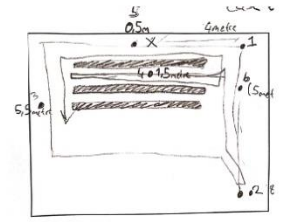


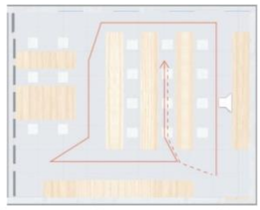
Figure 7-78 Case Study Experiments - Visual Analysis of Participant 06 in Simulated Environment

Case Study: Participant 06 - Soundwalk in Unity VR

Mind Map **Route Comparison**





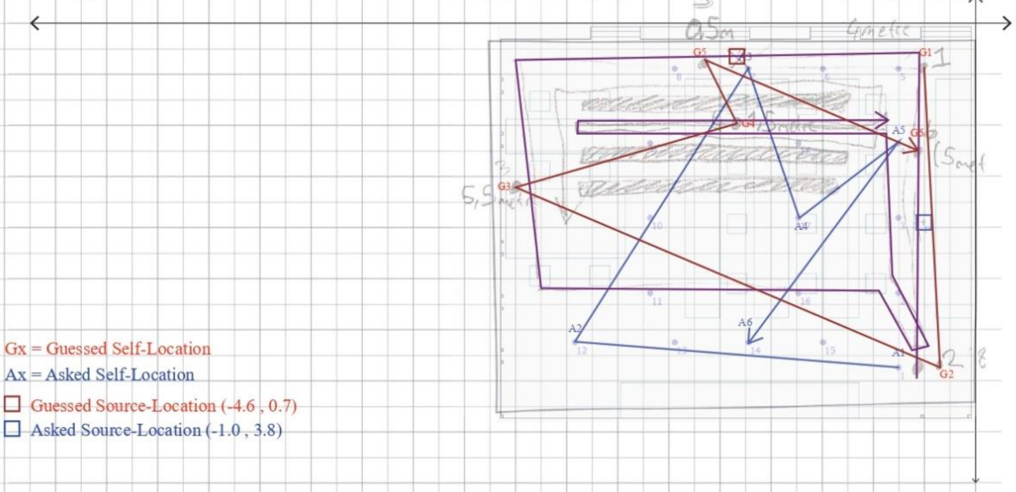


Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 43,1 m
Guessed Route Turning Points (by drawing): 8

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 31,7 m
Real Route Turning Point Number: 10

Listening Test



Rotated Listening Test

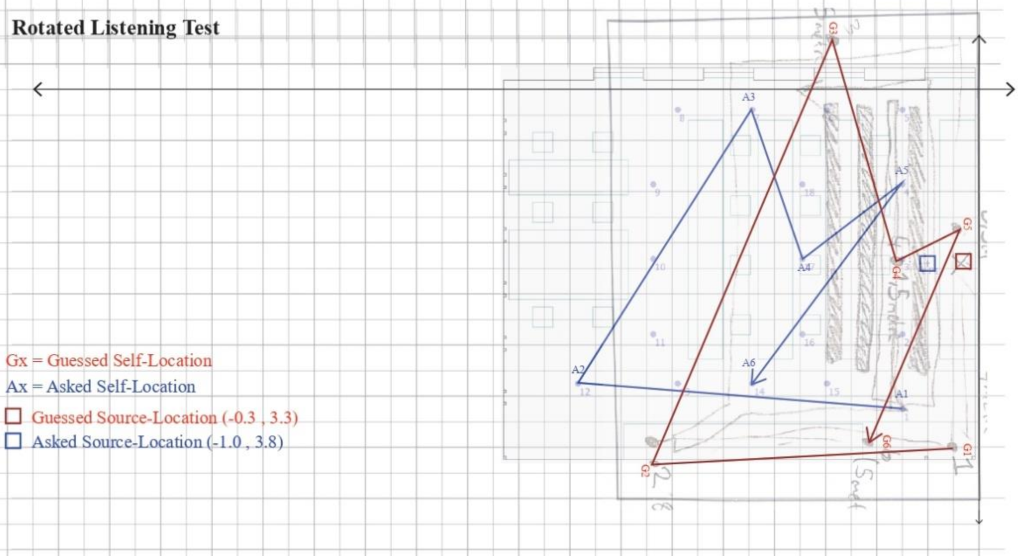
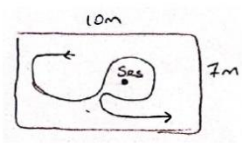


