TU WIEN Informatics

Auditory Sensory Substitution in Virtual Reality

for People with Hearing Impairments

DISSERTATION

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by

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Erklärung zur Verfassung der Arbeit

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Wien, 1. April 2023

Mohammadreza Mirzaei

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Abstract

The research presented in this dissertation focuses on sound source localization and audio visualization methods in VR for Deaf and Hard-of-Hearing (DHH) persons. Virtual Reality (VR) has great potential to improve DHH persons' skills, but most VR applications and devices are designed for hearing persons, making it harder for DHH persons to use VR. This dissertation starts with a brief overview of the auditory sensory substitution systems and the importance of audio visualization in DHH persons' daily lives. We discuss how VR can be used as an assistive technology for DHH persons in different areas, such as healthcare, learning, and entertainment. A background survey is conducted to understand DHH persons' requirements in VR to facilitate a better VR experience for them and address some challenges encountered at the early stages of designing an assistive haptic VR system for DHH persons.

The dissertation continues by describing different development phases of our proposed VR assistive systems, including hardware and software designs. We present and evaluate a haptic VR suit that helps deaf persons complete sound-related VR tasks by coding the audio information from a VR environment to vibrotactile cues using four vibro-motors to demonstrate the four main directions of incoming audio (front, back, left, and right). We mount haptic devices on different positions of deaf persons' bodies to investigate their preferred positions and understand if different setups of a haptic VR suit affect completing sound-related VR tasks. Following the results from the haptic suit, we introduce and evaluate a new novel portable system for deaf persons called "EarVR" that analyzes 3-Dimensional (3D) sounds in a VR environment and locates the direction of the closest sound source to the user in real-time using two vibro-motors placed on the users' ears.

Then, we propose a novel audio visualization method in VR called Omni-directional particle visualization to investigate deaf persons' reaction times to visual stimuli and compare the result with other visualization methods. We investigate the effects of multi-modal information presentation in VR on deaf persons' VR experience. Finally, we introduce and evaluate a new novel assistive haptic VR system called "EarVR+," which is an upgraded version of the EarVR system by adding two Light-Emitting Diodes (LEDs) to demonstrate visual feedback. Our methods enhance traditional VR devices with additional haptic and visual feedback, which aids spatial sound localization in VR for deaf persons.

Contents

CHAPTER 1

Introduction

Improving the quality of life for people with disabilities is one of the main goals of scientists working on assistive technologies. Our work focuses on using Virtual Reality (VR) by Deaf and Hard-of-Hearing (DHH) persons. This thesis presents a novel assistive wearable haptic VR system that improves deaf persons' VR experience and helps them complete VR tasks designed for hearing persons. We also present a novel method for visualizing 3-Dimensional (3D) spatial sounds for deaf persons in VR environments using visual elements (particle system).

Our assistive haptic VR system analyzes 3D sounds in VR environments and shows the direction of the incoming sound to a deaf person using visual feedback, haptic feedback, and a combination method. It is low-cost and can be mounted on any desktop or mobile VR Head-Mounted Display (HMD).

Our proposed system and methods improve traditional VR devices with additional haptic and visual feedback, which aids spatial sound localization for deaf persons and makes VR more accessible for them than before. Furthermore, our user studies suggest the importance and benefits of our proposed methods for completing VR tasks among deaf persons, encouraging them to use VR technology.

1.1 Motivation

VR is one of the most remarkable technologies to provide excellent opportunities for people with disabilities. By creating a Virtual Environment (VE) that simulate a user's physical presence in 3D worlds, VR can help people with disabilities expand their skills and knowledge in ways that would not have been possible otherwise [1]. VR helps people with disabilities explore the world, which might be difficult or impossible in real life, by enabling them to engage safely in different activities without the limitations imposed by their disability [2, 1] (Figure 1.1).

Figure 1.1: VR for people with disabilities [3].

According to the World Federation of the Deaf (WFD), more than 70 million people worldwide have disabling hearing loss [4], which impairs communication and social interactions [5]. Based on a categorization from the World Health Organization (WHO), hard of hearing refers to people with hearing loss ranging from mild to severe who usually communicate through spoken language and can benefit from Hearing Aid (HA), Hearing Instrument (HI), Cochlear Implant (CI), and other assistive devices as well as captioning, while deaf people mostly have profound hearing loss, which implies very little or no hearing and often use sign language for communication [6]. Despite the significant advances in assistive technologies for deaf people, access to these technologies is hard for deaf people without proper financial support [7]. Also, most of these technologies have not been tested in VR.

Society is becoming more dependent on technology, and developing accessibility systems that help DHH persons fully participate in society, education, and business is crucial [8]. Thanks to new technological improvements in computer graphics, scientists have shown that VR offers different opportunities to help DHH persons improve their learning process and other skills [9, 10, 11]. Their skills can be improved in a secure and controlled VR environment with methods that might not be possible in the real world [12]. However, hearing loss limits the information available for interpreting and evaluating the user's performance [12], especially in VR environments [13].

Deaf persons cannot perceive audio or perceive it differently [14]. Still, they can use vision and other senses instead of hearing to follow visual effects that help them sense the events in environments [15, 16]. Previous research shows that DHH persons have better peripheral vision, a faster reaction time to visual stimuli, and a better reaction to visual flashes and lights than users without hearing problems [17, 18, 19, 20]. Hearing sounds is the interpretation of sensations and requires a closed feedback loop to continuously evaluate and control actions responding to the sound [12].

In real environments, the origins of sounds might move around the listeners, and they can locate where these origins are at any moment. Therefore, by adding 3D audio to the VE, listeners can sense events around them without depending on their eyes [21]. Audio information has different features based on physical and perceptual properties, such as amplitude, loudness, and frequency spectrum, and has many interpretations [22]. It has been discovered that deaf persons process vibrations in the same part of the brain used by hearing persons [23]. Therefore, audio and music information can be transmitted and perceived in ways other than hearing, such as visual and vibrotactile-based solutions. Due to the particular intrinsic nature of 3D audio and its wide usage in VR, a considerably higher amount of effort is needed to offer deaf persons a comprehensive and tangible view of using immersive audio techniques in VR. Most current research focuses on users with full hearing abilities, while deaf persons have limitations in perceiving audio in VR [13].

In this thesis, we scientifically explore the effects of using vibrotactile devices and different visualization methods, such as graphics, colors, and Light-Emitting Diode (LED) visualizations in VR, to improve immersive VR experience of deaf persons. This thesis includes methods that are traditionally employed in human factors to determine the effect of vibrotactile devices on deaf persons' sound localization, in addition to using different visualization methods. We explore deaf persons' vision and tactile sensation for perceiving the result of vibrotactile audio and the effect of visualization methods on their VR experience. We propose novel methods, such as new wearable haptic VR devices that work in real-time and new visualization methods for sound localization in VR for deaf persons, that offer possible applications for creating new systems in different VR areas for deaf persons.

Our proposed haptic VR device helps deaf persons to experience audio using tactile sensation and visual effects in VR environments designed for hearing persons. The device converts the input audio from VR (in real-time) to signals recognized by the sense of vision and touch of deaf persons. The final prototype consists of a new assistive haptic VR device with an Arduino [24] processing unit. It takes audio from the main computer on which a VR application runs and converts arbitrary audio input signals from VR to visual and vibration patterns of LEDs and vibro-motors mounted on our proposed device.

1.2 Problem Statement

Audio is an inseparable part of people's daily lives. Hearing environmental sounds, listening to music, attending concerts, and dancing are just activities that include audio, and many people enjoy them [25]. Audio is also essential in game development, especially in VR [26]. One of the main challenges in VR is how to immerse people into VEs more deeply by using 3D and spatial audio so that the environment feels more realistic [27]. Previous research shows that 3D audio improves the immersive experience in VR [28, 29, 22]. However, to the best of our knowledge, not many related publications investigated if a substitute for 3D audio is also practical for the immersive VR experience of deaf persons.

Deaf persons cannot interact well in VR environments because of a feedback loop gap (problem that produced by the assistive devices' microphone), which influences task performance [12]. Most VR applications, games, and devices, such as VR HMDs and haptic suits, are designed for persons without hearing problems, causing accessibility issues for deaf persons [30, 31, 32]. Hearing audio is essential in VR for many aspects, such as spatial awareness and sound localization [33]. Not being able to hear audio causes limitations in completing sound-related VR tasks by deaf persons, consequently losing their enthusiasm to use VR technology [34]. In sound-related VR tasks hearing audio and localizing target objects are mandatory in the VE to complete the task [35].

Completing sound-related VR tasks are almost impossible for profoundly deaf persons [13]. Also, hard of hearing persons who use HAs or HIs have issues experiencing audio in VR because most of the VR applications and games do not have optimized audio levels for this equipment, consequently causing annoying noise or unpleasant sounds for them, and a precise audio level in VR environments is required [36]. Additionally, the VR HMDs with embedded headphones are not designed for ears with mounted HAs, HIs, or CIs, which create unpleasant feeling of using VR for DHH persons. However, the feeling of touch and vision can be used to provide information from missing audio [37, 38].

Deaf persons cannot perceive VR environments well, so they are unwilling to use VR technologies [39]. These people have other abilities, such as better peripheral vision and tactile sensation, which help them perceive environments better [17, 18, 19, 20]. Previous studies show that by changing and adding particular elements in VR environments, deaf persons perceive the environments better (more effectively), e.g., by adding 3D sign-language interpreters and 3D symbols as assistants in VR environments [9, 40] or by using real-time subtitles in VR or Augmented Reality (AR) [41, 42, 43] (Figure 1.2).

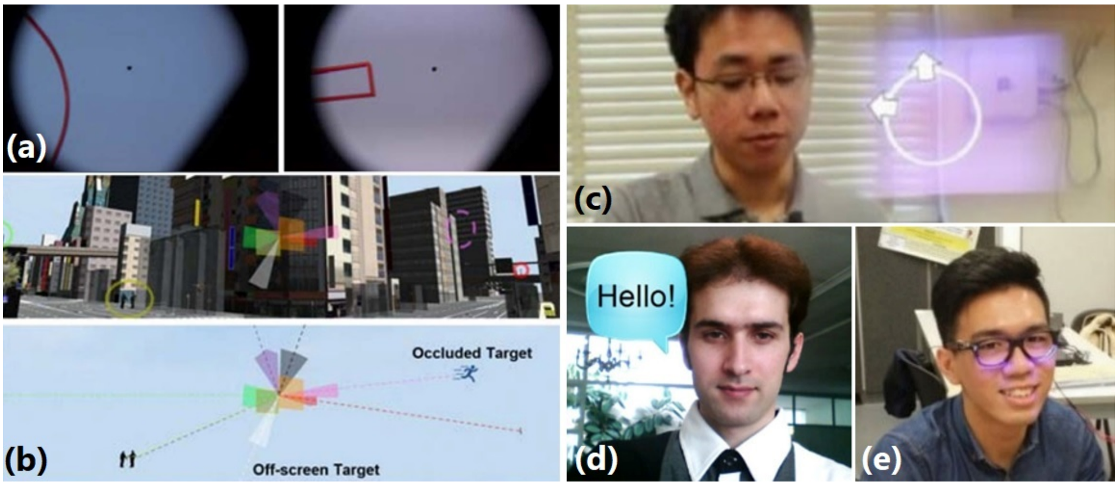

Figure 1.2: Using particular elements in VR/AR for DHH and hearing persons, a) HaloVR/WedgeVR [44], b) 3DWedge/3DArrow [45], c) Sound Awareness in AR [46], d) Audio-Visual Speech Recognition in AR [47], and e) Project PERI [48].

Therefore, audio is still the key point in all these studies and shows the importance of using audio to improve different activities, such as understanding the rhythm of music (different frequency responses), among deaf persons. However, more audio visualization methods concerning VR must be available for deaf persons. Some of the previous research is based on the visualization (visual effects) of the audio generated on the computer, and others worked on vibrotactile and haptic wearable devices and used vibrotactile systems for notification purposes [49]. The following questions arise:

1. What are the fundamental requirements for using VR among deaf persons?
2. How can we improve deaf persons' VR experience using haptic and visual feedback and combination methods?
3. How do different VR visualization methods affect deaf persons' VR experience?
4. How can deaf persons use VR applications and games designed for hearing persons?

Previous research showed that deaf persons' VR experience is different than hearing persons and designing a particular VR environment improves their VR experience [50, 51]. Researchers also showed that not every person with hearing loss is interested in VR, which strongly depends on an individual's association with the hearing or the deaf culture with a personal choice [39].

VR is widely used for distance learning and remote working, but VR options are minimal for people with hearing impairment. There are many challenges for deaf persons in VR that must be considered and addressed when developing a VR application [32]. For example, auto-captioning in audio meeting apps usually has a delay and needs to be consistently accurate, and video calls often lack the spatial context needed for communication in sign language for deaf persons. There is no sense of physical space in video meeting software, so deaf persons cannot communicate fluently in sign language, and their conversations take longer than usual [32].

VR solves these issues by restoring the sense of physical space needed for closed captions, called "Environmental Captioning" (Figure 1.3), but it still has many limitations. VR has not always been conducive to sign language because it traditionally relied on VR controllers. Also, hand tracking and gesture recognition for sign language is still challenging and unavailable in many VR applications [52, 53, 54].

It is possible to use a dialogue system linked to VR avatars, but these dialogues may only be pleasant for people with hearing problems. Based on previous studies that have already been mentioned in this section, such as N. Adamo-Villani [9], B. Agualló et al. [43], and F. W. Ho-Ching et al. [49], it should be possible to develop a low-cost and accessible system for deaf persons using a hybrid visualization method in VR, for example, a combination of vibrotactile haptic devices with visual effects, to improve deaf persons' sound localization in VR.

Figure 1.3: Making VR more accessible for the hearing impaired by using hand tracking (left) and closed captions (right) [32].

Overall, we see that deaf persons had equally positive appreciations regarding all solutions, and the positive feedback received in the case of vibrotactile outputs and visualization methods is highlighted in all of the previous studies. However, to the best of our knowledge, no study in this area used a combination of haptic feedback and visualization methods on deaf persons to achieve real-time sound source localization in VR environments. Most of the previous systems do not work in real-time, and designing a particular VR environment with pre-defined 3D objects, visualization methods, and VR tasks is necessary for deaf persons. Therefore, deaf persons cannot use most VR applications and games designed for people without hearing problems.

1.3 Objective and Contribution

This thesis investigates ways to ease using audio techniques and visualization methods for deaf persons interested in VR. We conduct comprehensive studies to develop, analyze, and compare haptic feedback and visualization techniques in VR by focusing on deaf persons. We introduce a new wearable VR haptic system for deaf persons that helps them use VR applications designed for persons without hearing problems. We combine different methods, such as hardware methods (vibro-motors and LEDs) and visualization methods (graphic arrows and particle system), to use tactile sensation and vision of deaf persons to analyze the effect of using different modalities in VR environments among deaf persons.

Auditory sensory substitution technologies, such as vibro-motors and visual effects, improve the immersion and sound awareness among deaf persons in VR. We developed a VR suit to analyze the optimal number of using haptic devices (vibration motors) and the preferred body positions for mounting the vibro-motors among deaf persons when doing sound localization in VR. Also, we propose different visualization methods (modalities), such as audio, visual, haptic, and a combination of them, to analyze the effect of using different modalities on completing sound-related VR tasks among deaf persons.

We improve the functionality of the methods and make them more accessible for deaf persons. We investigate various VR information presentation methods, such as using vibrotactile devices, LED indicators, and different visualization methods. Using vibrotactile devices (vibro-motors) in a VR suit led us to implement a new wearable VR haptic device for deaf persons to do real-time sound localization in VR. Adding visualization methods, such as arrow indicators and visual effects (particle system) in VR environments, helped us investigate if combining visualization methods with the vibrotactile method affects deaf persons' sound localization in VR. Following the results, we added LED indicators to our proposed wearable VR haptic device to investigate the effect of using visual hardware indicators (LEDs) vs. visual software indicators (graphic arrows and particle system) near using the vibrotactile method.

Following the results, we propose and develop a novel visualization method in VR for deaf persons and an innovative assistive wearable haptic VR device that works in real-time. This method improves deaf persons' immersive experience and sound awareness in VR based on their vision and tactile sensation using vision and on-skin vibrations, and helps deaf persons use VR application and games designed for hearing persons. Furthermore, a survey study was conducted among DHH persons to understand which VR environmental sounds are more important to visualize for these users and which visualization method is more beneficial. VR developers can use this data to design and implement better VR applications and optimize future VR haptic devices for DHH persons.

This thesis's main goal is developing an applicable assistive haptic VR device with new method for deaf persons to help VR developers implement VR applications and games that are usable for deaf and hearing persons. We aim to improve deaf persons' VR experience and encourage them to use VR technology. The results of this thesis can be widely used in future projects trying to make VR or AR applications for deaf and hearing persons with some features which help deaf persons take advantage of VR technology in their life. In summary, the main research contributions of this thesis are:

1. Identifying the information presentation requirements of deaf persons in VR, such as audio and visual information, including multi-modal information presentation methods.

2. Proposing a novel visualization method in VR for deaf persons that helps them perceive 3D audio in VR, eventually improving their VR experience and encouraging them to use VR technology.

3. Designing and developing a novel assistive haptic VR device for deaf persons helps them use VR applications and games designed for persons without hearing problems.
4. Creating guidelines for VR developers that help them build VR applications and games for deaf and hearing persons.

1.4 Methodology

In this thesis, we investigate different aspects of using VR by deaf persons and eventually develop an assistive haptic VR device that improves deaf persons' VR experience. We categorized this research into four phases. These phases were performed in order of priority, beginning from phase one, and have unique research questions and hypotheses that are not necessarily dependent on the other phases, but the results of each phase led to the implementation of the subsequent phases. Overall, the results of all phases led to conclude the thesis. To maintain the coherent structure of the thesis, details of these phases are described in different chapters. The four phases of this research are as follows:

- **Phase One:** In this phase, we start our research by reviewing the literature and testing how effective VR haptic suits are for deaf persons. We find the optimal number of vibro-motors and the most influential body sections deaf persons prefer for mounting. We also study whether deaf persons can locate sounds in VR environments using tactile sensation. We developed a haptic VR suit for deaf persons to visualize 3D audio in experiments related to this phase.
- **Phase Two:** In phase two, we present a novel wearable haptic VR system called "EarVR" based on phase one's result, enabling deaf persons complete sound-related VR tasks. Our proposed system can be mounted on any VR HMD and works as a real-time assistant to receive the sounds from the VR environment and show the directions of sounds to a deaf person. It controls vibro-motors after processing the direction of incoming sounds and helps deaf persons locate audio sources in VR environments. This system helps developers create VR applications and games for deaf and hearing persons.
- **Phase Three:** In phase three, we study whether deaf persons' strong vision and better peripheral view in real environments can also help them in VR by investigating different visualization methods. We propose a new innovative visualization method called "Omni-directional particle visualization" and compare it with other visualization methods to investigate if it improves deaf persons' interactions in VR environments.
- **Phase Four:** In phase four, we optimized the EarVR system from phase 2 using the results of phase 3 by adding a hardware visualization method (LED indicators) to investigate the new system's results, called "EarVR+." We also investigate the possible limitations of our proposed systems and our visualization method by designing more complex VR environments.

At the early stages of this study, a qualitative survey including closed and open-ended questions was conducted among DHH persons to evaluate the participants' attitudes and opinions regarding VR and to manage the basis for conceptualizing approaches that helped us design a practical assistive system and understand how we can provide a better VR experience for deaf persons. The survey responses were coded and analyzed using descriptive statistics and frequency distributions. Qualitative and qualitative analyses were also conducted on the data of each phase to investigate possible patterns or relationships among results and check if our hypotheses for each phase are supported.

We recruited different groups of participants (new participants) for each of our experiments. The participants were recruited through flyers, posters, social media postings, and emails, which will target individuals who meet the study criteria, such as familiarity with VR technology and having tried VR at least once. The control group (persons without hearing problems) was selected from university staff, and DHH participants were selected from the DHH community. We selected DHH participants who did not use HIs, HAs, or CIs since these assistive devices were not tested in VR properly [36] and further studies are required about using them in VR.

For experiments that required profoundly deaf participants, we selected deaf persons with no hearing in both ears who were chosen the profoundly deaf and not using HA or CI options in our consent form (Appendix-A 6.3). We did not examine the deafness level of participants and only trusted their answers. Because of the difficulties of recruiting deaf participants in the country of conducting the experiments (Iran), we welcomed all deaf volunteers willing to engage in our studies. Therefore, we recruited participants with no counterbalancing males and females. Informed consent was obtained from each participant prior to any study activities. Also, for participants under 18 years old, parental consent was obtained, and the presence of one parent was required (without applying their opinion to the participant's opinion).

All participants were aware of VR safety warnings that were carefully stated in our consent form and signed it stating that they have no physical or emotional problems with using VR. However, we asked all participants to experience a demo VR environment different than our experiments' VR environments to ensure they did not have any VR symptoms.

1.4.1 Ethical Aspects

There was no designated institutional review body or research ethics committee to evaluate human research participation at TU Wien at the time of conducting the experiments of this study (Appendix-B 6.3). Also, it is not mandatory to submit non-medical, non-clinical behavioral studies to formal research ethics reviews in Austria and Iran. However, we considered the important ethical considerations to protect the rights of the participants in our study. We ensured that participants were chosen fairly and not based on discriminatory criteria.

Additionally, we ensured that participants were informed of the risks and benefits of participating in the study and that their privacy was protected. We ensured that participants were not coerced or compensated in any way for their participation and that they were allowed to withdraw from the study at any point. Furthermore, we ensured participants that the information collected was confidential and that appropriate measures were in place to protect the data.

1.4.2 Resulting Publications

The results of this PhD dissertation are published in the following peer-reviewed publications:

1. Mohammadreza Mirzaei, Peter Kán, and Hannes Kaufmann. "EarVR: Using Ear Haptics in Virtual Reality for Deaf and Hard-of-Hearing People." In the journal of IEEE Transactions on Visualization and Computer Graphics, vol. 26, pp. 2084-2093, 2020.

2. Mohammadreza Mirzaei, Peter Kán, and Hannes Kaufmann. "Head Up Visualization of Spatial Sound Sources in Virtual Reality for Deaf and Hard-of-Hearing People." In the proceedings of the 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pp. 582-587, 2021.

3. Mohammadreza Mirzaei, Peter Kán, and Hannes Kaufmann. "Multi-modal Spatial Object Localization in Virtual Reality for Deaf and Hard-of-Hearing People." In the proceedings of the 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pp. 588-596, 2021.

4. Mohammadreza Mirzaei, Peter Kán, and Hannes Kaufmann. "Effects of Using Vibrotactile Feedback on Sound Localization by Deaf and Hard-of-Hearing People in Virtual Environments." In the journal of Electronics, Special Issue of Advances in Tangible and Embodied Interaction for Virtual and Augmented Reality, 10(22):2794, 2021.

1.5 Thesis Organization

The thesis continues as follows:

Chapter 2 discusses the background and related work related to audio sensory substitution systems and the effects of using visual and haptic feedback systems on DHH persons' daily lives. This chapter covers the challenges of visualizing audio for DHH persons in different environments, such as VEs, and different VR applications with haptic devices for DHH persons.

The proposed methods overview and the concepts we design to enable deaf persons' accessibility in VR are presented in Chapter 3. This chapter contains the analysis of surveys conducted with DHH persons at the early stage of the research to understand their requirements in VR and to make important decisions for the design part of a system that visualizes VR audio in real-time for deaf persons using haptic and visual approaches.

Chapter 4 describes the initial design and evaluation of our prototype systems consisting of visual and haptic approaches, which are aimed to provide enhanced audio visualization in VR for deaf persons. This chapter describes the technical details of the system and different design optimizations and requirements for deaf persons.

Chapter 5 covers all experiments and results obtained during this thesis development, including the reviews of the initial design of the prototype systems, exploring the different methods of presenting visual and haptic cues to deaf persons, and details of all of the user studies conducted for each system design.

Finally, Chapter 6 concludes the dissertation by summarizing the entire main findings of this thesis and outlining possible future work. This chapter also includes the applicable design methods from this thesis as design guidelines that help VR developers understand deaf persons' requirements in VR environments and knowledge about the effect of using different VR visualization methods on deaf persons for developing immersive VR applications and games for deaf and hearing persons.

CHAPTER 2

Background and Related Work

This chapter briefly overviews the auditory sensory substitution systems and the importance of audio and visualizing it for DHH persons in VR. We briefly explain the role of VR in human life and discuss how VR can be used as an assistive technology to help DHH persons in different areas, such as healthcare, learning, and entertainment. This chapter includes a fundamental overview of visual and haptic feedback and some current methods and techniques related to sound source localization and multi-modal spatial object localization in VR. This chapter will provide the background and technologies used in this dissertation. However, due to the wide range of research areas related to the topic, we only mention the important works and focus more on VR topics.

2.1 Tactile Sense

The sense of touch and tactile feedback are essential for humans because they help interact with the environment, people, and digital technology, by providing information about physical objects and ambient conditions [55]. The sense of touch is the ability to respond to tactile stimulation even when the person is unresponsive to other external events, such as visual and auditory stimulations [56]. The sense of touch happens because actuators in our skin stimulate our somatosensory nervous system [57]. The somatosensory system is complex and contains sensory neurons that respond to changes at the surface or inside the body. This system is divided into several sub-modalities that allow us to distinguish between textures of objects, feel pressure, vibrations, temperature, pain, and position and movement of body parts [58]. Skin is the most significant sensory organ in our body and includes three main layers [59]:

1. Epidermis: the melanin content in this layer is the cause of the skin color.
2. Dermis: contains the nourishing blood capillaries.

3. Hypodermis (subcutaneous layer): functions as an adhesive layer to connect the tissue to the body.

Each layer contains cutaneous sensory receptors and four main types of touch-sensitive receptors and mechanoreceptors that each are specialized to respond to different types of mechanical stimulations (Figure 2.1-a). Merkel receptors respond to pressure and can explore shapes, details, and textures. Meissner corpuscles respond to low-frequency vibrations (around 50 Hz) and can be used to perceive motion across the skin. Ruffini corpuscles respond to skin stretch. Pacinian corpuscles respond to vibrations (around 10-500 Hz) and percept texture by moving the fingers on a surface [60]. Pacinian and Meissner corpuscles are very important for sensing vibrations and providing haptic feedback in the human body [61]. However, the perception of tactile stimuli often involves the coordinated activity of different types of neurons working together [60]. Each time a stimulus exceeds the sensory threshold, the related receptors transfer information to the brain by using nerve fibers of the sensory nervous system through the following three main pathways [60] (Figure 2.1-b):

1. Medial Lemniscus (in the spinal cord).
2. Ventrolateral system.
3. Somatosensory pathways to the cerebellum.

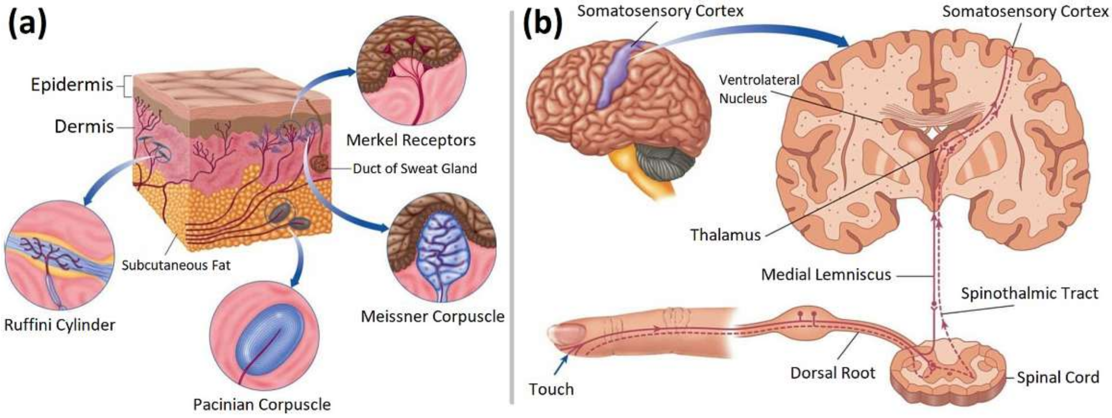

Figure 2.1: a) Human skin anatomy, and b) Sensory nervous system pathways [59].

The transmission time of the stimulus from different body parts is related to the distance from the brain. For example, the transmission time of a signal from one toe to the brain takes approximately 35 milliseconds, but only about 5 milliseconds from the nose to the brain [62]. Also, touch perception is interpreted for its semantic meaning based on the interpretation context [63]. Therefore, many things, such as age [64], gender [65], and culture [66], can affect how we perceive tactile stimuli and haptic interaction.

2.1.0.1 Vibrotactile and Haptic Feedback

We can induce our tactile sensation using electric mechanical actuators called "Vibrotactile Devices." These devices are small and lightweight and can be mounted on different body parts to produce vibrations over the skin [67]. Vibrotactile devices can provide different vibration frequencies and amplitudes for particular stimuli so that the users can distinguish them [68, 69]. The main advantages of these devices are 1) Inexpensive, 2) Low-powered, 3) Reliable and 4) Portable [70, 71].

Vibrotactile feedback has been researched since the late 1970s through pager devices and has been shown to be an effective way of stimulating tactile cues in the human body [72, 73]. Vibrotactile devices are used in almost all mobile devices to engage the user's visual attention. Vibrotactile devices are also used as sensory aids for deaf persons [74]. We usually employ audio, visual, and haptic modalities in our daily interaction with the environment. For example, in typing on a mobile phone with a virtual keyboard, all visual, audio, and haptic modalities combine to mimic a mechanical keyboard's functionality in our brain. Previous studies have shown that vibrotactile feedback in touchscreen devices improves users' typing speed, accuracy, and subjective experience [75, 76].

Vibrotactile feedback includes or even substitutes audio and visual feedback. In a bright environment, vision can be controlled using glasses with anti-reflective lenses; in a boisterous environment, audio can be controlled using noise-canceling headphones. We can use wearable tactile actuators to induce the haptic sensation in users' bodies by mounting the actuators directly on the skin and creating pressure, skin stretch, friction, electrical muscle stimulation, or vibration [77]. Another approach for delivering the haptic sensation without direct skin contact is called air pressure or ultrasonic vibration. Figure 2.2 shows some wearable tactile actuators that can be used for different approaches.

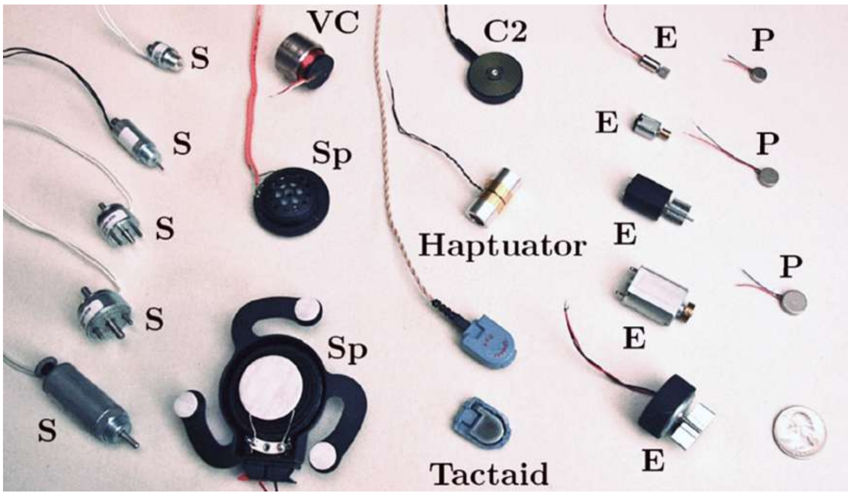

Figure 2.2: Sample actuators for vibrotactile display. *S: solenoids. *VC: Voice coil. *Sp: Audio speakers. *E: Shafted/cylindrical motors. *P: Shaftless/pancake motors. *A quarter coin for scale [77].

Designing a vibrotactile system requires considering different encoding parameters of the human nervous system, such as wave-form, frequency, amplitude, location, duration, and rhythm [78, 79]. A wave-form is a graphic representation of the shape of a wave that indicates its characteristics, such as frequency and amplitude, and can be a sine wave, a square wave, a triangle wave, a saw-tooth wave, or a combination of these wave-forms as a complex wave (Figure 2.3) [80]. The sine wave is a common choice among researchers because most vibrotactile actuators can produce it. We should also consider that altering the shape of the wave signal can affect the perceived roughness of the stimulus through the skin [81].

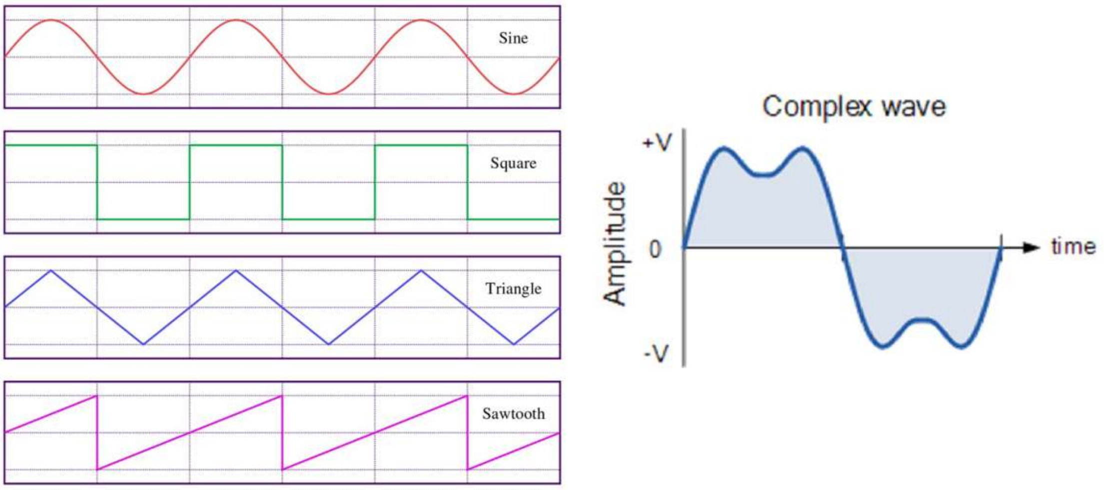

Figure 2.3: Different types of wave-forms [82].

Frequency can be altered to produce different sensations by activating different receptors [83]. The skin can trigger a response to the vibrotactile frequency in the range of 20 to 1000 Hz, and the sensitivity of the Pacinian corpuscles changes based on the frequency with maximal sensitivity around 200 to 250 Hz [84]. Frequencies within the 100 to 300 Hz range are described as smooth vibrations [85]. This frequency range is considered optimal frequencies for different body locations by researchers [79]. Additional information about sound reception in the auditory and vibrotactile systems is shown in Table 2.1.

Acoustic Variable	**Auditory System**	**Vibrotactile System**
Dynamic Range	0 to 130 dB	0 to 30-35 dB
Freq. Range	20 to 20,000 Hz	10 to 400-500 Hz
Optimal Freq. Range	300 to 3000 Hz	40 to 400 Hz
Time for Full Development of Sensation	0.18 sec	1.2 sec
Difference Limen for Freq.	0.2%	5% to 10%

Table 2.1: Comparision of auditory and vibrotactile modes [74, 86]

Amplitude refers to the magnitude or intensity of the vibration and defines the strength of the waveform signal [87]. The range of stimulus values for the amplitude of a waveform signal should be kept between the detection and pain threshold for most use cases. The stimulus's shape, frequency, and amplitude are known as spectral parameters [87]. Fingers, palms, and facial areas of the body are considered locations sensitive to tactile stimulation [88]. The same intensity of stimulus applied to different spatial locations creates sensations that are perceived differently [79]. Duration has relatively distant bounds of acceptable values as the skin is sensitive to detecting a stimulus [87]. Vibrotactile feedback with a duration of only 20 milliseconds has been successfully used in many types of research [89]. Increasing the stimulus duration will decrease the information transferred to the brain [63]. Also, some users have reported annoying feelings for notifications with more than 200 milliseconds in duration [90]. Rhythm enables encoding and sending more information through the body [87]. Humans can distinguish time gaps of only 5 milliseconds in successive pulses [91]. Therefore, the temporal sensitivity to touch is worse than hearing (0.01 ms) but better than vision (25 ms), allowing us to encode and transfer large amounts of information to the brain with rhythmic on/off pulses [92]. Also, a previous study has shown that a person can quickly identify differences among tactile rhythm patterns by increasing the stimulus duration [63]. In VEs, the vibrotactile feedback should mimic a physical touch feeling of the virtual object surface, and this process aims at inducing haptic imagination [93]. We can immerse the user in the VE using visual and auditory senses. Therefore, even partial tactile information about the environment can induce powerful haptic imagination [94, 95].

Haptic feedback devices apply forces and torque onto the different sections of users' bodies, such as arms and legs. We can categorize them into five categories: force feedback, vibrotactile feedback, electro-tactile feedback, ultrasound feedback, and thermal feedback.

Force feedback: Force feedback devices appeared first and are the most studied devices (Figure 2.4). These devices affect the ligaments and muscles through the skin into the musculoskeletal system. They are large and move together with a human and impact large areas of the body, such as an arm or a leg. They are also complex because they have to provide a person with sufficient freedom of movement [96].

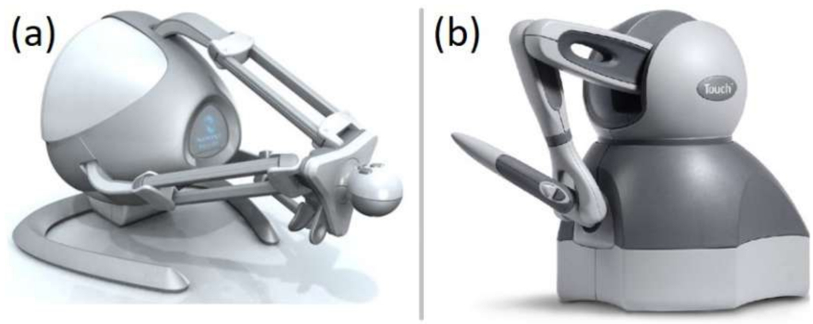

Figure 2.4: Commercial haptic devices, a) Novint Falcon haptic device, and b) Geomagic Touch, (previously SensAble Phantom Omni) [96].

Vibrotactile feedback: Vibrotactile feedback is the most common type of haptic device. Vibro-motors can apply pressure to a particular human skin area. They are simple, low-cost, low-powered, easy to use, and widely used in many devices, such as mobile phones, vibrating video game controllers, and steering wheels. Vibro-motor technology can be categorized into the following three main categories [97]:

1. Eccentric Rotating Mass-motors (ERM).
2. Linear Resonant Actuators (LRA).
3. Piezoelectric Actuators (PA).

ERMs build from standard Direct Current (DC) motors (with a DC voltage source) attached to an unbalanced weight [77]. They are available in two form factors: 1) Cylindrical form, which is also called "Pager Motors" (Figure 2.5-a), and 2) Coin form, which is called "Coin Vibro-motors" (Figure 2.5-b). Because most of the parts in ERMs are mechanical, moving them generates some noise and heat. Therefore, using them in all scenarios and devices is impossible.s [98].

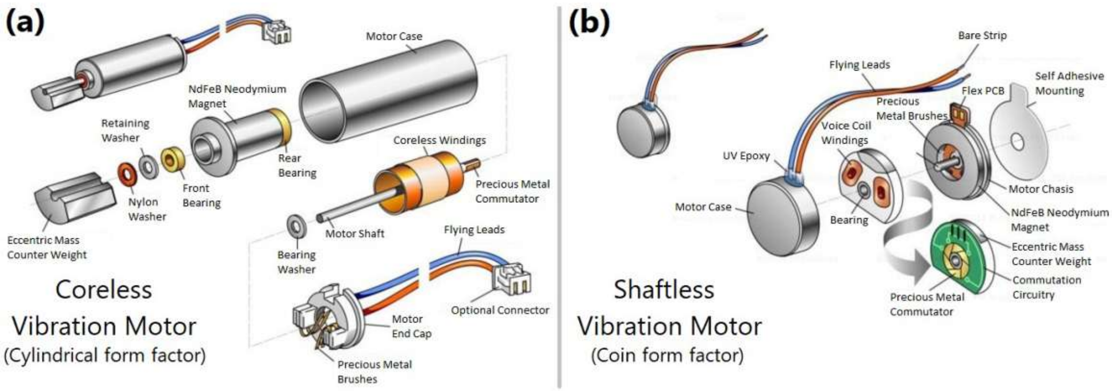

Figure 2.5: Inside ERM vibration motors: a) A cylindrical form factor, b) A coin form factor [97].

LRAs are very popular in haptic feedback applications because they have low haptic response times and long life. They use an internal magnetic mass and spring with an electrical current in the voice coil, driven by Alternating Current (AC) signals, that causes the mass to displace (Figure 2.6). They also have some advantages over ERMs. LRAs can vibrate at a fixed resonant frequency, so varying the vibration amplitude does not affect the vibration frequency. Also, they have a longer life, improved haptic response times, less delay accelerating, and less noise because of the lack of mechanical moving parts [77]. However, they are more expensive than ERMs and are limited in vibration strength because they are limited in size, and varying the AC drive signal by a few hertz will significantly affect the output amplitude [77].

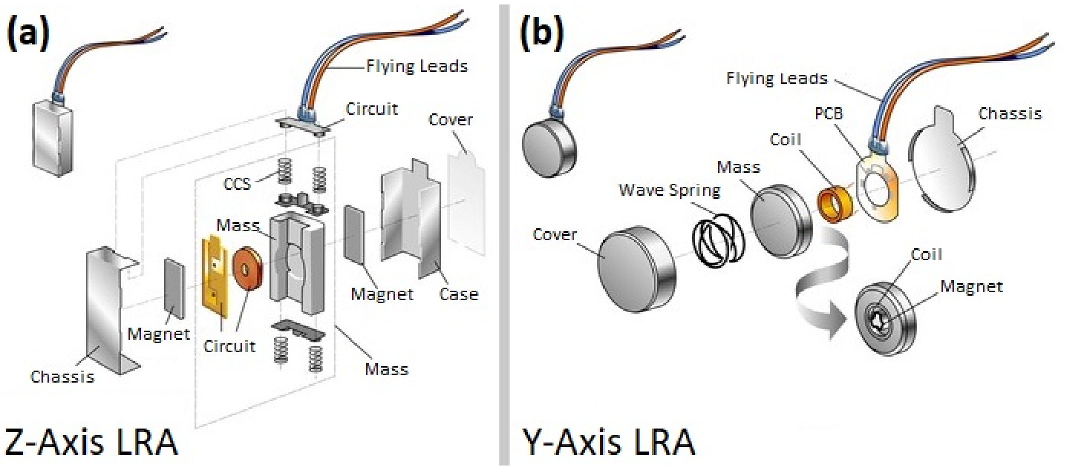

Figure 2.6: Inside LRA vibration motors: a) Z-Axis LRA, and b) Y-Axis LRA [97].

PAs produce a small displacement with a high force capability when voltage is applied [98] (Figure 2.7). They allow for more precise control of stimulus parameters than ERMs and LRAs [99]. Therefore, they are used in particular applications, such as ultra-precise positioning and the generation and handling of high forces or pressures in static or dynamic situations [98]. The main disadvantage of PAs is that they have low stimulus intensity and require high activation voltage, which can be a severe problem when used in direct skin contact [100].

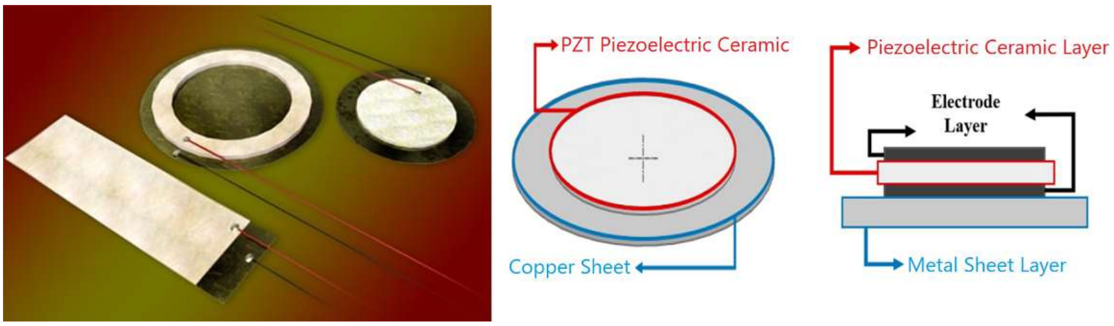

Figure 2.7: The PAs structure [98].

Electro-tactile feedback: Electro-tactile feedback affects both receptors' electrical impulse nerves. This type of haptic feedback device can induce the sense of objects' texture or other touch senses in the users' bodies by using electrical impulses [101]. By changing the electrode parameters, such as the current, voltage, material, or size, we can induce different sensations on the skin (Figure 2.8). The main advantage of the electro-tactile feedback systems compared to other haptic devices is the absence of mechanical or moving parts that make it possible to create a wide range of sensations only by using electrical impulses that cannot be possible with other feedback systems [101].

