SoundModVR: Sound Modifications in Virtual Reality to Support People who are Deaf and Hard of Hearing

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Previous VR sound accessibility work substituted sounds with visual or haptic output to increase VR accessibility for deaf and hard of hearing (DHH) people. However, deafness occurs on a spectrum, and many DHH people (*e.g.*, those with partial hearing) can also benefit greatly from having more control over the audio instead of substituting it with another modality. In this paper, we explore the possibilities of modifying sounds in VR to support DHH people. To understand the best modification features for this goal, we designed and implemented 18 VR sound modification tools spanning four categories, including prioritizing sounds, modifying sound parameters, providing spatial assistance, and adding additional sounds. We evaluated our tools in five diverse VR scenarios with 10 DHH people, finding that our tool can improve DHH users' VR experience, but could be further improved by providing more customization options and decreasing distraction. We then compiled a Unity toolkit from select tools and conducted a preliminary evaluation with six Unity VR developers. Findings show that our toolkit is easy to use and debug but could be enhanced through modularization and better documentation. We close by discussing further implications of sound modification in VR.

CCS CONCEPTS • Human-centered computing~Accessibility~Accessibility technologies

Additional Keywords and Phrases: Accessibility, virtual reality, deaf and hard of hearing, sound, customization.

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1 INTRODUCTION

Previous work in VR sound accessibility for deaf and hard of hearing (DHH) users has focused on substituting sounds with visual or haptic outputs [27, 40, 44], such as closed captions for in-game dialogs or vibrations to represent environmental explosions. While promising for some specific sounds, visual and haptic feedback could lead to information overload [26] and hinder accurate information delivery due to bandwidth differences with auditory stimuli [24, 55]. Moreover, not all DHH users require complete substitution of sounds. Deafness occurs on a spectrum, and DHH individuals could have different hearing levels [11, 69]. Some users can hear sounds to some extent. For these users, the application can use sound modification techniques like increasing volume, shifting frequencies to audible ranges, or reducing background noise to deliver sound information seamlessly. Indeed, such customization may offer a more intuitive experience than a complete sensory substitution, as indicated by DHH participants in prior evaluations of VR sound substitution systems [27, 41].

In this paper, we explore modifying and customizing sounds in VR to better support the needs of users with partial hearing. Inspired by features explored in previous work, such as sound prioritization [57], directional sound enhancement [56], frequency-specific gain adjustment [17, 54], and spatial sound localization [40, 45], we designed 18 sound modification tools that allow developers to incorporate sound accessibility into their apps. These include four sound *prioritization* tools (*e.g.*, prioritizing important speech or a keyword), five *parameter modification* tools (*e.g.*, adjusting the frequency, volume, or speed), six *spatial assistance* tools (*e.g.*, assisting with directions of sound sources), and three *additional sounds* tools (*e.g.*, adding custom audio notifications for inaccessible sounds).

To elicit reactions to our tools and explore the future of VR sound modification for accessibility, we conducted a user study (Study 1) with 10 DHH participants. In this study, we designed five common VR scenarios that utilize sounds (*e.g.*, a calm forest tour, a simulation of office conversations, a tense shooting game) and implemented our tools into each scenario. The participants experienced our scenarios through a VR device, rated the tools for their effectiveness in conveying sounds, and responded to questions about the overall experience and user interface. We found that our tools increased immersion, made sound information more accessible, and enhanced the overall experience of participants. Participants also provided improvement suggestions such as offering further customization, reducing distraction and discomfort, as well as supporting better integration with the existing app's goals.

While our tools improved the DHH experience, we also needed to evaluate whether developers can easily incorporate them into their applications. Consequently, we selected nine tools from Study 1 (two or three from each category) and packaged them into a Unity toolkit. We then conducted a preliminary evaluation (Study 2), where six Unity VR developers remotely implemented the sound accessibility tools into their Unity projects and provided feedback about their usability. Overall, the participants found the toolkit easy to use and appreciated its potential to improve the accessibility of their apps for people with partial hearing. However, they also suggested further modularizing the toolkit and including better documentation such as a tool choice guide.