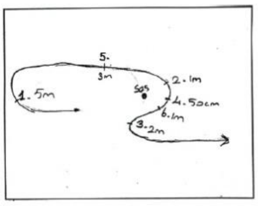
Figure 7-79 Case Study Experiments - Visual Analysis of Participant 06 in Immersive Environment

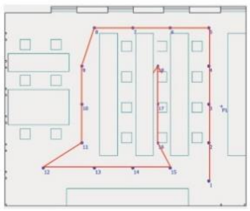
Case Study: Participant 07 - Soundwalk in Odeon

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 15,3 m
Guessed Route Turning Points (by drawing): 10

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 25,1 m
Real Route Turning Point Number: 7

Listening Test

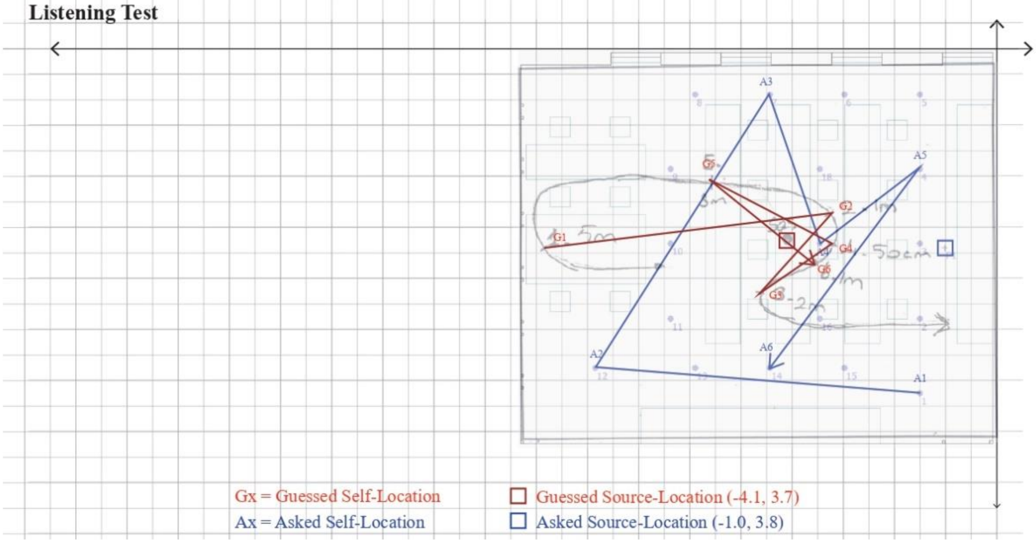


Figure 7-80 Case Study Experiments - Visual Analysis of Participant 07 in Simulated Environment