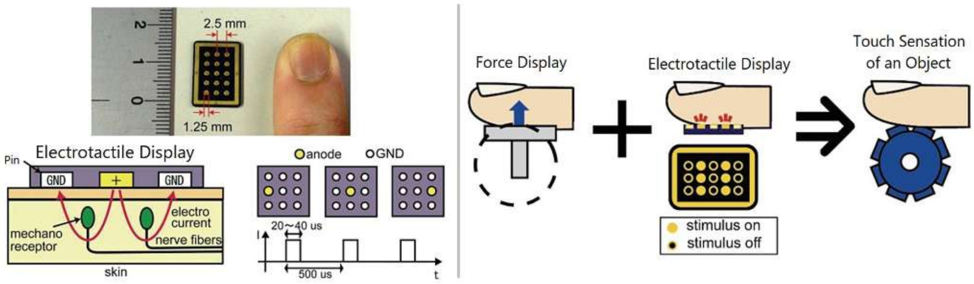

Figure 2.8: Touch sensation by integration of electro-tactile and force displays [101].

Electro-tactile feedback systems are also very compact and customizable. The main downside of the electro-tactile feedback systems is that the user has to wear additional devices on their body. As an example of the electro-tactile feedback system, TACTILITY is a European Horizon 2020 project that tries to use electro-tactile feedback in VR by mimicking the characteristics of natural tactile feedback and increasing the quality of immersive VR experience [102] (Figure 2.9).

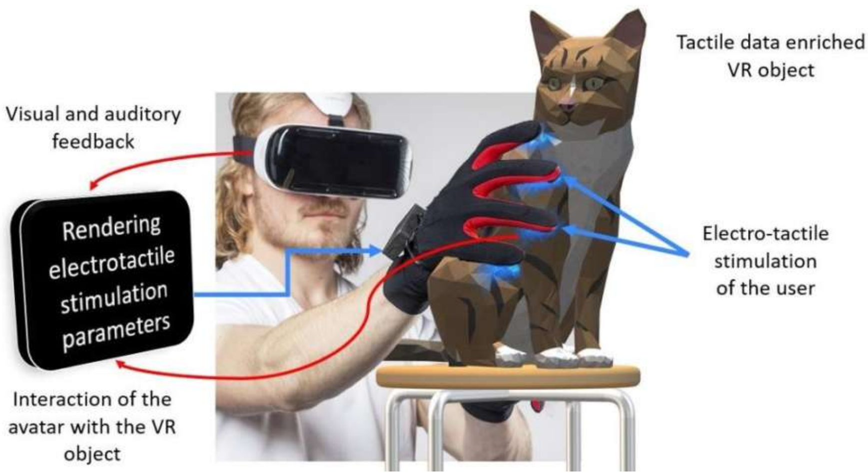

Figure 2.9: TACTILITY project [102].

Using vibrotactile devices, researchers developed wearable haptic suits for different purposes, such as navigation and orientation awareness. A. Meier et al. [103] show an evaluation of vibrotactile on-body feedback focusing on pedestrian navigation using different wearable device approaches, such as vibrating belts, wristbands, or shoes (Figure 2.10-a). R. W. Lindeman et al. [104] developed a wearable system to display vibrotactile stimuli on multiple body spots as a general-purpose controller in the military (Figure 2.10-b). S. Hashizume et al. [105] developed a wearable vibration device with multiple speakers in the form of a jacket to improve the quality of music experience and entertainment (Figure 2.10-c). Wearable vibrotactile devices even went to space through work from J.B.F. van Erp et al. [106], who developed a vibrotactile vest to support astronauts' orientation awareness in the International Space Station (ISS).

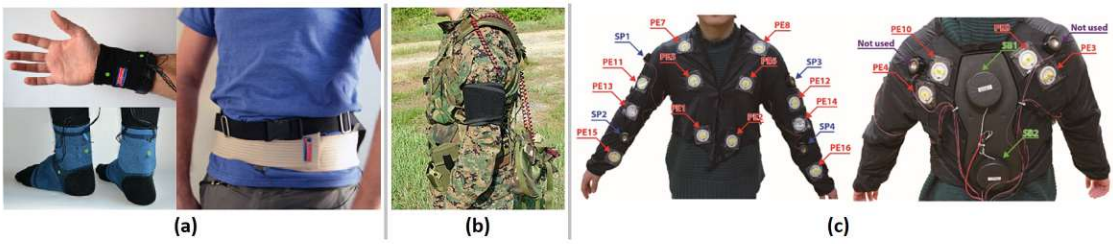

Figure 2.10: a) Wearable devices for pedestrian navigation [103], b) Military vibrotactile suit [104], and c) The LIVEJACKET [107].

Haptic VR suits represent the next step towards true immersion in VR using the sense of touch, especially in VR gaming [108]. They send haptic feedback from head to toe using different accessories and increase the realism of the VR experience (Figure 2.11). Few companies developed fully integrated smart VR suits with haptic and biometric feedback systems, such as TeslaSuit [1] and bHaptic TactSuit [2].

Figure 2.11: a) TeslaSuit, and b) bHaptic TactSuit and its accessories.

Ultrasound feedback: Ultrasound is a high-frequency sound wave. To create ultrasound feedback, we need to use several devices called "Emitter." These emitters can create invisible tangible interfaces in mid-air so the user can feel it through the skin. The emitter arrays can also be mounted on VR HMD devices. Sand et al. [107] proposed an ultrasonic mid-air tactile feedback system for HMDs to enhance 3D user interfaces in VR. Their result shows that the system can improve the user experience in VR compared to no tactile feedback (Figure 2.12).

[1]Available Online: https://teslasuit.io/products/teslasuit-4/ (accessed on 10 October 2022)
[2]Available Online: https://www.bhaptics.com/tactsuit (accessed on 10 October 2022)

Figure 2.12: An Ultra-haptics ultrasonic mid-air haptics device [107].

The interaction volume becomes limited if ultrasound feedback is used on HMDs because the user cannot extend hands very far from the device, and the distance of hands is limited to the Field-Of-View (FOV) of the haptic device. However, compared to other wearable haptic devices, it has spatial freedom, and the focal point can be translated quickly inside the interaction volume to create volumetric shapes and present surface texture that feel like magic to the user [109].

Ultrasound feedback can create simple interfaces that rely on the user's hand touching virtual objects [110], but rendering complex volumetric shapes using hand tracking without tangible surfaces is almost impossible or very difficult using this technology [111]. It can control a virtual user interface, such as buttons, switches, and sliders, or sense ephemeral elements like wind or rain, feeling the surface texture, density, weight, and feedback from a collision [112]. The main advantage of ultrasound feedback is that users do not need to wear additional accessories such as gloves, but as a disadvantage, it is expensive and usually less perceptible than other haptic feedback technologies [113].

Thermal feedback: It is possible to use particular actuators to create heat and cold feelings on the skin called "Thermal Feedback." These particular actuators are small "Peltier" devices that can provide thermal feedback perceived differently depending on the body's parts that touch them [114] (Figure 2.13).

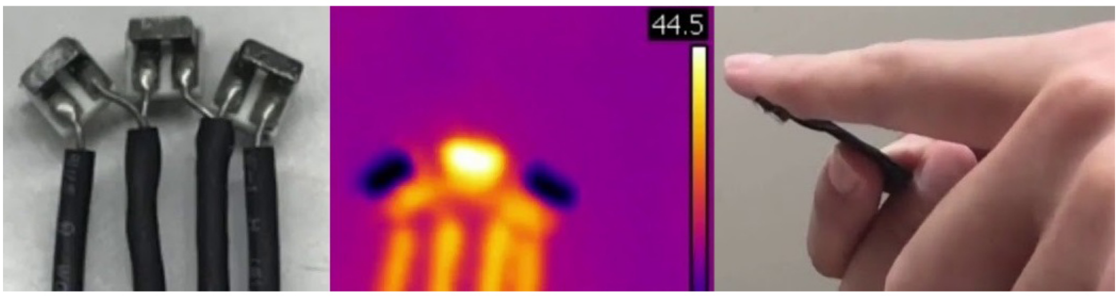

Figure 2.13: ThermalBitDisplay with three peltier device [114].

Recently, researchers examined that temperature sensation can be an essential aspect of VR. PThey have shown that applying thermal displays to different body sections, such as the hands [115, 116], the lower back [117], or VR HMDs [118], improves the immersive VR experience among users (Figure 2.14).

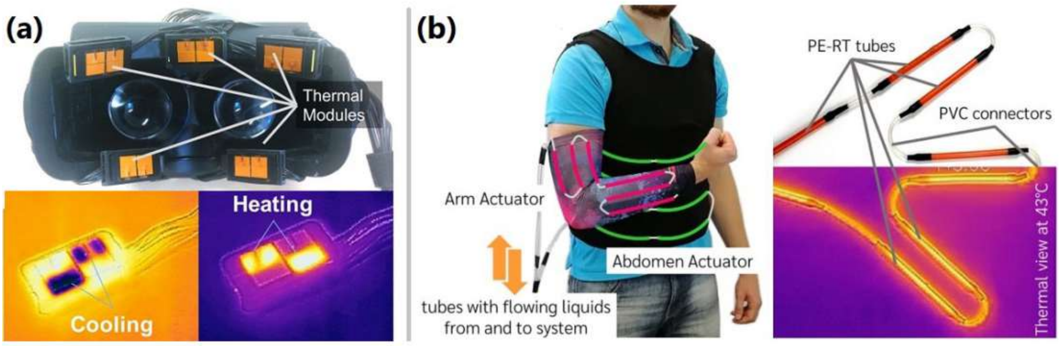

Figure 2.14: a) The ThermoReality system [118], and b) The Therminator system [115].

In our research, we use ERM coin vibro-motors, also known as shaft-less or pancake vibrator motors (Figure 2.5-b). They are low-cost, compact, convenient to use, and have a different range of diameters (generally 8-14mm). Coin vibro-motors are a popular choice for different applications, such as mobile phones, wearable haptic devices, and medical instruments, due to their small size and enclosed vibration mechanism. They are suitable for haptic research, particularly in wearable devices. We can integrate these types of vibro-motors into many designs because they have no external moving parts, and also they are designed to be easy to mount and can be fixed in any place with self-adhesive or other mounting systems. More technical details are explained in Chapter 4.

2.2 Visual Sense

Vision is one of the human senses that help us understand an object's visual quality and perceive specifications, such as color, luminosity, shape, and size of objects [119]. Vision is also unique in its ability to provide visual exteroceptive information about the near and far environment that helps control human locomotion and adaptive locomotor behavior [120, 121]. Energy in the form of light enters our eyes through the cornea and passes through the pupil. The light then passes through the lenses, which helps to focus the image. Finally, the light hits the retina at the back of the eyes, comprising two primary cells called "cones" and "rods." Cones are heavily involved in color vision, and rods are essential for seeing movement but only transmit information to the brain in black and white [122, 123]. All information from the cones and rods leaves each eye through the optic nerves, which cross at the optic chiasm so that both sides of the brain (left and right hemispheres) get information from each eye. The information passes through the Lateral Geniculate Nucleus (LGN) from the optic chiasm, and then it goes to the primary visual cortex (known as V1), which is located in the occipital lobe of the brain [122, 123].

2.2.0.1 Visual Feedback

Visual feedback is output from a system, such as a video game or display, allowing the user to interact better with the system [124]. Previous studies, such as Noble et al. [125], have shown a potentially confounding influence of visual feedback on brain activation during a motor task [125]. Also, some studies, such as Lin et al. [126], have shown the feasibility and acceptability of real-time visual feedback in rehabilitation exercises. VR provides many possibilities to study user interactions in virtual environments. In particular, it allows researchers to explore different use cases of visual feedback to improve user interactions. Park et al. [127] studied different visual representations of gesture interactions in VR games (Figure 2.15). They showed that using different visual feedback systems in VR improves users' gestures effectively.

Figure 2.15: Different VR visual feedback models for user gestures [127].

Also, Geiger et al. [128] and Prachyabrued et al. [129] presented user studies that show the effects of using visual feedback in VR for grasping virtual objects (Figure 2.16). Their results show that users are supported most when additional hand color feedback is provided in the VR environment [128, 129]. Overall, all the research in this area suggested that using different visual feedback in VR improves the user's VR experience.

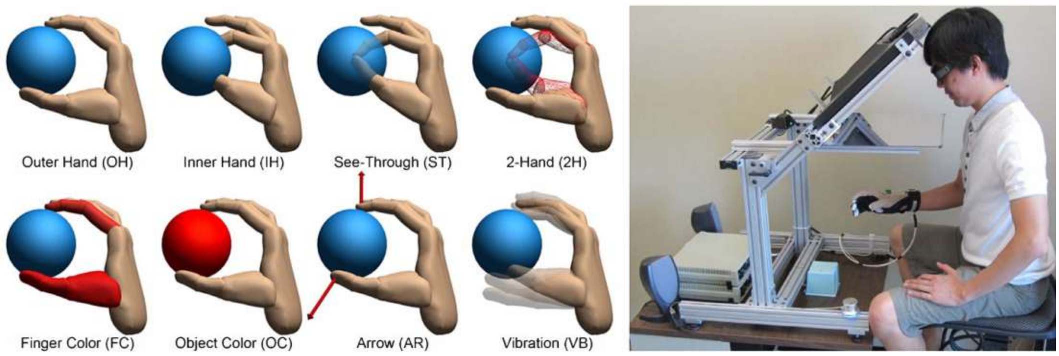

Figure 2.16: Visual feedback for grasping virtual objects in VR environments [129].

2.3 Auditory Sense

In connection with the other senses, hearing helps us experience our environment and our mutual dependence on it, thereby ensuring a smooth coexistence with our fellow individuals by assisting us in developing adaptive behavior within our environment and society [130]. Therefore, intact hearing is crucial for an individual normal and physiological development and maturation, as it secures communication [130]. However, the highly complex physical, biochemical, and neurobiological processes of hearing are hidden from the casual observer's eye, who take hearing for granted. The consequences of missing or dysfunctional hearing are multi-dimensional. They may include emotional, interpersonal, behavioral, physical, and psychological aspects [131].

Our ears consist of three major areas: the outer ear, middle ear, and inner ear [132]. The hearing process starts with the outer ear. Audio waves pass through the outer ear and cause vibrations at the eardrum. Then, the eardrum and three small middle ear bones amplify the vibrations as they travel to the inner ear. The vibrations pass through fluid in a snail-shaped structure in the inner ear called "Cochlea" [133]. Once the sound waves reach the inner ear, they are converted into electrical impulses, and the auditory nerve sends them to the brain. In the end, the brain translates these electrical impulses into sound (Figure 2.17).

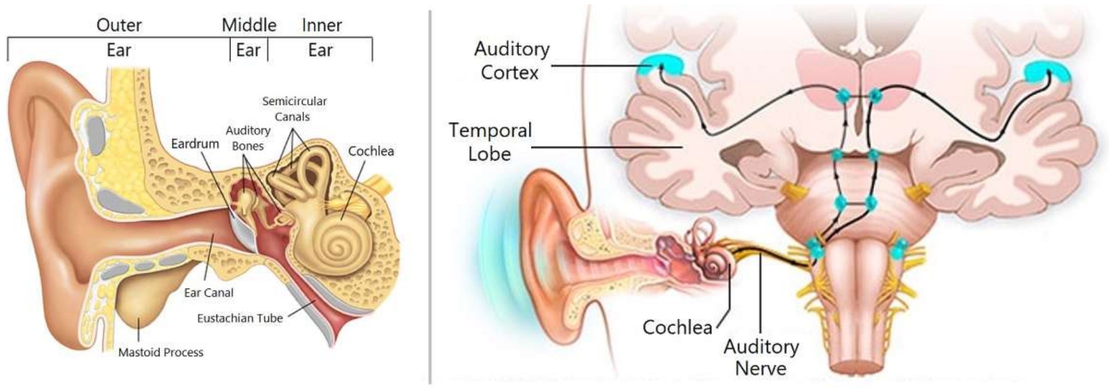

Figure 2.17: The anatomy of human hearing system [132].

2.3.0.1 Visualizing Audio

Using maps and pictures as visual elements have been used for many years to help people in different ways, such as thinking, navigating, and communicating with other people. This type of data representation using visual elements is called "Visualization" [124]. Recent advances in audio analysis and visualization techniques help develop audio visualization tools that reflect what people hear. Audio visualization is mostly referred to as "Music Visualization," which interprets sound with images, lights, and colors by interpreting digital or electrical signals of the audio and mapping them to visual elements [134].

Currently, many different music visualizers are developed, each with a different audio interpretation. Mitroo et al. [135] presented one of the earliest studies that used a computer-based approach to visualize music. This study shows that we can use particular music attributes, such as loudness, notes, chords, and pitch, to create a colorized composition of moving objects (Figure 2.18).

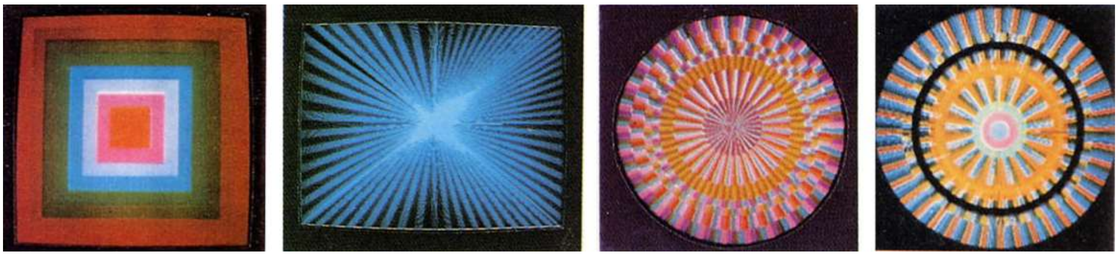

Figure 2.18: Early photographic reproductions of "Musical Paintings" [135].

Since then, researchers have tried to create more complex music visualizations by using computer algorithms. Jones et al. [136] and Evans [137] tried to create guidelines for computer musicians interested in music visualization with different techniques by analysis of visual music. The results from most of these researches are already included in many current and early commercial products, such as iTunes™ or WinAMP™, to visualize music. We can categorize music visualization into two main categories: augmented-score and performance-dependent [138]. The augmented-score visualizations focus on showing the connections between musical pieces and graphical elements by using computer graphics, and the target audience of this category is people with musical backgrounds.

Previous studies, such as Hiraga et al. [139], show the possibility of using this type of music visualization for music learning. The performance-dependent visualizations depend on different music parameters, such as volume, tempo, pitch, and instruments, that can be extracted from the music. With this visualization, developers can map the music's features to visual elements, such as different 3D objects with various colors and lights, and create real-time animations [140, 141].

Researches show the importance of visualizing audio and music for DHH persons. Several devices have been built to translate sound and music into a vibration pattern that the skin can feel. P. L. Brooks and B. J. Frost [142], in an early experiment in 1983, developed a tactile vocoder device to aid lip-reading by providing a tactile sensation of the frequency content of a sound through vibration motors mounted on the forearm. This device's principle has influenced further research, such as SkinScape by E. Gunther and S. O'Modhrain in 2002 [84], to represent music for DHH persons. In another study, Fulford et al. [143] show the multiplicity of experiences and opinions regarding music among people with hearing impairments and presented the particular demands that are hearing impairment places on studying these groups of people.

Merchel et al. [144] identified vertical whole-body vibrations using a self-made electrodynamic shaker. They show that the vibrations perceived on the body's surface have a significant role in the perception of music and connect to the perception of quality, for example, in a concert experience (Figure 2.19-a). This research shows that gaining access to whole-body vibrations is a crucial aspect of deaf musical experience, where bodily contact is made with a vibrating speaker cone for gaining access to reproduced sound when high-volume and bass-heavy music is being played. S. Nanayakkara et al. [145] combined tactile and visual perceptions in a model made of a vibrating chair and a computer to display the visual effects of the music to users (Figure 2.19-b). A. Baijal et al. [146] created an improved version of the haptic chair called "Emoti-Chair," a sensory substitution system to bring a high-resolution audio-tactile version of music to the body (Figure 2.19-c).

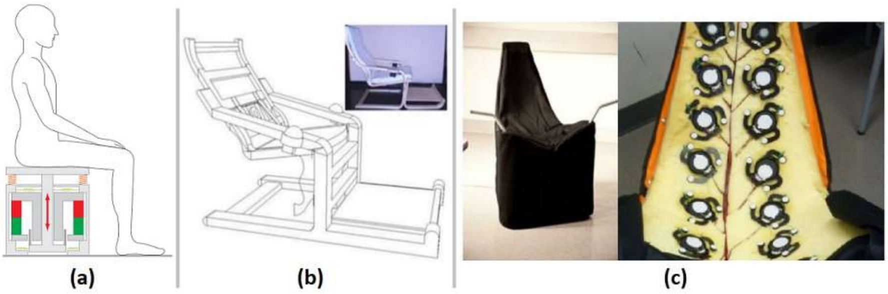

Figure 2.19: a) Vibration chair with electrodynamic shaker [145], b) The Haptic-Chair [144], and c) The Emoti-Chair [146].

The Emoti-Chair (Figure 2.19-c) was developed to explore the transition of audio-based music into vibrotactile-based music to make it easier and more accessible for DHH persons to feel sounds and music, and initial studies have shown that it is possible to convey the dynamic properties of music through the Emoti-Chair [146]. Some other researchers showed another aspect of visualizing audio and music for DHH persons using vibrotactile devices in haptic suits (Figure 2.20).

Figure 2.20: Left: The fashion that lets you feel music (BBC News) [147], and Right: Synesthesia suit for VR [148].

These haptic suits convert the different music frequencies to vibrations, and users can understand the rhythm and beats of the music through their bodies in real and virtual environments. The results show that these systems could provide a music experience that is not possible by listening to music through traditional digital methods and improve DHH persons' audio and music experiences in different environments [149, 150].

2.3.0.2 Hearing Loss and Deafness

Hearing loss can occur for many reasons, such as damage to the inner ear, gradual buildup of earwax, ear infection and abnormal bone growths or tumors, and ruptured eardrums, but there is another term called "Deafness." Deafness has different definitions in cultural and medical contexts, and it is essential to distinguish between the different levels of hearing impairments. The severity of hearing impairment is categorized by how much louder volumes need to be set before detecting a sound [151].

People without hearing problems have hearing thresholds of 20 dB or better in both ears. A person who cannot hear as well as a person without hearing problems is said to have hearing loss that may be mild, moderate, severe, or profound. Hearing loss causes difficulty in hearing daily speech or loud sounds and can affect one ear or both ears. People with hearing loss ranging from mild to severe are called "hard of hearing" and usually communicate through spoken language and can benefit from HA, CI, and other assistive devices, as well as captioning. People with profound hearing loss, with very little or no hearing, are called "deaf" [6].

Deafness is the condition where the affected person cannot entirely perceive sound. As sound is also perceived through the bones in the skull, it is assumed that only five percent of people who have been diagnosed as deaf show a total lack of sound perception [152]. Most deaf people are born with their condition, either caused by medical risks and diseases during pregnancy or due to hereditary factors [152]. Many deaf people use sign language as a means of communication, which deaf people have used throughout history. Each country has its native sign language, which might include variations. The 2013 edition of Ethnologue currently lists 137 sign languages [153].

Hearing loss is associated with substantial adverse effects on the quality of life of DHH individuals, which are only slightly reversible with hearing aids [4]. Several studies show that DHH adults, for example, noticed effects on their job performance due to their deteriorated hearing [154, 155]. For the hearing impaired, understanding communication requires concentration and compensational tools, like lip-reading, a combination of information, and the contextual frame [156].

According to WHO, over 430 million people worldwide are affected by some degree of hearing loss, and it is estimated that nearly 2.5 billion people are projected to have some degree of hearing loss, and at least 700 million will require hearing rehabilitation by 2050 [6]. In Europe alone, there are 47.9 million adults who are living with disabling hearing loss [157]. The WHO estimated in 2021 [158] that 196 million people have some degree of hearing loss in the WHO region of Europe and that 57.3 million have a moderate or higher grade of hearing loss. It is estimated that 236 million people in Europe will have some degree of hearing loss by 205. The EuroTrak Surveys in a series of European countries show that, on average, 65% of Europeans with hearing loss do not use hearing aids. [159]. Furthermore, 80 percent of those with disabling hearing loss come from low and middle-income countries worldwide [6]. Considering these numbers, hearing loss is a pervasive worldwide phenomenon. It is expected that the numbers will increase to 25 percent in the following years due to the aging population and factors such as more significant exposure to noise, diseases, and pollution [160].

Many deaf musicians worldwide show that deafness is not a barrier for DHH persons to perceive audio and be creative by participating in audio-related activities. Dame Evelyn Glennie is a world-renowned percussionist who has been profoundly deaf since the age of 12 but feels the pitch of her concert drums and xylophone and the flow of a piece of music through different parts of her body, from fingertips to feet [161]. She believes that DHH persons can feel vibrations through their bodies as well as other people hearing audio. She also mentioned the following statement in one of her essays:

"We can also see items move and vibrate. If I see a drum head or cymbal vibrate or even see the leaves of a tree moving in the wind then subconsciously my brain creates a corresponding sound..." [161]

This essay is encouraging because it shows DHH persons experience audio and music thought vibrations and create a corresponding sound of moving objects with their brain. Therefore, different audio visualization techniques could help DHH persons to perceive more information about different environments. Some previous studies show the possibility of creating unique displays to inform DHH persons about the sounds in the environments by using visualization techniques. Matthews et al. [162], Ho-Ching et al. [49], and Jain et al. [163] developed visual displays to provide non-speech sound awareness in an environment for DHH persons. They show that DHH persons could use visual cues to recognize and find sound sources in the environment using audio visualization techniques (Figure 2.21).

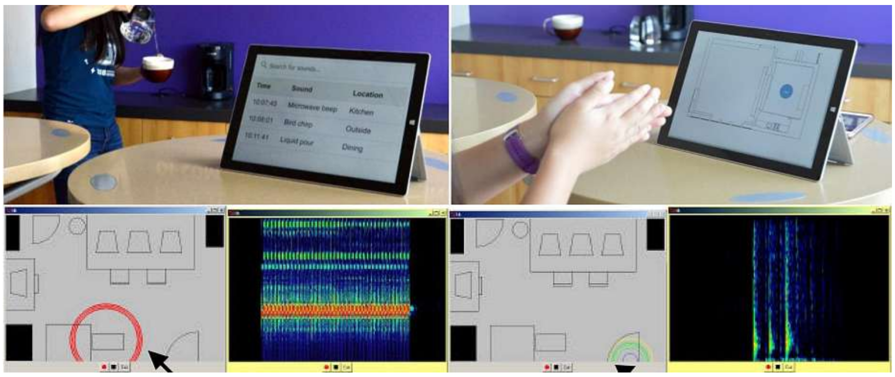

Figure 2.21: Using audio visualization techniques to distinguish the different sound sources in the environment for DHH persons [49, 163].

In another study, Matthews et al. [164] conducted design interviews with DHH persons to gather a rich set of visual design preferences and requirements for peripheral visualizations of non-speech audio to DHH users. They show that DHH persons prefer visual displays that are easy to interpret, glance-able, and appropriately distracting [164]. Most DHH persons in their study wanted to identify sounds around them and view and customize a history of identified sounds. They reported that during an interview, one of the DHH participants expressed her interest in music and felt the music vibrations through the floor or speakers. It is an exciting result because it encourages us to use a combination of haptic and visualization techniques to provide a better experience of feeling the environments for DHH persons.

2.3.0.3 Assistive Technologies for DHH Persons

Assistive technology or assistive devices for DHH persons often refer to devices that help a person with hearing loss or voice, speech, and language disorders to communicate more meaningfully and participate more fully in their daily lives by accessing auditory information in a variety of ways [165]. DHH persons use amplification devices such as HA, CI. Assistive devices are described with different names, such as Assistive Listening Devices (ALDs), Augmentative and Alternative Communication devices (AAC), or alerting devices. These devices can be used with or without HA or CI.

Hearing Aids (HA): A hearing aid is a small electronic device that a hard-of-hearing person wears in or behind the ear. It magnifies sound vibrations that enter the ear and help a hard-of-hearing person listen, communicate, and participate in daily activities in quiet and noisy situations [166]. A hearing aid has three main components: a microphone, an amplifier, and a speaker (Figure 2.23). The hearing aid receives sound through a microphone, converts the sound waves to electrical signals, and sends them to an amplifier. The amplifier increases the power of the signals and sends them to the ear through a speaker.

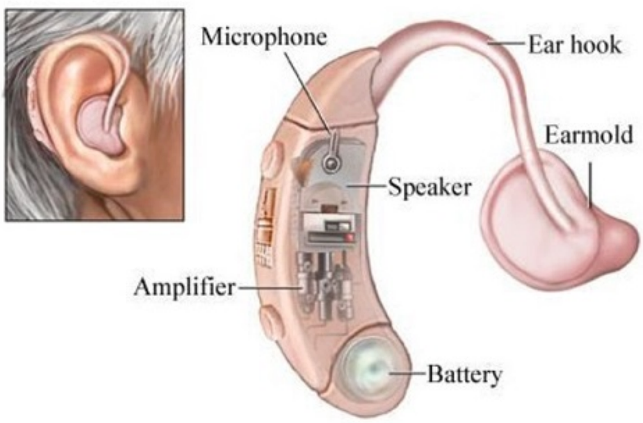

Figure 2.22: A hearing aid's main components [167].

Cochlear Implants (CI): A cochlear implant is a complex electronic device that can help a profoundly deaf or severely hard-of-hearing person to provide a sense of sound [168]. The implant consists of two main parts: an external part that sits behind the ear and an internal part that is surgically placed under the skin. An implant consists of a microphone, speech processor, transmitter/receiver, and an electrode array (Figure 2.23). Sound signals are captured by the microphone, processed by the speech processor, and then transmitted to the internal receiver. The receiver converts the sound signals into electrical impulses, which then transmitted to an electrical array in the cochlea [168, 169].

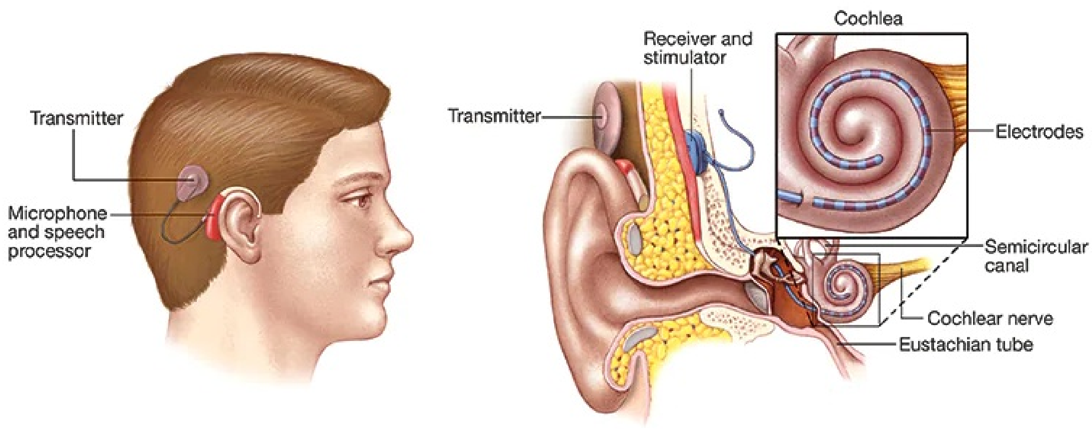

Figure 2.23: A cochlear implant's main components [169].

Assistive technology for DHH persons has improved significantly over the past few decades. B. Tessendorf et al. [170] developed a wireless multimodal hearing system with new features for HI users that enables them to control HI devices using gestures and body movements. There are other advances in assistive technologies for DHH persons, such as using powerful processing chips, advanced signal processing techniques, and even artificial intelligence [171]. These technologies have not been tested in VR for DHH users. All of the current VR HMDs are designed for hearing persons, and the required standards for a DHH person wearing a HA or CI are not met. Also, HAs and CIs are optimized to receive natural environment sounds and are not optimized for the output audio from a VR HMD's headphones [36]. These issues cause severe problems for DHH persons using VR and require future studies.

2.4 Sensory Substitution

Sensory Substitution (SS) refers to using one sensory modality to supply environmental information generally gathered by another sense while preserving some of the critical functions of the original sense [172, 173]. The idea of SS was introduced in 1969 by Paul Bach-y-Rita to use one sensory modality, mainly taction, to gain environmental information to be used by another sensory modality, mainly vision [174, 175].

Our knowledge about brain mechanisms and cognitive processes changed drastically during the last decade, and SS helped us understand new insights related to human perceptions. Thanks to technological advances and scientific achievements, SS has become a natural alternative for restoring some functions of defective sensory organs, such as sight in case of blindness or hearing in case of deafness [172]. When a person becomes blind or deaf, they generally do not lose hearing or seeing [176]. They lose their ability to transmit sensory signals from the periphery (retina for vision and cochlea for hearing) to the brain [177]. Persons who become deaf lose the peripheral structures relating to sound transduction (the cochlea), and in some cases, they lose their balancing ability too [178].

SS system input can reach many brain structures, anatomically and physiologically, related to the lost sensory modality [177]. So, providing information from artificial receptors offers an opportunity to restore function [179]. Scientists have shown that SS systems may help people by restoring their ability to perceive a particular defective sensory modality using sensory information from a functioning sensory modality [179]. For example, we can use visual or tactile sensations to provide auditory signals about the external environment for DHH persons. Figure 2.24 shows the structure of a SS system. Generally, it consists of three components: a sensor, a coupling device, and actuators [180].

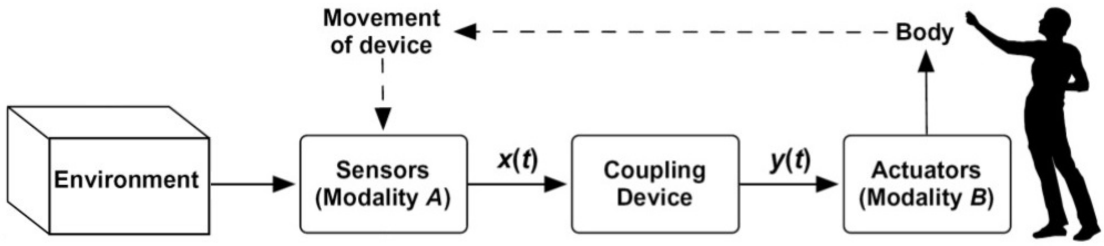

Figure 2.24: Structure of a SS system [180].

Sensors capture information "x(t)" from the environment and transmit it to a coupling device. A sensor can be a modality that receives or emits signals (receiver such as a camera or a microphone and emitter such as a laser projection or an ultrasound device). The range, location, accuracy, or user control of sensing devices may differ depending on the system [181]. However, independent of its other characteristics, the sensor should enable autonomous handling by the user [181]. The coupling device converts the received information into signals "y(t)" for activating a display of actuators (sensory display) [181]. This display sends impulses to a human sensory modality which forwards the information to the brain.

Depending on the sensory modality, stimulation may be, for example, realized through loudspeakers or a tactile display. The choice of coupling device and display strongly depends on the kind of associated human sensory pathways [181, 180, 182]. SS devices provide helpful support for impaired people, and in this thesis, we use them to help DHH persons. Future technological progress may promise exciting developments in the field of accessibility as well as in the field of sensory augmentation.

2.5 VR and Rehabilitation

VR refers to a computer-generated simulation in which a person can interact within an artificial 3D environment using electronic devices, such as particular HMDs, suits, or gloves fitted with sensors [183]. VR has dominated technology headlines in recent years with its ability to immerse users in a virtual world. VR technology can be applied across various fields, such as education, the military, sport, and healthcare. Healthcare is an important application where VR can have a significant impact [184]. VR is widely used in medical training, medical marketing, patient treatment, and disease awareness. Healthcare professionals use virtual models in VR environments to prepare themselves for working on real bodies. VR can transport surgeons into a very professional surgery room to explore the human body areas that are hard to achieve in a real environment (Figure 2.25).

Figure 2.25: Osso VR medical training platform [185].

VR can also treat mental health issues effectively [186], such as VR exposure therapy for treating Post-Traumatic Stress Disorder (PTSD) and anxiety disorder [187, 188]. Rehabilitation is also another area that uses the benefits of VR. VR is widely used in different types of therapy, such as physiotherapy, with the help of advanced medical robots (Figure 2.26).

Figure 2.26: VR for therapy, a) Lambda Health System [189], b) Interactive VR simulation for spinal cord injuries [190]

Researchers are investigating novel methodologies to improve and make motor rehabilitation more engaging and effective. VR has recently emerged as a valuable technology to change conventional therapy by incorporating rehabilitation methods in a low-cost and novel approach. VR-based therapy can provide a positive learning experience and be engaging and motivating [191].

Different tasks can be tailored to the patient's needs with VR-based therapy using imitation or video-game-like activities [191]. The advantage of VR is that the possibilities are essentially endless. VEs can be customized by designing tasks that fit the individual's cognitive and physical impairments, which is critical in maximizing brain reorganization and reactivating those brain areas involved in motor planning, learning, and execution, and maintaining engagement [192, 193].

2.5.1 VR for Impaired People

VR provides opportunities for socialization, adventure, and experiences for people who may not enjoy themselves in the real world, but accessibility is still a significant challenge in VR, especially for people with different impairments [31]. People with particular impairments, such as autism, social anxieties, and mental health challenges, do not access all technological and educational opportunities. They find comfort and safety in virtual social apps and experiences, but many do not have access to VR technology. Many impaired VR users discover they can access visual worlds and experiences they cannot access in the real world [31].

As VR becomes more prominent, developers should consider the needs and opinions of people with impairments, including making them part of the development process, to build games and experiences that are truly accessible to a wide range of users. People with different impairments can be categorized as physically, visually, and hearing impaired.

2.5.1.1 Physical Impairments

Physical Impairment in the context of the Americans with Disabilities Act (ADA) of 1990 is defined as any physiological disorder, condition, cosmetic disfigurement, or anatomical loss affecting one or more of the following body systems, such as neurological or musculoskeletal, that substantially limits one or more major life functions [194]. VR means the potential to try out-of-reach experiences for physically impaired people, such as climbing or swimming, perhaps for the first time.

Dean et al. [195] used VR to educate physically impaired children by providing a chance to practice driving virtual motorized wheelchairs safely within a computer-generated VR environment [195]. The study shows that VR-based training significantly improved the wheelchair-driving skills of physically impaired children in actual reality. They show that children with severe orthopedic disabilities can acquire essential functional skills in VR without taking the risks of learning to drive in the real world and the cost of obtaining an actual wheelchair while they learn [195].

A software called "WalkinVR Driver" [196] aims to make VR games and applications more accessible for physically impaired people. This software simulates different moving mechanisms in VR for people with cerebral palsy, spinal cord injury, traumatic brain injury, muscular dystrophies, spinal muscular atrophies, neuropathy, and orthopedic problems. It enables them to move and walk freely in VR environments using VR controllers (Figure 2.27).

Figure 2.27: VR for physically impaired people, the WalkinVR Driver Software [196].

2.5.1.2 Visual Impairments

Visual impairment is a decreased ability to see to the degree that causes problems not fixable by usual means, such as glasses [197]. It is also called vision impairment or vision loss. Visually impaired people may need adaptive training and equipment to improve with daily activities, such as reading and walking. In visual impairment, blindness is used for complete or nearly complete vision loss [198]. VR for visually impaired people is not new, and previous studies show the effect of using VR for this group of people. Many groups are working on enhancing the interaction of visually and even blind people with computers by using VR. Lécuyer et al. [199] developed the "HOMERE," a multimodal system dedicated to visually impaired people exploring and navigating virtual environments (Figure 2.28).

Figure 2.28: VR for visually impaired people, the HOMERE System [199].

The HOMERE System provides the user with different sensations when navigating inside a virtual world, such as force feedback corresponding to the manipulation of a virtual blind cane, thermal feedback corresponding to the simulation of a virtual sun, and auditory feedback in spatialized conditions corresponding to the ambient atmosphere and particular events in the simulation [199].

Commercial products such as VisionBuddy [200] and IrisVision [201] show the possibility of using VR HMDs to help persons with low vision (Figure 2.29). These devices stream the image in real-time from any streaming device, such as a TV or embedded camera, directly into the VR HMDs and maintain a high-quality resolution. They provide live image corrections and enhancement algorithms which result in a high-quality image projected at different magnification levels onto the eyes of a low-vision person so that they can read or see the environment better [200, 201].

Figure 2.29: VR HMDs for low vision community: Vision Buddy V2 (left) [200], Iris Vision (right) [201].

According to 2018 WHO data, over 217 million people have moderate to severe vision impairment worldwide [202]. People with severe vision loss due to different disorders, such as diabetic retinopathy, age-related macular degeneration, and glaucoma, often rely on assisted care at home and work. They often experience physical and economic pain and psychological changes that impact their quality of life. Medically validated and approved VR wearable devices help visually impaired people carry on with their daily routines like walking, going outside, cooking, and reading, and offer greater independence and gain the functionality of their life.

2.5.1.3 Hearing Impairments

As mentioned before, hearing impairment occurs when there is a problem with or damage to one or more ear parts. Based on a report from the "Northside" hospital in the U.S. [203], hearing loss is the most common birth anomaly. People who lose hearing after learning to speak and hear cannot adjust to their communications and relationships because hearing has been an essential aspect of their lives.

Deaf persons read lips and use sign languages for their daily communications; sometimes, there is an interpreter to translate spoken language. New technologies, such as real-time captioning of videos and voice-recognition software, help deaf persons to attend school and university and participate in activities with people without hearing problems. However, they still have many limitations in using most of today's new technologies, affecting deaf persons' educational skills [9].

VR provides excellent opportunities for DHH persons to improve their learning skills in a controlled VR environment. Paudyal et al. [11] designed a VR classroom for DHH persons called "DAVEE" (Figure 2.30). DAVEE helps DHH persons to ask questions and receive their answers in every classroom session. With this system, DHH students can also interact with other students in the virtual class and record it for offline usage. The result of this study shows the effects of using VR to improve the communication of DHH students in the classroom.

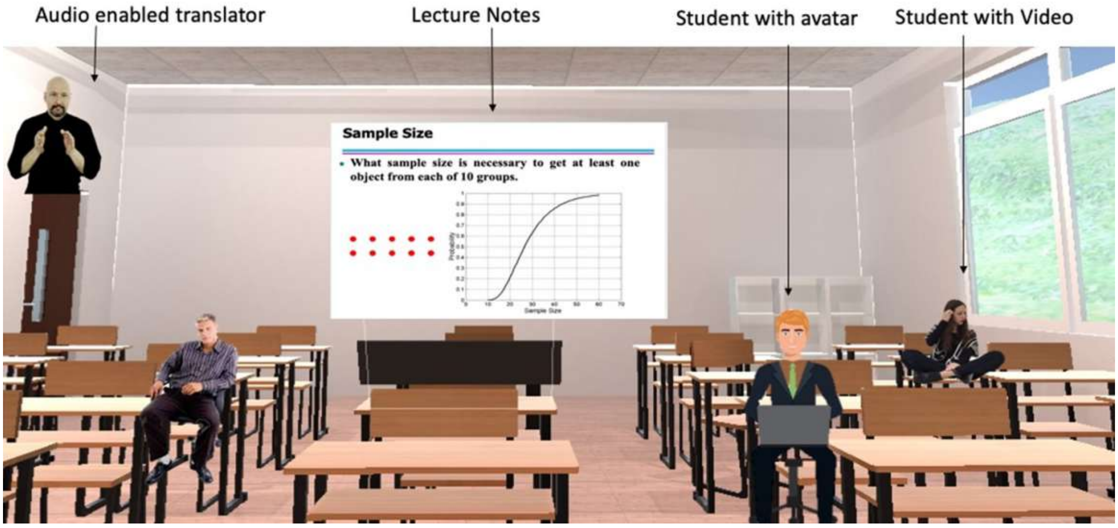

Figure 2.30: A Deaf Accessible Virtual Environment for Education (DAVEE) [11].

Te'ofilo et al. [50] developed a system for interpreting speech, converting it to text, and showing it as subtitles in a VR environment. This system helps DHH persons attend live theaters and understand the dialogues. Based on the results, more DHH persons desire to attend and enjoy live theaters using their proposed system (Figure 2.31).

2.5.2 VR in Accessibility Research

Using VR in accessibility research to include impaired people comes from research at least two decades ago. The technology has been applied to a wide range of accessibility topics, targeting people with learning disabilities, anxiety and phobias, life quality for spinal cord injured patients, and people fighting along with post strokes [31]. Recently, more researchers have been following the possibilities of VR accessibility to socialize with visually and auditory-impaired people.

Figure 2.31: VR in live theaters for DHH persons [50].