In summary, our work contributes: (1) a set of 18 VR sound modification tools to increase VR accessibility for DHH users with partial hearing, (2) a study with 10 DHH individuals, providing insights into the effectiveness of our tool across five common VR situations, and (3) preliminary insights from a study with six VR developers, evaluating the potential usability of our toolkit. Our toolkit is open-sourced on GitHub: github.com/AccessibilityLab/SoundModVR.

2 RELATED WORK

We cover prior work in VR accessibility for DHH users, sound modification and customization, and, more broadly, general VR accessibility.

2.1 Current VR Technologies for DHH Users

Prior work in VR for DHH users has primarily focused on providing speech accessibility through closed captioning. For example, Agulló *et al.* evaluated captions in immersive environments like 360-degree content using a focus study with 10 DHH people and four professional subtitlers and a pilot study with a group of mixed hearing ability, including two DHH people [2, 3]. They concluded that users favored subtitles that are always visible, arrows to indicate sound source locations, and the option to personalize the level of detail in captions. Teófilo *et al.* conducted a case study with 43 DHH users by deploying VR headsets for a theater performance [62]. They suggested VR/AR as a promising medium for live event captioning. The *ImAc* project explored subtitling, audio description, and sign language in immersive TV production [46]. These systems are promising explorations, primarily to make spoken content accessible.

As the needs of DHH users extend beyond speech accessibility [6], prior work has also explored visual and haptic interfaces to substitute non-speech sounds in VR (*e.g.*, in-game notifications, background music, or object sounds). For example, Jain *et al.* [27] explored multiple visual and haptic prototypes to substitute sounds in different categories in VR, including text for notification sounds, waveforms for ambient sounds, abstract visualization for rhythms, wideband haptic belt for ambient sound, and smartwatch vibration for critical sounds. This work also conducted a study with VR developers, finding a need to include developer-specific customization options. Li *et al.* [40] built the SoundVizVR system that combines sound characteristic indicators and sound type indicators to visualize loudness, duration, location, and type of sound sources to DHH users. They also evaluated their tool with developers, revealing game design practices and ways to optimize the developer experience [41]; these findings inform our developer toolkit. Finally, Mirzaei *et al.* evaluated a multi-modal system consisting of audio, visual, and haptic feedback, finding that DHH people favored it to localize sound sources [44, 45].

The evaluations of these systems show promise in helping DHH users understand or localize sounds in a VR scene [27, 40, 44, 45]. However, sensory substitution risks cognitive overload, especially in sound-intense scenarios [26, 27], and may not be intuitive [39]. Furthermore, since deafness occurs on a spectrum [11], not all DHH users necessarily need full substitution of sounds. Indeed, in the aforementioned Jain *et al.* work [27], participants with partial hearing desired additional features to help them better access the sonic environment, including customizing the frequency of sounds, configuring the volume of individual sounds, and reducing background noise. Inspired by this work, we propose a new direction of modifying and customizing sounds in VR with the aim of providing a less disruptive and more intuitive experience for DHH users with partial hearing.

2.2 Sound Modification and Customization

Different DHH users have different levels of deafness, different lived experiences, as well as different patterns of hearing, signing, or interacting with software [16, 38, 53]. To accommodate DHH users' diverse needs and preferences, multiple genres of sound accessibility technologies have included personalization and customization as part of their features, including hearing aid technologies [4, 5, 17], traditional media audio [54, 57, 58, 64], and game sound configurations [8, 29, 78, 79].

Commercial hearing aids provide personalization through filtering and amplifying specific frequencies [65], allowing users to self-adjust the frequency gain [17]. Aldaz *et al.* developed a smartphone app that enabled users to switch the directionality and reduce noise in their hearing aids [5]. Alamdari *et al.* [4] presented a human-in-the-loop deep reinforcement learning approach that personalizes hearing aid compression to improve hearing perception. Despite the popularity of adaptable hearing aids, they cannot support all desired sound accessibility features, such as individual sound modification, prioritization, or localization. Hence, more work was needed in the VR Sound Modification space.