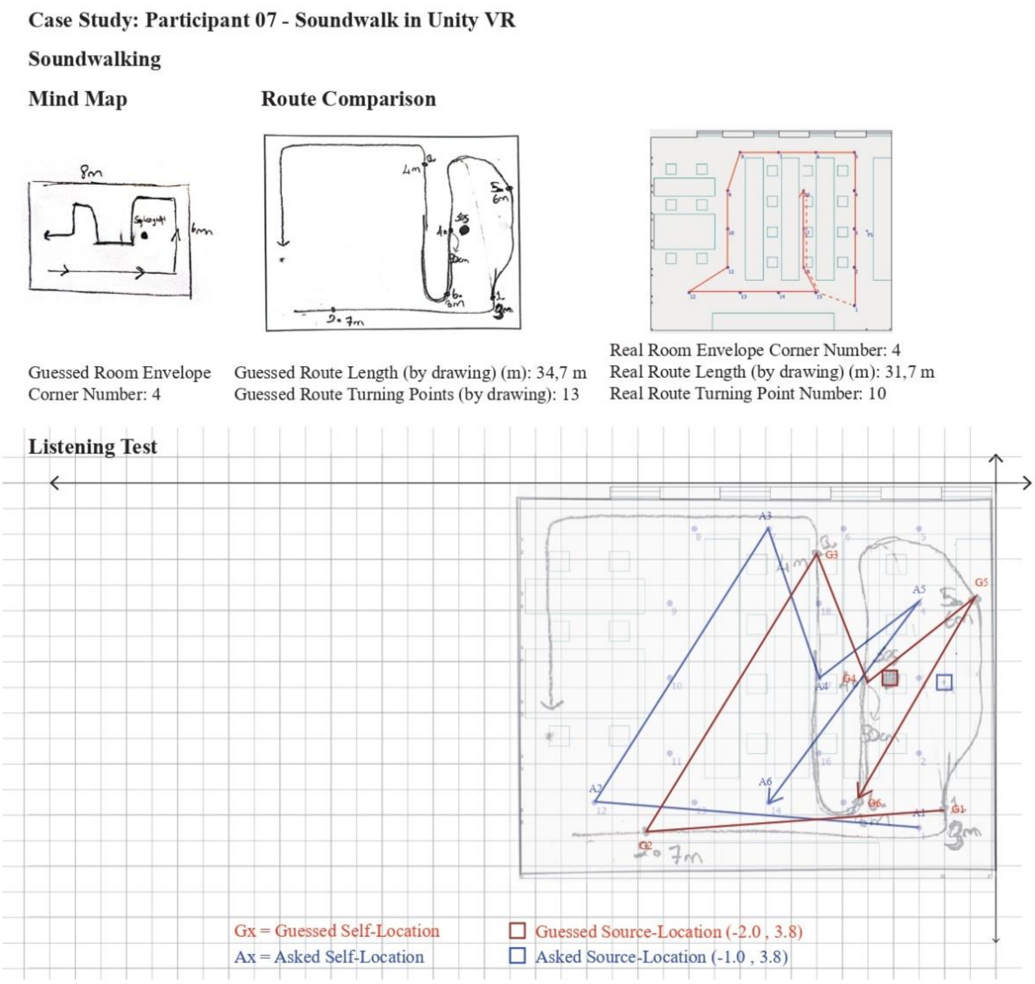
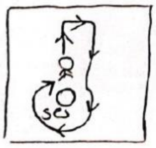


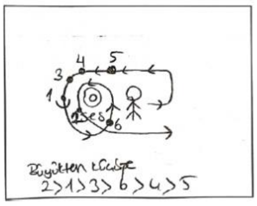
Figure 7-81 Case Study Experiments - Visual Analysis of Participant 07 in Immersive Environment

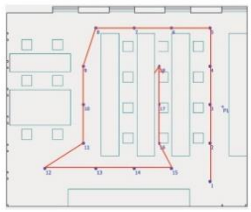
Case Study: Participant 08 - Soundwalk in Odeon

Soundwalking

Mind Map | **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 16,3 m
Guessed Route Turning Points (by drawing): 14

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 25,1 m
Real Route Turning Point Number: 7