VR benefits often included improved safety and adherence to programs, documentation, and individualization capabilities [204]. For example, in autism research, psychology scientists considered that VR might improve the treatment of persons with Autism Spectrum Disorder (ASD) by increasing the frequency and customization of role-playing tests while demanding fewer resources (e.g., teachers, parents, and schools) [205, 206] (Figure 2.32). Some other scientists consider VR technology capabilities to automate and personalize therapies and improve final results [191].

Figure 2.32: VR for helping ADHD kids to access learning environments [206, 207].

2.6 VR Methods for DHH Persons

Previous research shows the benefits of using VR for DHH persons, especially for accessibility in education and entertainment, but there are still many limitations for DHH persons to use VR. VR Developers try to reduce the number of these limitations by using new methods that specialize for DHH persons. This section introduces methods that help DHH persons use VR with more attention and benefit.

2.6.1 3D Symbols in VR Environments

People without hearing problems benefit from all their senses in a VR environment for an immersive experience. They use environmental sounds to focus on a particular object or task, but DHH persons cannot easily find sound objects in a VR environment. Using 3D symbols in the DHH person's FOV is one of the ways that VR developers can draw the user's attention to a certain point or task in a VR environment. Passing et al. [208] used 3D symbols to improve DHH children's induction skills and social interactions (Figure 2.33). They show that 3D objects will positively affect the ability of DHH children to use inductive processes when dealing with shapes [208]. This study indicates that practicing in a VR environment, including 3D symbols, significantly improves inductive thinking used by DHH children.

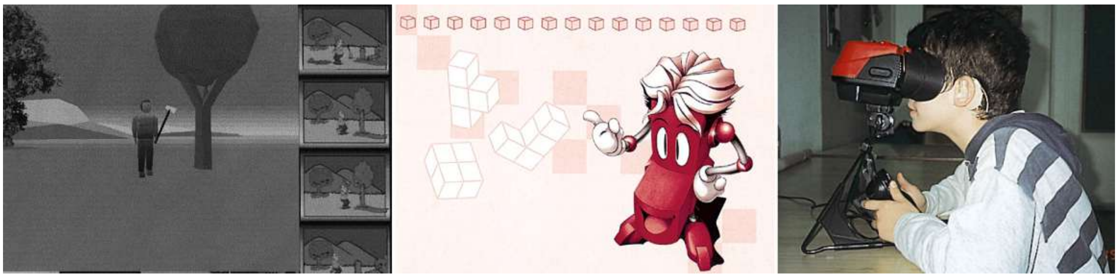

Figure 2.33: Using 3D symbols in VR to improve DHH children's induction skills [208].

2.6.2 3D Sign Language Interpreter in VR Environments

Deaf persons have difficulties accessing information or communicating with people without hearing problems [209]. Communication is an essential difficulty that deaf persons face with hearing people because not all hearing persons know sign language, which is the mother language among deaf persons [210]. Sign language translators can interpret speech into sign language so deaf persons can understand it.

Although deaf persons do lip-read to understand speech, sign language translators are more efficient [211]. According to the WFD, there are more than 130 types of sign languages all over the world [212], such as American Sign Language (ASL), British Sign Language (BSL), German Sign Language (DGS), Australian Sign Language (Auslan), Indian Sign Language (ISL), Persian Sign Language (PSL), Arabic Sign Language (ArSL), and many more.

Sign language translators are widely used in different applications to help deaf persons communicate with hearing people [213]. Recently, researchers used the benefits of these systems for deaf persons in portable devices by using 3D avatars that can translate speech to sign language. Ahmed et al. [214] proposed the "Deaf Talk" system that bridges the communication gap between deaf and hearing persons using 3D avatars and Microsoft Kinect V2 (Figure 2.34).

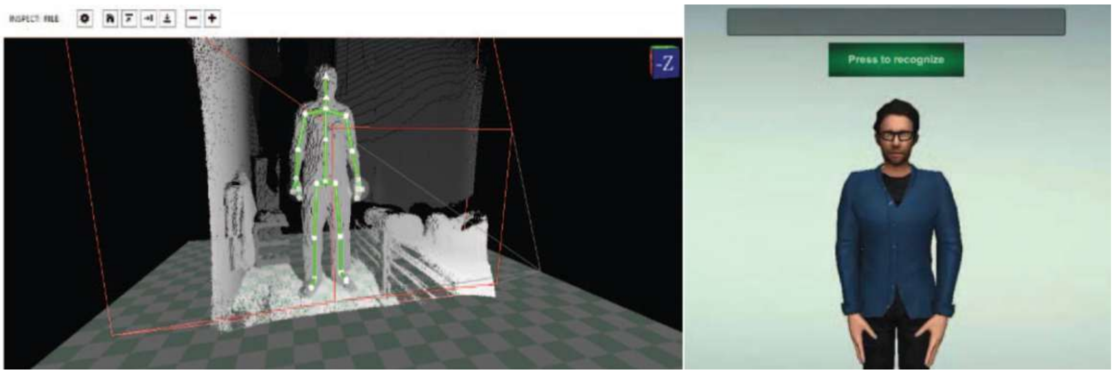

Figure 2.34: Deaf Talk system with Kinect V2 [214].

The "Deaf Talk" system acts as a sign language interpreter and translator to provide a dual mode of communication between sign language speakers and natural language speakers [214]. This study shows that the software-based solution based on Kinect V2 offers a mechanism through which people with hearing and speaking disabilities can communicate naturally with the rest of the world with an accuracy of 87 percent for speech-to-sign language conversion and 84 percent for sign language to speech conversion [214].

SiMAX [215] is another handy software approach that uses a 3D sign language translator to help DHH persons. It uses learning databases to translate input text into 3D animated sign language by providing a high-quality translation rendered by digital 3D avatars (Figure 2.35).

Figure 2.35: SiMAX software for DHH users [215].

2.7 DHH Persons' Challenges in VR

Accessibility is more focused on issues related to vision or mobility, and engineers and developers need to consider whether their designs and applications are accessible to individuals who are DHH [216]. Captioning is one of the most remarkable ways to make videos accessible for DHH persons, but unfortunately, most video content on the internet is not captioned. Non-intelligent automatic captioning software is also inaccurate because of missing capitalization and punctuation or blending captioned lines that make it hard to decode the captions [217]. Therefore, DHH persons can only access some video content, especially learning videos that are the most important. This topic becomes very important when discussing new technologies such as voice control and VR. There are many ways that DHH persons could benefit from technology. One example is text telephones (TTY), developed in the 1960s to help DHH persons access telephones, or an ASL videophone by AT&T particularly designed for DHH persons in 1964.

Voice control is already used in various technologies, including smartphones and smart home devices, but almost all of these technologies are inaccessible for DHH users because most DHH persons cannot use their voices properly [218]. Automatic Speech Recognition (ASR) is now accurate thanks to its significant progress with the advancement of Artificial Intelligent (AI) technology, and DHH persons can use it in communication and accessibility applications. Still, this technology is not widely used with other technologies and has few user experiences, which makes it limited for persons users. ASR technology should use different input methods, such as typing or a touch screen, to ensure it will be accessible for DHH persons. Therefore, future research and development are required with DHH participants to improve the uses and applications of ASR technology [219].

Many of the changes that could make new technology accessible to DHH persons could also benefit other groups, including older adults, non-native speakers of English, and those with learning disabilities [220]. Therefore, it is essential to notice DHH persons' challenges in using and accessibility of new technologies, such as VR. VR and related technologies show the possibility of using these technologies for DHH persons' accessibility, but there are still so many VR contents that are not accessible for DHH persons. Most VR contents emphasize auditory cues for tasks like navigation and finding particular objects, also called "sound localization" [221]. Deaf persons usually do not have any problem understanding the visual content of the VR environment because they use their vision, but they have problems completing sound-related VR tasks and doing sound source localization in VR [13].

Some previous studies tried to use a captioning technique or sign language interpretation in the VR environment [222, 223], but using these techniques makes DHH persons unable to notice all the visual materials in the environment. For example, in a VR classroom with a 3D sign language interpreter or caption, DHH persons have to look back and forth between the instructor, slides, notes, captions, or a 3D interpreter. Therefore, they need to fully immerse themselves in the VR environment, which is one of the main challenges of VR developers who want to develop a VR application for DHH users.

2.7.1 Sound Source Localization and Immersive VR Experience

Sound source localization is detecting the location of a sound source in an environment, which is crucial in daily human life [224]. The brain utilizes subtle differences in intensity, spectral, and timing cues to localize sound sources [225]. We detect the position of a sound source in a 3D environment, such as azimuth, height, and distance, using our hearing sense (Figure 2.36), and it is based on three types of complementary cues and varies according to the acoustic characteristics of the sound [226].

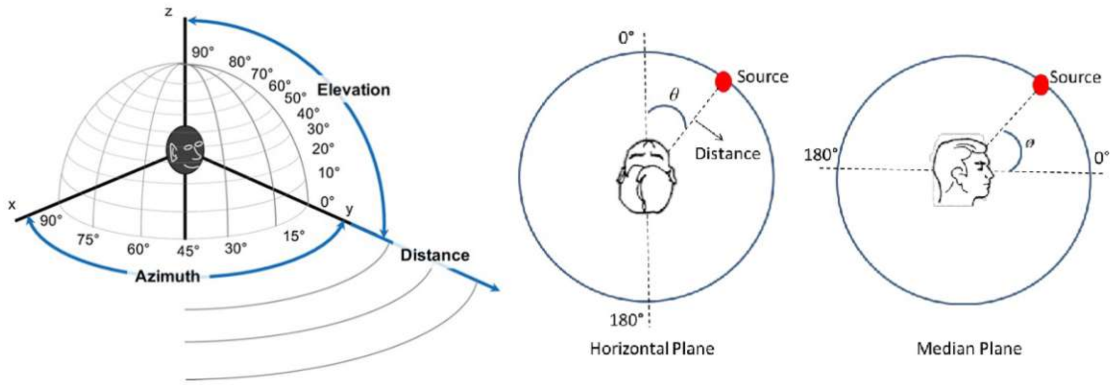

Figure 2.36: Polar coordinates used to locate a sound source in an x-y-z perpendicular 3D space centered on the hearer [226].

These types of cues are two binaural cues, including Interaural Time Difference (ITD) and Interaural Level Difference (ILD), and one monaural spectral cue called Head-Related Transfer Function (HRTF). Sound source localization depends not only on hearing senses but has evolved over the years within a multisensory environment [227]. Previous studies have shown that spatial hearing evolved with other sensory systems, such as vision, under ecological pressures [228].

In VR, using 3D audio helps users make sound localization more manageable and helps users to immerse in the VR environment [229]. However, sound source localization is also affected by visual stimuli [230], and using different visualization techniques in VR also helps users complete sound-related VR tasks [231, 232]. Visual attention is essential in VR because it avoids processing unnecessary information by the brain and helps users focus only on the essential parts of the VR environment [233].

The advancement of VR tools, such as HMDs, has significantly improved immersive VR experience [234]. Audio and visual stimuli play essential roles in VR. Using different audio and visual techniques increases the immersion in VR significantly [235]. For example, when spatial audio is used as an auditory stimulus, the user can locate different sounds in the VR environment and react to them by head or body movements.

Using different visualization techniques in VR also obliges DHH persons to pay more attention to particular objects and have a far more exciting VR experience [232]. C.J. Hughes et al. [236] and E. Oncins et al. [237] use immersive media technologies, such as VR and 360° videos, to create accessible media for DHH persons by visualizing captioning and subtitles. Appropriate visual effects in VR change the user experience and reduce simulator sickness [238].

Recent studies have shown that haptic feedback also plays an essential role in VR in addition to audio and visual stimuli [239]. Oliviera et al. [240] have designed a vibrotactile HMD for spatial awareness in virtual and real environments. They show that using haptic feedback devices around the user's head helps them find objects in the azimuthal plane more efficiently and faster in VR environments (Figure 2.37).

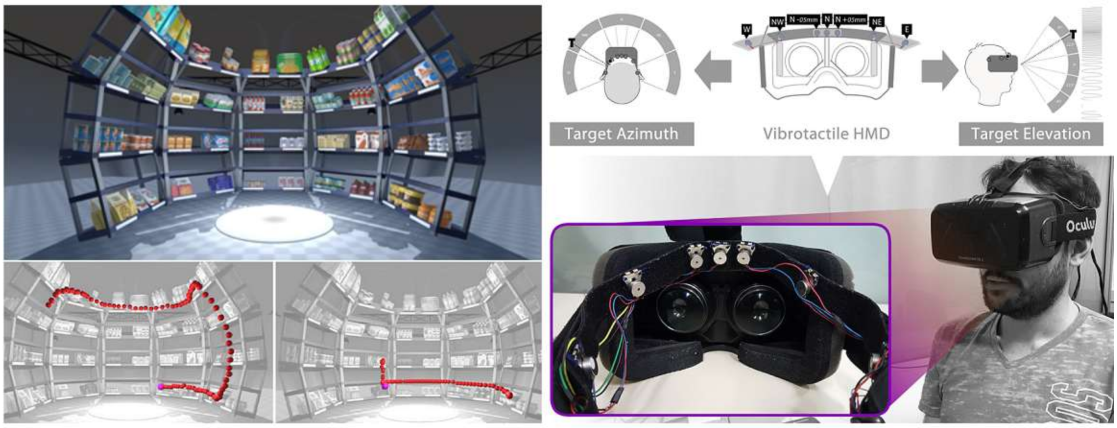

Figure 2.37: VR vibrotactile HMD [240].

DHH persons use visual and haptic stimuli rather than audio stimuli [241]. Previous research has shown that DHH individuals preferred to use visual and haptic feedback in wearable and mobile sound awareness technologies, such as haptic on a smartwatch and visual on a HMD [242], but to the best of our knowledge, none of these methods are used together (in real-time) to help DHH persons in VR.

2.7.2 Multi-modal Spatial Object Localization in VR

Information visualization techniques improve task performance, support cognitive processes, and eventually increase the feeling of immersion in VR [243]. People use multiple different perceptual modalities to interact with the world naturally [244]. Gruenefeld et al. [44] and Yu et al. [45] developed and evaluated HaloVR/AR (Figure 2.38-a), WedgeVR/AR (Figure 2.38-b), and 3DWedge/3DArrow (Figure 2.38-c). They show that their proposed visualization techniques would significantly improve out-of-view objects' search time and direction estimation performance when FOV is high enough.

Bork et al. [245] proposed the "Mirror Ball" and the "3D Radar" as two approaches for visualizing out-of-view objects in Mixed Reality (MR) environments (Figure 2.38-d). They demonstrated that different visualizations encourage distinct object-targeting approaches in MR. Also, Biocca et al. [246] and Hsieh et al. [247] proposed methods for AR that guide a user's attention to any object in AR environments interactively. They show that these techniques, such as "Attention Funnel" by Biocca et al. [246] (Figure 2.38-e), could increase the consistency and the speed of the user's search and decrease the mental workload in AR [246], and try to minimize the effects of human FOV limitations, amplify when combined with the FOV limitations of VR and AR HMDs.

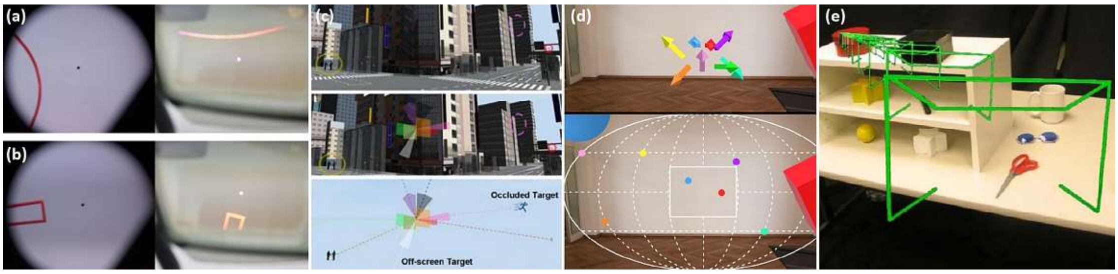

Figure 2.38: Multi-modal object localization methods in VR/AR [44, 45, 245, 246].

Paying attention to requirements about presenting information in VR for DHH persons is essential because they perceive VR environments differently. Many studies, such as Ho-Ching et al. [49], Matthews et al. [162], and To'efilo et al. [50], suggested that using visual stimuli helps DHH persons improve their VR interaction. They show that DHH persons use visual cues to recognize and find sound sources in the environment.

According to Jain et al. [248], Kasozi et al. [249], and Brains [250], the average reaction time of a person to different environmental events is about (not precisely) 0.25 seconds for visual, 0.17 seconds for audio, and 0.15 seconds for haptic stimuli. Previous studies have shown that DHH persons have a faster reaction time to visual stimuli and better peripheral vision than persons without hearing problems [18, 20, 19].

Overall, almost all of the previous research focused on different aspects of using visualization methods and multi-modal information presentation in VR and AR, and some of them demonstrated the benefits of using these techniques for DHH persons. To the best of our knowledge, no comprehensive research in this area compares the effects of using different visualization techniques and multi-modal information presentation on deaf persons to achieve real-time spatial object localization, sound localization, and task completion in VR environments.

CHAPTER 3

Requirement Analysis

Understanding deaf persons' requirements when using VR is essential in the design process of an assistive system. This chapter addresses some challenges encountered at the early stages of designing an assistive system for deaf persons to facilitate a better experience in VR.

At the beginning of this chapter, we reveal the findings from a background survey conducted with DHH persons from different backgrounds and different levels of hearing impairment to manage the basis for conceptualizing approaches that helped us design a practical assistive system and understand how we can provide a better VR experience for deaf persons. This survey was essential because, to the best of our knowledge, there needs to be well-defined information on the requirements of deaf persons in VR.

To answer fundamental questions of this thesis related to deaf persons' VR experience, we investigate different parameters, such as haptic and visual stimuli, and the differences between perceiving the stimuli among DHH and persons without hearing problems that make a VR experience different among them. Then, we propose different approaches for visualizing audio in VR for deaf persons in a practical assistive system working in real-time.

At the end of this chapter, we described different development phases of our proposed systems, allowing deaf persons to have a better VR experience by finding a suitable mapping between visualizing audio in different approaches, such as haptic feedback, visual feedback, and a combination of haptic and visual methods based on the result of our survey among DHH participants.

3.1 Background Survey

Before starting the system's design phase, a survey was conducted among 100 DHH persons with different backgrounds from the DHH community (65 men, 35 women, 15 to 55 years old, M = 34.07, SD = 11.047). Among all of the participants, there were 50 partially deaf participants (group 1) with different degrees of hearing and not using HA or CI (36 men, 14 women, M = 36.26, SD = 10.669) and 50 profoundly deaf participants (group 2) with no hearing in both ears (29 men, 21 women, M = 31.88, SD = 11.088).

All participants could read and write Persian (native) and English languages and lip-read Persian for communication. We asked them to complete an eleven-question survey addressing the needs and preferences of DHH persons eager to use VR. We presented each question in Persian text for participants (the English version of the questionnaire is also prepared in Appendix-C 6.3). Also, an expert in Persian sign language was available to participants upon request. However, no such request was made by the participants. We categorized the survey questions into three following main categories, using unique codes for each section:

- Code "VRt": Questions related to using VR technology among DHH persons.
- Code "VRj": Questions related to VR enjoyment factors for DHH persons.
- Code "VRv": Questions related to preferred visualization methods in VR among DHH persons.

We formulated our hypotheses as follows:

- H1. Partially deaf persons are more familiar with VR technology than profoundly deaf persons.
- H2. Partially deaf and profoundly deaf persons are willing to participate in VR experiences.
- H3. Partially deaf persons use VR more frequently than profoundly deaf persons.
- H4. Partially and profoundly deaf persons prefer to use mobile phones and VR HMDs to experience VR.
- H5. Partially and profoundly deaf persons prefer to use haptic and visual feedback to visualize audio in VR.

The survey questions are summarized in Table 3.1, including the unique code for each question. We organized our background survey questions in a way that helps us investigate the following fundamental issues related to DHH persons who are eager to use VR technology:

- How much are DHH persons engaged in VR activities?
- What types of VR applications are preferred by DHH persons?
- How much the level of deafness affects the willingness to be involved in developing a new assistive VR device among DHH persons?
- Which factors of the VR environment are essential for a better VR experience among DHH persons?
- What are DHH persons' preferred visualization methods and devices in VR?
- How much does partial hearing among partially deaf persons affect their use of VR technology compared to profoundly deaf persons?

Question Code	Question	Answers
VRt1	Are you familiar with VR technology?	Yes, No
VRt2	Are you willing to be involved in developing a new assistive VR device that would enhance your VR experience?	Yes, No
VRt3	Did you try any VR activities or games before?	Yes, No
VRt4	How many times have you used VR before (*Only 1 Answer*)	Never Used VR, Only 1 Time, 2 to 10 Times, 11 to 50 Times, More than 50 Times
VRt5	What type of VR devices do you like to use? (*Only 1 Answer*)	Mobile Phone VR, VR HMDs, Both
VRt6	What type of assistive technology do you think will help DHH users more in VR? (*Multiple Answers*)	Sound Amplification, Subtitle Display, Sign-Language Interpreter, Hardware Assistant
VRt7	What improvement in VR do you think will have the best impact on creating VR applications or games for DHH users? (*Multiple Answers*)	Better Visual Display, Better Audio, Add Haptic Feedback, Add Visual Feedback, Add Sense of Smell, Add Sense of Taste, Add Sense of Movement or Rotation
VRt8	What is the main reason for not using VR, in your opinion? (*Multiple Answers*)	Costly, Not Usable, Inaccessible, Lack of Content, Motion Sickness, Dislike, Not Immersive
VRj1	Which of the following factors do you think is essential for DHH users to enjoy VR? (*Multiple Answers*)	Spatial Presence, Environmental Feedback, Interactivity, Realism, Motion Sickness Reduction
VRv1	Which of the following audio categories is the most important to visualize in a VR environment for a DHH user? (*Multiple Answers*)	Human Sounds, Animal Sounds, Music, Sounds of Things, Natural Sounds, Environmental and Background Sounds, Source-ambiguous Sound
VRv2	Please rank the following visualization methods in order of importance for DHH users.	Haptic, Visual, Force, Thermal Likert-Scale: 1 = Least Important 5 = Most Important

Table 3.1: Background survey questions and answers.

We did not exclude any participants' responses in the final analysis of the results. Also, we did not ask about the detail of each question. For example, in a question about familiarity with VR, we did not expect to know how the participant became familiar with VR technology. The participant could be familiar with VR using news or trying it before. We summarized the findings of the survey questions in the following subsections.

3.1.1 VR Technology for DHH Persons

DHH persons cannot hear audio and perceive it differently, so usually, they are not eager to use VR technology because most VR applications and games include audio. In our questionnaire, we asked about participants' familiarity with VR technology (Code: VRt1), their willingness to be involved in VR development experiences (Code: VRt2), if they had taken part in any VR activities or games (VRt3), and how many times they used VR (VRt4). The result of the VRt1, the VRt2, and the VRt3 questions is shown in Table 3.2.

	VRt1		**VRt2**		**VRt3**		
Participants	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Total**
Partially Deaf	46	4	48	2	32	18	50
Profoundly Deaf	28	22	49	1	4	46	50
Total	74	26	97	3	36	64	100

Table 3.2: Reported answers of partially and profoundly deaf participants regarding familiarity with VR (VRt1), being willing to be involved in VR experiences (VRt2), and trying VR (VRt3).

A Chi-Square test of independence was performed (with $\alpha = 0.05$) to examine the relation between partially and profoundly deaf groups and the number of responses for VRt1, VRt2, and VRt3 questions. The test indicates a significant relation between the variables in VRt1 question ($\chi^2_{1,N=100} = 16.840$, p <0.001, minimum cells' expected count = 13), and VRt3 question ($\chi^2_{1,N=100} = 34.028$, p <0.001, minimum cells' expected count = 18), but no significant relation in VRt2 question ($\chi^2_{1,N=100} = 0.344$, $p = 0.558$, minimum cells' expected count = 1.5, Fisher's exact test's p-value = 1). Analysis of the results is summarized as follows (although further analysis is needed to confirm these findings):

- ***For VRt1 question:*** 46 out of 50 partially deaf participants (92%) and 28 out of 50 profoundly deaf participants (56%) selected "Yes" as the answer, which shows partially deaf participants were more likely familiar with VR technology than profoundly deaf participants. This result supports our H1 hypothesis.

- ***For VRt2 question:*** 48 out of 50 partially deaf participants (96%) and 49 out of 50 profoundly deaf participants (98%) selected "Yes" as the answer, which shows partially and profoundly deaf participants were willing to participate in VR experiences. This result supports our H2 hypothesis.

- ***For VRt3 question:*** 32 out of 50 partially deaf participants (64%) and 4 out of 50 profoundly deaf participants (8%) selected "Yes" as the answer, which shows partially deaf participants more likely to use VR than profoundly deaf participants.

The number of responses for the VRt4 question among both groups of participants is shown in Figure 3.1. A Shapiro-Wilk test of normality with $\alpha = 0.05$ was conducted to determine whether variables are approximately normally distributed. The test and a visual inspection of the histograms indicate that the number of responses was not approximately normally distributed for partially and profoundly deaf groups in VRt4 question (partially deaf group: $W = 0.777$, $p < 0.001$, and profoundly deaf group: $W = 0.303$, $p < 0.001$).

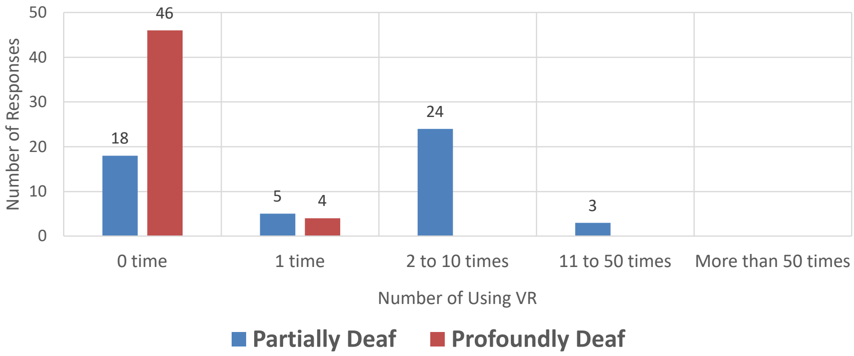

Figure 3.1: Usage of VR among DHH participants.

A Mann-Whitney U test using an $\alpha = 0.05$ was conducted to determine whether there is a significant difference in number of using VR between partially and profoundly deaf groups. The results indicate significant difference between groups ($U = 496$, $p < 0.001$). Analysis of the result shows that the number of using VR in the partially deaf group is statistically significantly higher than the profoundly deaf group. Therefore, our H3 hypothesis is supported. The results show that participants in the profoundly deaf group are not willing to use VR as much as partially deaf participants. In the partially deaf group, 32 out of 50 participants (64%) reported using VR at least once or more. However, in the profoundly deaf group, only 4 out of 50 participants reported using VR only once (8%), and 46 out of 50 participants reported never using VR (92%). Among 27 partially deaf participants who used VR at least twice or more, 19 participants commented that after using VR between 7 to 16 times, they became disappointed and lost their motivation (related to their level of deafness). We selected a part of a participant's comment in the partially deaf group (translated into English) and showed it in the following. The key points are highlighted and used for our qualitative analysis.

- Participant 24: *"I played a VR shooter game, but the game would be over very fast and I lost every time! It disappointed me and made me sad, because it was hard for me to detect enemies' sounds as fast as other players!..."*

DHH participants believed that almost all VR activities and games depend on audio (environmental sounds), and they cannot participate in those VR activities. Although, more literature reviews and further analysis are required to confirm if a different level of hearing impairments affects the number of using VR among partially deaf persons.

The result of the VRt5 question is shown in Figure 3.2. A Chi-Square test of independence was performed (with $\alpha = 0.05$) on each group separately to examine the relation between preferred VR devices for partially and profoundly deaf groups. The test indicates a significant relation between the variables in both groups (partially deaf: $\chi^2_{1,N=50} = 49.120$, p <0.001, minimum cells' expected count = 16.7, and profoundly deaf: $\chi^2_{1,N=50} = 77.560$, p <0.001, minimum cells' expected count = 16.7).

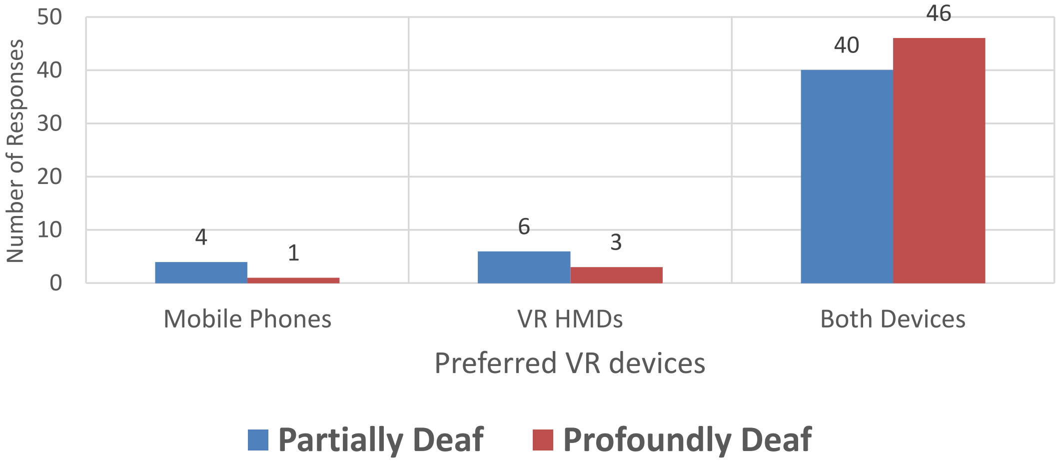

Figure 3.2: Preferred VR devices among DHH participants.

Analysis of the result in partially and profoundly deaf groups show that in both groups, participants prefer to use mobile phones and VR HMDs (both devices) for their VR experience compared to using only mobile phones or only VR HMDs. Therefore, our H4 hypothesis is supported. Although, further analysis is needed to confirm this finding.

The result of the VRt6 question (multiple responses) is shown in Figure 3.3. In the VRt6 question, we asked participants about their preferred type of assistive technology in VR. We categorized the four main following assistive technologies for DHH persons that can be used in VR:

- *Sign-Language Interpreter:* Using 3D models (humans or hand models) to interpret audio information of VR environments to sign language.
- *Subtitle Display:* Showing audio information in VR environments using text-based subtitle style.
- *Sound Amplification:* Using HAs or amplifiers for increasing the volume level of sounds in the VR environment.
- *Hardware Assistant:* Using hardware devices, such as haptic and visual devices, to provide environmental information using tactile and visual sensation.

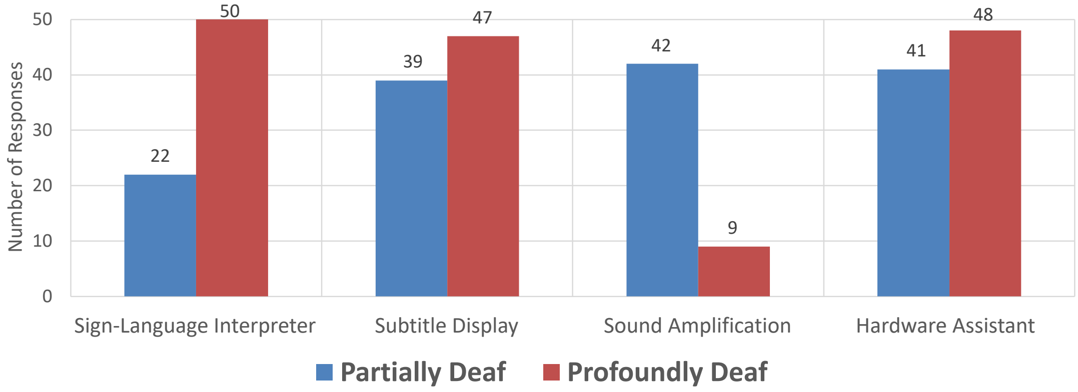

Figure 3.3: Preferred types of assistive technologies in VR among DHH persons.

The descriptive statistics for multiple responses to the VRt6 question show that both groups believe assistive technologies benefit DHH persons in VR. Our initial observation shows differences between the result of the sign-language interpreter and sound amplification. We believe the difference in hearing level among participants of both groups causes the variation of answers. However, further analysis is required to confirm it in VR.

The result of the VRt7 question is shown in Figure 3.4. Analysis of the result using descriptive statistics for multiple responses suggests that both groups believe adding haptic and visual feedback to a VR application or game will affect DHH persons' VR experience. Although, further analysis is needed to confirm this finding.

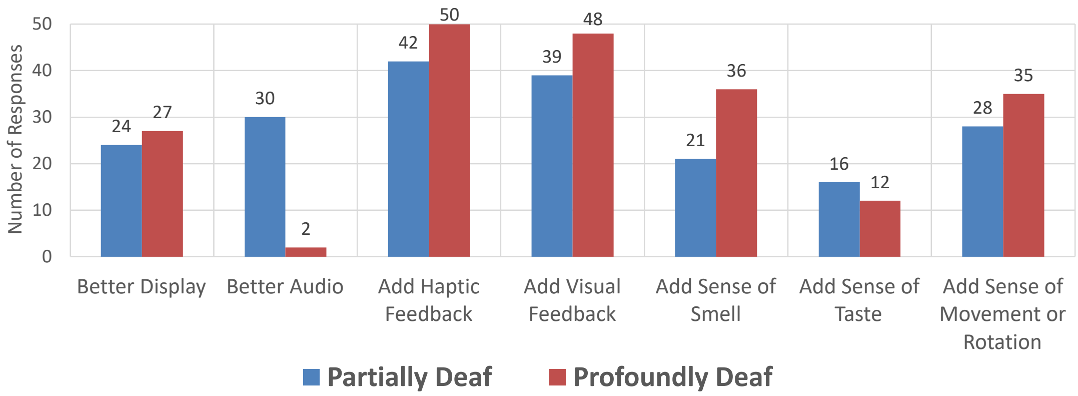

Figure 3.4: Practical VR improvements for DHH users.

The result of the VRt8 question is shown in Figure 3.5. The options for this question were chosen from an online survey we did among the DHH community. Analysis of the result using descriptive statistics for multiple responses suggests that both groups believe lack of content and inaccessibility are two important reasons for not using VR among DHH persons. Although, further analysis is needed to confirm this finding.

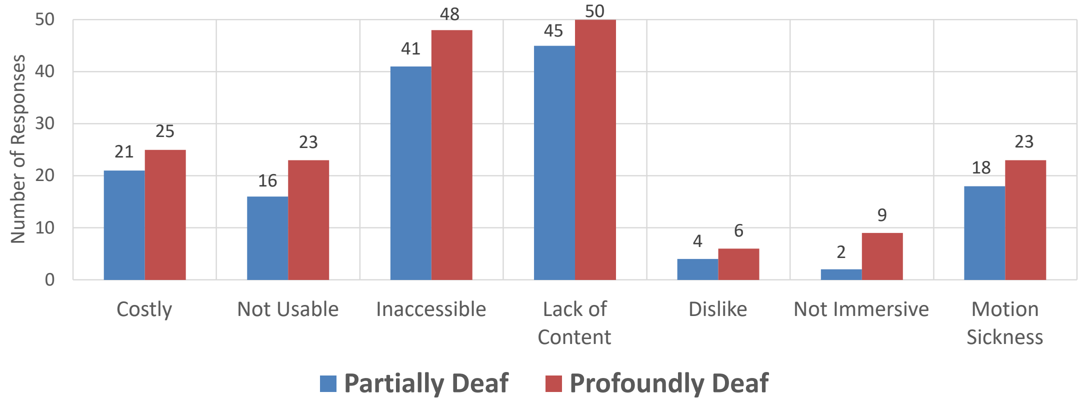

Figure 3.5: Reasons for not using VR among DHH persons.

Participants in both groups commented that they could not find any VR activity or game with a particular feature for DHH persons, primarily because of the lack of content, so they were unwilling to use VR. We selected four comments of DHH participants from both groups (translated into English) and showed them in the following. The key points are highlighted for our qualitative analysis.

- Participant 34: *VR is Amazing! I have always wanted to try VR, but I can't use and enjoy it! I tried a VR game once, and realized that I couldn't even pass one level because I couldn't find the enemies in the VR environment resulting in me not being able to beat the level! I even tried a puzzle VR game. It was a little more playable because I didn't need to focus on incoming enemies' directions! The main problem though, was that the game had a lot of different sounds which I couldn't recognize! and I couldn't enjoy the game at all because of that! This experience made me very sad and disappointed.*
- Participant 17: *I am a deaf person. I have some particular requirements. I need to know about the sound object positions or feel the audio in the environment. Unfortunately, only some of them are included in VR games which are not very practical for me! Therefore, I'm not very eager to use VR technology, at least until I know that it can support my main requirements.*
- Participant 82: *I love VR, but I can't use it! There are so many sound objects in the environment in different VR games and I can't locate them at all!!! Some VR games have a lot of visual effects which help me feel the game better, but they can become very annoying because it seems that a lot of these effects don't have any purpose, and they just randomly appear in the environment!*
- Participant 26: *I never thought that one day I could use and enjoy VR! VR is a great technology, and it can help deaf persons in many cases, especially in education. One day one of my friends suggested that I try a VR game with*

> *some built-in features for deaf users. I tried it, and it was very enjoyable! The game's main character could communicate to people using sign language, and the game had a very calm environment with attracting and pleasing visual effects to notify users of a particular object or path! It was a great experience for me. After that, I tried to find similar games, but unfortunately, I couldn't find any in the market!!! There are probably more games like this, but there is no easy way for a deaf person to find them .There is no sign showing if the game is suitable for deaf users which is not very pleasant for me!*

Almost all VR applications and games in the market are designed for hearing persons, and DHH persons have difficulties finding a VR application or game with particular built-in features [251]. Recently, VR developers tried to add some features to some VR games, but there is no particular sign that could help DHH persons easily find them. Therefore, DHH persons have trouble finding suitable VR applications or games. Consequently, they will not search for VR applications or games and will give up using VR.

Results in this section, such as preferences of mobile phones and VR HMDs, hardware assistant, adding haptic and visual feedback in VR, and focusing on inaccessibility and lack of content in VR among partially and profoundly deaf persons, helped us to design our proposed assistive VR systems in a way that helps deaf persons to use any VR application or game in the market designed for hearing persons without worrying about limitations and features of them.

3.1.2 VR Enjoyment Factors for DHH Persons

Enjoyment is a feeling of pleasure that users experience because of being exposed to some particular media stimulus [252]. Investigating the enjoyment factors in VR requires a precise analysis of the psychological and physiological effects of using VR among users. We did not do a psychological analysis for this thesis, so we only focused on essential enjoyment factors of VR experiences from DHH users' perspectives to understand the enjoyment effects of those factors. We selected five essential VR enjoyment factors from previous studies, such as Shafer et al. [253, 254] and Melo et al. [255]. We asked both groups of participants to answer the VRj1 question about the importance of these enjoyment factors in VR.

- *Spatial Presence:* The sense of being in a VE.
- *Interactivity:* Interacting with virtual objects in a VE.
- *Environmental Feedback:* Engaging users' senses in VEs using multimodal feedback.
- *Realism:* Creating a VE very similar to the real world.
- *Motion Sickness Reduction:* Using motion sickness reduction methods.

The result of the VRj1 question is shown in Figure 3.6. Analysis of the result using descriptive statistics for multiple responses suggests that both groups of participants believe environmental feedback, spatial presence, and interactivity are essential VE enjoyment factors in VR for DHH persons. Although, further experiments and analysis are needed to confirm this finding and investigate if the suggested VR enjoyment factors affect DHH persons' VR experience.

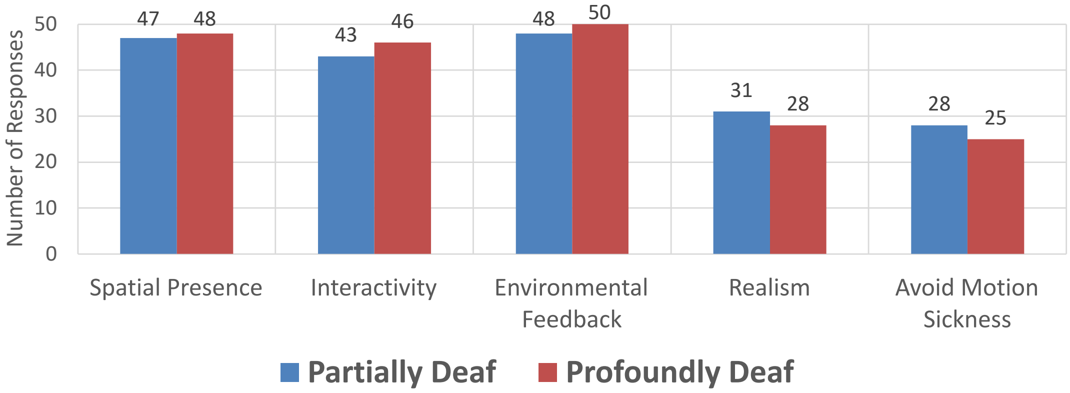

Figure 3.6: The importance of VR enjoyment factors for DHH persons.

Spatial presence is the feeling of "being there" in a virtual environment and is related to many factors, such as using 3D audio and visualization techniques [256]. 3D audio is a crucial factor in an immersive VR experience [257]. It helps increase the feeling of immersion in VR and can draw users' attention to different directions, such as behind, below, above, left, and right. Profoundly deaf persons have more difficulties than partially deaf persons achieving spatial presence in a VR environment [258]. The importance of spatial presence as an enjoyment factor differs among partially deaf persons based on their level of deafness. Also, some research shows that people feel sounds and haptic cues with their muscles [259] and faces [260]. Therefore, using haptic devices in VR affects the feeling of spatial presence [258]. Spatial presence is also connected to interactivity and environmental feedback, usually studied under laboratory conditions. Using these factors simultaneously helps DHH persons achieve spatial presence in VR.

3.1.3 Preferred Audio Visualization Methods for Deaf Persons

Visualizing audio for deaf persons is important because it helps them understand the audio, for example, in music applications. It also helps deaf persons locate sound sources in environments if a proper method for visualizing audio is used. To the best of our knowledge, in most previous studies that already used visualization methods for DHH persons, the study was conducted with a proposed method that only helps DHH persons understand some particular features of the environmental audio, such as rhythm and wave bass in music visualization software. However, we can use proper visualization methods for sound source localization.

We asked DHH participants two questions about their preferred audio categories (VRv1) and audio visualization methods (VRv2) for sound source localization in VR. For the VRv1 question, we used the Google AudioSet ontology [1] with seven main audio categories shown in Table 3.3. For the VRv2 question, we used haptic, visual, force, and thermal feedback as the main answers for different ways of getting feedback from a VR environment on a 5-point Likert scale question (1 = Least Important, and 5 = most important):

Audio Category	Example Sounds
Human Sounds	human voice, whistling, respiratory sounds, human locomotion, digestive, hands, heart sounds, heartbeat, otoacoustic emission, human group actions, etc.
Animal Sounds	domestic animals, pets, livestock, farm animals, working animals, wild animals, etc.
Music	musical instrument, music genre, musical concepts, music role, music mood, etc.
Sound of Things	vehicle, engine, domestic sounds, home sounds, bell, alarm, mechanisms, tools, explosion, wood, glass, liquid, miscellaneous sources, specific impact sounds, etc.
Natural Sounds	wind, thunderstorm, water, fire, etc.
Source-Ambiguous Sounds	generic impact sounds, surface contact, deformable shell, onomatopoeia, silence, other source-less, etc.
Channel, Environment, and Background Sounds	acoustic environment, noise, sound reproduction, etc.

Table 3.3: Audio categories in Google AudioSet ontology.

The result of the VRv1 question is shown in Figure 3.7. Analysis of the results using descriptive statistics for multiple responses shows that overall, both groups reported the sounds of things category as one of the essential audio categories for DHH persons to visualize in VR. Although, further analysis is needed to confirm this finding.

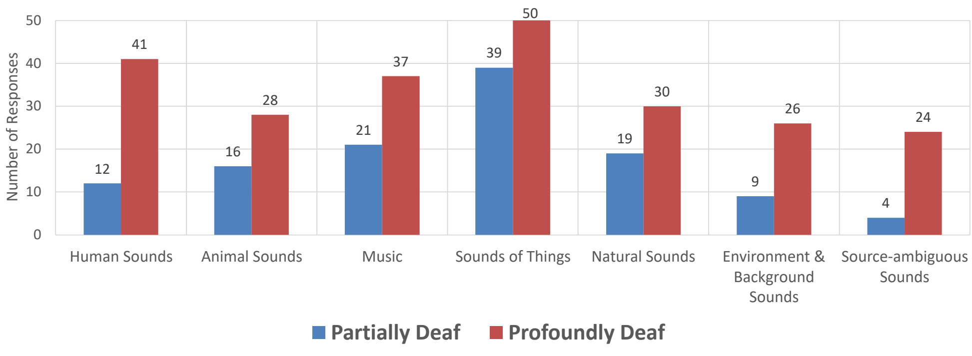

Figure 3.7: The preference of different audio categories to visualize in a VR environment among DHH persons.