Sound personalization has been applied to general audio accessibility in traditional media, focusing on volume adjustment based on frequency, category, and importance. Ward *et al.* [64] summarized the dimensions of personalization in object-based audio, which are speech-to-noise ratio, the spatial distance between sounds, and additional redundant information like captions. Shirley *et al.* [58] implemented a multi-dimensional audio system and evaluated it with 14 DHH viewers, allowing them to independently control the audio levels of speech, music, and effects of TV sounds. Another work by the same author [57] proposed incorporating narrative importance metadata into object-based accessible audio for DHH individuals, allowing for prioritization by adjusting audio levels based on narrative importance–a feature we extend to VR. Rennies *et al.* [54] developed presets covering typical frequency-dependent hearing threshold elevations to support frequency gain personalization on traditional headphones. We extended and explored the above features in VR with DHH users through our prioritization and parameter modification tools.

Besides research literature, many commercial games have incorporated sound personalization and modification features [8, 77–79], which informed our toolkit. For example, in addition to allowing users to switch between stereo and mono sounds, Fortnite [8] enables users to independently adjust the music volume, sound effects, dialogues, voice chat, and cinematics. The Last of Us Part II [78] featured an enhanced listening mode, which triggers audio cues at the target's location and changes the pitch of the audio cues based on the target's height. Games like Minecraft and The Sims 4 support users uploading custom sounds for notifications [29, 79].

In summary, prior work has addressed various aspects of sound modification and customization, including sound directionality, noise reduction, prioritizing sounds based on assigned importance, frequency-gain adjustment, independent sound control, spatializing sounds, and dynamic pitch adjustment for spatial guidance. Our work not only extends these features to VR but also evaluates other novel features, such as prioritizing based on keywords, speed adjustment, and hearing range adjustments.

2.3 General XR Accessibility Research

As the prevalence of XR (Virtual Reality and Augmented Reality) has increased over the last decade, researchers and practitioners have begun to target XR accessibility. In 2020, the World Wide Web Consortium (W3C) published its XR Accessibility User Requirements [80]. In 2020, the XR Association published a chapter about accessibility in their Developer's Guide [81]. Researchers started developing specialized VR experiences and VR accessibility toolkits for different user groups, including blind and low-vision users [28, 32, 35, 70], neurodivergent users [7, 20, 51], and motor-impaired users [18, 49, 63]. Here, we review work most closely related to ours.

A major inspiration for our work stems from Zhao *et al.* [71], who developed a set of visual tools to help users with partial vision loss (*i.e.*, low vision) better access VR content by modifying the existing visual information (instead of substituting it with audio or haptic feedback). They used techniques such as changing contrast, remapping inaccessible elements such as peripheral information or color into accessible range, and highlighting semantically important objects in the scene to make visual information more salient. Evaluation with 11 blind and low vision (BLV) participants showed that users could complete the designed VR tasks more quickly and accurately with these tools. This work also developed a toolkit called SeeingVR [71] and performed a study with six VR developers, uncovering guidelines such as interaction techniques for easy adjustment, which directly informed the design of our toolkit.

Another closely related work to ours is Chang *et al.* [12], who presented a sound rendering framework, SoundShift, consisting of sound manipulators like a prioritizer that delays unimportant audio and feature shifters that adjust volume, frequency, or duration. Their system, when implemented, aims to help BLV users better perceive and differentiate mixed-reality soundscapes. These features inspired the design of our toolkit to enhance sound while requiring minimal cognitive load.

We build on the above work to explore several sound customization tools with both DHH users and VR developers, with the aim of making VR accessible for users with partial hearing.

3 SOUND MODIFICATION TOOLS

We designed 18 sound modification tools that allow users and developers to customize sounds and auditory scenes in a VR app. These tools were informed by prior VR work with DHH users [26, 27, 40], accessibility features in VR games (*e.g.*, Fortnite [8], The Last of Us Part II [78]), accessibility features in modern phones and apps (*e.g.*, live listen feature in iOS), as well as experiences of one of our authors, who identifies as hard of hearing. We divide these tools into four categories based on the sound properties they manipulate.

The *prioritization* tools (PT1-PT4) dynamically adjust the volume of sounds based on developer or user-assigned priority. The *parameter modification* tools (PM1-PM5) adjust loudness, pitch, and persistence characteristics to suit individual users' needs and preferences. The *spatial assistance* tools (SA1-SA5) convey information about the spatial location of sounds and configure how multiple sounds blend in space. The *additional sounds* tools (AS1-AS3) introduce extra sounds into the scene either to convey critical information such as location or to generate an affective state. We explain each tool below.