Listening Test

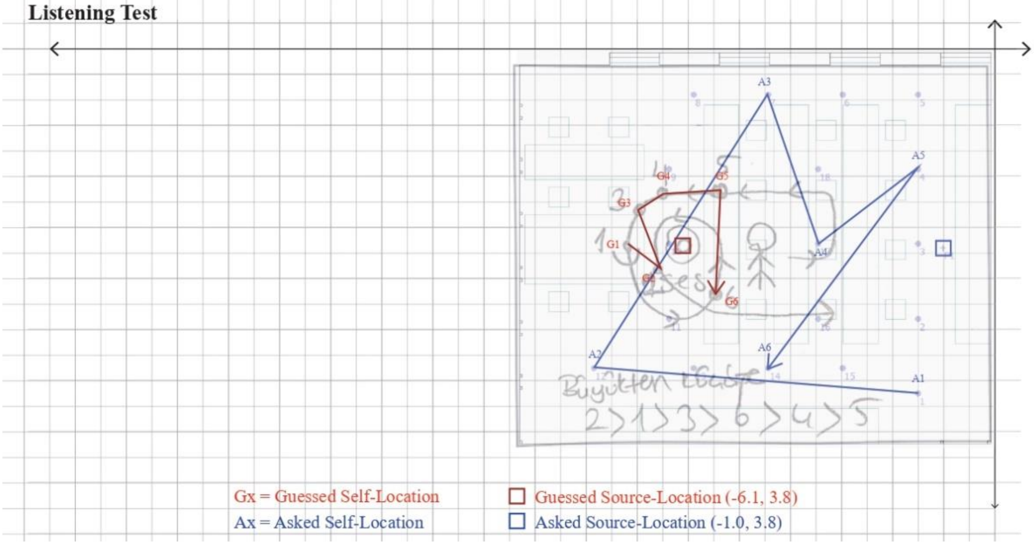
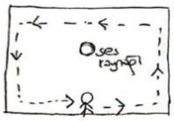


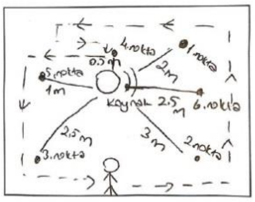
Figure 7-82 Case Study Experiments - Visual Analysis of Participant 08 in Simulated Environment

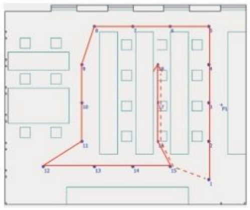
Case Study: Participant 08 - Soundwalk in Unity VR

Soundwalking

Mind Map **Route Comparison**







Guessed Room Envelope Corner Number: 4

Guessed Route Length (by drawing) (m): 30,4 m
Guessed Route Turning Points (by drawing): 8

Real Room Envelope Corner Number: 4
Real Route Length (by drawing) (m): 31,7 m
Real Route Turning Point Number: 10

Listening Test

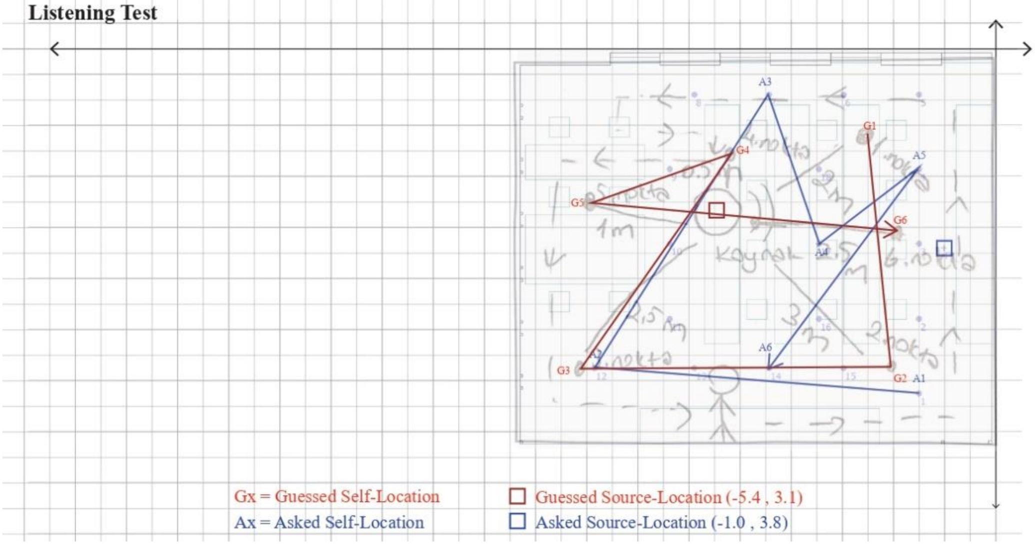


Figure 7-83 Case Study Experiments - Visual Analysis of Participant 08 in Immersive Environment