[1]Available Online: https://research.google.com/audioset/ontology/index.html (accessed on 5 October 2021)

The result of the VRv2 question is shown in Figure 3.8. A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the number of responses was not approximately normally distributed for partially and profoundly deaf groups in VRv2 question (partially deaf group: haptic feedback ($W = 0.665$, $p < 0.001$), visual feedback ($W = 0.757$, $p < 0.001$), force feedback ($W = 0.813$, $p < 0.001$), thermal feedback ($W = 0.753$, $p < 0.001$), and profoundly deaf group: haptic feedback ($W = 0.198$, $p < 0.001$), visual feedback ($W = 0.412$, $p < 0.001$), force feedback ($W = 0.877$, $p < 0.001$), thermal feedback ($W = 0.859$, $p < 0.001$).

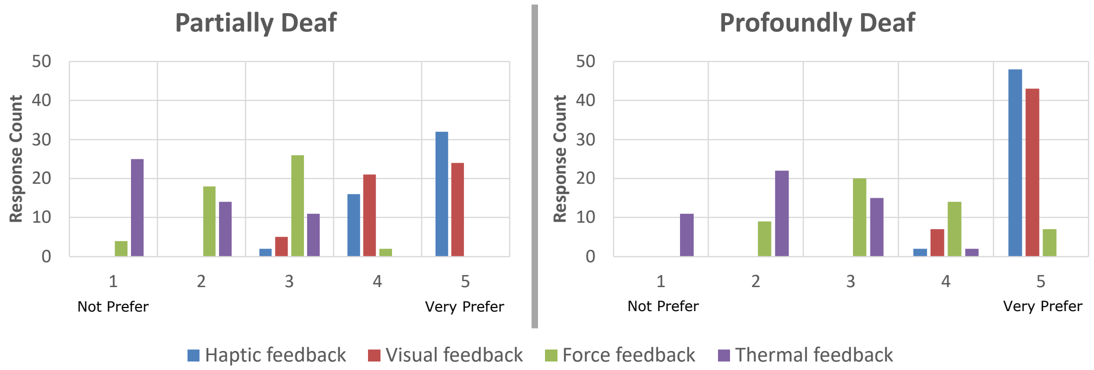

Figure 3.8: Preferred audio visualization methods in VR among DHH users.

A Mann-Whitney U test using an $\alpha = 0.05$ was conducted to determine whether there is a significant difference in visualization methods between partially and profoundly deaf groups. The results indicate a significant difference in each answer (Table 3.4). The result shows that the visualization methods are more suitable for profoundly deaf participants than partially deaf participants (significant differences are marked with a star (*) symbol near the p-value).

Haptic Feedback	Visual Feedback	Force Feedback	Thermal Feedback
U = 848 * $p < 0.001$	U = 757.5 * $p < 0.001$	U = 647 * $p < 0.001$	U = 891 * $p = 0.009$

Table 3.4: Mann-Whitney U test results of different visualization methods in partially and profoundly deaf groups.

Haptic, visual, forced, and thermal feedback are types of sensory feedback to enhance the user experience in various applications. Since our main goal was to use them together to create an immersive and interactive VR user experience, we considered them dependent samples. Therefore, a Friedman test with a significance level of $\alpha = 0.05$ is used to test for differences between partially and profoundly deaf groups. The test revealed a statistically significant difference in visualization methods for each group of participants (partially deaf: $\chi^2_{1,N=50} = 143.906$, $p < 0.001$; profoundly deaf: $\chi^2_{1,N=50} = 142.203$, $p < 0.001$).

A post hoc Wilcoxon signed-rank test with Bonferroni correction resulting in a significance level set at $\alpha < 0.008$ was conducted to examine the significant difference between the individual answers for each group of participants. The results of the Wilcoxon signed-ranked test are shown in Table 3.5. The results show that in each group of participants, haptic and visual feedback rated significantly higher (more preferable) than other visualization methods. This result supports our H5 hypothesis. Although, further analysis is needed to confirm this finding.

Partially Deaf	Visual Feedback	Force Feedback	Thermal Feedback
Haptic Feedback	Z = - 3.317 * p <0.001	Z = - 6.652 * p <0.001	Z = - 6.338 * p <0.001
Visual Feedback	—	Z = - 6.694 * p <0.001	Z = - 6.413 * p <0.001
Force Feedback	—	—	Z = - 5.879 * p <0.001

Profoundly Deaf	Visual Feedback	Force Feedback	Thermal Feedback
Haptic Feedback	Z = - 2.236 p = 0.025	Z = - 5.834 * p <0.001	Z = - 6.264 * p <0.001
Visual Feedback	—	Z = - 5.916 * p <0.001	Z = - 6.327 * p <0.001
Force Feedback	—	—	Z = - 6.551 * p <0.001

Table 3.5: Wilcoxon test results on preferred visualization methods among partially and profoundly deaf groups.

Overall, the results of this section indicate the importance of visualizing sounds of things, such as alarms, bells, and vehicle sounds, in VR for DHH persons using haptic and visual feedback methods. These types of sound visualization are used in alerting devices that help DHH persons do their daily work safely and are considered safety materials, especially in real-life emergencies [261, 262, 6].

3.2 Proposed Methods for Deaf Persons

Based on the results of our questionnaire, we considered three main approaches for visualizing audio in VR for DHH persons. We designed a concept system with particular hardware and software for each approach to investigate the effects of using them in VR for DHH persons. Our proposed audio visualization methods are as follows:

- **Haptic Feedback Approach:** Using vibrotactile haptic devices (vibro-motors) in a haptic VR suit to investigate the effects of these devices on the sound source localization ability of DHH persons in VR environments.
- **Visual Feedback Approach:** Using different visualization methods such as visualization in 3D space and visualization in the Heads-Up Display (HUD) to investigate the effects of these methods on the sound source localization ability of DHH persons in VR environments.
- **Haptic+Visual Feedback Approach:** Using a combination of haptic and visual methods using vibro-motors and LEDs (as a hardware implementation of visualization in the HUD) to investigate the effects of using both approaches on the sound source localization ability of DHH participants in VR environments.

3.3 Summary

In this chapter, we presented the results of our questionnaire among DHH participants. We showed that haptic and visual feedback are preferred for DHH persons to visualize audio in VR. The questions with the "VRt" code showed that DHH persons are willing to use VR, but some limitations do not let them have a good VR experience. These limitations are significant for profoundly deaf persons because they cannot hear audio, but partially deaf persons hear some sounds based on their degrees of hearing impairments.

Our observations indicated partially deaf persons use VR more than profoundly deaf persons. It means that even hearing a minimal sound has a noticeable impact on VR experiences among DHH persons. Therefore, attention to the requirements of profoundly deaf persons is essential to design a system that can help them have a good VR experience.

We also showed that DHH persons prefer to use mobile phones and VR HMDs. Therefore, we designed our assistive system as a portable system independent of VR devices for mobile phones and VR HMDs. DHH persons believe that haptic and visual feedback impact their VR experience and are helpful for audio visualization in VR. Therefore, we use haptic, visual, and a combination of them in our proposed system to investigate the effects of using these methods on deaf persons' VR experience.

The results of this chapter helped us to propose an assistive VR device for DHH persons based on their actual requirements and desires. Our foremost goal is to offer a comprehensive guideline to VR developers enabling them to create new VR environments, including different haptic and visualization methods that DHH persons and persons without hearing problems use without worrying about hearing limitations.

VR accessibility and lack of content in VR are two main problems that cause the unwillingness to use VR among DHH persons. There are many VR applications and games in the market that DHH persons cannot use [251]. Therefore, we designed our proposed system in a way that helps DHH persons use almost all of the current VR applications and games in the market without worrying about the built-in features for DHH persons.

The survey results in this chapter were only used for our system design process and helped us to understand fundamental information about DHH persons' VR requirements. Therefore, further comprehensive surveys with precise statistical analysis are required to fully understand DHH persons' VR requirements and investigate their VR experience.

CHAPTER 4

System Description

This chapter describes the hardware parts and software design of our proposed prototype systems designed to enrich the VR experience for deaf persons by enhancing sensory input information from tactile and visual channels. Our proposed systems have three main components: visual display (VR HMD), haptic feedback stimulator (vibro-motors), and visual feedback stimulator (LEDs).

The first section of this chapter describes our proposed haptic VR suit for deaf persons that can code the audio information from a VR environment to vibrotactile cues using four vibro-motors to demonstrate the four main directions of incoming audio (front, back, left, and right). Our proposed haptic VR suit was developed based on an initial concept guided by information from our background survey conducted with DHH persons described in Chapter 3.

In the second section of this chapter, we introduce a novel portable system for deaf persons called “EarVR” that analyzes 3D sounds in a VR environment and locates the direction of the closest sound source to the user in real-time using haptic feedback. Our proposed system notifies the user about the sound direction using two vibro-motors placed on the user’s ears. The EarVR system is developed based on the study results obtained from our proposed haptic VR suit described in Chapter 5.

Finally, in the third section of this chapter, an upgraded version of the EarVR system is explained. We added two additional LEDs to the EarVR system as visual feedback and called the new system "EarVR plus" (EarVR+). The EarVR+ automatically analyzes 3D spatial audio and indicates the closest sound source’s direction in real-time by combining haptic and visual feedback. Deaf persons can select either haptic or visual feedback or a combination in the system’s settings.

4.1 Haptic VR Suit

In VR, vibration devices are usually used in haptic VR suits or other wearable devices, such as haptic gloves, to improve VR experience [263]. A few versions of vibrotactile-based VR suits are available in the market, such as "TactSuit" [1] and "TeslaSuit" [2], but they have not been tested with deaf persons. Haptic VR suits help users perform sound-related VR tasks, such as navigation and sound awareness [103, 103], but comprehensive studies are required to investigate the effects of using different setups of haptic VR suits on deaf persons for sound localization in VR.

4.1.1 Mapping Audio to Haptic

Our goal is to investigate if using a haptic VR suit with different setups affects DHH persons' sound localization in VR. We designed a haptic VR suit with four vibro-motors to demonstrate the four main directions of incoming sounds (front, back, left, and right) for deaf persons (Figure 4.1).

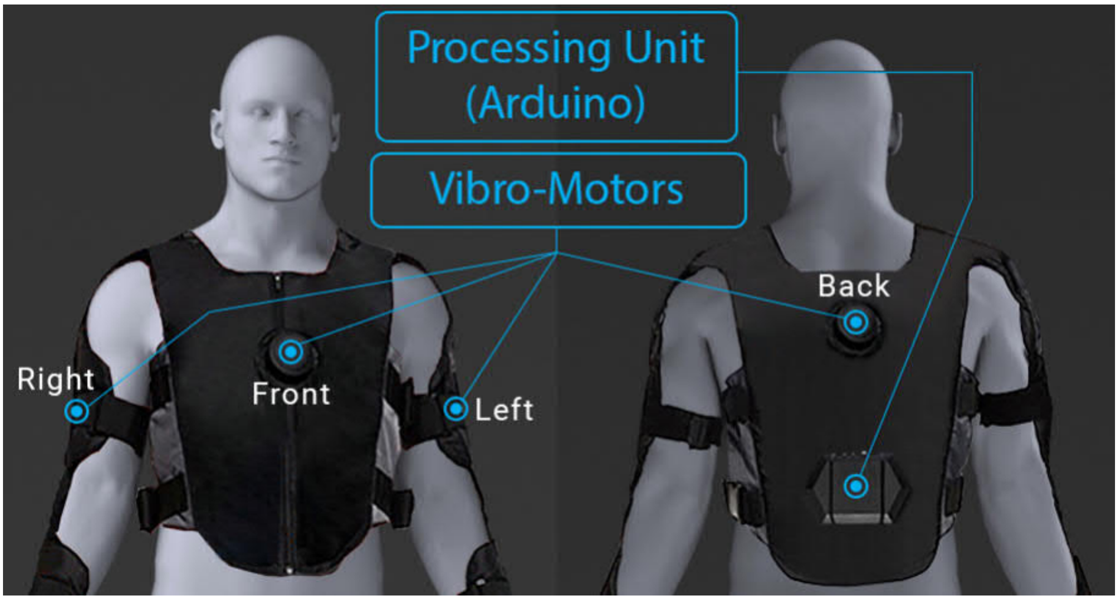

Figure 4.1: The concept design of our proposed haptic VR suit for deaf persons.

Our proposed VR suit delivers vibrotactile cues to deaf persons' bodies from VR environments. The vibro-motors are controlled wirelessly using an Arduino processing unit [3] with a Bluetooth module. Therefore, wiring the processing unit does not impose movement restrictions on deaf persons.

[1]Available Online: https://www.bhaptics.com/(accessed on 5 October 2021)
[2]Available Online: https://teslasuit.io/(accessed on 5 October 2021)
[3]Available Online: https://www.arduino.cc/ (accessed on 5 October 2021)

4.1.2 System Design Requirements and Solutions

We defined the following fundamental design requirements and solutions for our proposed haptic VR suit:

- *Easy to Wear:* The VR suit should be lightweight and easy to use for deaf persons. -> We used lightweight fabric to minimize the struggles of wearing the suit. Also, it fits different body sizes easily using adjustable ribbons.
- *Free Movement:* The VR suit should not limit deaf persons' movements; they must be able to make a full range of motions in VR. -> We used a Bluetooth connection and assembled the processing unit in a small portable package.
- *Adjustable haptic devices:* The VR suit should let deaf persons adjust the haptic devices' positions (vibro-motors). -> We mounted vibro-motors using adjustable Velcro tapes on the suit.
- *Accessible and Low Cost:* The VR suit should be low-cost and accessible for deaf persons. -> We used available and inexpensive materials and hardware to design our proposed VR suit.
- *Software Architecture:* The VR suit should show the direction of sound objects to deaf persons using haptic feedback stimuli (vibro-motors). -> Our software architecture used a unique indexing system that maps sound directions to proper vobro-motors mounted on the VR suit.

4.1.3 System Limitations

We had to focus on our project budget in the design process of the haptic VR suit. Since this project was self-funded, we could not use advanced haptic VR suits in the market. Therefore, we designed our haptic VR suit with only four vibro-motors to demonstrate the four main directions of incoming sound. This design limited us in testing different features of advanced haptic VR suits, such as advanced haptic feedback (full body support), motion capture, or biometric sensors on deaf persons' VR experience.

Also, our proposed haptic VR suit needs a pre-defined VR environment, meaning that VR developers must design a particular VR application or game for the VR suit by specifying the exact positions of sound sources in the VR environment. This limitation causes deaf persons cannot use the VR suit for all VR applications and games in the market.

4.1.4 Technical Details

System Architecture: The system structure of our proposed haptic VR suit is shown in (Figure 4.2). The scheme consists of four main layers with different components as follows:

- **VR Layer:** Includes a VR-ready workstation (Personal Computer (PC) or Laptop) that runs a VR application designed with Unreal Engine 4 (UE4) game engine [4], UE4 blueprint scripts for detecting the audio sources in the VR environment, and UE4Duino plugin [5] to communicate with the Arduino over serial COM ports.
- **Communication Layer:** Uses Bluetooth network devices to connect to the serial COM port and communicate wirelessly to the processing layer via a Bluetooth network.
- **Processing Layer:** Includes an Arduino Pro Micro as the central processing unit, an HC-06 Bluetooth module, and a Lithium-ion (Li-ion) battery.
- **Haptic Layer:** Includes four ERM coin vibro-motors to transfer vibrations over deaf persons' bodies.

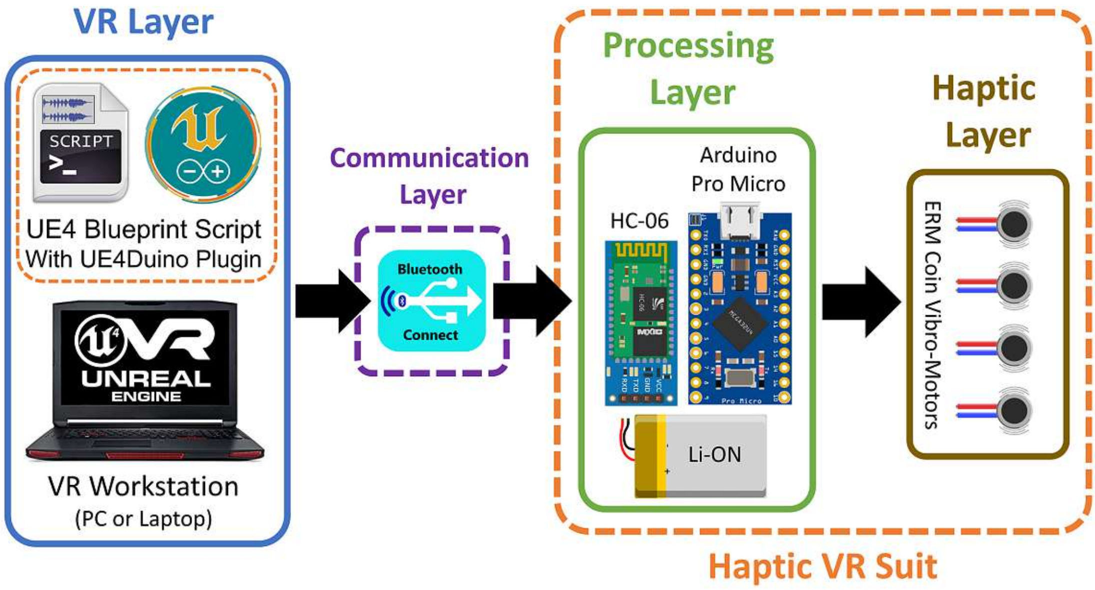

Figure 4.2: The system structure of our proposed haptic VR suit for deaf persons.

The VR layer runs the VR application developed with the UE4 game engine. The VR application uses a custom script to determine the sound position in the VR environment and send proper signals to the Arduino using UE4Duino plug-in. The UE4Duino plug-in helps send the proper commands to the serial COM port connected to the Bluetooth device of the VR workstation (e.g., an embedded device or a Bluetooth network card). After detecting a sound direction, the VR layer sends the proper signal related to the direction of the sound to the processing layer via a Bluetooth network.

[4]Available Online: https://www.unrealengine.com/ (accessed on 5 October 2021)
[5]Available Online: https://github.com/RVillani/UE4Duino (accessed on 5 October 2021)

The haptic suit includes the processing and the haptic layers. The processing layer receives the signals from the VR layer wirelessly using an HC-06 Bluetooth module connected to the Arduino unit. The Arduino controls the ERM coin vibro-motors mounted on the VR suit (in the haptic layer) by sending proper on or off signals to each vibro-motor.

4.1.4.1 Hardware Design

We assembled the whole processing layer of the haptic VR suit in a mountable package on the back of the VR suit. This design enables us to change the position of the processing unit on the suit if necessary. The whole package is powered by a customized rechargeable Li-ON battery with a capacity of 8000mAh and a voltage of 7.4V. We used four 10-14mm ERM coin vibro-motors with an operating voltage range of 3V to 4V at 40–80mA with a frequency of 150–205Hz. The prototype version of our proposed haptic VR suit is shown in Figure 4.3.

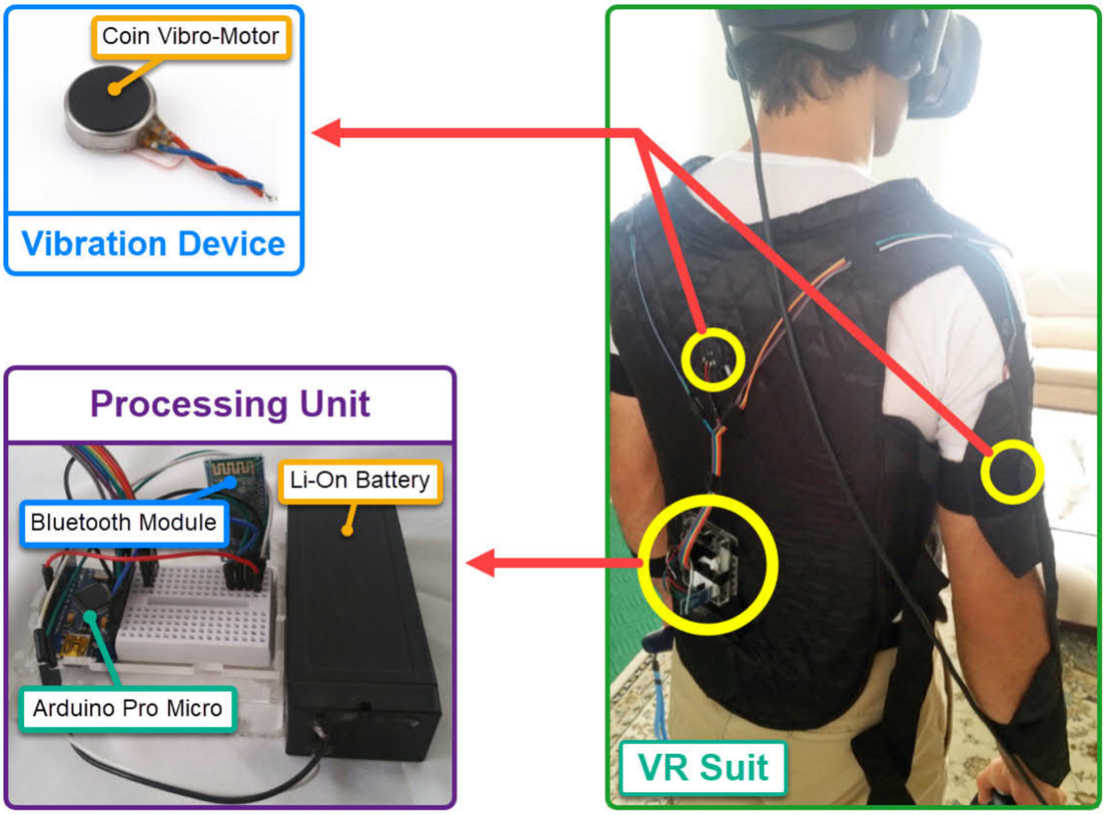

Figure 4.3: The prototype version of our proposed haptic VR suit for deaf persons.

The flat surfaces of vibro-motors are close to the body enabling the user to feel the vibrations well. Previous studies, such as Rupert [264] and Toney et al. [265], have reported that a major problem is difficulty in maintaining good contact between vibro-motors and the users' bodies. They suggest that active motors should be optimally fit in their positions with an appropriate degree of pressure to ensure the perception of haptic feedback. Therefore, we designed our prototype haptic VR suit with Velcro tapes to help maintain the vibro-motors in their fixed positions on the suit during the tests. The Velcro tapes also allow users to easily change the positions of vibro-motors on their bodies if necessary. An HTC Vive Pro VR HMD is used to show the VR environment while connected to a powerful VR-ready laptop with an Intel Core-i7 processor, 16 Gigabytes of RAM, Nvidia GeForce GTX 1080 GPU, and a 64-bit Windows 10 Operating System (OS).

4.1.4.2 Software Design

The software design of our proposed haptic VR suit includes two main sections: Implementation of the VR layer and implementation of the processing and the haptic layers. Each layer includes particular software components, as shown in Figure 4.4 for controlling vibro-motors on the haptic suit.

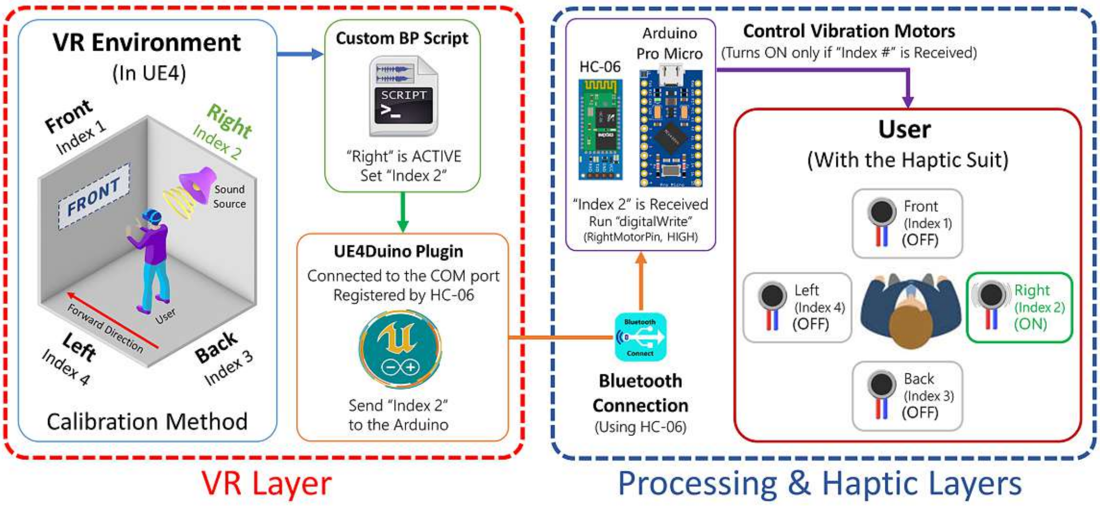

Figure 4.4: Software architecture of the haptic VR suit.

Implementation of the VR Layer:

We designed a simple VR task with the UE4 game engine using a custom UE4 blueprint (BP) script and the UE4Duino plugin for the VR layer. We implemented a unique calibration method to map the sound source positions in the VR environment (front, back, left, and right) to the vibro-motors on the haptic suit. This method lets us know the exact positions of the sound sources concerning the user's orientation in the VR environment. In this method, we added a "FRONT" label to one of the four walls in the VR environment to show the front/forward direction of the system. Then, we asked the users to start the task by standing in front of this wall (Figure 4.5).

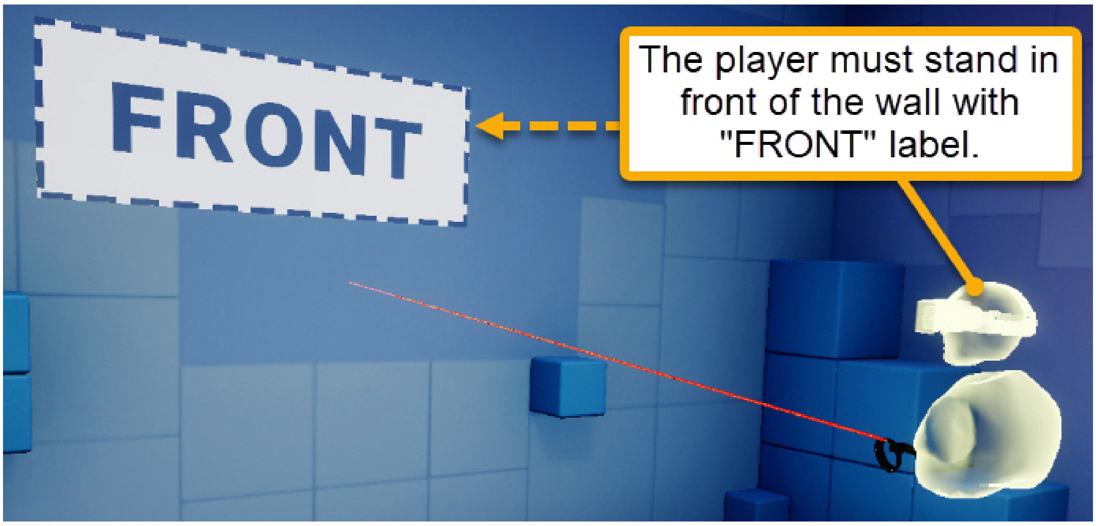

Figure 4.5: The VR environment with the "FRONT" label position.

The positions of all four vibro-motors on the VR suit were carefully mapped in our custom UE4 BP script using the FRONT label mechanism. We used the FRONT label as an index corresponding to the vibro-motor mounted on the front of the VR suit. Therefore, the script can control this procedure in each run, and as soon as a sound object appears in the VR environment, it will send the proper index related to the direction of the sound source to the UE4Duino plugin. Then, the plugin, which is already connected to the COM port registered by the Bluetooth module (HC-06), will send the direction index to the processing layer for controlling the correct vibro-motors on the haptic suit. The HC-06 module receives signals from the VR station over the Bluetooth network. More details related to the procedure of our calibration method are explained in Chapter 5.

Implementation of the Processing and the Haptic Layers:

For the processing and haptic layers, Arduino Integrated Development Environment (IDE) was used to develop the code for the Arduino Pro Micro. We used the "digitalWrite()" built-in function to set up high or low values for vibro-motors' pin-outs in Arduino to turn them on or off. Therefore, when the Arduino receives the sound direction signal (including the index label) from the HC-06 Bluetooth module, it turns on the proper vibro-motor on the suit related to the received index label in its full resonance vibration frequency (150-205Hz).

Based on a design guideline for tactile devices by J.B. van Erp [266], the intervals of the vibro motors were set to 250ms to provide the minimum effective duty cycle (the ratio of the on-time to the off-time of vibro-motors). However, the vibration duration can be changed depending on the VR scenario. Each vibro-motor continues its duty cycle (after turning on) until the user finds and eliminates the sound object.

4.2 EarVR System

Following the proposed haptic VR suit's results explained in Chapter 5, we introduced a novel prototype system that is more portable and user-friendly than the VR suit for deaf persons. We called this new system "EarVR" which includes all of the VR suit's features and some new additional features. Also, we used comments from the DHH community when designing the EarVR system. For example, deaf persons commented that they prefer small and light-weight assistive systems, so we suggest using low-power processing unit and small coin vibro-motors in the final design of the EarVR prototype.

4.2.1 Design Optimization

The results of our user study for the haptic VR suit (described in Chapter 5) show that using more than two vibro-motors and installing them on different positions of the user's body does not have a noticeable effect on locating the audio sources among deaf persons. Also, we found that deaf persons prefer their upper body for vibro-motor placements, especially their ears (described in Chapter 5). Therefore, after final reviews, we optimized our haptic VR suit design by changing it to the EarVR system capable of performing the following tasks:

- Analyzing VR sounds and determining the direction of the closest sound to deaf persons in real-time.
- Sending the result to deaf persons' ears through vibrotactile feedback.
- Helping deaf persons accomplish the given VR tasks.

The VR suit can be used only in pre-defined VR environments; however, the EarVR system works in real-time and can be used with almost all desktop and mobile phones' VR applications and games with the possibility to be mounted on any VR HMD. Our main goal for proposing the EarVR system is to implement a portable system that fulfills deaf persons' requirements for sound localization in VR. The EarVR system acts as an assistant to a deaf person by locating sound sources in the VR environment. It provides the direction of the closest sound source for a deaf person using two vibro-motors placed in the user's ears.

To the best of our knowledge, no research in this area uses vibro-motors in deaf persons' ears to achieve sound source localization in VR using haptic feedback. The EarVR system works in desktop and mobile VR and does not need a pre-designed VR application or game. It helps VR developers design applications and games for deaf persons and persons without hearing problems.

4.2.2 System Design Requirements and Solutions

We defined the following fundamental design requirements and solutions for our proposed EarVR system:

- *Real-time:* The EarVR system should work in real-time. -> The EarVR system is designed to process audio information on an external processing unit (Arduino) instead of the VR application or game. Therefore, the system works in real-time, and there is no need to design a particular VR application or game for deaf persons.
- *Portable and light-weight:* The EarVR system should be portable, lightweight, and mountable. -> We assembled the EarVR system in a small and lightweight package with the possibility of mounting it on any VR HMD.
- *Easy and ready to use:* Deaf persons should be able to use the EarVR system without any complexity. -> We designed the system so that as soon as it is connected to the VR devices, it is ready to use without any required hardware or software setup.
- *Accessible and low cost:* The EarVR system should be low-cost and accessible for all deaf persons. -> We used available and inexpensive hardware to design the EarVR system so the final cost is low (less than the haptic VR suit).

4.2.3 System Limitations

The EarVR system needs the following two essential requirements that are related to VR applications or games:

1. *Mute option for background music:* For the EarVR to work properly, it is necessary to mute the background music in the VR application or game before connecting the EarVR to the VR HMD.
2. *3D Audio:* The EarVR system works based on the input stereo audio, so it is important to use 3D audio in the VR application or game.

If any of these requirements are not fulfilled, the EarVR system cannot detect the direction of incoming sound. However, most VR developers consider these two factors in their application designs to improve the quality of the VR application or game, and they are not necessarily for deaf persons. Therefore, our proposed EarVR system works with any VR application and game that support the mentioned requirements.

Also, the EarVR system is a mountable device and needs to be mounted on VR HMD. Since there are different types of VR HMDs in the market with different shapes, mounting the EarVR system on VR HMDs could be difficult for deaf persons. However, the whole system is packed in a small package, making it easier to mount for users.

4.2.4 Technical Details

System Architecture: The EarVR system consists of hardware and software components. Similar to our proposed haptic VR suit explained in Section 4.1, the EarVR system architecture consists of four main layers, with fundamental changes shown in Figure 4.6.

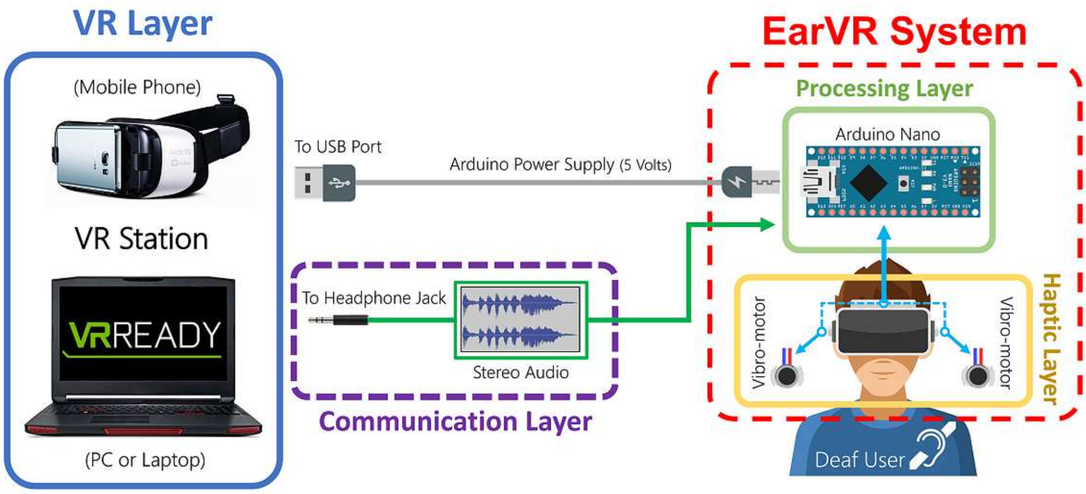

Figure 4.6: The EarVR system architecture.

The four main layers of the EarVR system are as follows:

- **VR Layer:** Includes a VR station (PC, laptop, or mobile phone) that runs a VR application.
- **Communication Layer:** Uses a 3.5mm headphone jack to send the stereo audio from the VR station to the processing layer.
- **Processing Layer:** Includes an Arduino Nano as the central processing unit to analyze the input stereo sound from the VR station and send the proper commands to the haptic layer.
- **Haptic Layer:** Includes two ERM coin vibro-motors to transfer vibrations over deaf persons' ears.

The VR layer runs any VR application or game that can be run on a desktop or mobile phone VR station. Despite the haptic VR suit that needs a pre-designed VR application, the EarVR system can be used with any VR application or game in the market that supports the two main requirements of the system, which are the mute option for background music and the 3D audio. The audio in the VR environment will transfer to the processing layer using the communication layer, which is a 3.5mm headphone jack connected to the output audio jack of the VR station. Then, the audio will be processed (real-time) in the processing layer (Arduino Nano), and the louder stereo channel will be determined. In the end, the processing layer will send the proper on/off signal to the haptic layer.

The EarVR system includes the processing layer and the haptic layer. This system architecture helps us implement the EarVR system in a small and portable form. The whole system is powered by a Universal Bus Controller (USB) cable connected to the VR station's USB ports which can also be replaced with an external Li-ON battery.

4.2.4.1 Hardware Design

The EarVR hardware prototype is shown in Figure 4.7. It consists of an Arduino Nano (ATmega328) and two coin vibro-motors (14mm) for the left and right ears. A stereo audio cable and a USB cable are also used to connect the system to the VR station. The Samsung Odyssey VR HMD is used to display the VR environment. It has dual 3.5" AMOLED (1440x1600 dots) screens, 110 degrees FOV, and AKG 360 degrees spatial sound headphones which are very useful for our work. We mounted EarVR on the Samsung Odyssey VR HMD. The Arduino is placed on top of the VR HMD, and vibro-motors are placed inside the AKG headphones. However, as mentioned before, it is possible to use any VR HMD. The VR HMD is connected to a powerful VR-ready laptop with similar specifications mentioned in the haptic VR suit section.

Arduino hardware design ranges from 8-bit micro-controllers to fully-featured 32-bit ARM processing units. Arduino provides many advantages for academic purposes, such as being inexpensive, mobile (low-power), open-source and cross-platform, and extensible software and hardware [24]. However, despite its advantages, Arduino has some limitations, especially regarding the processing power of Digital Signal Processing (DSP) projects. There are some particular projects based on the Arduino designed for DSP [267, 268]. Previous research shows that Arduino can be used for real-time digital audio processing [269].

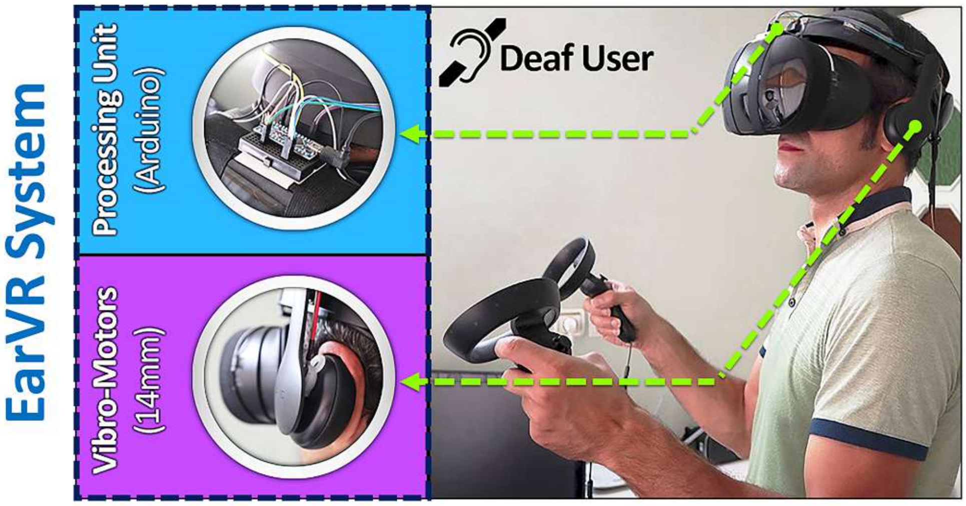

Figure 4.7: The prototype version of EarVR system designed for deaf persons.

For our use case, we need to perform a frequency analysis and switch on or off the vibro-motors without using Pulse Width Modulation (PWM). No additional hardware is needed because the processing power of the Arduino Nano is sufficient to analyze the input stereo sounds and to control two vibro-motors, and it helps keep our prototype as simple as possible.

EarVR only needs to connect to a headphone jack and a VR station USB port to provide audio information and the Arduino Nano's operating voltage (5V). As we mentioned, a rechargeable Li-ION battery can also provide the necessary power. Also, we can use the headphone jack on mobile devices with a USB On-The-Go (OTG) cable for mobile VR (Figure 4.8).

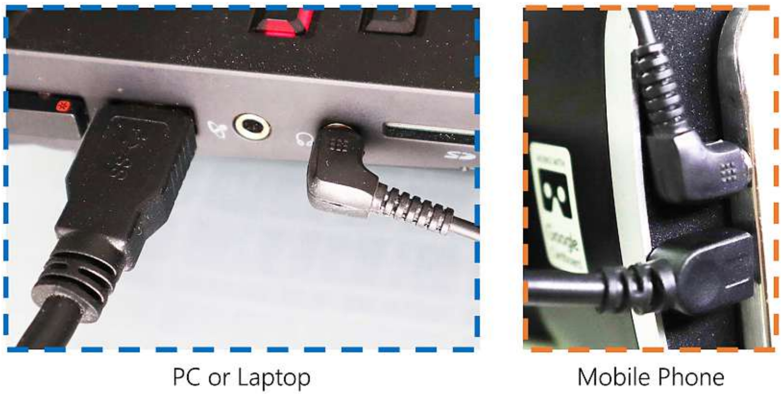

Figure 4.8: EarVR connections through headphone jack and USB port: PC or laptop (left), or mobile phone (right).

We also attached soft and flexible plastics to the vibro-motors. It allows users to put vibro-motors inside their ears without unpleasant feelings when using VR HMDs without embedded headphones, such as Samsung Gear VR or Google Daydream (Figure 4.9).

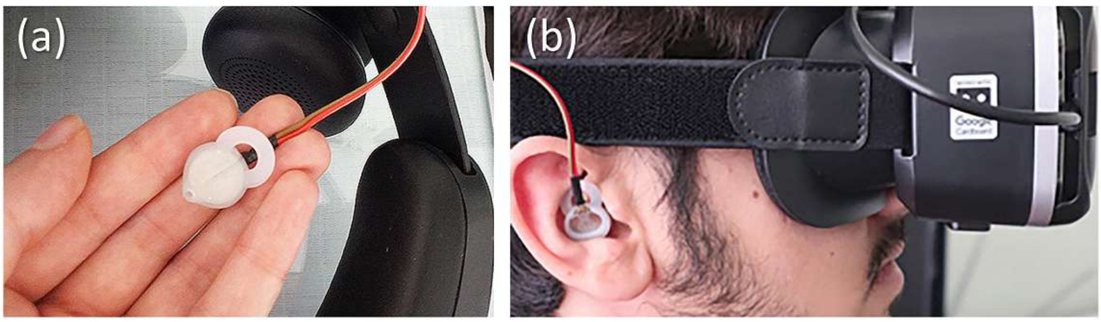

Figure 4.9: (a) Using soft cover for vibro-motors, and (b) Putting vibro-motors in the ears.

4.2.4.2 Software Design

Most of our work in the software design of the EarVR system was focused on the Arduino code because the EarVR system works in real-time without any dependency on VR applications. We developed a particular sound analyzer algorithm for the Arduino to process and analyze input stereo sound channels from any VR device by analyzing the left and right stereo channels and controlling the two vibro-motors (Figure 4.10).

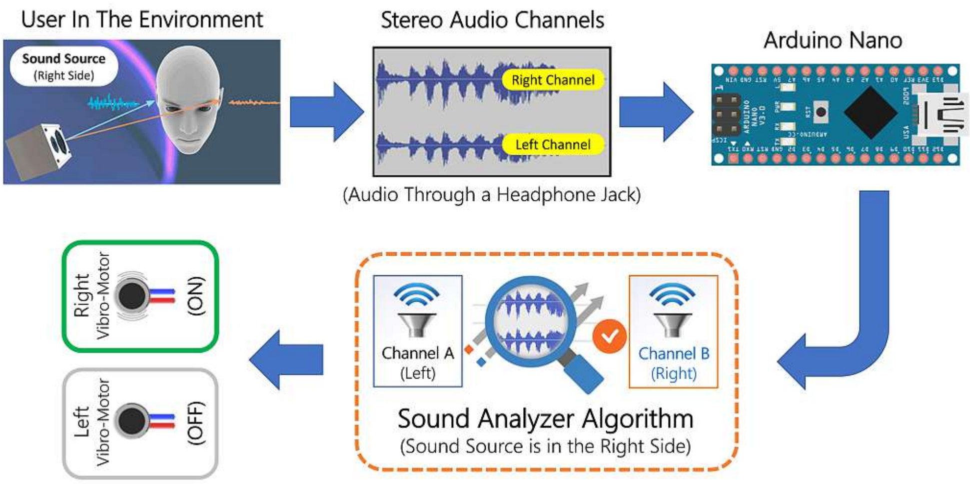

Figure 4.10: Software architecture of the EarVR system.

Implementation:

We developed a sound analyzer algorithm using the Fast Fourier Transform (FFT) library for Arduino and custom codes. Since the Arduino has low computational power, the Arduino FFT library is used to calculate the intensity of input audio channels using the proper sample size for the Arduino Nano (between 16 points (4ms) to 128 points (53ms)) without using complex FFT functions to prevent over-processing in the Arduino and consequently allowing the system to work in real-time. We deployed the final code to Arduino using the Arduino IDE. One of the features of our algorithm is that it can take and process sounds from any environment. The EarVR system works in real-time and analyzes the positions of sounds (left or right side of the user's head) in the VR environment using this method. Therefore, designing a particular VR application or game is not required for the EarVR system. The left vibro-motor (on the left ear) will vibrate if the intensity of the left channel is detected higher than the right by the sound analyzer algorithm and vice versa. Therefore, the user knows the direction of the incoming sound. If the intensity is equal in both channels, the vibro-motors will not vibrate. In this case, there are two main situations: 1) The sound source is in front of the user, which is easy to find because the user can see it, and 2) The sound source is behind, above, or below the user. If users cannot find the sound source in front or behind, they pay attention to the above or below.