3.1 Prioritization Tools

Speech Prioritization (PT1): Since DHH people may have difficulty distinguishing speech from background sounds [43, 47, 59], we provide a speech prioritization tool, which can lower the volume of co-occurring environmental sounds during important speech.

Group Prioritization (PT2): During multiple simultaneous groups of conversations, a user might want to focus on sounds from one group. The group prioritization tool reduces the volume of all other surrounding conversations. This tool was inspired by the cocktail-party phenomenon [10], whereby hearing users can switch listening to a “conversation group” based on preference. Besides speech, this feature can also be used to prioritize a group of sounds, for example, sounds emanating from only the leading cars in a virtual car race game.

Keyword Prioritization (PT3): During long speeches, DHH people have requested to be alerted to specific keywords [30] to increase the ease of accessing specific information. This tool allows users or developers to assign keywords to monitor, which, when detected, plays a notification sound. It also restores the volume of the spoken content to its original level if other tools have lowered it.

Direction-Based Prioritization (PT4): Directional amplification of sounds has been known to effectively reduce noise and improve comprehension; it is a common feature in hearing aids [1, 21, 56]. Our tool amplifies the sounds within the 10-degree arc on each side in the direction the user faces while simultaneously reducing the volume of sounds coming from other directions.

3.2 Parameter Modification Tools

System Frequency/Volume Adjustment (PM1): Many DHH users have frequency-specific hearing loss [25, 42, 66]. This tool enables users to shift the frequency range of sounds, as well as adjust the volume system-wide.

Sound Frequency/Volume Adjustment (PM2): Many games allow users to adjust individual sounds or certain groups of sounds [8, 15, 78]. Similarly, this tool enables users to adjust the frequency and volume of individual sound sources.

Frequency Contrast Enhancement (PM3): Since increasing visual contrast has been shown to help low-vision users in VR [71], we propose that increasing the frequency contrast of co-occurring sounds may improve clarity and comprehension for DHH users. This tool adjusts the frequencies of adjacent sound sources, elevating one while lowering the other to enhance their distinction.

Speech Speed Adjustment (PM4): Prior research suggests slowing down speech to improve comprehension for DHH users [67]. This tool allows users to adjust the speed of individual speech sources.

Beat Enhancement (PM5): Inspired by visual and haptic efforts to help DHH users enjoy music [19, 50, 52], we designed a beat enhancement tool that boosts the rhythm of music sounds by dynamically increasing and decreasing the volume along with the beats.

3.3 Spatial Assistance Tools

Left-Right Balance (SA1): To accommodate users with differential hearing in both ears [37], we designed this tool that enables them to adjust the system sound balance to either the left or right, thereby equalizing stereo sounds and amplifying the sound on their preferred side.

Shoulder Localization Helper (SA2): The ability to discern sound direction is crucial for locating spatial sound events–a challenging task for some DHH people [27, 44]. Inspired by VR assistants like Sighted Guide for BLV users [13], this tool provides auditory cues ("To your left" or "To your right") and captions to indicate the direction of important in-game sounds.

Hearing Range Adjustment (SA3): Too many spatial sounds could be undesirable [31]. This tool allows users to adjust the range for sound activation, enabling them to choose desired audio from various spatial sources based on distance.

Sound Distance Assistance (SA4): Auditory distance perception plays a major role in spatial awareness but could be challenging for DHH users [14, 34]. This tool aids in perceiving distance by modulating sound pitch based on the user's proximity to the source: pitch decreases as distance increases and vice versa.

Live Listen Helper (SA5): The iOS Live Listen feature [76, 82] turns an iPhone into a microphone, allowing users to hear better in noisy environments by moving the phone close to the sound source. Similarly, this tool isolates the sound from a source when nearby, muting all others. Users can move it around the scene to isolate the sounds they desire.

Silence Zone (SA6): Developers might overlap the range of multiple ambient sound sources to introduce a transition to a new area [31]. This tool increases contrast between spatial sounds by including a silence zone between them, facilitating better auditory transitions for DHH users while traversing a VR scene.