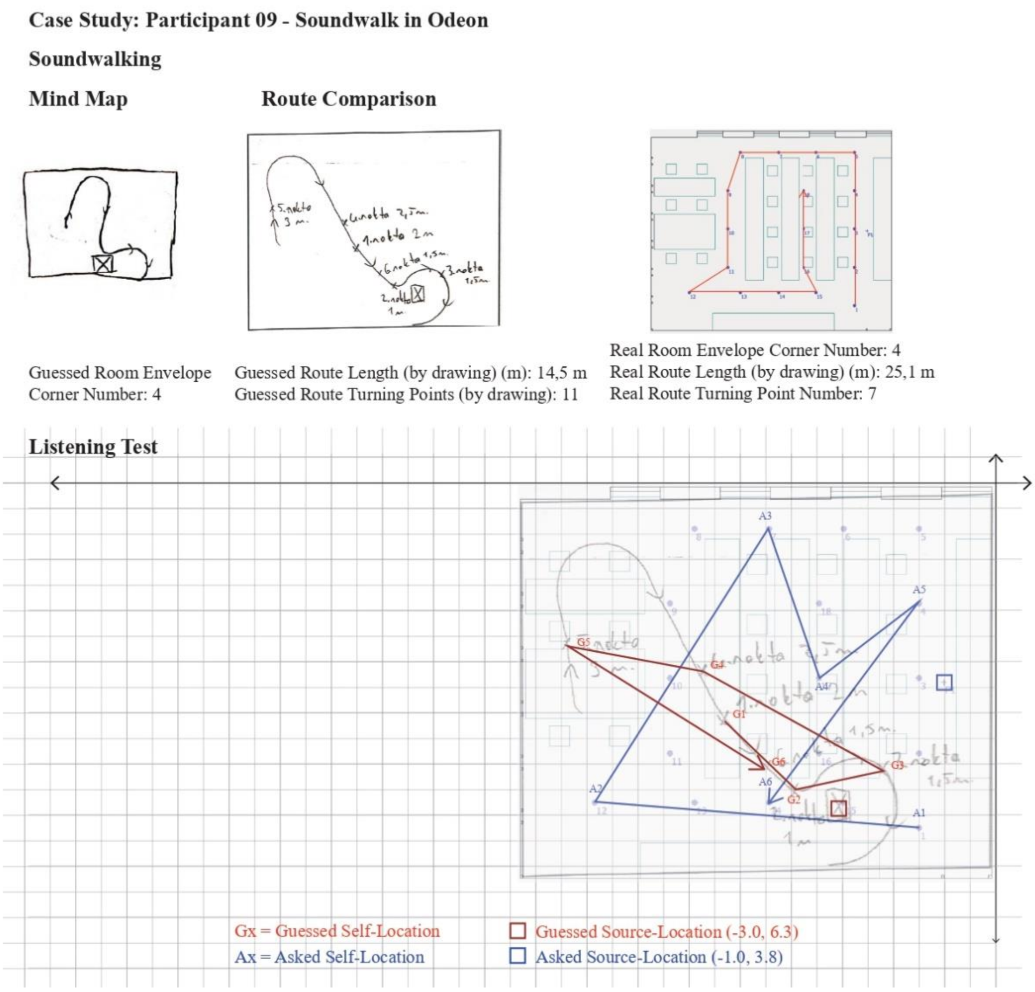


Figure 7-84 Case Study Experiments - Visual Analysis of Participant 09 in Simulated Environment