The input stereo sound has a frequency range between 44 kHz to 48 kHz through stereo channels which depends on the sound card's specification (output from PC or mobile phone) and the audio files used in the VR environments. Based on a design guideline for tactile devices by J.B. van Erp [266], the intervals of the vibro-motors were set to 250ms (similar to the haptic VR suit). The duration of vibration can be changed depending on the VR scenario.

We set only one voltage level for vibro-motors to turn them on or off (3 Volts = on). It means that if the Arduino detects a sound, it turns the vibro-motor on (related to the sound direction) at its full resonance vibration frequency, usually between 170 Hz to 240 Hz, depending on the coin vibro-motor specification. Based on a research guideline by K. Myles and J.T. Kalb [270], the recommended range for effective and comfortable tactile-only communication on the head is between 32 Hz to 64 Hz [271]. Therefore, for using the vibro-motors in the ears (for VR HMDs without embedded headphones), we set the resonance vibration frequency to 45 Hz by controlling the voltage level of the vibro-motors.

We decided to switch on or off the vibro-motors instead of controlling their speed with PWM to keep the system as simple as possible and avoid using additional circuit boards. The vibro-motors can switch extremely fast and are controlled by a low-current source. Our goal was to indicate the direction of the closest sound to the user in real-time, so using PWM was unnecessary. In preliminary experiments, we noticed that using the power of vibration to indicate the loudness of the incoming sound as a continuous indicator instead of a binary one (on or off) causes confusion for users in complex VR scenarios with multiple sound sources and increases the processing load on the Arduino. Therefore, further precise experiments and analysis are needed to investigate the effects of using PWM on detecting the distance of sound objects to the users in VR environments.

4.3 EarVR+ System

Previous studies, such as Codina et al. [18] and Soto-Rey [20], show that DHH persons have stronger vision than hearing persons and also have a faster reaction time to visual stimuli. Our proposed EarVR system described in Section 4.2 uses only haptic feedback (vibro-motors) to provide information about the location of spatial sounds in VR for DHH users. We study whether the performance of DHH persons in sound localization tasks in VR environments is better with haptic feedback, visual feedback, or a combination of visual and haptic feedback. Therefore, inspired by the results of our proposed EarVR system and the results of an additional study related to the effects of using visualization methods on VR sound localization for DHH persons that is described in Chapter 5, we proposed a new novel system called "EarVR+." We enhanced the EarVR system with additional visual feedback using LED visualization. The additional LED visualization enables us to study differences in task performance using only visual feedback, only haptic feedback, or a combination of visual and haptic feedback.

4.3.1 Technical Details

System Design Requirements and System Limitations: Our proposed EarVR+ system works similarly to the EarVR system with the exact system design requirements and system limitations, but we used two LED indicators with different colors in addition to two coin vibro-motors. The additional LED indicators help deaf persons to find sound sources in the VR environment using their vision.

System Architecture: The system architecture of the EarVR+ system is shown in Figure 4.11. The system structure is similar to the EarVR system (described in Section 4.2), but in the EarVR+ system, the central processing unit (Arduino Nano) controls vibro-motors and LEDs mounted on the VR HMD.

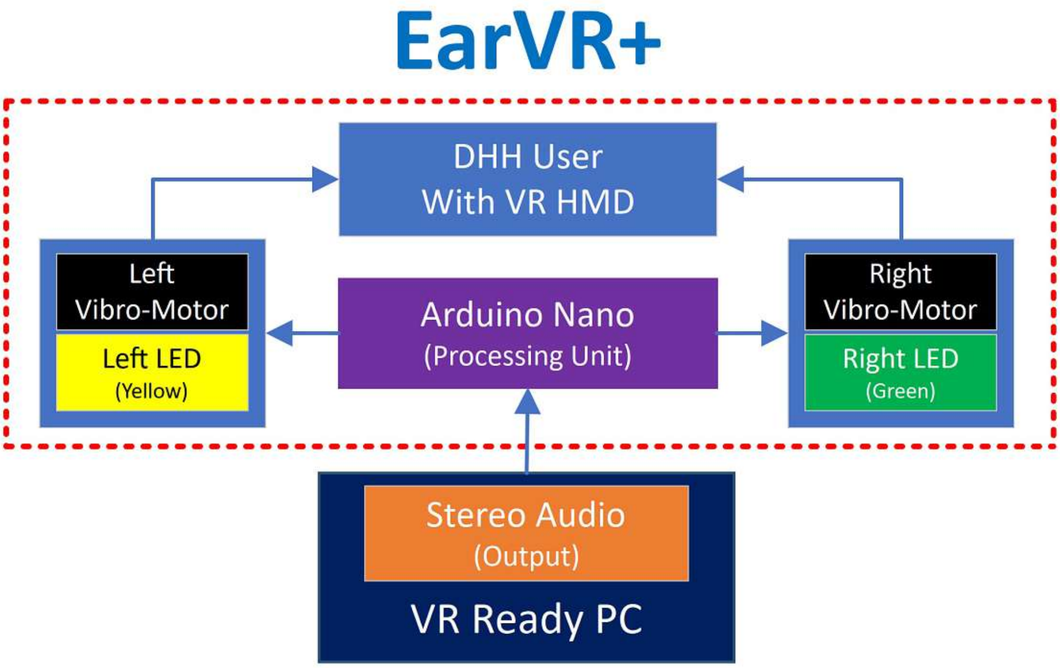

Figure 4.11: The EarVR+ system architecture.

4.3.1.1 Hardware Design

The prototype version of our proposed EarVR+ system is shown in Figure 4.12. In the EarVR+ system, two 5mm LED indicators with different colors are connected to 220Ω resistors, in addition to two 10-14mm coin vibro-motors with 3V operating voltage and 170-240Hz vibration frequency. We conducted a pre-study with deaf participants to determine which LED colors (red, green, blue, yellow, and white) are preferable for deaf persons (described in Chapter 5).

We used a 45Hz vibration frequency for vibro-motors by controlling the voltage level previously suggested in the EarVR system. The vibro-motors can be mounted behind the HMD's headphones or inside users' ears, and the LEDs are mounted beside VR HMD's lenses (Figure 4.12). Similar to the EarVR system, each vibro-motor is covered with soft and flexible plastic, so users can put them inside their ears with no unpleasant feelings when using VR HMDs without headphones. Also, coin vibro-motors have low-noise level feedback preventing unwanted distractions (if the system is used for hard of hearing or hearing persons), and the LEDs' response time is less than one millisecond (ms), which is much faster than most of the coin linear vibration motors in the market (>50ms). These numbers are too small to be recognizable by users [250]. The VR HMD is connected to a powerful VR-ready laptop with similar specifications mentioned in the haptic VR suit and the EarVR systems.

Figure 4.12: Our proposed EarVR+ system with LED indicators.

4.3.1.2 Software Design

The software implementation of the EarVR+ system is similar to the EarVR system, but in the new system, the Arduino controls LEDs and vibro-motors. Therefore, we used Arduino's "digitalWrite()" built-in function to set up high or low values for LEDs and vibro-motors' pinouts to turn them on or off. The software structure of the EarVR+ system is shown in Figure 4.13.

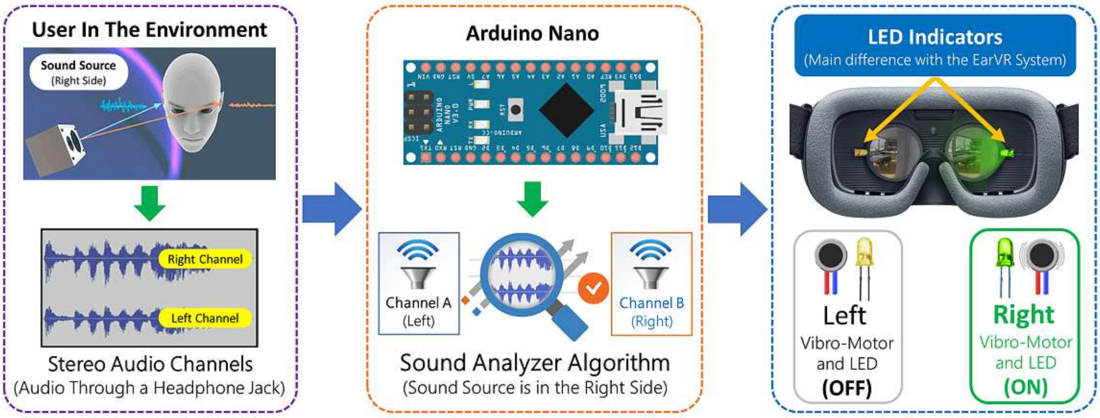

Figure 4.13: The software structure of the EarVR+ system.

Similar to the EarVR system, in the EarVR+, the Arduino analyses the audio level of input stereo audio (the left and right stereo channels) and detects the incoming audio direction in real-time relative to the user. If the audio level in the left channel is higher than the right channel, the system sets the sound's direction to the left side and vice versa. Then, it turns on or off the LEDs and vibro-motors based on the direction of the sound (left or right) and according to the user's choice (simultaneously or separately).

4.4 Summary

The hardware and software design of a system is an essential part of developing a successful, efficient, reliable, scalable, and cost-effective system. In this chapter, we described the hardware and software design of our proposed assistive VR systems for deaf persons. We proposed a haptic VR suit, EarVR, and EarVR+, to investigate if they affect deaf persons' sound localization in VR.

The layering design of our software structure for each system allows developers to scale up or down the systems as needed. Since each layer is designed independently, adding or removing components is easy. Our hardware and software design for the EarVR/EarVR+ systems lets them work real-time with any VR application and game in the market, and users can mount them on any VR HMDs.

We tried to minimize our proposed system's limitations by selecting proper components, such as wireless modules for the VR suit and flexible vibro-motor covers for the EarVR/EarVR+, to prevent imposing systems limitations on deaf persons, such as movement restrictions and unpleasant feelings in the ears. However, using advanced components such as advanced haptic devices and powerful processing units would benefit future systems designs.

CHAPTER 5

Experiments and Results

This chapter describes our experiments and the results of each proposed system described in Chapter 4. A formal user study is conducted with deaf participants with no hearing in both ears and not using HA or CI for each proposed system (new participants in each experiment) to evaluate the effectiveness of systems and methods on sound source localization in VR among deaf persons.

We start our experiments with the haptic VR suit, and following its results, we continue the experiments for EarVR and EarVR+ systems. Before the EarVR+ experiment, we conducted a particular experiment to investigate if different perceptual modalities to interact with VR environments affects sound source localization among deaf persons. This experiment helped us design and organize a better and more practical experiment for the EarVR+ system.

In the haptic VR suit experiment, we investigate the capabilities and effects of using the suit and its different setups among deaf persons on sound source localization in VR. In the EarVR experiment, we analyze the effects of different aspects of in-ear vibrotactile haptic feedback on accomplishing sound-related VR tasks among deaf persons. Finally, in the EarVR+ experiment, we investigate whether visual, haptic, or combination methods affects sound source localization among deaf persons in VR environments.

5.1 Haptic VR Suit for Deaf Persons

The experiment presented in this section addresses the effects of using a haptic VR suit and its different setups on sound source localization by deaf persons in VEs. Our main questions for this experiment are as follows:

1. What are the effects of haptic VR suits on deaf persons' sound localization in VR?
2. How do different setups of a haptic VR suit affect sound localization in VR among deaf persons?
3. How does a different number of vibration devices used in a haptic VR suit affect deaf persons' VR sound localization?

Our research questions help us understand the important implications of deaf persons' experiences related to sound localization in VR environments. Our main hypotheses in this experiment are as follows:

- H1. Deaf persons complete sound-related VR tasks faster when using different haptic VR suit setups rather than not using a haptic VR suit.
- H2. Increasing the number of vibro-motors on a haptic VR suit does not significantly affect the performance of deaf persons' VR sound source localization.

We investigate if a deaf person can do sound localization in a VR environment using a haptic VR suit (vibrotactile feedback) and if different setups and numbers of vibro-motors on the suit affect their experiences. Our main goal in this experiment is to find if haptic VR suits can help deaf persons complete sound-related VR tasks by doing sound localization using vibration devices.

5.1.1 Experiment Design

For this experiment, we use our proposed haptic VR suit described in Chapter 4. The suit has four vibro-motors to demonstrate the four main directions of incoming sounds (front, back, left, and right) from VR environments to deaf persons.

We conduct a test to investigate the effects of mounting vibro-motors on different sections of deaf persons' bodies, such as thighs, arms, and ears. At the end of the test, we ask participants to fill out a questionnaire about their preferred position for mounting the vibro-motors and the discomfort score of different setups of our proposed haptic VR suit. We fit the VR suit for each participant before the test and asked them to wear thin clothes for the main experiment to ensure that they felt the vibrations from all four vibro-motors on the haptic VR suit.

The VR task is designed with the UE4 game engine, including the "FRONT" label mechanism described in Chapter 4. In this VR task, the player spawns in the center of an enclosed VR room and can only rotate around. The player starts the VR task by pressing the grip button on the VR controller after standing in the mentioned position and selecting sound sources (speakers) by pressing the trigger button on the VR controller with the help of a ray-cast laser pointer, as shown in Figure 5.1. The task is designed so that every time it is started, only one sound source (speaker) appears randomly at one of the four fixed positions in the VR environment (front, back, left, and right).

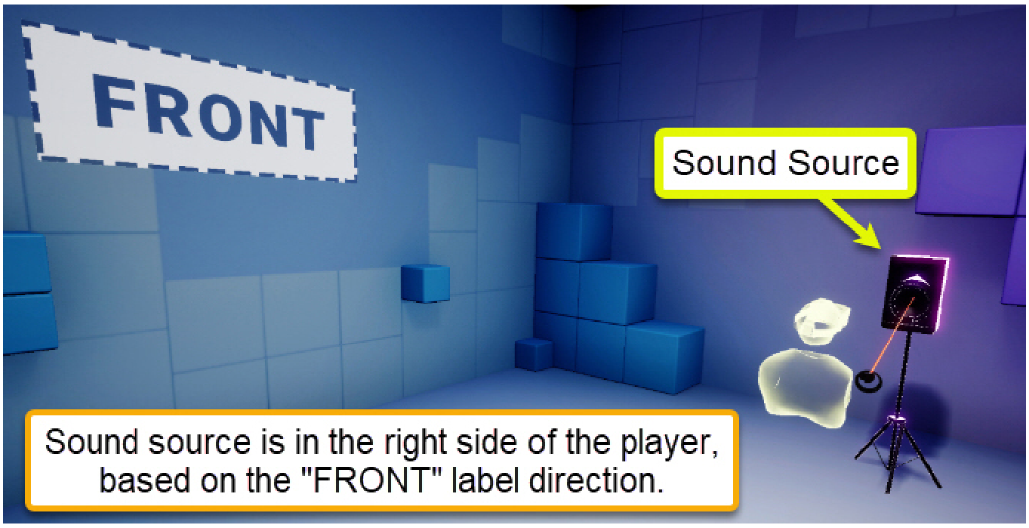

Figure 5.1: The haptic VR suit task environment; Sound source position is based on the "FRONT" label direction.

5.1.2 Main Experiment

We prepared three different setups of our proposed haptic VR suit. Two fixed vibro-motors were used to represent the front and back directions, but the positions of the other two were changed in different setups as follows:

1. ***Setup 1:*** Two vibro-motors mounted on the upper body front and back and two on the left and right sides of the thighs (left side of the left thigh and right side of the right thigh), Figure 5.2-a;
2. ***Setup 2:*** Two vibro-motors mounted on the front and back and two on the left and right sides of the arms (left side of the left arm and right side of the right arm), Figure 5.2-b;
3. ***Setup 3:*** Two vibro-motors mounted on the front and back and two on the left and right ears, Figure 5.2-c.

We called these setups “Setup 1 (thighs)”, “Setup 2 (arms)”, and “Setup 3 (ears),” respectively. We also considered an additional setup without using the haptic suit or other assisting tools. In this condition, deaf persons have to search and find sound sources in the VR environment only by using vision and rotating around to find the rendered 3D model of the sound source (speaker) without the help of a haptic suit. The sound source 3D model (speaker) will become highlighted when the user selects it using the ray-cast pointer effect. We call this additional condition “Setup 0 (no suit)” and compare the results of using the VR suit in setups 1 (thighs), 2 (arms), and 3 (ears) with this new condition.

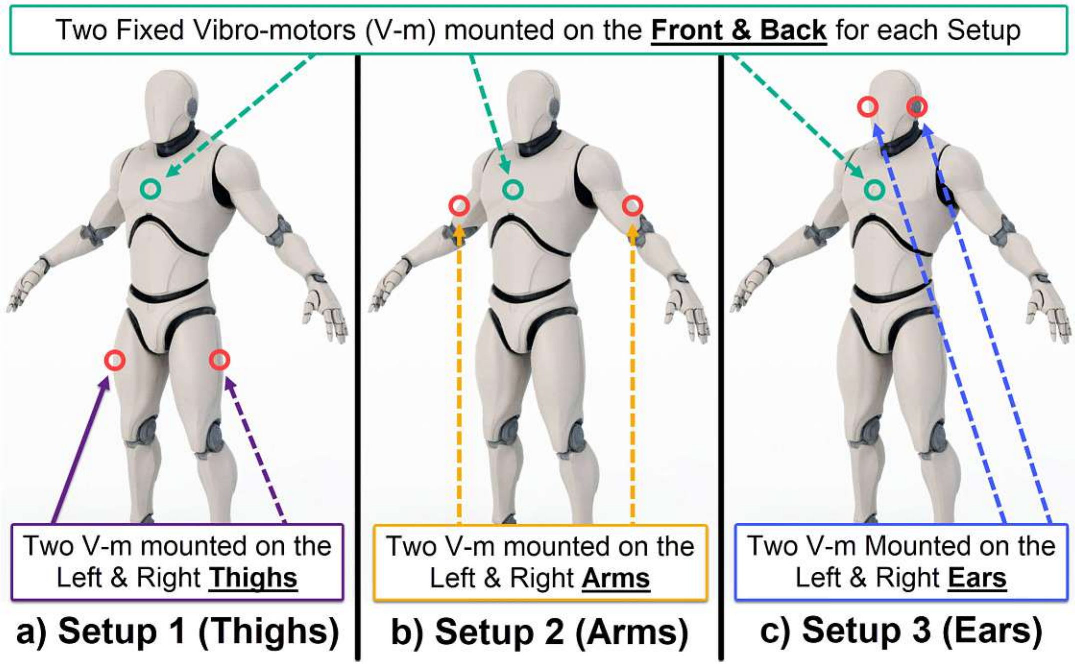

Figure 5.2: Our suggested setups for the haptic VR suit.

Participants:

We recruited 20 deaf participants from the deaf community with no hearing in either ear and not using HA or CI (12 men, 8 women; 20 to 40 years old, M = 30.4, SD = 6.142) using the criteria mentioned in Chapter 1. We carefully stated all VR safety warnings in our consent form (Appendix-A 6.3), so all participants were aware and signed the form before the main experiment.

The goal of our experiment, the equipment, and the test environment were introduced to all participants. We asked each participant to wear the haptic suit with different setups before the main experiment because this was the first time the participants had tested a haptic VR suit. They could withdraw from the experiment if they felt uncomfortable with the suit's setups. However, all of the participants remained in the experiment. Then, we asked them about their opinion for different setups of the VR suit in an open-ended question. In addition, for setup 3 (ears), we asked participants to answer a multiple-choice question about their preferred position on the head (behind the ears, in-ears, and temples) for mounting the vibro-motors.

Post-Questionnaire for Setup 3 (Ears):

The result of a question about participants' preferred position on the head is shown in Figure 5.3. Analysis of the result using descriptive statistics indicates that all participants preferred mounting the vibro-motors inside the ears (in-ears) compared to the temples or behind the ears. Therefore, we selected the in-ear position for mounting the virbro-motors.

We attached soft and flexible plastics to the ears' vibro-motors to prevent unpleasant feelings when deaf persons put the vibro-motors inside their ears (described in chapter 4). Deaf participants commented that putting vibro-motors inside their ears felt like wearing earphones. Although, further analysis is needed to confirm if using soft and flexible plastics with vibro-motors affects deaf persons' VR experience.

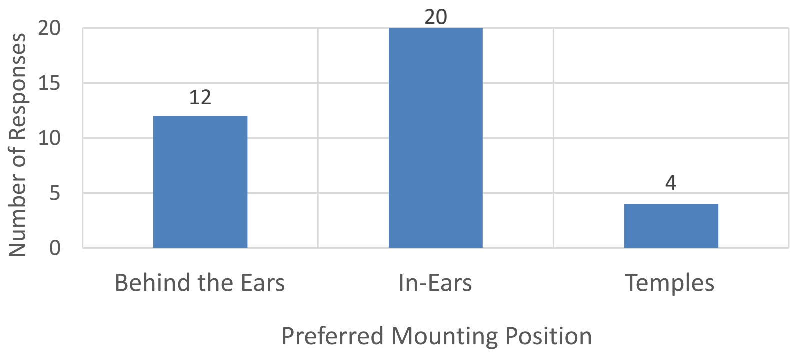

Figure 5.3: Deaf persons' preferred head position for mounting vibro-motors.

5.1.2.1 Task and Procedure

We asked each participant to play each condition (setup) for ten rounds. The player starts the VR task by pressing the grip button on the VR controller. After starting the VR task, one speaker appears randomly at one of the four main positions in the VR environment (front, back, left, and right) based on the player's starting position. Every time a speaker appears in the VR environment, a vibro-motor related to the speaker's position vibrates (controlled by the Arduino) so the player can find the correct speaker position and select it. It means that the vibro-motor on the player's chest vibrates when the sound is in front of the user, the one on the back vibrates when it is behind the user, and the left and right vibro-motors vibrate based on the respective sound location. After selecting the speaker, it disappears, and the player has to face the wall labeled "FRONT" to start the next round. This process continues until the player selects ten speakers (completing ten rounds).

We asked the participants to complete each setup in one day, starting with setup 0. Starting the experiment with setup 0 (no suit) and then setup 1 (thighs) was necessary for our future study because using the sense of touch in the lower body as a cue for audio direction was very unusual among deaf participants. Therefore, we fixed the order of setups to setup 0 (no suit) on day 1, setup 1 (thighs) on day 2, setup 2 (arms) on day 3, and setup 3 (ears) on day 4.

Although the VR environment randomly changed in each test for each participant, since the same participants were tested on different days and a fixed order of VR suit setups was used, this experiment may have had some learning effects on participants. Therefore, further experiments and analysis are needed to confirm the findings of this experiment.

5.1.2.2 Measures and Data Analysis

For each setup, the completion time of every round was saved for the player. Then, the average task completion time of the setup was calculated for that player. In the end, all players' overall average task completion times were calculated for the setups. We asked participants to answer a question about the discomfort scores of setups, with the possibility of changing answers at the end of the experiment (after completing all the setups). However, no one changed the answers.

To determine the preferred setup, we used a questionnaire at the end of the experiment with a 5-point Likert-scale question ("1 = most negative" and "5 = most positive") about the setup that is more desirable to use for deaf persons. Also, we collected discomfort scores ranging from 1 to 10 (lower value = more comfortable) to identify the discomfort level of each setup. We calculated the preference score and discomfort level by averaging the participants' scores for each setup at the end of the experiment. Then, we analyzed the data for each setup based on the participants' average task completion time and their responses to questions about discomfort score and preferred setup.

5.1.2.3 Results

The average task completion time of each setup is shown in Figure 5.4. Deaf persons completed the VR task with average task completion times of 27.05 seconds for setup 0 (no suit) (SD = 1.20), 23.39 seconds for setup 1 (thighs) (SD = 1.16), 21.7 seconds for setup 2 (arms) (SD = 0.97), and 21.41 seconds for setup 3 (ears) (SD = 1.32). A Shapiro-Wilk test of normality with $\alpha = 0.05$ was conducted to determine whether variables are approximately normally distributed. The test and a visual inspection of the histograms indicate that the data was approximately normally distributed for each setup (setup 0 (no suit): $W = 0.943$, $p = 0.277$, setup 1 (thighs): $W = 0.952$, $p = 0.391$, setup 2 (arms): $W = 0.948$, $p = 0.334$, and setup 3 (ears): $W = 0.968$, $p = 0.717$).

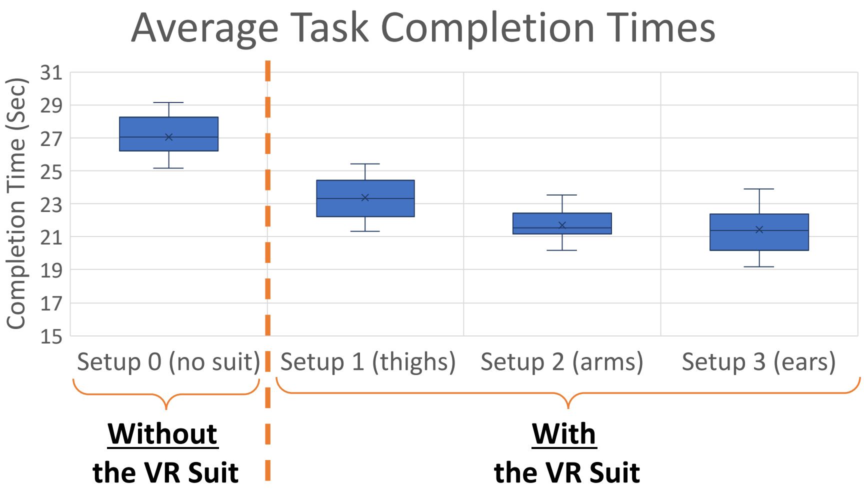

Figure 5.4: Average task completion times of each haptic VR suit setup.

A repeated-measures analysis of variance (ANOVA) test with a significance level of $\alpha = 0.05$ was conducted to explore the effect of VR suit setups (setups 0, 1, 2, 3) on the task completion time. Mauchly's test of Sphericity did not indicate any violation of sphericity ($\chi^2(5) = 7.144$, $p = 0.211$), and therefore, a sphericity was assumed. The results indicate a statistically significant effect of suit setups on the task completion time ($F_{3,57} = 118.224$, $p < 0.001$, partial $\eta^2 = 0.862$).

Post hoc comparisons using the Bonferroni adjustment revealed that the task completion time significantly changed from setup 0 (M = 27.05, SD = 1.20) compared to setup 1 (M = 23.39, SD = 1.16), setup 2 (M = 21.7, SD = 0.97), and setup 3 (M = 21.41, SD = 1.32). It also significantly changed from setup 1 compared to setups 2 and 3, but not significantly changed from setup 2 compared to setup 3. The pairwise comparison on the mean difference of VR suit setups is shown in Table 5.1 (significant differences are marked with a star (*) symbol near the p-value).

VR Suit Setups	**Setup 1 (Thighs)**	**Setup 2 (Arms)**	**Setup 3 (Ears)**
Setup 0 (No VR Suit)	Mean Diff. = 3.655 * p <0.001	Mean Diff. = 5.349 * p <0.001	Mean Diff. = 5.634 * p <0.001
Setup 1 (Thighs)	—	Mean Diff. = 1.694 * p <0.001	Mean Diff. = 1.979 * p <0.001
Setup 2 (Arms)	—	—	Mean Diff. = 0.285 $p = 1.0$

Table 5.1: Pairwise comparison on the mean difference of VR suit setups using the Bonferroni adjustment (95% Confidence Interval for differences).

Comparing setups 1, 2, and 3 vs. setup 0 indicates that using a haptic suit with different setups affects the task completion time of deaf persons in VR. Therefore, our H1 hypothesis is supported by this experiment. In addition, the results show that the arms and ears are preferred to the thighs for mounting the vibro-motors. Deaf participants commented that feeling the sense of touch on their upper body, such as arms and ears, was more familiar as a warning sign to focus attention in a particular direction than the sense of touch on their lower body (thighs).

We assume that mounting vibro-motors on the upper body affects completing sound localization tasks in VR among deaf persons. However, studies such as R. Ackerley et al. [272] have shown differences in sensitivity, direction discrimination, and pleasantness of touch perceptions across human skin. Still, future studies are required to confirm our experiment's finding and understand why the arms and the ears are preferable to the thighs for VR sound localization in deaf persons' opinion.

Figure 5.5 shows the average responses to a question about discomfort scores of setups 0 (no suit), 1 (thighs), 2 (arms), and 3 (ears). Analysis of the result using descriptive statistics shows that deaf participants rated setup 0 (M = 1.15, SD = 0.489) more comfortable than setup 1 (M = 9.3, SD = 1.129), setup 2 (M = 5.75, SD = 1.832), and setup 3 (M = 3.8, SD = 2.016). Also, comparing setups of the VR suit shows that setup 3 was rated more comfortable than setups 1 and 2.

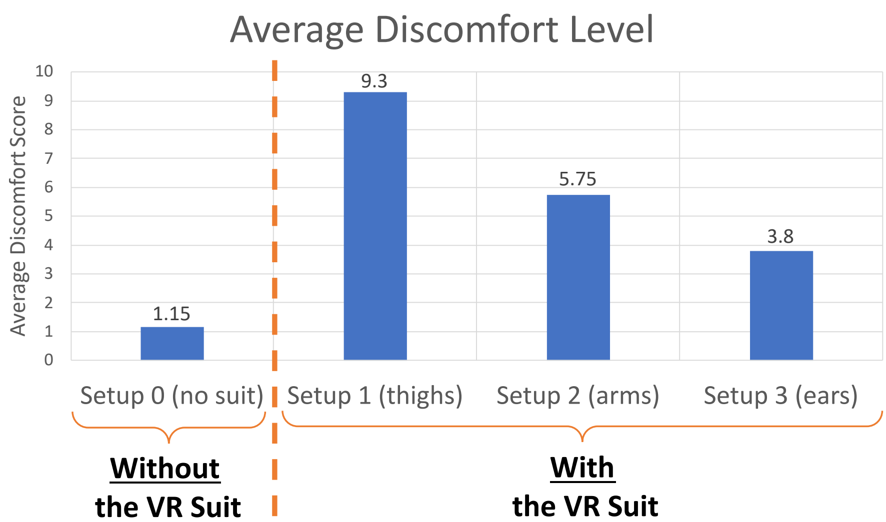

Figure 5.5: Average discomfort level of each haptic VR suit setup.

Figure 5.6 shows the responses to a question about the desire to use setups. Analysis of the result using descriptive statistics shows that deaf participants preferred to use at least one setup with the VR suit (setup 1: M = 3.45, SD = 0.671, setup 2: M = 4.6, SD = 0.681, setup 3: M = 4.9, SD = 0.308) compared to setup 0 (M = 1.35, SD = 0.671).

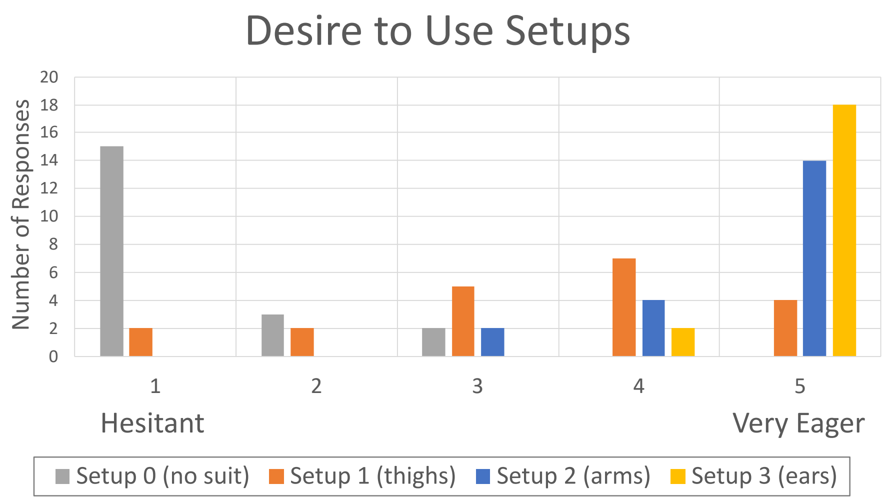

Figure 5.6: Desire to use the haptic VR suit's setups among deaf persons.

Deaf participants commented that although setups with the suit (setups 1, 2, and 3) felt uncomfortable compared to setup 0 (no suit), they found setups 1, 2, and 3 helpful compared to setup 0 (no suit) in VR. They commented that setups 1, 2, and 3 helped them complete the VR task faster than setup 0 (no suit). In addition, deaf participants preferred setup 3 (ears) more than other setups. Although, further experiments and analysis are required to confirm these findings. Overall, the results of the average discomfort score and desire to use setups helped us design our next proposed system in a way that has less discomfort and be preferable for deaf persons.

5.1.3 Experiment with the Number of Vibro-Motors

In the previous experiment, 18 out of 20 deaf participants commented that they preferred using an assistive system in VR without a VR suit. Therefore, we conducted another experiment without the VR suit and with only two vibro-motors mounted in deaf persons' ears. We used soft plastic covers for each vibro-motor to minimize the unpleasant feeling of mounting them inside the users' ears, as explained in Chapter 4. All participants commented that putting vibro-motors inside their ears felt like using regular earphones without any unpleasant sensation. Although, further experiments and analysis are needed to confirm it.

This new condition is very similar to setup 3 (ears), and we used the same VR task explained in the previous experiment. The only difference is removing the VR suit and the two vibro-motors on the front and back. In the new condition, when the sound source is in the front, none of the vibro-motors vibrate because the player can see the sound source immediately, and when the sound source is in the back, both of the vibro-motors in the left and right ears vibrate at the same time. We determined if participants could handle the new situation for sound source localization in VR and compared the result with the result of using the VR suit.

5.1.3.1 Measures and Data Analysis

We called the new condition "Setup 4 (Only Ears)," and we tested setup 3 (ears) from the main experiment and this new setup on a new group of deaf participants comprising 10 deaf persons from the deaf community (7 men, 3 women; 25 to 35 years old, M = 28.3, SD = 3.52), with no hearing in either ear and not using HA or CI) with the same procedure explained in the previous experiment. Each participant completed setup 3 (ears) and setup 4 (only ears) tests on one day randomly.

After finishing both tests, we asked the participants to complete a questionnaire about the discomfort score and the desire to use each setup. Then, we calculated the average task completion time, discomfort level, and the desire to use each setup and compared the results.

5.1.3.2 Results

Figure 5.7 shows the average task completion time of setup 4 (only ears)-without the VR suit compared to setup 3 (ears)-with the VR suit. Participants completed the VR task with an average task completion time of 21.058 seconds for setup 3 (ears) and 21.389 seconds for setup 4 (ears only). A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the data was approximately normally distributed for both setups (setup 3 (ears): $W = 0.982$, $p = 0.973$, ans setup 4 (only ears): $W = 0.923$, $p = 0.384$).

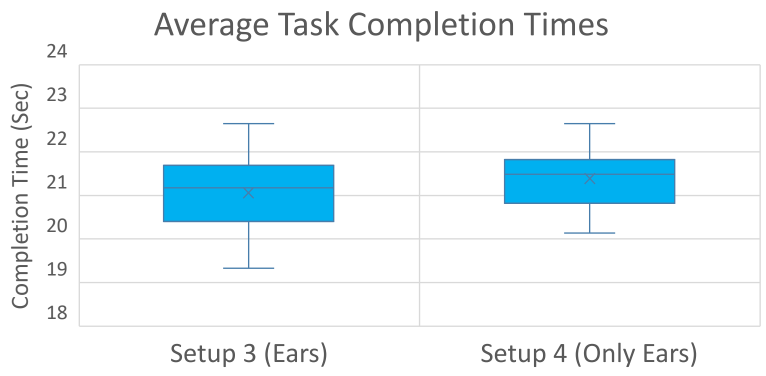

Figure 5.7: Average task completion times of setup 3 (ears)-with the VR suit and setup 4 (only ears)-without the VR suit.

A paired-samples t-test with $\alpha = 0.05$ was conducted to evaluate the impact of using the VR suit on the task completion time. The test indicates that there is no significant difference (t_9 = -1.442, p = 0.183) in the average task completion time of setup 3 (ears)-with the VR suit (M = 21.058, SD = 0.932) and setup 4 (only ears)-without the VR suit (M = 21.389, SD = 0.763). The result indicates that using the VR suit with four vibro-motors does not significantly affect the average task completion time of deaf persons compared to using only two vibro-motors in the ears (without the VR suit). Therefore, our hypothesis H2 is supported in this experiment. Although, further analysis is needed to confirm this finding.

The average responses to the question about discomfort scores of setup 3 (ears) and setup 4 (only ears) is shown in Figure 5.8. Analysis of the result using descriptive statistics shows that deaf participants rated setup 4 (only ears)-without the VR suit (M = 1.9, SD = 0.876) more comfortable than setup 3 (ears)-with the VR suit (M = 7.5, SD = 1.716).

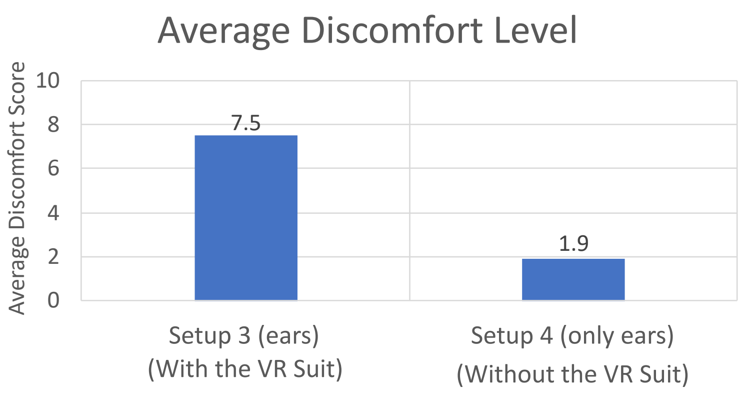

Figure 5.8: Average discomfort level of setup 3 (ears)-with the VR suit and setup 4 (only ears)-without the VR suit.

Figure 5.9 shows the number of responses to questions about the desire to use setup 3 (ears)-with the VR suit and setup 4 (only ears)-without the VR suit. Analysis of the result using descriptive statistics shows that deaf participants preferred to use setup 4 (only ears) (M = 4.9, SD = 0.316) more than setup 3 (ears) (M = 2.0, SD = 0.816) for completing sound-related VR tasks. Although, further analysis is needed to confirm these findings. Overall, this is an exciting result because it suggests developing small portable VR assistive devices for deaf persons without using VR suits.

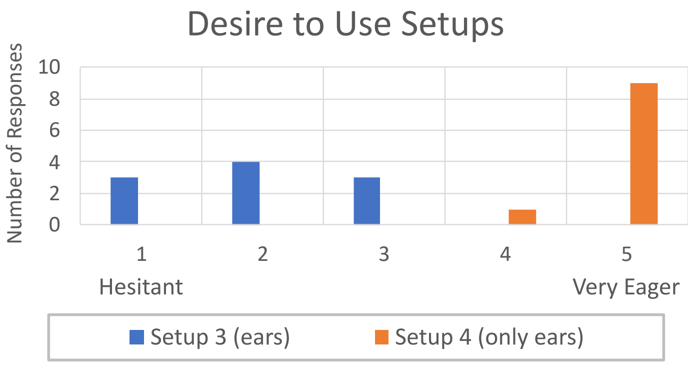

Figure 5.9: Results of the desire to use setup 3 (ears)-with the VR suit and setup 4 (only ears)-without the VR suit among deaf persons.

5.1.4 Discussion

The results of our first experiment suggest that deaf persons complete sound-related VR tasks significantly faster using our proposed haptic VR suit than without haptic feedback. In addition, the results for the discomfort level and the desire to use different setups show that deaf persons prefer mounting the vibro-motors on their upper body sections, such as arms and ears, compared to lower body sections, such as thighs, when using the haptic VR suit. However, the results of our second experiment suggest that deaf persons prefer mounting vibro-motors in their ears when not using a haptic VR suit. According to these results, our H1 and H2 hypotheses in this experiment are supported, but more studies are required to understand why deaf persons react differently to tactile sensations from different parts of their bodies in VR.

In our study, the first experiment of different VR suit setups was entirely new to deaf participants, and we had a limited budget that did not let us use advanced haptic VR suits, so we limited the number of vibro-motors to four on a custom VR suit and limited the directions of incoming sounds to the front, back, left, and right. In addition, we only tested our suggested VR suit setups on the same group of participants on different days and in a fixed order. Although the VR environment randomly changed in each test for each participant, the fixed order of the setups in our first experiment may have had some learning effects on the participants. Therefore, it is essential to randomize the order of conditions across participants in future works.

5.2 EarVR: In-Ear Haptics for Deaf Persons

This section presents experiments related to our proposed EarVR system, explained in Chapter 4. We study the effects of using EarVR on deaf persons in VR environments and examine deaf persons' VR experience, sound source localization, VR task completion time, and desire to use the EarVR system. Our main questions for this experiment are:

1. What are the main parameters in completing sound-related VR tasks for deaf persons which affect VR task completion time?

2. How does the EarVR system affect deaf persons' VR usage?

Our proposed EarVR system is a new VR approach for deaf persons and has never been tested before in different VR scenarios, and we needed to obtain some basic information about using it among deaf persons in an initial step. Therefore, we conduct a pilot experiment to test the system and formulate our hypotheses. Then, we design our main experiments to check the functionality and acceptability of the EarVR system among deaf persons.

5.2.1 Pilot Experiment

Participants:

We recruited two new groups of people for the EarVR pilot experiment. Group 1 (control group) consisted of 5 persons without hearing problems from university staff (3 men, 2 women; 18 to 50 years old, M = 33.6, SD = 12.54), and Group 2 consisted of 5 deaf persons (no hearing in both ears and not using HA or CI) from the DHH community (4 men, 1 woman; 18 to 45 years old, M = 32.2, SD = 10.7) who volunteered to do our test with the same recruitment procedure of our previous study.

All participants were familiar with VR technology and had tried it at least once. They also did not have any physical or emotional problems with using VR. VR safety warnings were carefully stated in our consent form (Appendix-A 6.3), and all volunteers were aware of them and signed the consent form.

5.2.1.1 Task and Procedure

We designed a simple VR game using the Unity3D [1] game engine (version 2019.1.5f1) for our pilot experiment and asked the participants to play it. In this VR game, the user was placed in the center of the VR environment, and four speakers (3D objects) were placed around him (left, right, front, back). The VR environment of our pilot experiment is shown in Figure 5.10.

[1] Available Online: https://unity.com/ (accessed on 5 October 2021)

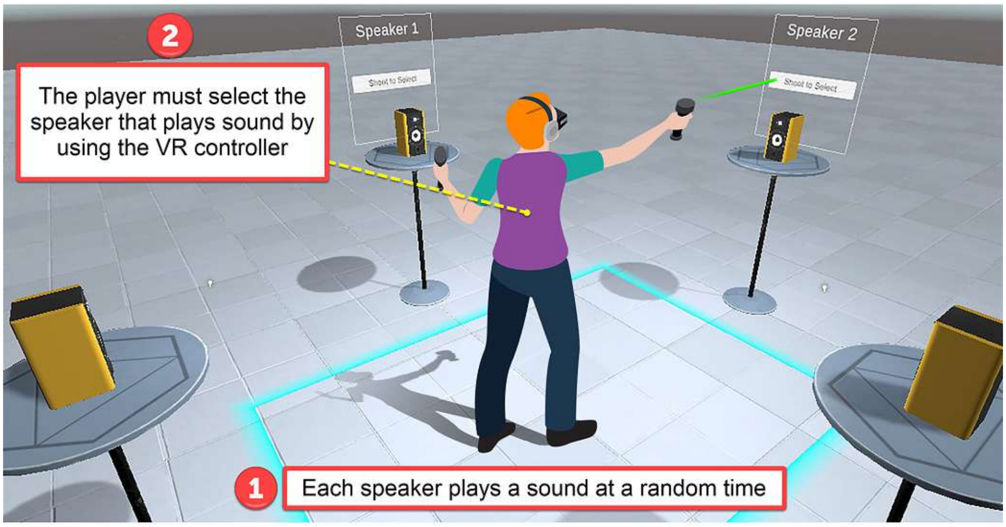

Figure 5.10: The VR environment of the EarVR pilot experiment.

In this game, one speaker starts playing a continuous sound (loop wave) at a random time, and the user must select it using a VR controller as a pointer. All the speaker 3D models in the VR environment are identical, and there is no graphical sign of playing sound on the active speaker.