3.4 Additional Sounds Tools

Smart Notification (AS1): Games like Fortnite and Persistence [8, 73] use directional icons to provide localized hints for important sound information. This tool enables users to receive a notification sound at the sound source location when important sounds are played.

Custom Feedback Sounds (AS2): Many VR apps include feedback sounds that respond to user actions, but DHH users may struggle to discern these built-in sounds. Inspired by games that support sound customization, like Minecraft [29] and The Sims 4 [79], we developed this tool to offer users a wider range of sound options for specific actions, including variations in pitch, volume, and style.

Calming Noise (AS3): Sound therapy has used calming noises to alleviate tinnitus [23], a symptom connected to deafness [33, 83]. This tool enables users to select among white noise, pink noise, and rain sounds to add to the VR environment.

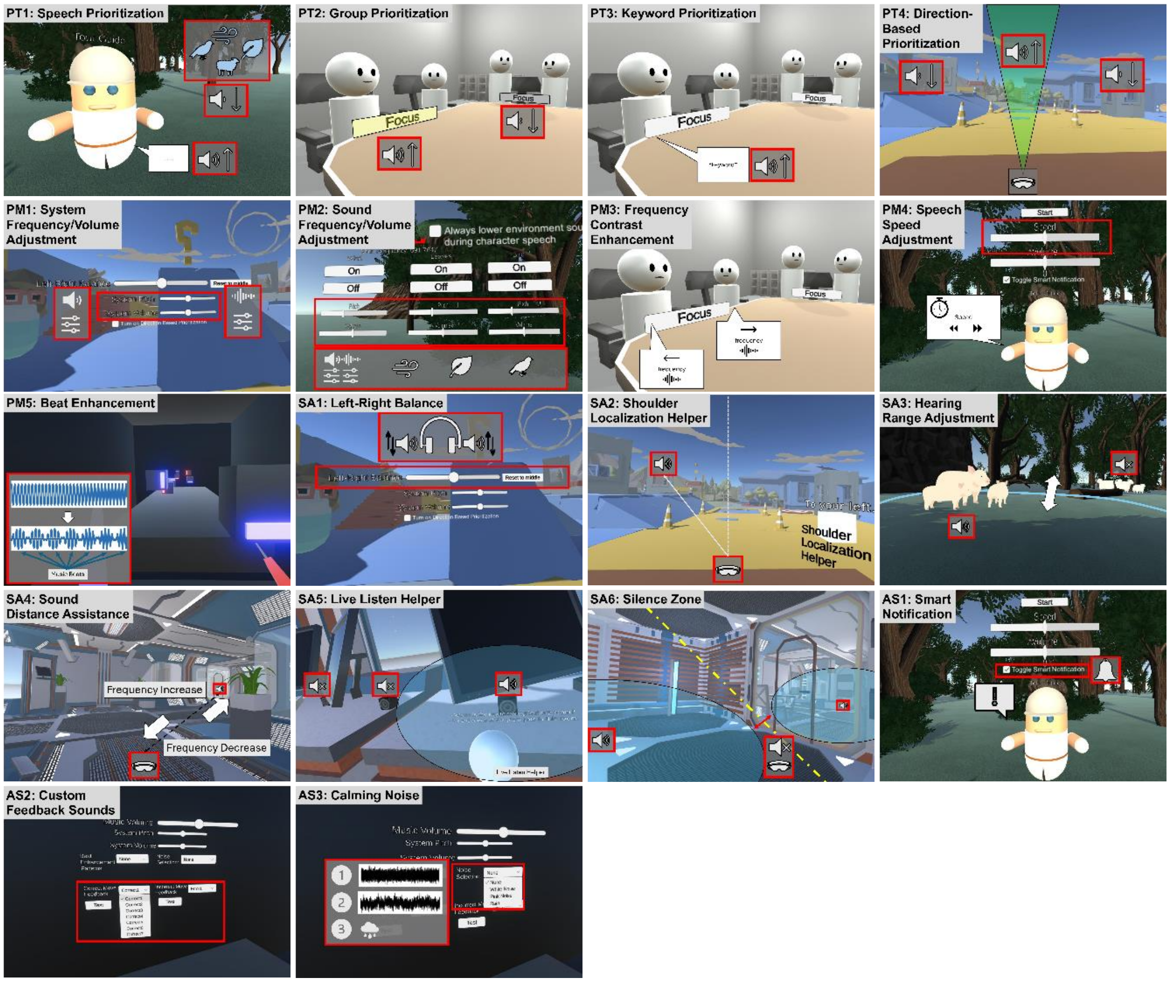


Figure 1: SoundModVR's 18 sound modification tools. These include *prioritization* tools (PT1-PT4), *parameter modification* tools (PM1-PM5), *spatial assistant* tools (SA1-SA6), and *additional sounds* tools (AS1-AS3). The images include the VR screenshots of scenarios used in Study 1 with overlaid graphics (*e.g.*, red boxes, volume icon, callout textbox) to showcase the tool functionalities.

3.5 Implementation

To incorporate the toolkit into an app, developers first choose the tools tailored for their app (*e.g.*, speech speed adjustment tool for a narration-focused app), assigning some tools to activate automatically during gameplay (*e.g.*, smart notification) and some to be manually toggled by the users (e.g., direction-based prioritization). Then, users interact with the app, enabling/disabling tools either in the beginning (for system-level tools) or as they appear (for scene-specific tools). They can further customize the tools using a settings menu placed in the scene (see Fig 2), allowing them to adjust tool parameters to fit their hearing abilities. The level of customization varies per tool and can be configured by the developers.

Each tool utilizes a C# script to detect game events or collect user input, linked to one or more Audio Sources in Unity. These scripts are attached by developers to specific GameObjects in the Unity scene. To implement these tools, we relied on Unity's native AudioSource and AudioMixer functions.

4 STUDY 1: EVALUATION WITH DHH USERS

To assess our tools, we conducted a scenario-based evaluation. We used the 10 VR app categorizations from Jain *et al.* [26] and combined similar categories (*e.g.*,“Sports & Fitness” and “Shooting Games”), resulting in 5 categories. We designed five scenarios to cover these categories (Relax+Travel+Movies, Social, Sports+Shooting+Racing, Puzzle, Music+Art) and conducted a usability study with 10 DHH people.