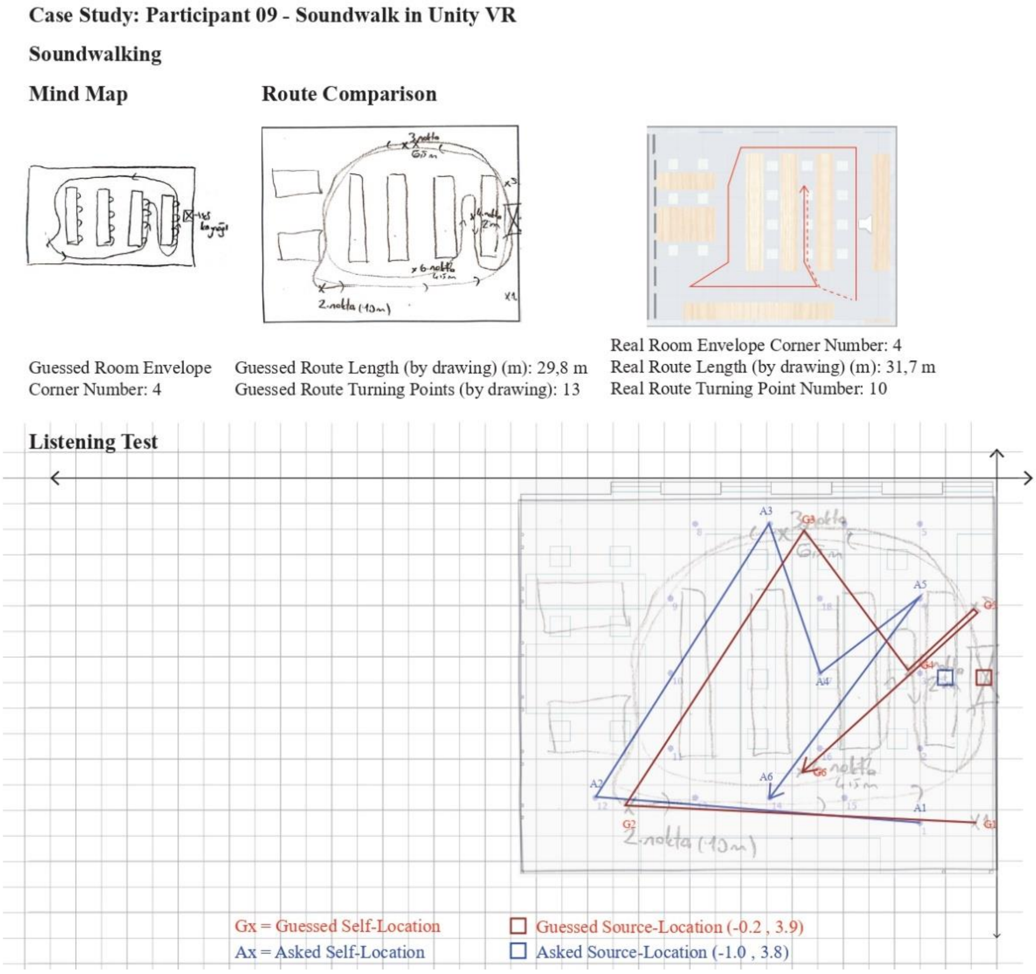


Figure 7-85 Case Study Experiments - Visual Analysis of Participant 09 in Immersive Environment

E. Head Movements of the Participants in Case Study Experiments

Table 7-8 Head Movements of the Participants in Immersive Environment in Case Study Experiments

Participant 01: NA
Participant 02:
First Soundwalk – No head movement.
Second Soundwalk – No head movement.