If the user selects the correct speaker, the next random speaker will start playing a sound. This process will continue four times. After selecting the fourth speaker, the task completion time of the user is recorded, which shows the user's success in completing the given task (win state). If the user selects the wrong speaker, the game will be over, and it will be recorded as a failure for the user (game-over state). Users can play the game three times in total (three rounds) if they want. In this experiment, each participant experienced two following conditions:

1. ***With EarVR:*** The EarVR system is mounted on the VR HMD as a haptic VR assistive system.
2. ***Without EarVR:*** Only VR HMD is used without any assistive system.

5.2.1.2 Results

Control Group (Hearing Persons):

The results are shown in Table 5.2. Participants in control group could complete the game on an average completion time of 5.84 seconds without EarVR (SD = 0.352) and 5.34 seconds with EarVR (SD = 0.230). Each user in this group played the game at least two times. Two members played two times, and the other three played three times.

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the average completion time was approximately normally distributed in the control group for both conditions (without EarVR: $W = 0.914$, $p = 0.492$, and with EaVR: $W = 0.943$, $p = 0.685$), but was not approximately normally distributed in the number of plays and number of wins (without EarVR: $W = 0.684$, $p = 0.006$, and with EarVR: $W = 0.552$, p <0.001).

Control Group (Hearing Persons)		Player				
		1	2	3	4	5
Without EarVR	Plays	3	2	2	3	3
	Wins/Game Overs	3 / 0	2 / 0	2 / 0	3 / 0	3 / 0
	Average Completion Time (Sec)	5.8 SD = 0.556	5.5 SD = 0.141	5.6 SD = 0.141	6.4 SD = 0.624	5.9 SD = 0.472
With EarVR	Plays	3	3	2	3	3
	Wins/Game Overs	3 / 0	3 / 0	2 / 0	3 / 0	3 / 0
	Average Completion Time (Sec)	5.4 SD = 0.208	5.3 SD = 0.208	5.1 SD = 0.141	5.7 SD = 0.200	5.2 SD = 0.152

Table 5.2: Pilot experiment's results for persons without hearing problems.

A paired-samples t-test with $\alpha = 0.05$ was conducted on the average completion time and a Wilcoxon signed-rank test with $\alpha = 0.05$ was conducted on the number of plays and number of wins to evaluate the impact of using EarVR system on the average completion time, number of plays, and number of wins. The paired-samples t-test indicates a significant main effect of using EarVR system on the average completion time of the control group ($t(4) = -5.270$, $p = 0.006$). The Wilcoxon test did not elicit a statistically significant difference in the number of plays and number of wins ($Z = -1.0$, $p = 0.317$) in the control group (no game over).

Deaf Persons:

The results are shown in Table 5.3. The results were different among deaf persons compared to the control group. Without EarVR, none of the deaf participants could complete the game successfully even once. Three participants did not want to play the game after the first failure. Two others tried it twice but were disappointed in finishing the task because they failed both times. However, with EarVR, all deaf participants could complete the game at their first attempt with an average completion time of 5.7 seconds (SD = 0.149).

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the average completion time was approximately normally distributed in the deaf persons group for with EaVR condition ($W = 0.987$, $p = 0.967$), but was not approximately normally distributed in the number of plays, number of wins, and number of game overs (without EarVR: $W = 0.684$, $p = 0.006$, and with EarVR: $W = 0.552$, p <0.001).

Deaf Persons		Player 1	Player 2	Player 3	Player 4	Player 5
Without EarVR	Plays	1	2	1	1	2
	Wins/Game Overs	0 / 1	0 / 2	0 / 1	0 / 1	0 / 2
	Average Completion Time (Sec)	None	None	None	None	None
With EarVR	Plays	3	3	3	2	3
	Wins/Game Overs	3 / 0	3 / 0	3 / 0	2 / 0	3 / 0
	Average Completion Time (Sec)	5.5 SD = 0.416	5.7 SD = 0.251	5.9 SD = 0.500	5.6 SD = 0.282	5.8 SD = 0.655

Table 5.3: Pilot experiment's results for deaf persons.

A paired-samples t-test with $\alpha = 0.05$ was conducted on the average completion time and a Wilcoxon signed-rank test with $\alpha = 0.05$ was conducted on the number of plays, number of wins, and number of game overs to evaluate the impact of using EarVR system on the average completion time, number of plays, number of wins, and number of game overs. The paired-samples t-test indicates a significant main effect of using EarVR on average completion time of the deaf persons group ($t(4) = 80.610$, p <0.001). The Wilcoxon test also revealed a statistically significant main effect of using EarVR on the number of plays ($Z = -2.070$, $p = 0.038$), number of wins ($Z = -2.121$, $p = 0.034$), and number of game overs ($Z = -2.070$, $p = 0.038$) in the deaf persons group.

5.2.1.3 Discussion and Hypotheses

In the pilot experiment, the average task completion time of deaf persons was 5.7 seconds with EarVR (SD = 0.149), and the average task completion time of the control group was 5.84 seconds without EarVR (SD = 0.352). An independent-samples t-test with $\alpha = 0.05$ was conducted to compare the average completion time of the control group and the deaf person group. The test suggested that the average completion times of two groups were close without a significant difference ($t(8)$ = - 0.814, $p = 0.439$).

The result shows that using the EarVR system helps deaf participants complete the VR task successfully. We formulated the following hypotheses based on the results of our pilot experiment:

- H1. Using the EarVR system improves the VR task completion time of deaf persons compared to using a standard VR setup without the EarVR system.
- H2. Using the EarVR system improves the VR task completion time of persons without hearing problems compared to using a standard VR setup without the EarVR system.
- H3. Using the EarVR system, deaf persons can complete sound-related VR tasks more successfully than without the EarVR system.
- H4. Deaf persons perform more VR tasks using the EarVR system than a standard VR setup without the EarVR system.

5.2.2 Main Experiment

Participants:

We recruited volunteers using the same recruitment method as our pilot experiment for the main experiment. Some volunteers had no experience using VR before but were keen to participate in our experiment voluntarily. Therefore, we asked them to play a VR demo game for 10 minutes before our main experiment (the demo game was completely different from the main experiment). They all signed the consent form before playing the demo game and were aware of potential VR health effects. We also observed them as they played, and we were ready to stop them if they showed any cybersickness symptoms mentioned in the study of A. Ng et al. [273]. After this introduction, the volunteers could choose whether to participate in our main experiment. Finally, we selected 40 volunteers in two groups of 20 who experienced no side effects when using VR, such as cybersickness.

Group 1 (control group) included 20 persons without hearing problems (14 men, 6 women, 15 to 50 years old, M = 30.23, SD = 11.188). Group 2 included 20 deaf persons with no hearing in both ears and not using HA or CI (12 men, 8 women; 15 to 50 years old, M = 31.85, SD = 10.713). In order to test our hypotheses, we divided each group of 20 participants into two groups of 10. Groups 1.1 and 1.2 (control groups) included 7 men and 3 women and Groups 2.1 and 2.2 (deaf persons groups) included 6 men and 4 women. We asked the members of groups 1.1 and 2.1 to do the given tasks without EarVR and groups 1.2 and 2.2 with EarVR. We analyze the effect of EarVR on the task completion time, number of plays, number of wins, and number of game overs of all groups.

5.2.2.1 Experiment Design

For the main experiment, we developed two task-based sound-related VR games using the Unity3D [2] game engine (version 2019.1.5f1). Google's Resonance Audio Software Development Kit (SDK) [3] was used to add 3D audio to the objects in the VR environment. The SteamVR v2 plugin [4] was utilized to program the VR controllers.

We designed two tasks for two particular purposes:

- ***Task 1 - Find the Cube:*** For measuring VR task completion times.
- ***Task 2 - Find the Correct Cubes:*** For counting VR task completions.

The VR environment for both tasks is an enclosed room with a different design, and the user spawns in the center (Figure 5.11). The base room 3D model is from Google Resonance Audio SDK [5], which we improved for our project. 3D audio is essential for EarVR because the signal processing code inside the Arduino analyzes input 3D sounds (stereo channels), and it does not work in VR applications with background music (background music must be muted before using the EarVR system). Limitations of the EarVR system described in Chapter 4.

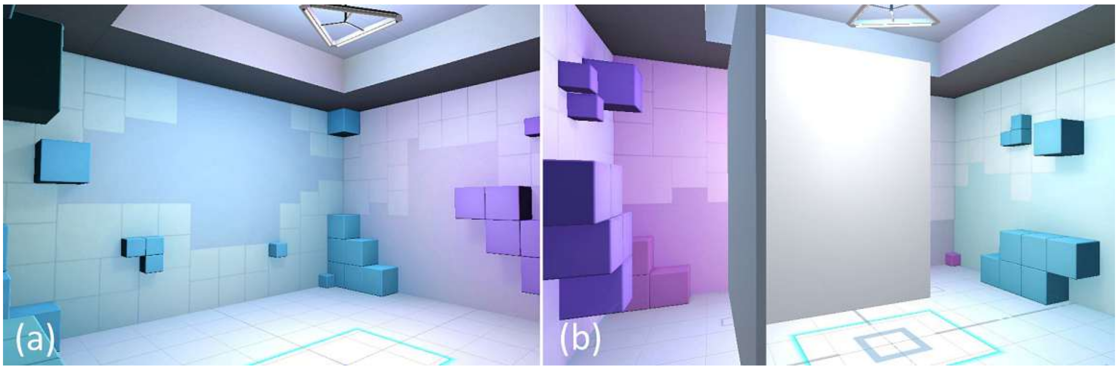

Figure 5.11: VR environment designs for testing EarVR: (a) Task 1 - Find the Cube, and (b) Task 2 - Find the Correct Cubes.

Two groups of people were tested in this experiment: (1) deaf persons and (2) the control group (hearing persons). We stored and analyzed the results for each group. Our goal was to determine the effects of using EarVR on the speed of completing VR tasks and the desire to use VR technology among deaf persons.

[2]Available Online: https://unity.com/ (accessed on 5 October 2021)
[3]Available Online: https://resonance-audio.github.io/resonance-audio/ (accessed on 5 October 2021)
[4]Available Online: https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647 (accessed on 5 October 2021)
[5]Available Online: https://resonance-audio.github.io/resonance-audio/ (accessed on 5 October 2021)

5.2.2.2 Task and Procedure

Task 1: Find the Cube

In Task 1, ten identical cubes are spawned one after another in random positions of the VR environment. Each cube produces continuous 3D sounds generated by Resonance Audio SDK without a reverb effect (only spatialized). The intensity of the sound the user hears changes based on the distance from the cube (for deaf persons, it is the input sound to the Arduino). The user is placed in the center of the room (fixed position) and can only rotate around to find the cube. The user must aim at each cube and push the trigger button on the VR controller to select the cube. If the user aims at the cube, the cube's color changes. A ray cast effect (laser pointer) is designed to show the aiming point to the user (Figure 5.12).

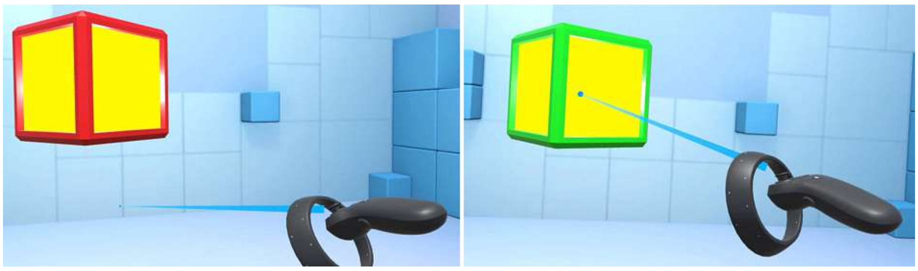

Figure 5.12: Task 1 - Find the Cube.

The cube will be eliminated after getting selected, and another cube will spawn in a random position. The process will continue until all ten cubes are selected. Finally, the user's task completion time will be saved (for each user). This task has no game over mechanism, and all users can complete the game at the end.

Task 2: Find the Correct Cubes

In Task 2, ten identical cubes are spawned simultaneously in random positions of the VR environment separated by walls, as shown in Figure 5.13. Only five of these ten cubes will generate continuous 3D sounds. The cubes are identical and have no signs to show the user which one is generating sounds, and also, all of them generate similar sounds.

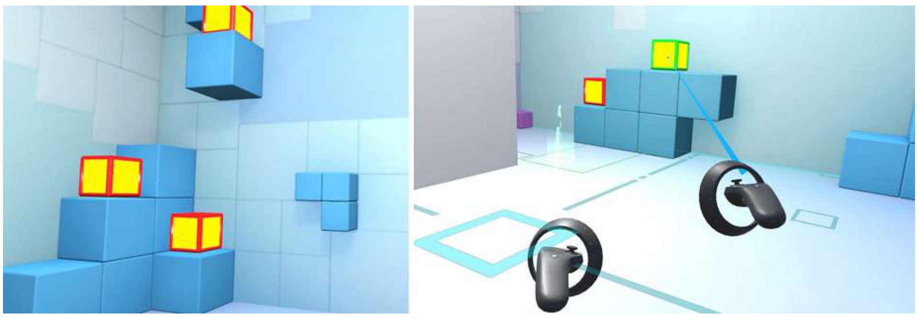

Figure 5.13: Task 2 - Find the Correct Cubes.

For this task, the user is placed in the center of the room and can move around using a teleportation system to search the areas behind the walls. The user can use the VR controller's trigger button to select the cubes and the touchpad button to teleport around. We also designed the task so that two cubes (either one or both generating sounds) would never spawn side by side. This task is completed (win state) only if the user finds the correct five cubes (generating sounds) and selects them one by one. If the user selects the wrong cube (not generating sound), the game will be over (game-over state). Users can play the game between 1 to 10 times, depending on their desire. The gameplay time of each user is limited to 5 minutes, meaning the game will be over if the user cannot finish the task in 5 minutes. The number of ”Win” and ”Game Over” for each user is recorded. The task completion time is not essential for this game because, in this task, we only focused on the number of wins and game overs for each user. Task 2 is more challenging for deaf persons than hearing persons, and we investigate the effects of completing the task successfully or unsuccessfully on the number of playing the task, specifically among deaf persons and compare it with the results of hearing persons. Furthermore, the task completion time was already tested in task 1.

5.2.2.3 Results

We started our analysis by looking at each users' task completion time, number of plays, number of wins, and number of game overs. The results of Task 1 and Task 2 with and without EarVR conditions (for each group) help us to investigate the EarVR's effects on each group. It also showed us the desire to do VR tasks among groups with and without using the EarVR system.

Task 1 Results:

Figure 5.14 shows the completion time of task 1 for the control and deaf persons groups. Members of the control group were able to complete the task with an average completion time of 14.9 seconds without EarVR (SD = 1.729) and 12.6 seconds with EarVR (SD = 1.350) which is 2.3 seconds faster on average. Members of deaf persons group were able to complete the task with an average completion time of 29.6 seconds without EarVR (SD = 6.802) and 14.7 seconds with EarVR (SD = 1.567) which is 14.9 seconds faster on average.

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that in the control group, the completion time was approximately normally distributed for both EarVR conditions (without EarVR: $W = 0.937$, $p = 0.521$, and with EarVR: ($W = 0.896$, $p = 0.198$). The test also indicates that in the deaf persons group, the completion time was approximately normally distributed for both EarVR conditions (without EarVR: $W = 0.952$, $p = 0.691$, and with EarVR: $W = 0.945$, $p = 0.609$).

A paired-samples t-test with $\alpha = 0.05$ was conducted to evaluate the effect of using EarVR system on the completion time of the control and deaf persons groups. In the control group, the test indicates a significant difference ($t(9) = - 4.116$, $p = 0.003$) in the completion time of with EarVR condition (M = 12.6, SD = 1.350) and without EarVR condition (M = 14.9, SD = 1.729). In the deaf persons group, the test also indicates a significant difference ($t(9)$ = - 6.657, p <0.001) in the completion time of with EarVR condition (M = 14.7, SD = 1.567) and without EarVR condition (M = 29.6, SD = 6.802). These results support our H1 and H2 hypothesis of this experiment.

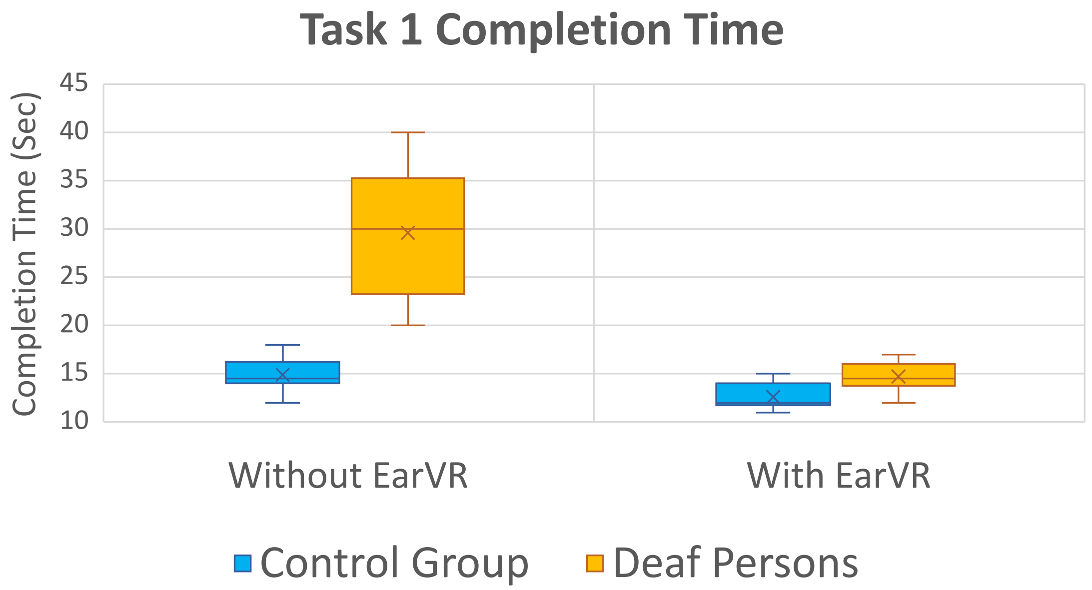

Figure 5.14: Task 1 completion time for the control and deaf persons groups.

Analysis of the results for task 1 shows that deaf persons were able to complete the task faster with EarVR compared to those without EarVR. They completed the task in an average time of 14.7 seconds (SD = 1.567), close to the average completion time of persons without hearing problems without EarVR (14.9 seconds, SD = 1.729). The independent-samples t-test with $\alpha = 0.05$ suggested that these completion times were close without a significant difference ($t(18)$ = 0.271, p = 0.789). Although, further analysis is needed to confirm these findings.

Task 2 Results:

In task 2, we focused on the number of plays, number of wins, and number of game overs in each group, and the completion time was not important in this task because it already tested in task 1. Figure 5.15 shows the number of plays (without EarVR: M = 3, SD = 1.155, and with EarVR: M = 4.2, SD = 1.317), the number of wins (without EarVR: M = 2.2, SD = 0.789, and with EarVR: M = 3.9, SD = 0.994), and the number of game overs (without EarVR: M = 0.8, SD = 0.789, and with EarVR: M = 0.3, SD = 0.483) for the control group.

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that in the control group, the number of plays was approximately normally distributed for both EarVR conditions (without EarVR: $W = 0.953$, $p = 0.703$, and with EarVR: $W = 0.942$, $p = 0.575$), but the number of wins was only approximately normally distributed in with EarVR condition ($W = 0.886$, $p = 0.152$) and not in without EarVR condition ($W = 0.820$, $p = 0.025$). Also, the number of game overs was not approximately normally distributed for both EarVR conditions (without EarVR: $W = 0.820$, $p = 0.025$, and with EarVR: $W = 0.594$, p <0.001).

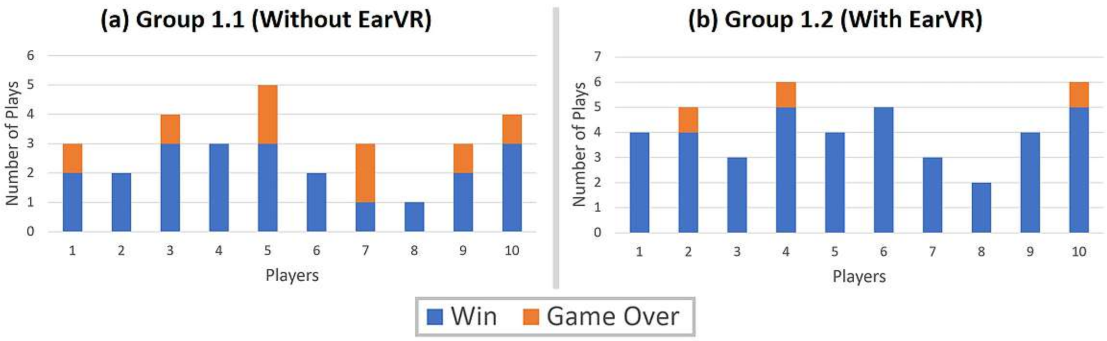

Figure 5.15: Task 2 results for the control group.

A paired-samples t-test with $\alpha = 0.05$ was conducted to compare the number of plays between the two conditions of using EarVR in the control group. The test indicates a significant difference in the number of plays between the two conditions of using EarVR ($t(9) = 2.449$, $p = 0.037$). This result shows that the number of plays increased significantly in the control group by using EarVR compared to not using EarVR.

Wilcoxon signed-rank tests with $\alpha = 0.05$ were conducted to compare the number of wins and number of game overs between the two conditions of using EarVR in the control group. The test revealed a significant difference in the number of wins (Z = - 2.754, p = 0.006), but no significant difference in the number of game overs (Z = - 1.406, p = 0.160).

Figure 5.16 shows the number of plays (without EarVR: M = 1.4, SD = 0.699, and with EarVR: M = 5.3, SD = 1.160), number of wins (without EarVR: M = 0, SD = 0, and with EarVR: M = 4.8, SD = 0.789), and number of game overs (without EarVR: M = 1.4, SD = 0.699, and with EarVR: M = 0.5, SD = 0.527) for the deaf persons group. As shown in Figure 5.16-a, nobody in this group without EarVR could complete (finish) the task even after a few tries, whereas everyone with EarVR completed the task (win) for at least three times (Figure 5.16-b).

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that in the deaf persons group, the number of plays was approximately normally distributed only for with EarVR condition ($W = 0.878$, $p = 0.124$) and not for without EarVR condition ($W = 0.650$, $p < 0.001$). The test also indicates that the data was not approximately normally distributed for the number of wins (with EarVR: $W = 0.820$, $p = 0.025$) and the number of game overs (without EarVR: $W = 0.655$, $p < 0.001$, and with EarVR: $W = 0.650$, $p < 0.001$).

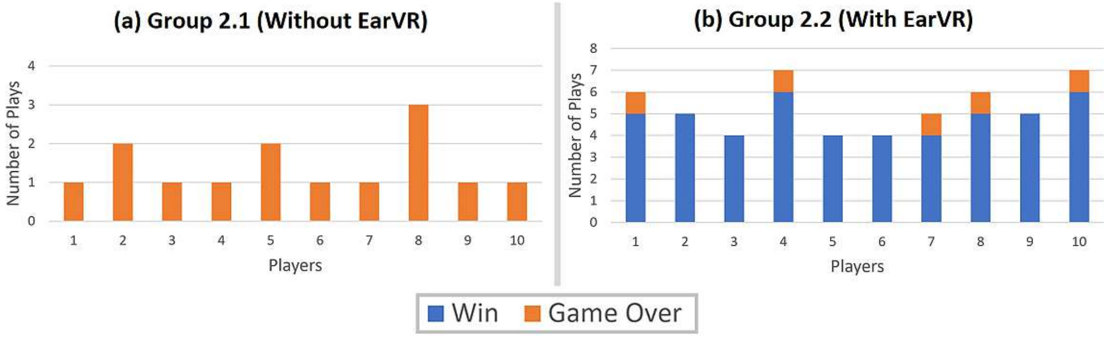

Figure 5.16: Task 2 results for the deaf persons group.

Wilcoxon signed-rank tests with $\alpha = 0.05$ were conducted to compare the number of plays, number of wins, and number of game overs between the two conditions of using EarVR in the deaf persons group. The test indicates a significant difference in the number of plays ($Z = -2.825$, $p = 0.005$), number of wins ($Z = -2.842$, $p = 0.004$), and number of game overs ($Z = -2.251$, $p = 0.024$). The results of this section support our H3 and H4 hypothesis, and indicate that using EarVR helps deaf persons to complete sound-related VR tasks successfully, improves the VR task completion time, and increase the number of using VR among them.

Deaf persons without EarVR were not able in completing the task after one or a few tries. Some of them requested to play the game again after their first or second game over, but they stopped trying when their efforts resulted in nothing, but using EarVR helps them complete the task successfully in their different tries. Also, using EarVR increased the total number of plays and wins among participants in the control group. It means that using EarVR not only helped participants in the control group to play the VR game more, but also helped them to win more in the VR game. Although, further analysis is needed to confirm these findings.

Previous studies, such as P. King [274], M. D. Molina et al. [275], M. Hudson et al. [276], and V. Hemovich [277], show effects of winning or losing game on the behavioural state of player in games and social activities, and their eagerness to play or not playing a game. Since, the number of wins and game overs in a game depends on different parameters that we did not consider in this experiment, further experiments and analysis is needed to confirm if EarVR has any effect on the number of wins and game overs in VR games.

5.2.3 EarVR Functionality Experiment

We designed a functionality test for the EarVR system to study its effects on deaf persons' VR experience in a complex VR game. We explored numerous free VR Games available on the market; however, none of them was suitable for our functionality test (with 3D audio and the mute option for background music). Many available VR games do not mention the use of 3D audio in their descriptions which made it hard to find a proper VR game for our functionality test. Therefore, we developed a VR game that supports EarVR's requirements, such as muting the background music and using 3D audio.

We used an open-source non-VR game available in the Unity3D projects called "Survival Shooter" [6] and changed it into a VR game (Figure 5.17). This game is score-based, and players get scored by eliminating enemies. We designed a VR HUD to show the player's health and scores. In addition, the game becomes harder (challenging) at higher levels. We asked all 20 deaf participants from previous tests to join in and play this VR game, and all agreed to play.

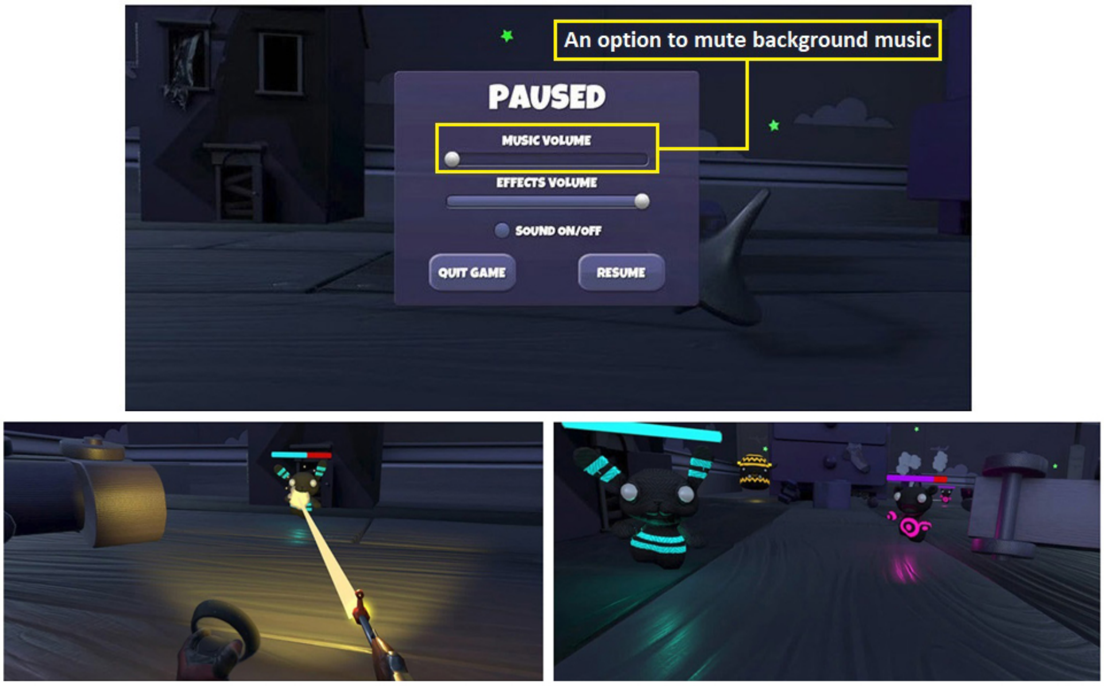

Figure 5.17: Our shooting VR game environment.

We divided deaf participants into two groups of 10 to create a sense of competition. Users in both groups played the game once, and their score was recorded. The user with the highest score in each group was chosen to play the final round to determine the winner.

[6] Available Online: https://learn.unity.com/project/survival-shooter-tutorial/ (accessed on 5 October 2021)

We rewarded the final winner with a present at the end (Figure 5.18) [7]. The passion and excitement among all deaf participants were delightful to observe. However, we did not statistically measure these factors, and further experiments and analysis are required. Ultimately, we asked all 20 deaf participants to fill in an anonymous survey about their experience playing the VR game. Our survey questionnaire consisted of questions with a 5-point Likert-scale (1 = most negative, 5 = most positive) and an open-ended question for participants' comments about their experience with EarVR.

Figure 5.18: Rewarding the winner of the competition (the figure is ONLY for presentation purposes).

We designed this experiment to study the ease-of-use, satisfaction, effectiveness, and desire-to-use EarVR among deaf persons. We analyzed the open-ended comments by using the participant's own words in MAXQDA [8] trial version through open-coding on two main categories of usability (effectiveness, ease-of-use) and user experience (satisfaction, desire-to-use), without imposing our own beliefs or biases [278].

5.2.3.1 Results

Figure 5.19 shows the survey results from 20 deaf persons who participated in the functionality test. The results without EarVR are based on the participants' experience from previous tasks. A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the data was not approximately normally distributed for all categories (ease of use: without EarVR ($W = 0.816$, $p = 0.002$), and with EarVR: ($W = 0.754$, p <0.001), satisfaction: without EarVR ($W = 0.608$, p <0.001), and with EarVR: ($W = 0.583$, p <0.001), effectiveness: without EarVR ($W = 0.701$, p <0.001), and with EarVR: ($W = 0.632$, p <0.001), desire to use: without EarVR ($W = 0.711$, p <0.001), and with EarVR: ($W = 0.544$, p <0.001). The comparisons of with and without EarVR conditions using Wilcoxon test indicated that using EarVR rated significantly better in terms of ease-of-use ($Z = -3.671$, $p < 0.001$, without EarVR: M = 1.95, SD = 0.759, and with EarVR: M =

[7] In this thesis, all figures with people's faces are ONLY for presentation purposes and DO NOT reveal any information about the identity of actual participants in our experiments.

[8] Available Online: https://www.maxqda.com/ (accessed on 5 October 2021)

4.20, SD = 1.056), satisfaction ($Z = -3.999$, p < 0.001, without EarVR: M = 1.35, SD = 0.489, and with EarVR: M = 4.70, SD = 0.571), effectiveness ($Z = -3.981$, $p < 0.001$, without EarVR: M = 1.45, SD = 0.605, and with EarVR: M = 4.65, SD = 0.587), and desire-to-use ($Z = -4.005$, $p < 0.001$, without EarVR: M = 1.50, SD = 0.688, and with EarVR: M = 4.75, SD = 0.444).

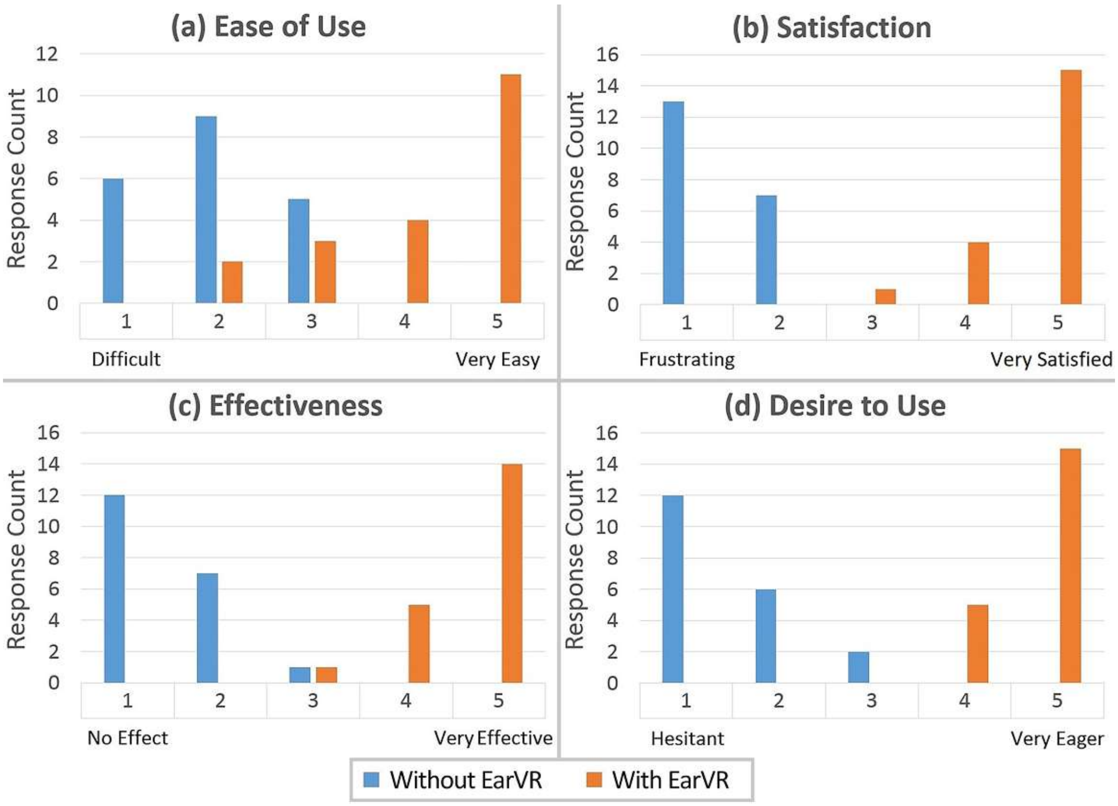

Figure 5.19: EarVR functionality test results.

The results indicates that deaf persons find EarVR helpful to use VR technology (Figure 5.19-a). They rated the effectiveness of EarVR high (very effective). They believed EarVR could help them complete tasks in different sound-related VR applications (Figure 5.19-c). The satisfaction rate of the EarVR was high (very satisfied). Deaf participants were satisfied with the EarVR functionality in VR applications and games (Figure 5.19-b). Finally, the desire-to-use EarVR was also high among deaf persons. Using EarVR, they experienced different than not using EarVR. Also, they wanted to repeat the VR experience (Figure 5.19-d). These results show the functionality of EarVR in VR applications and games among deaf persons. However, we did not consider different functionality factors in this experiment because of the scope of the research. Therefore, further experiments and analysis are needed to confirm these findings. A part of our qualitative analysis is shown in Table 5.4.

Code	Preference Reason	Freq. (%)
Desire to use	Repeat experience using EarVR	58
Effectiveness	EarVR helps to locate sound sources	46
Satisfaction	Enjoy using EarVR	34
Ease of use	EarVR is portable and ready to use	27

Table 5.4: Open-coding our qualitative data.

5.2.4 Discussion

Based on the results of our proposed VR suit, we discovered that using more than two vibro-motors and installing them on different parts of deaf persons' bodies does not have a noticeable effect on locating the audio sources. Observing how precisely deaf persons can detect sound sources using only two vibro-motors was interesting. In addition, we conducted a survey among the DHH community to find the best locations to put the vibro-motors. We found that deaf persons prefer their upper body for vibro-motor placement, especially their heads. Therefore, after final reviews, we decided to use two vibro-motors on the user's ears in our EarVR's prototype design.

The results of Task 1 show that deaf persons can complete the task significantly faster when using the EarVR system. It helped deaf persons to locate sound sources in the VR environment. Their average task completion time using EarVR was close to that of persons without hearing problems which were not using EarVR. Also, the results from persons without hearing problems indicate that using EarVR helped them complete the VR task faster than without using EarVR.

The results from Task 2 show that deaf persons complete sound-related VR tasks successfully using EarVR, which was not possible for them without using EarVR. Our functionality test's qualitative and quantitative results reveal that the EarVR system improves deaf persons' VR experience. According to the final results of Task 1 and Task 2, all of our hypotheses for this study (H1, H2, H3, and H4) are supported. Task 2 was designed to study if EarVR helps deaf persons complete VR tasks that they could not complete otherwise. In this task, sometimes two identical cubes were spawned near each other (either one or both generating sounds), making it difficult even for persons without hearing problems to complete the task. We added a condition in our development to prevent identical cubes from spawning near each other. If situations like this occur in sound-related VR applications, the objects are different or generate different sounds, which are distinguishable for persons without hearing problems.

The EarVR system has two main requirements for VR applications. The VR application must provide the option to mute background music and offer 3D audio. Using 3D audio in VR is growing rapidly, and we hope to see more VR applications with 3D audio in the future. The current VR games' complexity is higher than our designed tasks. Although EarVR can help deaf persons even in complex VR tasks, there are more parameters in VR environments that we should investigate in future studies.

Based on the results of our functionality test, we noticed that some deaf persons are not interested in VR without using assistive technology. It depends on an individual's association with the hearing or the deaf culture, and in the end, it is a personal choice [39]. We also designed a friendly competition between deaf persons and persons without hearing problems. We used the same VR game as in our functionality test. We wanted to see if deaf persons have the same excitement for competing with persons without hearing problems. In this competition, deaf participants used EarVR, and persons without hearing problems did not use EarVR. Both groups were excited about playing the VR game together. However, further precise experiments and analysis are needed to confirm whether the EarVR affects the competition feeling of a VR game between deaf and hearing persons. We assume that the EarVR system could decrease the fear of losing the game and improves the level of confidence among deaf persons. However, our assessment is only based on the observation of participants during the competition, and further studies and analysis on psychological effects are needed to substantiate this claim.

5.3 Multi-modal Spatial Localization for Deaf Persons

Information visualization techniques play an essential role in VR because they improve task performance, support cognitive processes, and eventually increase the feeling of immersion [279, 243]. Deaf persons have particular needs for information presentation [280], and they perceive VR environments differently [232]. In our previous experiments, we showed that adding particular features and using haptic methods help deaf persons by improving task completion time of sound-related VR tasks, increasing the number of using VR, and also helping them have a better VR experience.

Deaf persons use different perceptual modalities to interact with environments, and using visual stimuli helps them improve their interactions [281]. Previous research shows that deaf persons have better peripheral vision and a faster reaction time to visual stimulus compared to persons without hearing problems [17, 18, 19, 20]. Therefore, we designed an experiment to investigate deaf persons' reaction times to visual stimuli, specifically in VR environments. Our main questions for this experiment are as follows:

1. How do visual stimuli in VR environments affect deaf persons' VR experience?
2. What are the effects of using different visualization methods in VR on deaf persons' VR task completion?

We aim at finding the best way to use multi-modal information presentation in VR and compare its effect on deaf persons' VR experience. We also analyze the results of using multi-modal information presentation among deaf persons and control group (hearing persons) and try to find a solution to minimize the impact of deaf persons' hearing impairments in VR environments. The main contributions of our work in this experiment are summarized as follows:

- Identifying the information presentation requirements of deaf persons in VR environments.
- Introducing Omni-directional particle visualization as a novel information visualization method in VR for deaf persons.
- Investigating the best way of using multi-modal information presentation and its effect on deaf persons' VR experience.
- Providing a practical solution to minimize the impact of deaf persons' hearing impairments in VR.

5.3.1 Experiment Design

In our experiment, we study the effects of audio, visual, and haptic stimuli and a combination of them on deaf persons' VR task completion times and compare them to the control group. For this purpose, we first do a pre-experiment with two groups of volunteers (deaf persons and persons without hearing problems) to investigate which of our recommended visualization methods in VR is preferable to each group. We suggest two visualization methods for our pre-experiment:

1. Graphical visualization in the HUD.
2. Omni-directional particle visualization.

Ultimately, we use the best visualization method from the pre-experiment as a main visual stimulus in VR for our main experiment and review and analyze the final results based on that method. In summary, our pre-experiment focuses on visual information presentation, and our main experiment investigates multiple modalities for information presentation in VR. Our final results address multiple modalities in VR for deaf persons, which have not been well studied. Also, the results of this experiment help VR developers as guidelines to pay as much attention to deaf persons' VR requirements as persons without hearing problems and provide applicable products for deaf and hearing persons by choosing the best audio, visual, or haptic stimuli or a combination of them.

5.3.2 Spatial Localization in VR

We prepared a pre-experiment with our two suggested visualization methods (presentation in the HUD and Omni-directional particle visualization) to determine which visualization method in VR is preferable to the control and deaf persons groups.

Presentation in the HUD:

For presentation in the HUD, we designed two graphic arrows in the user's HUD that can only show the left and right directions of the object location based on the user's forward direction. This method is a basic demonstration of the 1 Degree-of-Freedom (1DoF) horizontal compass HUD systems used in different games to show targets' positions (the left or right) to players, even for the targets far from the player (Figure 5.20).

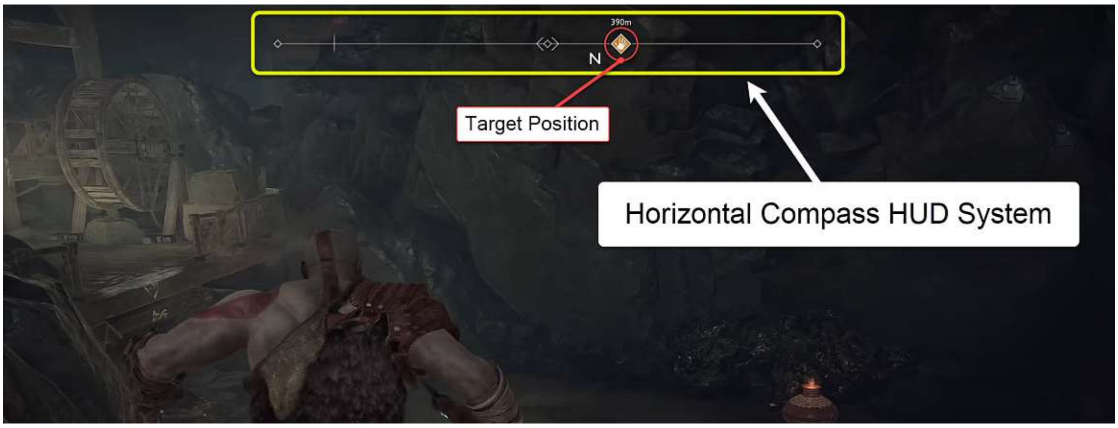

Figure 5.20: Horizontal compass HUD system in modern games.

In the HUD presentation, each arrow blinks for 5 seconds for each target object, beginning when the target object spawns in the VR environment, and then the arrow disappears. If the user can find and eliminate the target object in less than 5 seconds, the arrow will disappear immediately, and another arrow will appear with the next target object. The user can locate the target object in the VR environment by rotating the body or head to the given arrow's direction (Figure 5.21).

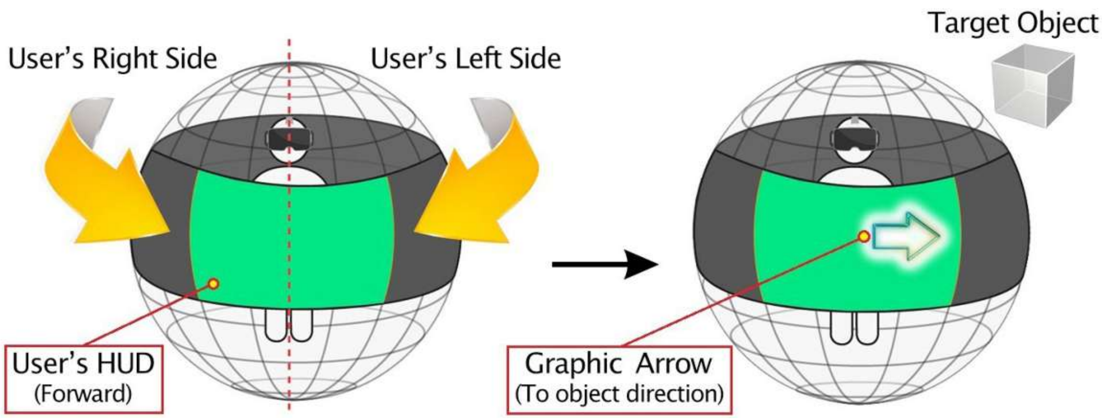

Figure 5.21: Presentation in the HUD (graphic arrow).

Our proposed EarVR system detects only two possible directions from stereo sound input (the left and right). Therefore, for our future study, we only visualize the left and right arrows in our HUD visualization (not diagonal directions) to ensure compatibility with the sound detection from the EarVR system.

Omni-directional Particle Visualization:

Our Omni-directional particle visualization method is a novel proposed method for deaf persons. It uses directionally moving particles in the environment from the target object, so the user can locate the target object as soon as particles appear in the user's FOV (Figure 5.22).

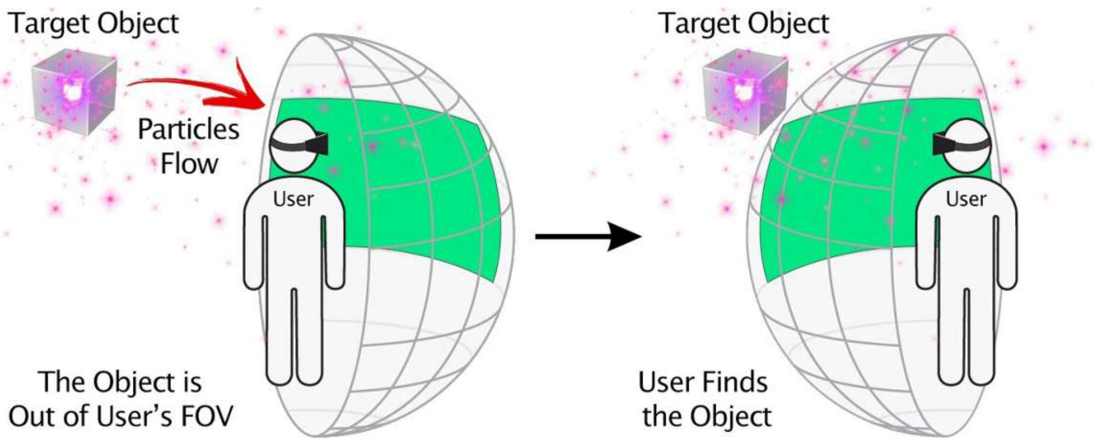

Figure 5.22: Omni-directional particle visualization (particles flow).

Our method uses a particle system that emits light beams from the particle source (target object) in all directions of the VR environment with emitted radiance related to the environment's dimensions and the user's distance from the object. In this method, each particle has motion, enabling the user to track the incoming particle's path in the FOV. Therefore, the user can find the particle source (target object) without searching. Our proposed method assumes that the user can infer an object's location based on the direction of particles flow (as they are coming from the target object) even if the target object is not visible in the user's FOV.

This method is flexible because developers can change the particle emitter intensity and color range of particles based on the VR environment's requirements. In our Omni-directional particle visualization method, we relaxed from the dependency on stereo sound detection. This method utilizes the known directional sound information from the VR application to enrich a user with 3DoF information.

In our pre-experiment, we call the conditions with these visualization methods "InHUD" and "InENV," respectively. We select the best visualization method from the pre-experiment as the main method for the visual modality in our main experiment. In our main experiment, we study four different modalities for deaf persons' spatial object localization in VR: audio, visual, haptic, and combination. We also considered an additional mode called "No Visualization (NoVIS)" as a baseline condition without any additional direction visualization towards the target object. Our main experiment aims to determine the effects of audio and visual modalities in a pre-designed VR application with haptic modality in a real-time system called "EarVR" on deaf persons' VR experience.

5.3.3 VR Environment Design

We used the UE4 game engine to design a VR game and asked all participants to play it. In this game, the user is placed in the center of the VR environment, and ten identical cubes (target objects) spawn one after another in random positions around the user. Our visualization methods are synchronized with the cube's audio starting time. The user could only rotate around to find the correct cube, aim at it and push the trigger button on the VR controller to select the cube. A ray cast effect (laser pointer) was designed to show the aiming point (Figure 5.23).

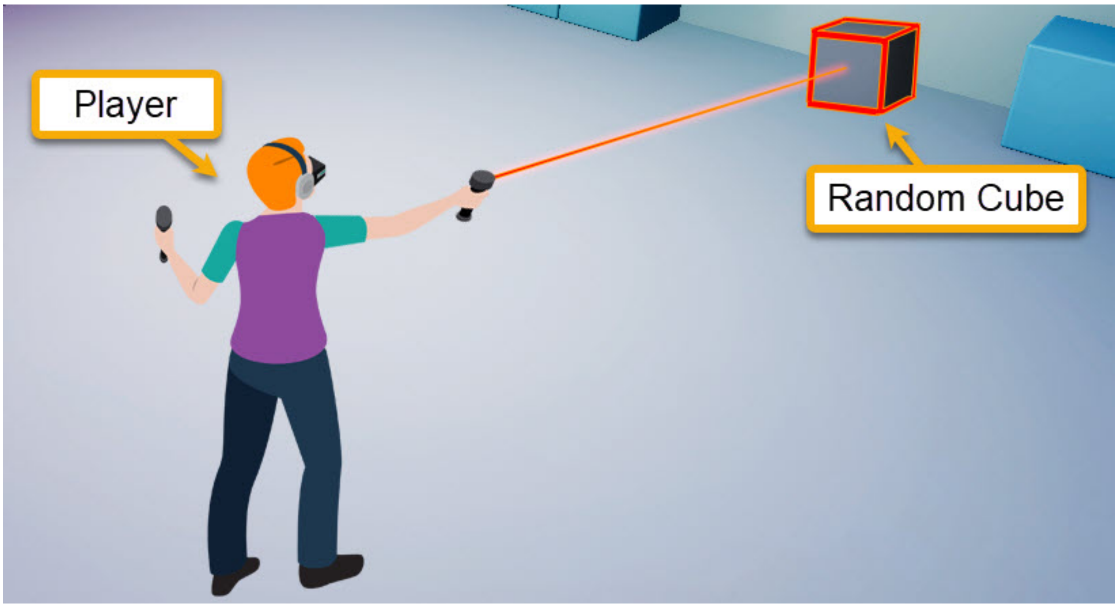

Figure 5.23: The VR environment in our experiment.

The cube is eliminated after getting selected, and another cube spawns in a random position. This process continued until all ten cubes were selected. Finally, the user's task completion time is saved for each user. Our main focus in these experiments is spatial and directional object localization in VR for deaf persons, finding the best modality for them and comparing the results with persons without hearing problems.

5.3.4 Pre-Experiment: Visual Spatial Localization

Because of the difference between deaf and hearing persons' perception of VR, we prepared a pre-experiment to analyze our two suggested visual presentations of spatial information in VR (InHUD and InENV). This experiment aims to find out which suggested visual presentation is preferable among both groups of participants. Our main experiment will use the preferred visual presentation as the visual stimulus.

Participants:

We recruited two new groups of participants for our pre-experiment. The control group consisted of 10 persons without hearing problems from the university staff (6 men, 4 women; 18 to 40 years old, M = 31.2, SD = 7.16), and the deaf persons group consisted of 10 deaf persons with no hearing in both ears and not using HA or CI from the DHH community (7 men, 3 women; 18 to 45 years old, M = 32.7, SD = 9.56) with the same recruitment methods in our previous studies. Participants were completely different from previous experiments, and all of them had at least experienced VR once before without having any physical and emotional problems using VR. We carefully stated all the VR safety warnings in our consent form (Appendix-A 6.3), and all the participants were completely aware of them and signed the form.

5.3.4.1 Experiment Design

We proposed two main visualization modes for the pre-experiment: 1) InHUD and 2) InENV. For the InHUD mode, we designed two directional arrows on the user's HUD. These two arrows can only show the left and right directions to the user (Figure 5.24). If the target object is on the user's right side, the right-side arrow appears and vice versa. In this case, the user can only use the arrow direction as a guide to the object location and search to find the target object in the guided area.

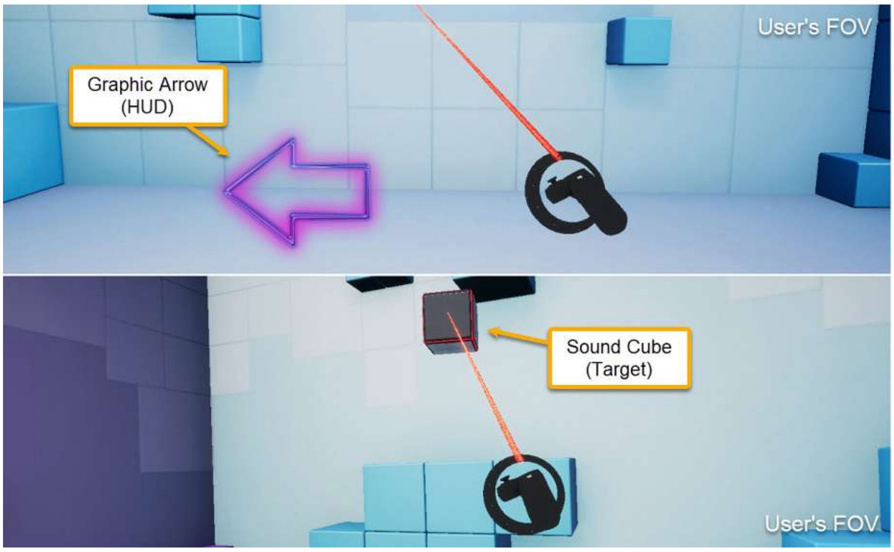

Figure 5.24: The InHUD mode.

For the InENV mode, we used our proposed Omni-directional particle visualization method by positioning a particle source on the target object's location. Users could find the object's direction and locate it in the VR environment as soon as they saw the incoming light beams in their FOV (Figure 5.25). In this case, the user can directly look at the target object without searching the environment.

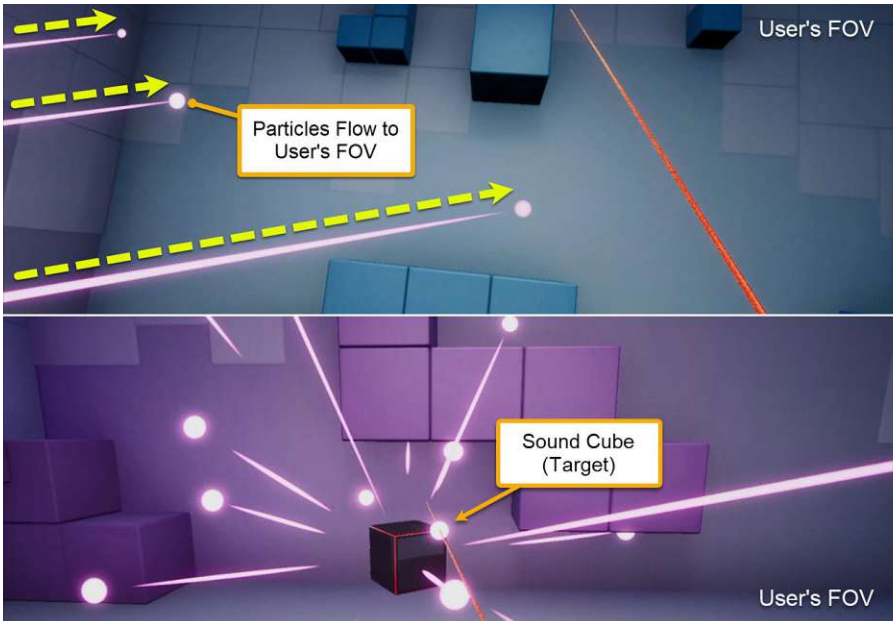

Figure 5.25: The InENV mode.

We also considered a third mode called "No Visualization (No-VIS)" mode as a baseline condition without any additional visualization of direction towards the target object. In this mode, the target objects (cubes) do not have any visual (except 3D presentation of the model) or auditory signs to reveal their positions, and users must find them one by one only by searching the VR environment by rotating their body or head.

For the pre-experiment, we used Samsung Odyssey VR HMD to display the VR environment. It has dual 3.5" AMOLED (1440 ×1600 dots) screens, 110-degree FOV, and AKG 360 degrees spatial sound headphones. We connected this VR HMD to a powerful VR-ready laptop with the exact specifications mentioned in our previous experiments.

5.3.4.2 Task, Procedure, and Data Analysis

We asked each user to play our VR game with three conditions: 1) NoVIS, 2) InHUD, and 3) InENV. For this experiment, only the visual stimulus was tested, which means that the target objects (cubes) did not have the audio stimulus, and users had to use their vision to find them in the VR environment. Since cubes spawn randomly, and in some cases, some of them may appear in the user's FOV one after another, the user might be able to select them faster. Therefore, we asked each user to complete this task 3 times for each condition. In the end, we calculated the average task completion time from these three trials and considered it the main average task completion time for each user.

At the end of this experiment, we asked users to answer a question about their desire to use each visualization technique with a 5-point Likert-scale (1 = most negative, 5 = most positive) and an open-ended question about their VR experience. We analyzed the open-ended comments by using the participants' own words in the MAXQDA trial version through open-coding on one category of user experience (desire-to-use) without imposing our own beliefs or biases [278].

5.3.4.3 Results

Figure 5.26 shows the results of average task completion times of each visualization condition (NoVIS, InHUD, and InENV) for both groups of participants (control group and deaf persons group). Participants in the control group were able to complete the task with an average completion time of 32.8 seconds in NoVIS mode (SD = 2.421), 20.3 seconds in InHUD mode (SD = 1.187), and 13.7 seconds in InENV mode (SD = 0.930). Participants in deaf persons group were able to complete the task with an average completion time of 33.2 seconds in NoVIS mode (SD = 1.069), 21.3 seconds in InHUD mode (SD = 1.231), and 12.7 seconds in InENV mode (SD = 0.874).

A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the completion time was approximately normally distributed in all conditions of each group (control group: NoVIS ($W = 0.936$, $p = 0.514$), InHUD ($W = 0.876$, $p = 0.117$), and InENV ($W = 0.907$, $p = 0.261$), and deaf persons group: NoVIS ($W = 0.876$, $p = 0.118$), InHUD ($W = 0.911$, $p = 0.285$), and InENV ($W = 0.956$, $p = 0.740$).

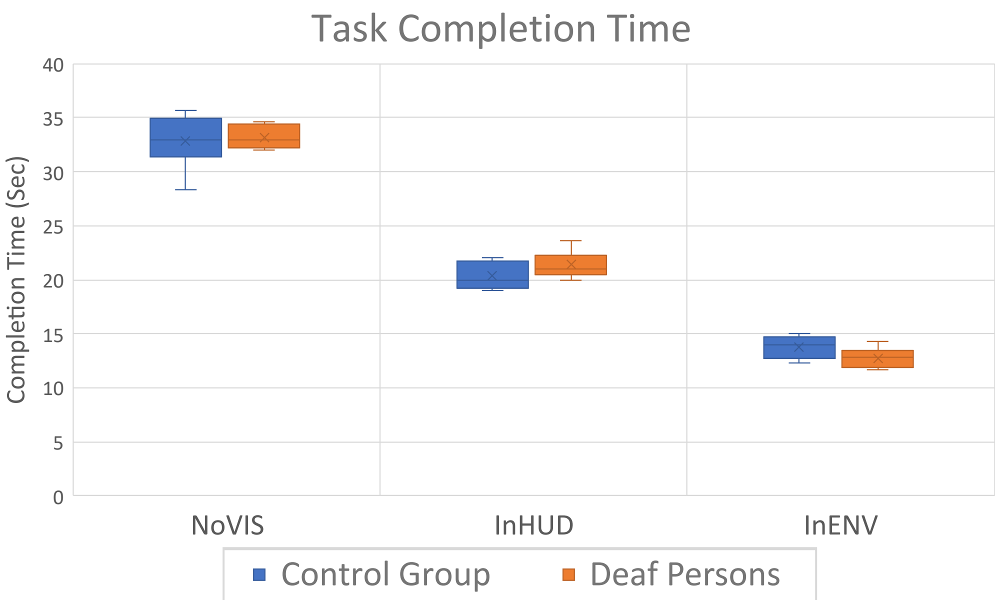

Figure 5.26: Task completion time of the control and deaf persons groups in pre-experiment.

A repeated-measures ANOVA test with a significance level of $\alpha = 0.05$ was conducted to explore the effect of different visualization methods on the task completion time of each group. Mauchly's test of Sphericity did not indicate any violation of sphericity in both groups (control group: $\chi^2(2) = 5.093$, $p = 0.078$, and deaf persons group: $\chi^2(2) = 0.658$, $p = 0.720$), and therefore, a sphericity was assumed. The results indicate a statistically significant effect of different visualization methods on the completion time of both groups (control group: $F(2, 18) = 348.537$, p <0.001, partial $\eta^2 = 0.975$, and deaf persons group: $F(2, 18) = 849.383$, p <0.001, partial $\eta^2 = 0.990$).

Post hoc comparisons using the Boneferroni adjustment revealed that in the control group, the completion time significantly changed from the NoVIS (M = 32.801, SD = 2.421) compared to the InHUD (M = 20.334, SD = 1.187), and InENV (M = 13.768, SD = 0.930). It also significantly changed from the InHUD compared to the InENV. The comparison also revealed a similar significant changes in the deaf persons group (NoVIS: M = 33.2, SD = 1.069, InHUD: M = 21.368, SD = 1.231, and InENV: M = 12.767, SD = 0.874). The pairwise comparison on mean difference of visualization conditions for the control group and deaf persons group is shown in Table 5.5 (significant differences are marked with a star (*) symbol near the p-value).

Control Group	**InHUD**	**InENV**
NoVIS	Mean Diff. = 12.467 * p <0.001	Mean Diff. = 19.033 * p <0.001
InHUD	—	Mean Diff. = 6.655 * p <0.001

Deaf Persons	**InHUD**	**InENV**
NoVIS	Mean Diff. = 11.832 * p <0.001	Mean Diff. = 20.433 * p <0.001
InHUD	—	Mean Diff. = 8.601 * p <0.001

Table 5.5: Pairwise comparison on mean difference of visualization methods for the control and deaf persons groups using the Boneferroni adjustment (95% Confidence Interval for differences).

An independent-samples t-test with $\alpha = 0.05$ was conducted to compare the completion time of each condition between the two groups. The test suggested the following results:

1. ***NoVIS mode:*** No significant difference of completion time between the two groups ($t(18)$ = - 0.477, $p = 0.639$).
2. ***InHUD mode:*** No significant difference of completion time between the two groups ($t(18)$ = - 1.911, $p = 0.072$).
3. ***InENV mode:*** A significant effect of using InENV mode on completion time between the two groups ($t(18)$ = - 2.479, $p = 0.023$).

The results show that the InHUD and InENV visualization methods help both groups complete the task faster than the NoVIS mode. Also, both groups of participants completed the task faster in the InENV mode compared to the InHUD mode. We also noticed that deaf persons completed the task significantly faster than the participants in the control group for the InENV mode, which is an exciting result. It suggests that deaf persons' better peripheral vision and faster reaction time to visual events may also help them complete tasks with visual stimuli faster in VR environments. Although, further experiments and analysis are needed to confirm this finding. Figure 5.27 shows the answers to the question about the desire to use the visualization techniques (after the pre-experiment) for both groups of participants. A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the number of responses to the InHUD mode was approximately normally distributed in both groups (control group: $W = 0.885$, $p = 0.149$, and deaf persons group: $W = 0.890$, $p < 0.172$).

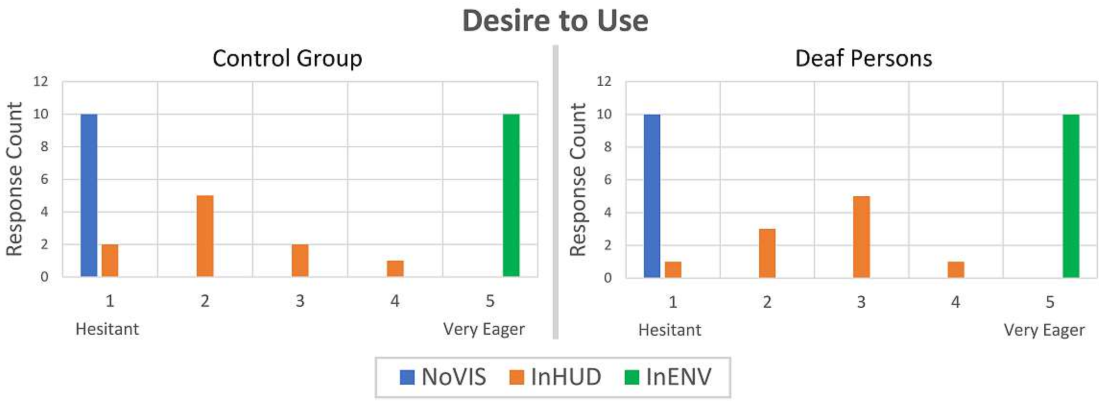

Figure 5.27: Desire to use of three visualization conditions for the control and deaf persons groups in the pre-experiment.

Analysis of the results using descriptive statistics shows that participants in both groups preferred to use at least one visualization method (either InHUD or InENV) in the VR environment (control group: NoVIS (M = 1, SD = 0), InHUD (M = 2.2, SD = 0.919), and InENV (M = 5, SD = 0), and deaf persons group: NoVIS (M = 1, SD = 0), InHUD (M = 2.6, SD = 0.843), and InENV (M = 5, SD = 0). Participants in both groups rated the InHUD and InENV modes higher than the NoVIS mode. The results also show that both groups rated the InENV mode higher than the InHUD mode for desire-to-use. Although, further analysis is needed to confirm these findings. The open-ended question analysis indicates that both groups found the InENV mode better than the InHUD and NoVIS modes. Some users reported cybersickness during the InHUD test, but not in the NoVIS and InENV modes. However, participants in both groups preferred the InHUD mode compared to the NoVIS mode. We did not perform any experimental tests for measuring the severity of cybersickness among participants during the InHUD mode test. Therefore, further experiments and analysis with a Simulation Sickness Questionnaire (SSQ) [282] is required to measure users' level of sickness symptoms in the InHUD mode.

5.3.4.4 Discussion and Hypotheses

Analysis of the pre-experiment results shows that both groups of participants completed the VR task significantly faster using at least one type of additional visual stimulus in the VR environment. The results indicate that using our proposed Omni-directional particle visualization method in the InENV mode is significantly more effective than using arrows in the InHUD mode. Also, both groups of participants preferred the InENV mode.

Although the InENV mode was significantly better than others because it provides more information for users, our pre-experiment shows that even the InHUD method is beneficial for deaf persons in VR environments compared to the NoVIS. We found that similar to the real environment, deaf persons' reaction time to visual events in VR is faster than persons without hearing problems, and it helps them complete visual-related VR tasks faster. We formulated the following hypotheses based on our pre-experiment results:

- H1. Visual stimuli are the fastest way to complete spatial localization VR tasks among deaf persons compared to audio and haptic stimuli.

- H2. Combining audio, visual, and haptic stimuli improves deaf persons' VR task completion time.

- H3. Visual and haptic stimuli are preferable to audio stimuli for deaf persons in VR environments.

5.3.5 Main Experiment: Multi-modal Spatial Localization

In our main experiment, we investigate our defined hypotheses. For this purpose, we study the effects of using different modalities (audio, visual, and haptic) and a combination of them (audio+visual+haptic called "AVH") on completing spatial object localization tasks in VR among two groups of participants: control group (persons without hearing problems), and deaf persons group. In this experiment, we analyze each group of participants' average task completion time to understand if using different stimuli in the VR environment affects completing the object localization task in VR.

Participants:

We recruited 40 new volunteers with the same recruitment method as our previous studies in two groups of 20, who were familiar with VR and experienced no side effects when using VR. We asked the participants to sign a consent form (Appendix-A 6.3) before taking part in the experiment. The control group included 20 persons without hearing problems (12 men, 8 women, 15 to 50 years old, M = 30.45, SD = 10.85). The deaf persons group included 20 deaf persons with no hearing in both ears and not using HA or CI (14 men, 6 women, 15 to 50 years old, M = 31.25, SD = 10.74).

5.3.5.1 Experiment Design

Our main experiment includes five modalities as five presentation methods for spatial object localization tasks. We defined the modalities as follows:

1. ***NoVIS:*** No visualization techniques.
2. ***Audio:*** Using 3D sounds.
3. ***Visual:*** Using InENV mode (Omni-directional particle visualization technique).
4. ***Haptic:*** Using the EarVR system.
5. ***Audio+Visual+Haptic (AVH):*** Using a combination of 3D sounds, Omni-directional particle visualization technique, and haptic feedback (EarVR).

We used the same VR game and hardware for the main experiment as our pre-experiment. In the NoVIS mode, we did not use any particular additional visualization techniques for target objects (cubes) except their 3D rendering in space (no audio, no visual, no haptic). We used the EarVR system for the haptic presentation, which assists deaf persons and helps them locate sound sources in the VR environment (described in Chapter 4). We mounted the EarVR system on the Samsung Odyssey VR HMD with no audio output from the VR HMD's embedded headphones.

5.3.5.2 Task, Procedure, and Data Analysis

In order to test our hypotheses, we asked both groups of participants to play the VR game (ten random cubes) with our new five presentation methods. Participants played the game three times for each condition, and the average task completion time was calculated for each user (similar to the pre-experiment procedure). At the end of this experiment, we asked users to answer a 5-point Likert-scale (1 = most negative, 5 = most positive) question about their desire to use each presentation modality and an open-ended question about their VR experience. We asked them to select their preferred presentation method by mentioning the reason in a paragraph. We analyzed the open-ended comments using the participant's own words in the MAXQDA trial version, similar to our pre-experiment.

5.3.5.3 Results

Figure 5.28 shows the task completion time of the control and deaf persons groups for five different presentation methods. Participants in the control group were able to complete the task with an average completion time of 33.6 seconds for NoVIS (SD = 1.750), 15.3 seconds for audio (SD = 0.532), 14.2 seconds for visual (SD = 0.693), 17.8 seconds for haptic (SD = 0.486), and 13.5 seconds for AVH (SD = 0.906). Participants in the deaf persons group were able to complete the task with an average completion time of 34.7 seconds for NoVIS (SD = 1.752), 34.6 seconds for audio (SD = 1.877), 13.7 seconds for visual (SD = 0.788), 18.1 seconds for haptic (SD = 0.649), and 13.2 seconds for AVH (SD = 0.792). A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the completion times were approximately normally distributed for all modalities in both groups (control group: NoVIS ($W = 0.966$, $p = 0.669$), audio ($W = 0.950$, $p = 0.361$), visual ($W = 0.955$, $p = 0.452$), haptic ($W = 0.916$, $p = 0.081$), and AVH ($W = 0.971$, $p = 0.772$), and deaf persons group: NoVIS ($W = 0.959$, $p = 0.531$), audio ($W = 0.962$, $p = 0.586$), visual ($W = 0.952$, $p = 0.396$), haptic ($W = 0.956$, $p = 0.473$), and AVH ($W = 0.947$, $p = 0.328$).

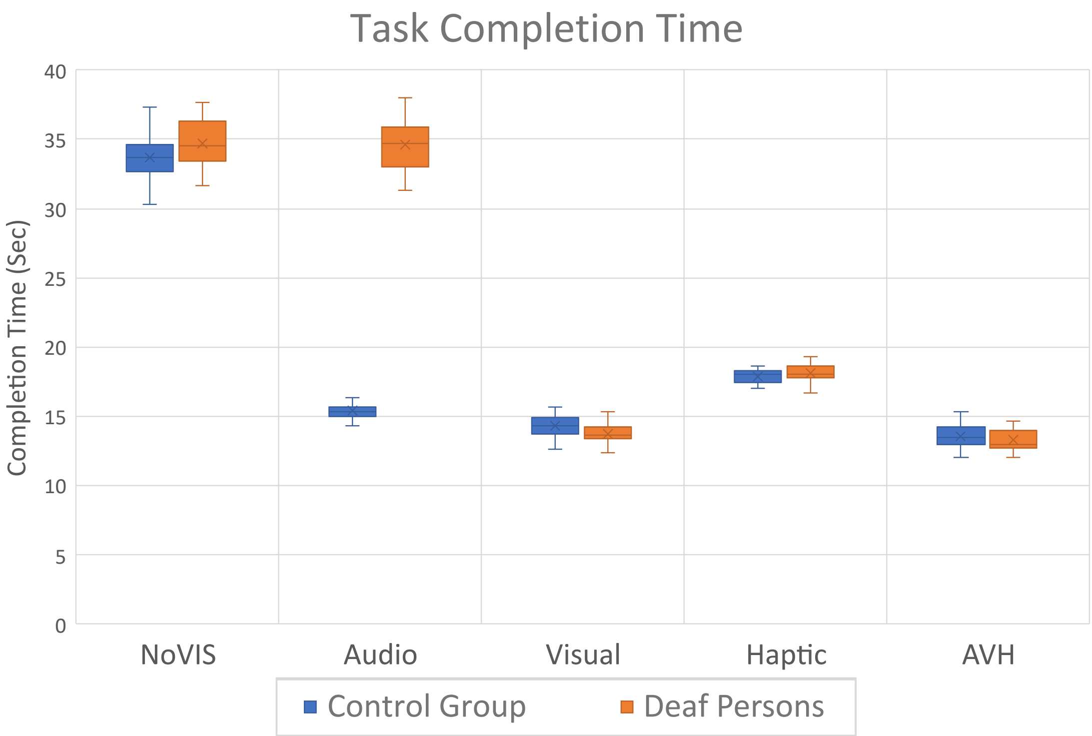

Figure 5.28: Task completion time for the control and deaf persons groups in the main experiment.

A repeated-measures ANOVA test with a significance level of $\alpha = 0.05$ was conducted to explore the effect of using different modalities on the task completion time of each group. Mauchly's test of Sphericity indicated that the assumption of sphericity has been violated in both groups (control group: $\chi^2(9) = 41.703$, p <0.001, and deaf persons group: $\chi^2(9) = 23.723$, $p = 0.005$), and therefore, a Greenhouse-Geisser correction was used. The results indicate a statistically significant effect of using different modalities on the completion time of both groups (control group: $F(1.788, 4) = 1673.141$, p <0.001, partial $\eta^2 = 0.989$, and deaf persons group: $F(2.651, 4) = 1709.887$, p <0.001, partial $\eta^2 = 0.989$).

The results of post hoc comparisons using the Boneferroni adjustment for each pair of modalities in both groups is shown in Table 5.6 (significant differences are marked with a star (*) symbol near the p-value).

Control Group	Audio	Visual	Haptic	AVH
NoVIS	Mean Diff. = 18.284 * p <0.001	Mean Diff. = 19.383 * p <0.001	Mean Diff. = 15.784 * p <0.001	Mean Diff. = 20.118 * p <0.001
Audio	—	Mean Diff. = 1.099 * p <0.001	Mean Diff. = - 2.5 * p <0.001	Mean Diff. = 1.834 * p <0.001
Visual	—	—	Mean Diff. = - 3.599 * p <0.001	Mean Diff. = 0.735 * p = 0.013
Haptic	—	—	—	Mean Diff. = 4.333 * p <0.001

Deaf Persons	Audio	Visual	Haptic	AVH
NoVIS	Mean Diff. = 0.117 p = 1	Mean Diff. = 20.966 * p <0.001	Mean Diff. = 16.633 * p <0.001	Mean Diff. = 21.467 * p <0.001
Audio	—	Mean Diff. = 20.850 * p <0.001	Mean Diff. = 16.516 * p <0.001	Mean Diff. = 21.350 * p <0.001
Visual	—	—	Mean Diff. = - 4.334 * p <0.001	Mean Diff. = 0.5 p = 0.278
Haptic	—	—	—	Mean Diff. = 4.834 * p <0.001

Table 5.6: Pairwise comparison on mean difference of modalities for the control and deaf persons groups using the Boneferroni adjustment (95% Confidence Interval for differences).

The test revealed significant differences for every pair of modalities for the control group. For the deaf persons group, the test indicated significant differences between all pairs of modalities except NoVIS vs. audio and visual vs. AVH. An independent-samples t-test with $\alpha = 0.05$ was conducted to compare the completion time of each modality between the two groups. The test suggested the following results:

1. ***NoVIS:*** No significant difference of completion time between the two groups ($t(38) = -1.925$, $p = 0.062$).
2. ***Audio:*** A significant effect of using audio modality on completion time between the two groups ($t(38) = -44.073$, $p < 0.001$).
3. ***Visual:*** A significant effect of using visual modality on completion time between the two groups ($t(38) = 2.2$, $p = 0.034$).
4. ***Haptic:*** No significant difference of completion time between the two groups ($t(38) = -1.201$ $p = 0.237$).
5. ***AVH:*** No significant difference of completion time between the two groups ($t(38) = 1.050$ $p = 0.3$).

Analysis of the results indicates that the completion time of using visual, haptic, and AVH modalities is shorter than NoVIS for both groups of participants. Participants in the control group used the audio modality benefits, but the audio did not affect the deaf persons group. Comparison of the results of audio, visual, and haptic modalities among members of the control group show that participants completed the task with an average completion time of "visual < audio < haptic" and members of the deaf persons group with an average completion time of "visual < haptic < audio." These results support our H1 hypothesis for this experiment and indicate that the visual modality is the fastest way to do the spatial localization VR task than audio and haptic modalities for both groups of participants.

The results show that the completion times using the visual modality in the deaf persons group are slightly better than the control group. We assume that this trend is caused by deaf persons' better peripheral vision and faster reaction time to visual events in the real world, which also helps them complete visual-related tasks faster in VR environments. For the control group, the AVH modality is significantly faster than all other modalities, but for the deaf persons group, there is no significant difference between AVH and visual modalities. This result supports our H2 hypothesis in this experiment. For deaf persons group, the AVH modality improves the completion time significantly compared to the audio and haptic modalities, but not the visual modality. Also, there is no significant difference in the AVH modality results between the two groups of participants. The control group used the benefits of audio, visual, and haptic modalities in AVH, and the deaf persons group relied more on the benefits of visual and haptic modalities in AVH. It seems that the advantages of using the audio modality for the control group and the advantages of using the visual modality for the deaf persons group created an interesting balance in the results of the AVH modality for both groups of participants. Although, further experiments and analysis are needed to confirm these findings.

The questionnaire's results about the preferred modality are shown in Figure 5.29. A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the number of responses to all modalities in both groups were not approximately normally distributed (control group: NoVIS (W = 0.351, p <0.001, M = 1.1, SD = 0.308), audio (W = 0.784, p <0.001, M = 4.3, SD = 0.733), visual (W = 0.544, p <0.001, M = 4.75, SD = 0.444), haptic (W = 0.814, p = 0.001, M = 3.3, SD = 0.801), and AVH (W = 0.433, p <0.001, M = 4.85, SD = 0.366), and deaf persons group: NoVIS (M = 1, SD = 0), audio (M = 1, SD = 0), visual (W = 0.495, p <0.001, M = 4.8, SD = 0.410), haptic (W = 0.723, p <0.001, M = 4.5, SD = 0.607), and AVH (W = 0.351, p <0.001, M = 4.9, SD = 0.308).

A Friedman test with $\alpha = 0.05$ revealed a significant differences for the desire to use among both groups (control group: $\chi^2 = 72.965$, $p < 0.001$; deaf persons group: $\chi^2 = 76$, $p < 0.001$). We analyzed the differences between individual modalities by post-hoc tests using Wilcoxon signed-rank test with a Bonferroni correction applied, resulting in a significance level set at $\alpha = 0.005$. Table 5.7 shows the Wilcoxon test results on the desire to use modality for the two groups (significant differences are marked with a star (*) symbol near the p-value).

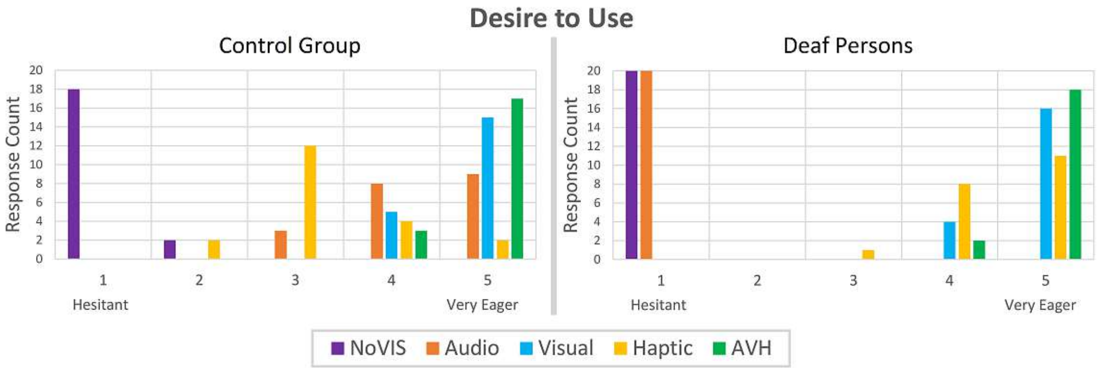

Figure 5.29: Desire to use modalities for the control and deaf persons groups in the main experiment.

Control Group	**Audio**	**Visual**	**Haptic**	**AVH**
NoVIS	Z = - 3.999 * p <0.001	Z = - 4.072 * p <0.001	Z = - 4.035 * p <0.001	Z = - 4.134 * p <0.001
Audio	—	Z = - 3 * p = 0.003	Z = - 3.879 * p <0.001	Z = - 3.317 * p <0.001
Visual	—	—	Z = - 3.852 * p <0.001	Z = - 1.414 p = 0.157
Haptic	—	—	—	Z = - 3.906 * p <0.001

Deaf Persons	**Audio**	**Visual**	**Haptic**	**AVH**
NoVIS	Z = 0 p = 1	Z = - 4.179 * p <0.001	Z = - 4.028 * p <0.001	Z = - 4.3 * p <0.001
Audio	—	Z = - 4.179 * p <0.001	Z = - 4.028 * p <0.001	Z = - 4.3 * p <0.001
Visual	—	—	Z = - 2.449 p = 0.014	Z = - 1.414 p = 0.157
Haptic	—	—	—	Z = - 2.828 p = 0.005

Table 5.7: Wilcoxon test results on desire-to-use modality for control group and deaf persons group.

The comparison between the answers for different modalities for the control group using the Wilcoxon test indicates significant differences for all pairs of modalities except AVH vs. visual. For the deaf persons group, the test indicates significant differences between all pairs of modalities except AVH vs. visual, AVH vs. haptic, visual vs. haptic, and audio vs. NoVIS. The analysis of the results shows that participants in the control group preferred all modalities except NoVIS, and participants in the deaf persons group preferred AVH, visual, and haptic modalities. These results support our H3 hypothesis in this experiment. Deaf persons prefer visual and haptic modality over audio modality. Participants of both groups believed that using haptic in the AVH modality makes it more effective than only visual or audio modalities. We did not conduct any experiment and analysis to investigate how deaf persons felt audio modality in this experiment. Therefore, further experiments and analysis are needed to confirm this experiment's findings and investigate if audio modality has any effects on deaf persons' VR experience.

5.3.6 Discussion

According to our main experiment's results, all of our hypotheses in this experiment are supported (H1, H2, and H3). Our pre-experiment results suggest that both groups of participants preferred at least one visual stimulus in the VR environment. Both groups preferred our proposed Omni-directional particle visualization method in the InENV mode rather than the arrow method in the InHUD mode.

Horizontal compass HUD systems (1DoF) and particle systems in different games are pervasive. Horizontal compass HUD systems are mainly used for object localization, helping the players estimate the targets' positions, even for the targets far from the player. Also, particle systems are mostly used for visual effects. However, hearing persons usually use a combination in addition to audio (as a guideline) to locate events in the game.

We used a pre-defined level of intensity for each modality and did not control the intensity of each stimulus, for example, control the brightness of the particles or the audio level in the environment. However, our result shows that using our proposed Omni-directional particle visualization method, deaf persons find objects faster in the VR environment. Humans have different thresholds for the intensity of different stimuli [283], so a future study is required to analyze the effect of using our proposed method with different intensities on deaf and hearing persons in VR.

Our observational analysis indicates that users in both groups felt cybersickness in the InHUD mode, but there were no noticeable issues among both groups in the InENV mode. Also, the InENV mode has some advantages in showing the target's exact position in the 3D environment compared to the InHUD mode. We assume that both groups preferred the InENV mode because of these reasons. Since this assumption is only based on observations and users' comments in the pre-experiment questionnaire, further detailed studies with SSQ are required to investigate the cybersickness feeling in the InHUD condition and the preference reasons for the InENV condition.

A remarkable finding from the pre-experiment is that despite the users' unpleasant feelings (cybersickness) in the InHUD mode, both groups still preferred this mode more than the NoVIS mode. This result indicates how important the visual stimuli in VR are for users, especially deaf persons. Our initial analysis in the pre-experiment and the final analysis in the main experiment show that deaf persons complete the given task in the VR environment with only visual stimuli faster than hearing persons. These results suggest that deaf persons' faster reaction time to visual events in real environments also helps them react faster to visual stimuli and complete tasks faster in VR environments.

However, faster reaction time to visual stimuli in VR depends on many important factors, such as light intensity and colors [284]. Therefore, further studies are required to analyze precisely the reasons for the better peripheral vision and faster reaction time of deaf persons to visual stimuli in VR environments.

Our final analysis in the main experiment shows that in a combination of different stimuli (AVH), both groups complete VR tasks faster than using no modality. The noticeable point in these results is that there is no significant difference between the results of deaf persons and hearing persons in the AVH modality despite deaf persons not being able to use the benefits of the audio modality. It seems that deaf persons' advantages in the visual modality and hearing persons' advantages in the audio modality create an interesting balance in the results of the AVH modality. Since our chosen statistical population was small and we also had no information on how professional our participants were in VR games, the results might differ considering the mentioned details and a larger statistical population. Therefore, further precise experiments and analysis with a more extensive and diverse statistical population are required.

The results of the desire to use modalities in the main experiment show that both groups preferred to use the AVH and visual modalities rather than other modalities. Although there is no significant difference in the results between the AVH and visual modalities among both groups, the results of our final questionnaire determined that users described the AVH modality as more applicable than the visual modality.

Our study used only two visualization techniques for the pre-experiment and one in the main experiment (from the pre-experiment) for object localization in the VR environment. Further experiments and analysis are needed to investigate the effects of using more visualization methods and spawning simultaneous objects in the VR environment on deaf persons' VR interactions. In our future study, we will create a more complex environment using our proposed visualization method and compare it with other techniques combined with a real-time haptic feedback system (the EarVR system).

5.4 EarVR+: Head Up Visualization for Deaf Persons

In our previous experiments, we showed that deaf persons have the opportunity to use audio in VR environments using haptic feedback and visualization methods. The results of our experiments and previous studies, such as Massiceti et al. [37] and Nava et al. [38], show that the feeling of touch and vision can provide information from missing audio. Our proposed EarVR system (described in Chapter 4) uses only haptic feedback and works in real-time, so it does not require a pre-designed VR environment; but for using different visualization methods, we need to design a particular VR environment, including the visual effects.

In our multi-modal visualization experiment, we suggested a method called "InHUD." We showed that the InHUD method helps deaf persons complete sound-related VR tasks. However, users felt cybersickness using the InHUD method in our previous experiment.

Still, users preferred the InHUD method to visualize audio in VR compared to not using any visualization method. The InHUD method and its results from our previous experiment led us to propose the EarVR+ system (described in Chapter 4). In the EarVR+ system, we used LEDs instead of the graphical arrows used in the InHUD method. Therefore, using the EarVR+ system, we can investigate the effects of visual, haptic, and combination methods in a hardware approach for deaf persons in VR without preparing a particular VR environment.

This section presents the experiment related to our proposed EarVR+ system. We evaluate differences in VR task performance using only visual, haptic, or combination methods among deaf persons to investigate which condition (corresponding to different senses) leads to faster performance in 3D sound localization tasks in VR. The EarVR experiment showed that haptic feedback helps deaf persons achieve similar performance in sound localization tasks to persons without hearing problems. The main research question in this experiment is:

1. How do visual, haptic, and combination methods in a hardware approach affect real-time sound localization performance in VR among deaf persons?

Our main hypothesis in this experiment is the following:

- H1. Deaf persons' vision is more effective than their tactile sensation in VR and improves their sound localization performance in VR environments.
- H2. Deaf persons prefer to use haptic devices and LEDs in an assistive system for their VR experience.

We conduct a user study to investigate our hypotheses and evaluate the proposed method for spatial sound visualization. Our experiment uses a within-group design to compare task performance under haptic, LED, and haptic+LED feedback conditions. Moreover, we use a post-experiment questionnaire to investigate the desire to use each visualization modality through subjective user feedback. We also compare the results of deaf persons with those without hearing problems. The main contributions of this experiment are as follows:

1. Introducing a novel method for spatial sound visualization in VR for deaf persons.
2. Combination of additional visual and haptic feedback in VR (hardware approach).
3. User study investigates the effect of different modalities on the performance of sound localization tasks in VR for deaf persons.

5.4.1 Pre-Experiment: Color Preference

We designed a simple test for 10 new participants, including five deaf persons from DHH community with no hearing in both ears and not using HA or CI (3 men, 2 women, 20 to 40 years old, M = 28.2, SD = 8.25), and five persons without hearing problems in a control group (4 men, 1 woman, 20 to 40 years old, M = 28.8, SD = 8.34), with the same recruitment method in our previous experiments, to determine the preferable LED colors in a pre-experiment. We asked each participant to wear a VR HMD with mounted EarVR+ to test different LED colors in a simple VR environment different than our main experiment VR environment. We used the default 3D model called "Cliff House" in the Microsoft Windows MR [9] portal application in Windows 10 OS as a VR environment (Figure 5.30).