(Table 7-8 continued)

Point 1 – Fast head movements to left and right (sound source direction) repeatedly.
Point 2 – No head movements.
Point 3 – Slight rotation of head towards the sound source direction.
Point 4 – Looked down first, Rotation of head towards opposite direction of the sound source.
Point 5 - Rotation of head towards the sound source direction.
Point 6 - No head movement.
Participant 03:
First Soundwalk – Tried to match the looking direction to the movement direction.
Second Soundwalk – Tried to match the looking direction to the movement direction.
Point 1 - Head rotates to left and right (sound source direction) repeatedly.
Point 2 - Head rotates to left and right (sound source direction) repeatedly.
Point 3 - Head rotates to left and right repeatedly. Sound source direction was in the middle of the head movement.
Point 4 – Head rotates in all directions with 90 degrees intervals (one of them is the sound source direction).
Point 5 - Head rotates in three directions: front, left (almost sound source direction), and right.
Point 6 - Head rotates in three directions: front, left and right (sound source direction).
Participant 04:
First Soundwalk – No head movement.
Second Soundwalk – No head movement.
Point 1 - Head rotates to left and right (sound source direction) repeatedly.
Point 2 - Head rotates to left then right (sound source direction) again.

(Table 7-8 continued)

Point 3 - Head rotates to right (sound source direction) then left again.
Point 4 – Looked down first, then looked in the direction of the sound source.
Point 5 - Head rotates to left and right (sound source direction).
Point 6 - Head slightly rotates to right, then rotates back to front (sound source direction).
Participant 05:
First Soundwalk – No head movement except small head rotation to left and right at the end.
Second Soundwalk – No head movement.
Point 1 - No head movement.
Point 2 - No head movement.
Point 3 - No head movement.
Point 4 – No head movement.
Point 5 - No head movement.
Point 6 - No head movement.
Participant 06:
First Soundwalk – Repeatedly rotating the head 360 degrees and, up and down head movement few times.
Second Soundwalk – Rotating the head 360 degrees and up and down at the start. Then no head movement except rotating the head towards the sound source when it is very close.
Point 1 - Head rotates to left and right (sound source direction).
Point 2 - Head rotates in three directions: front (sound source direction), left and right.
Point 3 - Head rotates to left (sound source direction), right and left again. Look down shortly.
Point 4 – Head rotates in three directions: right, left, front (sound source direction), and looks down shortly. Then right again.

(Table 7-8 continued)

Point 5 - Head rotates to right (sound source direction) and left back repeatedly.
Point 6 - Head rotates in all directions once.
Participant 07:
First Soundwalk – No head movement except small head rotation to left and right at the start.
Second Soundwalk – No head movement.
Point 1 - Slight rotation between adjacent wall at right and the sound source.
Point 2 – Head rotates to left then right (sound source direction) again.
Point 3 - No head movement except very slight rotation to left.
Point 4 – Head rotates to left and right. Sound source direction was in the middle of the head movement.
Point 5 - Head rotates in right back (sound source direction) and left.
Point 6 - Head rotates left and right front (sound source direction).
Participant 08:
First Soundwalk – No head movement.
Second Soundwalk – No head movement.
Point 1 - No head movement.
Point 2 - No head movement.
Point 3 - No head movement.
Point 4 – No head movement.
Point 5 - No head movement.
Point 6 - Head slightly rotates to right, then rotates back to front (sound source direction).
Participant 09:
First Soundwalk – Repeatedly rotating the head 360 degrees and, up and down head movement few times.
Second Soundwalk – Repeatedly rotating the head 360 degrees and, up and down head movement few times.

(Table 7-8 continued)

Point 1 - Head slightly rotates to front, right, and back. (None of them are the sound source direction)
Point 2 - Head rotates to left then right (sound source direction) again, looking down.
Point 3 - Head rotates to right (sound source direction) and looks up and down.
Point 4 – Head rotates to right then turn back to front (sound source direction).
Point 5 - Head rotates to right (sound source direction) and left back repeatedly.
Point 6 - Head rotates to right and front left (sound source direction), then looked down.