Figure 5.30: The Microsoft Cliff House VR environment.

Each participant tested five different LED colors: red, green, blue, yellow, and white, in a separate trial for each color. The trial of each color took 10 seconds, and the LEDs on the left and right sides would turn on or off during this period. In the end, we asked each participant to answer a question about the preferred color among all five LED colors and write their comments about the experience in an open-ended question (optional). The result of the color preference question is shown in Figure 5.31.

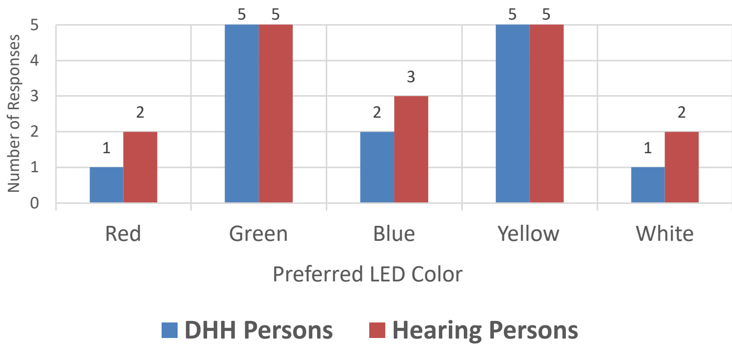

Figure 5.31: Preferred LED colors among the control and deaf persons groups.

[9] Available Online: https://www.microsoft.com/en-us/mixed-reality/windows-mixed-reality (accessed on 5 October 2021)

Analysis of the result using descriptive statistics for multiple responses shows that participants in both groups preferred green and yellow colors for LEDs compared to the other colors (control group: red (M = 0.4, SD = 0.548), green (M = 1, SD = 0), blue (M = 0.6, SD = 0.548), yellow (M = 1, SD = 0), and white (M = 0.4, SD = 0.548), and deaf persons group: red (M = 0.2, SD = 0.447), green (M = 1, SD = 0), blue (M = 0.4, SD = 0.548), yellow (M = 1, SD = 0), and white (M = 0.2, SD = 0.447)). Also, analysis of the comments shows that participants suggested using two different colors for the left and right attenuation. They believed using two different colors helped them better than using only one color for the left and right sides. The system is designed in a way (modular design) so that LEDs can be easily replaced with the color that users prefer. However, no one requested to change the green and yellow color LEDs. Still, further experiments and analysis are needed to investigate the effects of using different LED colors on deaf persons' VR experience.

5.4.2 Main Experiment

Participants:

We recruited 20 new participants for our main experiment in two groups of 10 with a similar recruitment process to our previous experiments, including 10 deaf persons with no hearing in both ears and not using HA or CI from the DHH community (7 men, 3 women; 20 to 42 years old, M = 32.4, SD = 6.93), and 10 persons without hearing problems as a control group from university staff and students (5 men, 5 women; 18 to 45 years old, M = 33.8, SD = 9.15). All participants had at least previously experienced VR once without any health issues. Also, we asked all participants to complete and sign a consent form (Appendix-A 6.3) related to the experiment.

5.4.2.1 Experiment Design

In order to test the EarVR+ system and find out if LEDs (as visual stimulus) or a combination of LEDs and haptic devices have any effects on sound localization for deaf persons compared to using only haptic devices, we designed a simple VR task using the UE4 game engine. In this task, the player spawns in the center of a VR room and should select ten identical cubes (target objects) that appear in the environment, one after another, in random positions around the player (Figure 5.32).

Each cube produces a continuous 3D sound in a loop. This sound is selected from one of the Google Resonance Audio SDK [10] samples. Whenever a cube appears in the environment, the Arduino analyses the sound and locates the cube's position based on the player's position. Then, it sends the proper turn-on or off signal to vibro-motors/LEDs so that the player can locate the cube in the environment. Each player should look around, find the cube, aim at the cube (using a ray cast effect) as fast as possible, and then eliminate the cube by pushing the VR controller's trigger button. As soon as the player

[10] Available Online: https://resonance-audio.github.io/resonance-audio/ (accessed on 5 October 2021)

eliminates one cube, another cube spawns randomly. This process continues until the player eliminates all ten cubes. The overall time of completing the task is saved for each player. We used task completion time (as a measure) to compare different conditions and a questionnaire to measure subjective responses about the desire to use each condition.

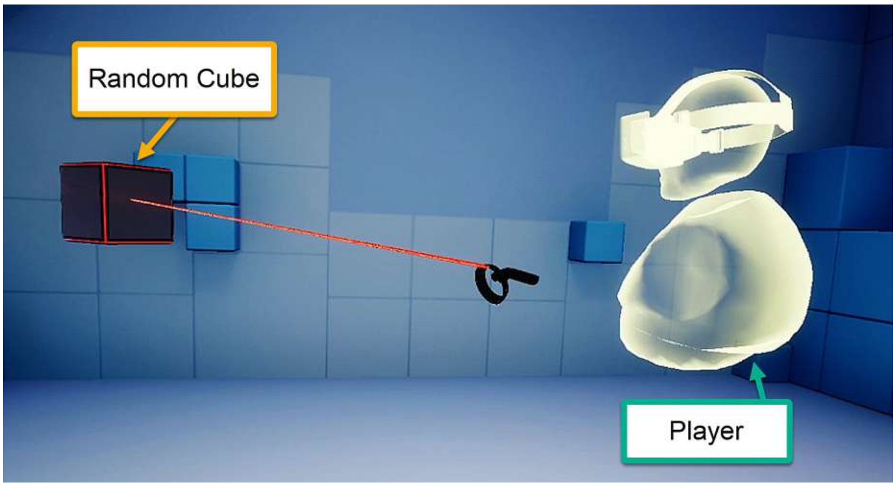

Figure 5.32: VR environment used in our main experiment of the EarVR+ system.

5.4.2.2 Task and Procedure

We asked each participant to complete the VR task three times for each of the following modes:

1. ***Haptic mode:*** Using only vibro-motors (haptic feedback).
2. ***LED mode:*** Using only LEDs (visual feedback).
3. ***Haptic+LED mode:*** Using vibro-motors and LEDs simultaneously (haptic+visual feedback)

We did not use output audio in any of these modes for both groups of participants, which means that each cube produced sound in the VR environment, but hearing players could not hear any sound from the VR environment by using audio output devices, such as VR HMD headphones.

The audio from the VR environment was analyzed only by the Arduino processor. We used coin vibro-motors with low noise level feedback, but hearing people could still hear some noises from vibro-motors in addition to feeling the vibrations. Therefore, we assumed that the haptic mode contained haptic plus white noise, but the main point is that hearing people could not hear any spatial audio from the VR environment, so they could not use audio as a benefit to localize VR sounds.

5.4.2.3 Measures and Data Analysis

The average task completion times of 3 trials for each mode were calculated and stored for each user separately. At the end of the test, we also asked users of each group to take part in a survey and answer a 5-point Likert-scale question ("1 = most negative" and "5 = most positive") about which mode is more desirable to use for them.

5.4.3 Results

The results of the average task completion time of each mode (haptic, LED, and haptic+LED) for both groups of participants are shown in Figure 5.33. Participants in the control group completed the task with an average completion time of 19.03 seconds in the haptic mode (SD = 1.023), 18.33 seconds in the LED mode (SD = 1.029), and 18.80 seconds in the haptic+LED mode (SD = 0.687). Participants in deaf persons group completed the task with an average completion time of 19.3 seconds in the haptic mode (SD = 0.934), 17.03 seconds in the LED mode (SD = 0.838), and 17.53 seconds in the haptic+LED mode (SD = 0.592). A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the completion time of all modes was approximately normally distributed in both groups (control group: haptic ($W = 0.940$, $p = 0.553$), LED ($W = 0.911$, $p = 0.285$), and haptic+LED ($W = 0.981$, $p = 0.969$), and deaf persons group: haptic ($W = 0.929$, $p = 0.438$), LED ($W = 0.925$, $p = 0.397$), and haptic+LED ($W = 0.874$, $p = 0.111$)).

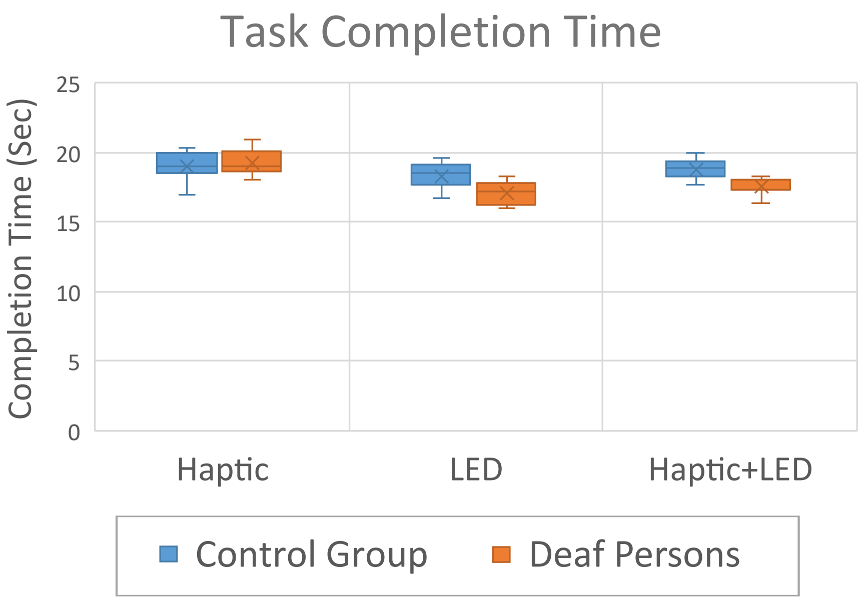

Figure 5.33: Task completion time for the control and deaf persons groups in the EarVR+ experiment.

A repeated-measures ANOVA test with a significance level of $\alpha = 0.05$ was conducted to explore the effect of different modes on the task completion time of each group. Mauchly's test of Sphericity did not indicate any violation of sphericity in both groups (control group: $\chi^2(2) = 0.738$, $p = 0.692$, and deaf persons group: $\chi^2(2) = 0.223$, $p = 0.894$), and therefore, a sphericity was assumed. The results indicate a statistically significant effect of different modes on the completion time of the deaf persons group ($F(2, 18) = 20.356$, p <0.001, partial $\eta^2 = 0.693$), but no significant difference in the control group ($F(2, 18) = 1.779$, $p = 0.197$, partial $\eta^2 = 0.165$).

The results of post hoc comparisons using the Boneferroni adjustment for each pair of modes in both groups is shown in Table 5.8 (significant differences are marked with a star (*) symbol near the p-value). The test revealed a statistically significant main effect of using LED vs. haptic, and also haptic+LED vs. haptic modes in deaf persons group, but no significant main effect of using LED vs. haptic+LED modes. Also, the test could not find any significant difference between each pair of mode comparison in the control group.

Control Group	**LED**	**Haptic+LED**
Haptic	Mean Diff. = 0.7 p = 0.288	Mean Diff. = 0.234 p = 1
LED	—	Mean Diff. = 0.466 p = 0.562

Deaf Persons	**LED**	**Haptic+LED**
Haptic	Mean Diff. = 2.269 * p <0.001	Mean Diff. = 1.77 * p = 0.005
LED	—	Mean Diff. = 0.499 p = 0.606

Table 5.8: Pairwise comparison on mean difference of modes for the control and deaf persons groups using the Boneferroni adjustment (95% Confidence Interval for differences).

An independent-samples t-test with $\alpha = 0.05$ was conducted to compare the completion time of each mode between the two groups. The test suggested the following results:

1. ***Haptic mode:*** No significant difference of completion time between the two groups ($t(18)$ = - 0.609, $p = 0.550$).
2. ***LED mode:*** A significant effect of using LED mode on completion time between the two groups ($t(18) = 3.101$, $p = 0.006$).
3. ***Haptic+LED mode:*** A significant effect of using haptic+LED mode on completion time between the two groups ($t(18) = 4.421$, p <0.001).

Analysis of the results indicates that adding LEDs to the system does not have a significant effect on the control group for completing the VR task faster, but it helps deaf persons complete the VR task faster compared to the result of using only haptic feedback. The results of deaf persons group suggest that they can complete the VR task faster in comparison to the haptic-only mode, which indicates the positive effect of using LEDs in the system for deaf persons. Also, comparing the result of LED mode and haptic+LED mode between the control group and deaf persons group suggests that the visual sense of deaf persons helps them react faster to LED lights and do the VR task faster than persons without hearing problems. These results support our H1 hypothesis for this experiment. Although, further experiments and analysis are needed to confirm these findings.

Figure 5.34 shows the frequencies of answers to the question about the desire to use the haptic (control group: M = 4.8, SD = 0.422, and deaf persons group: M = 2.6, SD = 1.265), LED (control group: M = 2.3, SD = 0.949, and deaf persons group: M = 4.9, SD = 0.316), and haptic+LED (control group: M = 1.5, SD = 0.850, and deaf persons group: M = 4.8, SD = 0.422) modes for both groups of participants. A Shapiro-Wilk test of normality with $\alpha = 0.05$ indicates that the number of responses to each mode were approximately normally distributed only for haptic mode in deaf persons group ($W = 0.930$, $p = 0.445$) and LED mode in control group ($W = 0.911$, $p = 0.287$), but were not approximately normally distributed in other modes (control group: haptic ($W = 0.509$, $p < 0.001$, and haptic+LED: ($W = 0.628$, $p < 0.001$), and deaf persons group: LED ($W = 0.366$, $p < 0.001$), and haptic+LED ($W = 0.509$, $p < 0.001$)).

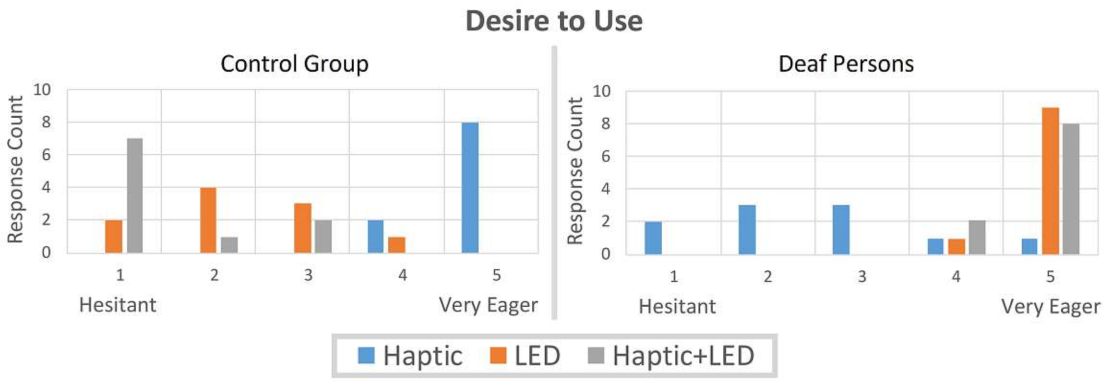

Figure 5.34: The desire to use different modes of the EarVR+.

Friedman test revealed a significant difference of using each mode in both groups (control group: $\chi^2 = 18.865$, $p < 0.001$, and deaf persons group: $\chi^2 = 17.429$, $p < 0.001$). We analyzed the differences between individual modes by post-hoc tests using Wilcoxon signed-rank test with a Bonferroni correction applied, resulting in a significance level set at $\alpha < 0.017$. The comparison between the answers of each group about the desire to use different modes using the Wilcoxon test is shown in (Table 5.9) (significant differences are marked with a star (*) symbol near the p-value).

The result indicates that using haptic mode was rated significantly higher than LED and haptic+LED modes in the control group. Also, in the deaf persons group, LED and haptic+LED modes were rated significantly higher than haptic mode. This result supports our H2 hypothesis in this experiment. Although, further experiments and analysis are needed to confirm this finding.

Control Group	LED	Haptic+LED
Haptic	Z = - 2.877 * p = 0.004	Z = - 2.850 * p = 0.004
LED	—	Z = - 2.530 p = 0.01

Deaf Persons	LED	Haptic+LED
Haptic	Z = - 2.699 * p = 0.007	Z = - 2.724 * p = 0.006
LED	—	Z = - 1 p = 0.317

Table 5.9: Wilcoxon test results on desire-to-use for the control and deaf persons groups.

5.4.4 Discussion

Participants in the control group rated haptic mode higher than LEDs and haptic+LEDs modes, and participants in the deaf persons group rated LED and haptic+LED modes higher than haptic mode. Although we did not use output audio in our experiment, participants in the control group believed that using haptic feedback with audio (if ambient sounds are played) is better than using LEDs because they can do sound localization using audio.

Some participants in the control group commented that the LED lights make it harder to react fast and concentrate on locating the target object, while LEDs and vibro-motors are activated in haptic+LED mode. We do not have enough evidence to explain why participants in the control group preferred only haptic feedback with audio. Therefore, further experiments and analysis are required to investigate the effect of LEDs on hearing persons' VR experience.

On the other hand, participants in the deaf persons group made no such comments on haptic+LED mode. Deaf persons preferred to use LEDs in LED and haptic+LED modes. They believed that LEDs help them more when combined with haptic feedback. Therefore, based on these results, our proposed EarVR+ system with LED indicators is more effective than the previous system (EarVR) with only haptic feedback and improves deaf persons' VR task completion time.

CHAPTER 6

Conclusion

This dissertation presented the systematic technological development and evaluation of novel prototype assistive systems and visualization methods for enhancing deaf persons' VR experience using human-centered design techniques. The different aspects of using VR technology among deaf persons, their actual requirements for an assistive system in VR, and their preferred visualization methods in VR were investigated and approached by this Ph.D. research. We developed novel assistive systems that help deaf persons in VR environments using visual, haptic, and a combination of haptic and visual feedback to let them complete sound localization tasks in VR and improve their VR experience. Furthermore, we introduced novel visualization methods in VR for deaf persons that enrich their ability to perceive audio information in VR using vision. The final results of our experiments showed that our proposed systems and visualization methods make VR technology more accessible for deaf persons.

Our main research questions in this thesis focused on investigating the use of VR technology among deaf persons and identifying ways of improving their VR experience by focusing on sound source localization in VR. The research questions will delve into the various aspects of VR usage among deaf persons, such as the fundamental requirements of using VR among deaf persons, methods of improving deaf persons' VR experience, effects of using different visualization methods on deaf persons' VR experience, and the possibility of using VR applications and games that designed for hearing persons among deaf persons. Overall, we found the following answers for our main research questions in this thesis:

- *What are the fundamental requirements for using VR among deaf persons?*
  - Our study identified several essential requirements for enabling a successful VR experience for deaf persons. These requirements include the importance of using haptic devices for sensory feedback, appropriate visual cues to help

compensate for the lack of auditory input in VEs, and the necessity of VR accessibility for deaf persons. Our findings suggest that careful consideration of these fundamental requirements is essential to ensure that VR technology is an effective tool for deaf persons and can be used to enhance their experience. Our research provides valuable insights into the fundamental requirements for using VR technology among deaf persons and highlights the potential of VR technology to provide an immersive and engaging experience for deaf persons and the need for further research to explore how deaf persons' VR experience can be optimized using appropriate haptic and visual feedback to provide the most benefit to this group of users.

- *How can we improve deaf persons' VR experience using haptic and visual feedback and combination methods?*
  - In our study, we implemented several strategies in different phases to improve the VR experience of deaf persons using haptic and visual feedback and combination methods. Our study shows that using haptic devices and different visualization methods in VR provides alternative means of conveying auditory information in VEs to deaf persons to improve their VR experience. Our research suggests that incorporating haptic devices and appropriate visual cues in a real-time VR assistive system improves and enhances the deaf persons' VR experience significantly, creating a more immersive and engaging VR experience that can promote VR accessibility for deaf persons.
- *How do different VR visualization methods affect deaf persons' VR experience?*
  - Our research suggests that using different VR visualization methods can have varying effects on deaf persons' VR experience. We show that using visualization methods with clear and detailed visual cues, such as colored particle systems and dynamic motion graphics, can help compensate for the lack of auditory input, enabling deaf persons to improve sound localization in VEs. On the other hand, using complex or cluttered visualization methods or visualization in the HUD may overwhelm deaf persons, leading to confusion or cybersickness in VR. Additionally, the result shows that the choice of visualization method can impact deaf persons' ability to perform certain VR tasks. Overall, using different visualization methods in VR can significantly impact the deaf persons' VR experience and should be carefully considered to ensure they are accessible, informative, and engaging for deaf persons.
- *How can deaf persons use VR applications and games designed for hearing persons?*
  - Deaf persons can use VR with adaptations and accommodations, such as sign language interpreters, closed captioning, and haptic/visual feedback, to effectively experience and interact with VEs. Using haptic devices and visual cues are common approaches that provide auditory information about the VEs to deaf persons enabling them to improve their VR experience. In almost

> all of the current approaches, there is a necessity to design a particulate VR application or game for deaf persons that limits them to use VR applications and games designed for hearing persons. Our research suggests different approaches, such as using haptic, visual, and combination methods using real-time VR assistive systems that enable deaf persons to use almost all VR applications and games in the market that are designed for hearing persons. Also, it suggests a guideline for VR developers that helps them to design VR applications and games for deaf and hearing persons without the need to add particular features to VR content by focusing on sound source localization.

In the first section of this chapter, a summary of contributions and findings is given, and in the second section, we propose a guideline for VR developers eager to develop VR applications and games for deaf and hearing persons. Finally, at the end of this chapter, we discuss the future work and open questions related to this thesis.

6.1 Summary

One of the main goals of this research project was to help deaf persons complete sound localization tasks in VR using visual, haptic, and combination methods and improve their VR experience. We started this dissertation by designing a questionnaire for deaf persons to identify their fundamental VR requirements and preferred methods. Then, we designed experiments in different phases using our proposed haptic systems to determine if deaf persons could complete sound localization tasks in VR. Completing each phase and the obtained results helped us improve and upgrade our proposed systems and eventually introduced a novel assistive system for deaf persons in VR called "EarVR+." This system helps deaf persons complete sound localization tasks in VR using their preferred haptic and visual methods and improves their VR experience. The summary of findings in each phase of this thesis is as follows:

Background Survey:

The findings from our initial background survey described in Chapter 3 helped us understand the fundamental requirements of DHH persons in VR and design an applicable VR assistive system for deaf persons. The results showed that DHH persons have some limitations, such as VR accessibility and lack of content, that prevent them from using VR. These limitations must be considered in assistive VR systems' design and development phases for deaf persons. We realized that visualizing audio in VR using different visualization methods benefits deaf persons. Most of the previous studies only focus on one of the feedback systems suggested for deaf persons, such as haptic or visual. However, the result of our background survey showed that haptic and visual feedback are essential for deaf persons to visualize audio in VR and improve their VR experience. The results also helped us consider some preferred essential factors by DHH persons in our design process, such as accessibility and portability.

We noticed that the lack of VR content is one of the main problems of DHH persons, especially for profoundly deaf persons, which prevents them from using VR technology. Therefore, we focused on proposing VR assistive systems and methods that can help deaf persons use the current VR content in the market without worrying about built-in hearing impairment features implemented in VR applications or games. Since we only focused on the system design process of our project, we only used questions in our survey related to understanding some basic information about DHH persons' VR requirements. Therefore, further comprehensive surveys with precise statistical analysis are required to fully understand DHH persons' VR requirements and investigate their VR experience.

Haptic Suit for Deaf Persons:

The findings from our proposed haptic VR suit experiment described in Chapter 5 showed that deaf persons complete sound localization tasks in VR significantly faster using a haptic suit. We found that increasing the number of vibration motors does not improve sound localization performance in VR among deaf persons. The results indicated that using a haptic suit with different setups affects the task completion time of deaf persons in VR and deaf persons preferred the upper body, such as arms and ears, rather than thighs, for mounting the vibro-motors. However, future experiments and analysis are required to understand why the arms and the ears are preferable to the thighs for VR sound localization in deaf persons' opinion.

Our quantitative and qualitative analysis for the VR suit experiment demonstrated that deaf persons prefer an assistive system without the VR suit and prefer mounting haptic devices (vibro-motors) in their ears. Also, our additional experiment showed no significant difference in the task completion time of using four vibro-motors with the VR suit compared to using only two vibro-motors in deaf persons' ears without the VR suit. Our study results led us to use an optimal number of two vibro-motors mounted in deaf persons' ears for designing our next proposed assistive VR system for them. This study ultimately led to an efficient design and saved resources and costs.

Because of our limited budget, we had to design our own haptic VR suit with simple haptic devices (vibro-motors) instead of using advanced haptic VR suits in the market. Therefore, we could not test the advanced features of haptic feedback devices in our experiment. Also, our proposed haptic VR suit needs a pre-defined VR environment that does not let deaf persons use it for all VR applications and games. Therefore, further experiments and analysis are required to investigate the effects of advanced haptic VR suits and real-time software design on deaf persons' VR experience.

In-Ear Haptics for Deaf Persons (EarVR):

The results of our proposed haptic VR suit experiments led us to optimize the suit's design and introduce a novel prototype assistive system for deaf persons called "EarVR." We also considered two essential design factors, accessibility and portability, from our background survey in the design process of the EarVR system.

We included a real-time audio processing algorithm to work with almost all VR applications and games in the market that support two EarVR system requirements: mute options for background music and 3D audio. Consequently, our findings showed that our proposed EarVR system improves deaf persons' sound localization in VR and their VR usage. The EarVR system helps VR developers to design VR applications or games that support deaf and hearing persons by considering the two requirements of the EarVR system.

Multi-modal Spatial Localization for Deaf Persons:

The findings of the EarVR experiments showed that using haptic feedback helps deaf persons complete sound localization tasks in VR and improves their VR experience. We investigated the effects of visual feedback on deaf persons' VR experience by conducting experiments for deaf persons' reaction times to visual stimuli in VR and finding the proper way of using multi-modal methods in VR for deaf persons. Our experiments introduced a novel visualization method called Omni-directional particle visualization for deaf persons. The results related to our proposed visualization method were significantly better (more effective) than traditional methods, such as visualization in the HUD. Also, we found that deaf persons preferred our proposed visualization method compared to other suggested methods. In the end, we combined our proposed visualization method with the haptic and audio methods and called it the "AVH" modality. Then, we compared the effects of the AVH modality on deaf and hearing persons with other suggested modalities.

The final results of our experiments in this section showed that the AVH and visual modalities were significantly better than other modalities among deaf persons. The noticeable point in the results of the AVH modality was that there was no significant difference between the results of deaf persons and hearing persons, which showed that deaf persons' advantages in the visual modality and hearing persons' advantages in audio modality created an interesting balance in the results of the AVH modality. Therefore, if VR developers use a proper combination of audio and visual effects in their VR applications or games, their design affects deaf persons' VR experience. However, further experiments and analysis are needed to confirm the effects of different visualization methods and complex VR designs on deaf persons' VR experience.

Head Up Visualization for Deaf Persons (EarVR+):

The findings from our previous studies and experiments led us to introduce a new system called "EarVR+" that helped us investigate the effects of visual, haptic, and a combination of visual and haptic feedback in a hardware approach on deaf persons' VR experience, without preparing a particular VR environment for them. The EarVR+ system uses the haptic feedback suggested in the EarVR system in addition to LEDs for visual feedback and improves deaf persons' sound localization tasks in VR. The results showed that the EarVR+ system is more effective than the EarVR system.

Our experiment results suggested that adding the proposed LED visualization of 3D spatial audio to a VR environment (either with or without haptic feedback) significantly improves deaf persons' VR task completion time. We believe our experiment results will provoke discussion about multi-modal feedback in VR and help design more accessible VR systems for deaf persons in the future. However, further experiments and analysis are required to investigate the effects of using LEDs on deaf persons' VR experience.

6.2 Guidelines for VR Developers

Our research project suggests some guidelines for VR developers who design haptic VR devices for deaf persons or prefer their VR applications and games to be usable for deaf and hearing persons using the EarVR/EarVR+ systems. In this way, there is no need to add particular features to VR content for deaf persons, and the focus is on sound source localization. Are suggested guidelines are as follows:

- ***Designing a Haptic VR Suit for Deaf Persons:***
    1. Deaf persons prefer mounting haptic devices (vibro-motors) on the upper body, such as arms and head, when using a haptic VR suit.
    2. Front and back haptic devices (vibro-motors) are not mandatory for sound source localization in VR.
    3. Haptic suits are not preferred by deaf persons for sound source localization in VR. They prefer compact and portable assistive haptic VR systems.
    4. Deaf persons prefer mounting haptic devices (vibro-motors) inside their ears, such as earphones, for sound source localization in VR.
- ***Multi-modal Visualization in VR Environments for Deaf Persons:***
    1. Using at least one visualization modality in the VR application or game, such as audio or visual effects, improves deaf persons' VR sound source localization and helps them to find target objects or objects that produce sound in VR faster.
    2. 3D audio in VR is more beneficial for partially deaf persons than for profoundly deaf persons and helps them to find target objects in VR faster.
    3. Using visual effects in a VR environment, such as our proposed Omni-directional particle visualization method, improves deaf persons' VR sound localization significantly.
    4. Navigational graphic elements in the VR HUD, such as graphical arrows, are not pleasant for deaf persons. They prefer visual elements, such as light or particle effects, attached to the objects in a VR environment.

- ***EarVR/EarVR+ (essential requirements):***
    1. Adding a mute option for background music (in the settings) and using 3D audio for sound objects in a VR application or game are essential for compatibility with the EarVR or EarVR+ systems.
    2. The EarVR and EarVR+ systems require an input stereo audio which can be supplied through a 3.5mm headphone jack on the VR-Ready station's sound card, mobile phones, or VR HMDs. The system's power can be supplied through a USB port or a Li-ON battery.

Developing VR applications or games with particular built-in features for deaf persons helps them use VR, but it also gives them a sense of separation from hearing persons and causes social isolation, which is not pleasant for them [285, 286, 287]. VR developers can consider our proposed guideline in their design process of an assistive haptic VR device or a VR application or game for deaf persons to improve their VR experience and benefit from the VR technology.

However, further precise experiments and analysis are required to investigate the effects of our proposed EarVR and EarVR+ system on deaf persons' psychological and social interactions in VR environments. We hope our proposed systems in this research project and future researches help deaf persons to use VR technology more than before and improve their VR experience.

6.3 Future Research

This research project showed the possibility of using our proposed assistive haptic VR devices and visualization methods to improve deaf persons' sound localization in VR environments. However, some open problems still need to be solved to design better assistive haptic VR devices or VR applications/games for deaf persons. This section discusses these problems and expresses our suggestions for future research.

Hearing Loss and Social Isolation:

During the data analysis of our background survey (Chapter 3) and consent forms, we noticed that deaf persons suffer from many psychological issues related to hearing loss, using new technologies, and social isolation (we cannot reveal these data to keep the confidentiality of deaf participants in our experiments). These issues were more pronounced among profoundly deaf persons than partially deaf persons. Most deaf participants did not prefer to be authenticated in public or talk about problems related to using new technologies in their comments.

There are several studies related to this topic, such as A. Bott et al. [288] and H. Anglin-Jaffe [289], but to the best of our knowledge, most of them did not consider using new technologies such as VR in their research. We believe that a thorough study of the usage of new technologies developed for hearing persons among deaf persons and further analysis of deaf persons' VR enjoyment factors would yield beneficial results for future research related to developing assistive VR technologies for deaf persons.

Advanced Haptic VR Suits:

Our haptic VR suit experiment was entirely new to deaf participants, and we had to make it simple because of our limited budget. Therefore, we limited the number of vibro-motors to four on a custom haptic VR suit and limited the directions of incoming sounds to the front, back, left, and right, eventually decreasing the complexity of the experiment for deaf participants. Also, we only used ERM coin vibro-motors. This setup did not let us investigate the results of using an advanced haptic VR suit with more vibration devices, including different types of actuators, such as piezoelectric haptic surfaces for producing a different range of vibrations, to show more directions (diagonal directions) of incoming sounds with the possibility of showing the distance of the sound object to deaf persons. Therefore, using an advanced haptic VR suit with more and different vibration devices will give us better information about perceiving sounds using haptic feedback among deaf persons in VR environments with multiple sound objects in future research.

Also, the results of mounting vibro-motors on different positions of deaf persons' bodies showed that they prefer mounting the vibro-motors on the upper body sections when using a haptic VR suit. We have no evidence of the reasons for preferring the upper body sections for mounting haptic devices in a VR suit among deaf persons. Therefore, further experiments and analysis are required in future research to understand why deaf persons react differently to tactile sensations from different parts of their bodies in a VR environment. Furthermore, we only tested our suggested VR suit setups on the same group of deaf participants on different days and in a fixed order. Although the VR environment randomly changed in each test for each participant, the fixed order of the setups in our first experiment may have had some learning effects on the participants. Therefore, it will be essential to randomize the order of conditions across participants in future research.

Expanding the Hardware:

Our proposed EarVR and EarVR+ systems use an Arduino processing unit that needs to be more powerful for complex audio analysis. Our proposed systems work only based on the distance of the closest 3D sound sources to the user and cannot distinguish different types of sounds. By expanding the hardware and using a powerful processing unit in future research, our proposed systems can distinguish different sounds in VR environments based on their level of importance. Also, they can analyze the effect of controlling the speed of vibro-motors and the color intensity of LEDs with PWM on determining the distance between the user and the sound object in the VR environment. Future research can also use RGB LEDs to categorize sound sources and map each category to a particular LED color.

In our experiments related to the EarVR+ system, some participants in the control group commented that the LED lights make it harder to react fast and concentrate on locating the target object while LEDs and vibro-motors are activated in haptic+LED mode. We do not have enough evidence to explain why persons without hearing problems prefer only haptic feedback with audio. On the other hand, deaf participants made no such comments on haptic+LED mode and preferred LEDs in LED and haptic+LED modes. Deaf participants believed that LEDs and haptic feedback improved their VR experience. Therefore, future research with precise experiments and analysis is required to investigate the effects of LEDs in VR HMDs on deaf and hearing persons' VR experience.

Different Visual Effects:

VR environments have become more interesting for users by using 3D audio and visual effects [33, 290]. In our multi-modal visualization experiment, we used a pre-defined level of intensity for each modality. Therefore, We could not control the intensity of each stimulus, e.g., the particles' brightness or the audio level. Humans have different thresholds for the intensity of different stimuli [283], so a future research is required to analyze the effect of using our proposed visualization methods with different intensities on deaf and hearing persons in VR.

Also, our observational analysis indicates that users in deaf and hearing persons groups felt cybersickness in the InHUD mode, but there were no noticeable issues among in the InENV mode. Since this assumption was only based on observations and users' comments in our experiment, future detailed studies with SSQ are required to investigate the cybersickness feeling in the InHUD condition.

Complex VR Scenarios:

Visualization techniques are essential for creating a complex and immersive VR environment. Using different visualization elements, such as 3D models, textures, animations, and lighting, can enhance a VR environment and makes it possible to create a realistic and immersive environment. In addition, using different visualization techniques can help create more detailed and interactive elements, such as interactive objects and characters, as well as more realistic environments. Therefore, VR developers can create more realistic VR environments and improve users' VR experience.

In our experiments, we used simple VR environments and a limited number of visualization techniques for VR sound localization among deaf participants. In future research, further experiments and analysis are required to investigate the effects of our proposed real-time haptic feedback systems (EarVR/EarVR+) with different visualization techniques in a complex VR environment on deaf and hearing persons' VR sound localization.

The end of this dissertation is a new beginning for all efforts that could use our proposed real-time haptic systems (EarVR/EarVR+) and methods for improving VR experience among the hearing-impaired community. We believe this dissertation will be helpful for the DHH community and that future research and development of assistive haptic VR systems will benefit from its results, resulting in higher interest and passion for using VR technology among deaf persons. We hope that VR technology becomes more accessible for all DHH persons and that more researchers be motivated to develop assistive VR systems to help deaf persons use VR without any limitations.

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Acronyms

3D 3-Dimensional. vii, 1

AC Alternating Current. 18

ADA Americans with Disabilities Act. 34

AI Artificial Intelligent. 41

AR Augmented Reality. 4

ArSL Arabic Sign Language. 39

ASD Autism Spectrum Disorder. 38

ASL American Sign Language. 39

ASR Automatic Speech Recognition. 41

Auslan Australian Sign Language. 39

BSL British Sign Language. 39

CI Cochlear Implant. 2, 28, 30, 46, 77, 85, 88, 92, 108, 113, 122, 123

DC Direct Current. 18

DGS German Sign Language. 39

DHH Deaf and Hard-of-Hearing. vii, 1

DSP Digital Signal Processing. 69

ERM Eccentric Rotating Mass-motors. 18

FFT Fast Fourier Transform. 71

FOV Field-Of-View. 22, 43

HA Hearing Aid. 2, 28, 30, 46, 50, 77, 85, 88, 92, 108, 113, 122, 123

HI Hearing Instrument. 2, 31

HMD Head-Mounted Display. 1, 21

HRTF Head-Related Transfer Function. 42

HUD Heads-Up Display. 57

IDE Integrated Development Environment. 65

ILD Interaural Level Difference. 42

ISL Indian Sign Language. 39

ITD Interaural Time Difference. 42

LED Light-Emitting Diode. 3

LGN Lateral Geniculate Nucleus. 23

Li-ion Lithium-ion. 62

LRA Linear Resonant Actuators. 18

MR Mixed Reality. 44

OS Operating System. 64

PA Piezoelectric Actuators. 18

PC Personal Computer. 62

PSL Persian Sign Language. 39

PTSD Post-Traumatic Stress Disorder. 33

PWM Pulse Width Modulation. 70

SDK Software Development Kit. 93

SS Sensory Substitution. 31

UE4 Unreal Engine 4. 62

USB Universal Bus Controller. 69

VE Virtual Environment. 1, 3, 53, 77, 130

VR Virtual Reality. vii, 1

WFD World Federation of the Deaf. 2, 39

WHO World Health Organization. 2, 28, 36

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Appendix-A

CONSENT FORM

Participant's Copy

PLEASE CONSIDER THIS INFORMATION CAREFULLY

Project Title: "   "

Purpose of the Research: This project aims to examine the effects of using our new proposed systems on Deaf and Hard-of-Hearing (DHH) persons in Virtual Reality (VR) environments.

What you will do in this Research: During the experiments, you will experience several scenarios in VR environments and will be asked to do some tasks by playing simple VR games. Your task completion time will be saved in each scenario. At the end of each test, you will fill in a questionnaire. We will analyze your data anonymously, along with the data of other participants.

Time required: You are expected to participate for approximately 20 minutes for each experiment.

Risks: Our conducted experiments are considered of "minimal risk." If you have never used VR, it may cause discomfort, such as cybersickness. So, please answer the questions of this form carefully and notice that participating in the tests is at your own risk.

Benefits: This is a chance for you to test new proposed systems for DHH users for the first time, tell your story about your experiences concerning your journey in the VR environment, and tell us your valuable comments to improve our proposed systems and our future studies.

Compensation: You will receive gifts, chocolate, cookies, and non-alcoholic drinks at the end of each experiment. You can also have a friendly discussion about your ideas and opinions.

Confidentiality: Your answers to the questionnaires will be kept confidential. At no time will your actual identity be revealed. The recording video files or images will only be used with your permission. Otherwise, all the files related to you will be deleted as soon as finishing our data analysis phase. The data you give us will be only used for our study. We will not use your name or information identifying you in any publications or presentations.

Participation and withdrawal: Remember that your participation is entirely **voluntary**. You **can choose** not to participate in part or all of the tests, and you **can withdraw** at any stage of the tests without being penalized or disadvantaged in any way. Finally, we reserve the right to stop you during the tests for any reason.

*** Please choose your answer to the following issues and sign below:**			
Do you understand this consent form?		☐ YES	☐ NO
Do you give your consent to be a subject in our experiments?		☐ YES	☐ NO
Can we use your photograph or recorded video in publications or presentations?		☐ YES	☐ NO
Have you ever suffered from severe vertigo or epilepsy?		☐ YES	☐ NO
Have you ever tried Virtual Reality (VR)?		☐ YES	☐ NO
Are you using any assistive device, such as a hearing aid or cochlear implants?		☐ YES	☐ NO
What is your level of deafness?	☐ Profoundly Deaf	☐ Partially Deaf	☐ Prefer Not to Say

Contact the Researcher: If you have questions or concerns about this research, please contact to:

Mohammadreza Mirzaei, Ph.D. Candidate at TU Wien, E-mail: mohammad.mirzaei@tuwien.ac.at

Agreement:

The nature and purpose of this research have been sufficiently explained, and I agree to participate in the experiments. I understand that I am free to withdraw at any time without incurring any penalty.

Name (Optional): ________________________________ Age (Optional): ______________

* Signature: ___________________________________ * Date: ______________

Appendix-B

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Vienna, 16/12/2022

To whom it may concern:

This letter is to inform the recipients that at the time when Mohammad Mirzaei was accepted as a PhD student at TU Wien (2017), there was no designated institutional review body, or research ethics committee, to assess human research participation at TU Wien.

Such a committee has been under development and piloted since 2020 and the submission for peer review by this body takes place on a voluntary basis. Under current legislation in Austria, it is not mandatory to submit non-medical, non-clinical behavioral studies (such as the user studies in question) to formal research ethics review.

If you have any further questions concerning research ethics review and its current state of development at TU Wien, do not hesitate to contact me.

Best wishes,

Marjo Rauhala

Marjo Rauhala

Head of Service Unit
Responsible Research Practices

Appendix-C

TU WIEN

Questionnaire

✱ **Please Answer the Following Questions:**

1)	**Are you familiar with VR technology?**	☐ Yes	☐ No
2)	**Are you willing to be involved in developing a new assistive VR device that would enhance your VR experience?**	☐ Yes	☐ No
3)	**Did you try any VR activities or games before?**	☐ Yes	☐ No
4)	**How many times have you used VR before? (Please select only one answer)**	☐ Never Used VR ☐ Only 1 Time ☐ 2 to 10 Times ☐ 11 to 50 Times ☐ More than 50 Times	

5) What type of VR devices do you like to use?
(Please select only one answer)

☐ Mobile phone VR (such as VR cardboard glasses, Samsung GearVR)
☐ VR Head-Mounted Displays (HMDs) (such as HTC VIVE, Oculus Rift/Quest)
☐ Both (Mobile phones and VR HMDs)

6) What type of assistive technology do you think will help DHH users more in VR?
(You can select multiple answers)

☐ Sound Amplification (e.g., hearing aid) ☐ Subtitle Display (e.g., text-based subtitle)
☐ Sign-Language Interpreter (e.g., hand models) ☐ Hardware Assistant (e.g., haptic and visual feedback)

7) What improvement in VR do you think will have the best impact on creating VR applications or games for DHH users?
(You can select multiple answers)

☐ Better Visual Display ☐ Better Audio
☐ Add Haptic Feedback ☐ Add Visual Feedback
☐ Add Sense of Smell ☐ Add Sense of Taste
☐ Add Sense of Movement or Rotation

8) What is the main reason for not using VR, in your opinion?
(You can select multiple answers)

☐ It is expensive (Costly).
☐ The technology is not good yet for DHH users (Not Usable).
☐ It is not accessible for DHH users easily (Inaccessible).
☐ There is not enough content (application or games) suitable for DHH users (Lack of Content).
☐ Motion sickness in VR (Motion Sickness).
☐ I do not like wearing VR headsets (Dislike).
☐ The experience is not immersive enough (Not Immersive).

9)	**Which of the following factors do you think is essential for DHH users to enjoy VR? (You can select multiple answers)**

☐ Spatial Presence (sense of being in VR)
☐ Environmental Feedback (engaging senses)
☐ Interactivity (Interacting with virtual objects)
☐ Realism (similarity to the real world)
☐ Motion Sickness Reduction

10)	**Which of the following audio categories are the most important to visualize in a VR environment for a DHH user? (You can select multiple answers)**

☐ Human Sounds (such as human voice, whistling, etc.)
☐ Animal Sounds (such as pets sounds, wild animal sounds, etc.)
☐ Music (such as musical instruments, music mood, etc.)
☐ Sounds of Things (such as vehicle sounds, alarm sounds, bell sounds, etc.)
☐ Natural Sounds (such as wind sound, thunderstorm sound, fire sound, water sound, etc.)
☐ Environment and Background Sounds (such as noises)
☐ Source-ambiguous Sounds (such as impact sounds, surface contact sounds, etc.)

11) Please rank the following visualization methods in order of importance for DHH persons:

	1 (Least Important)	2	3	4	5 (Most Important)
Haptic Feedback	○	○	○	○	○
Visual Feedback	○	○	○	○	○
Force Feedback	○	○	○	○	○
Thermal Feedback	○	○	○	○	○

*** Any comment or suggestion?**

Thank You So Much

If you have any questions, please ask the organizer of the questionnaire.