4.1 Scenarios

Scenario 1: Forest Tour. Our first scenario was built to evaluate our tool for nature sounds. The scene, based in a forest, contains background sounds of wind, leaves, and birds, three groups of animals making localized spatial sounds, and a tour guide providing important information. Captions are shown for all tour guide speeches[1]. The user moves automatically following the tour guide, passing the animal groups. We implemented six tools in this scenario. The *speech prioritization* (PT1) tool allows users to prioritize tour guide speech over environmental sounds. The *sound frequency/volume adjustment* (PM2) tool shifts the frequency and volume of each element of the environmental sound separately. The *speech speed adjustment* (PM4) tool adjusts the speed and volume of the tour guide’s speech. The *direction-based prioritization* (PT4) tool prioritizes the animal sounds that the user is facing. The *hearing range adjustment* (SA3) tool allows users to adjust the range of animals that they hear. The *smart notification* (AS1) tool plays a notification sound to capture attention when the tour guide speaks.

Scenario 2: Office Convo. This scenario is aimed to evaluate our tool for a noisy conversational environment. The scene is set in an office with six characters forming three groups of concurrent conversations. Captions are shown for all conversations. At the end, an important character enters the scene. The user observes the conversations and events but is not able to participate. This scenario contains five tools. The *group prioritization* (PT2) tool allows the user to prioritize a certain group of conversations. The *frequency contrast enhancement* (PM3) tool separates two voices close in distance and frequency. The *keyword prioritization* (PT3) tool notifies the user when a character mentions a keyword and temporarily increases its volume if lowered. The *calming noise* (AS3) tool allows the user to add white noise, pink noise, or rain sounds. The *shoulder localization helper* (SA2) will cue “to your left” about an important sound event on the left.

Scenario 3: Shooting Game. This scenario aims to evaluate our tool in a tense, fast-paced game where the locations of sound sources are important. In this playground scene, enemies shoot the user from various locations and are accompanied by footsteps during movement, gunshots when firing, and grunting upon being attacked. The user is instructed to remain stationary and shoot the enemies with a weapon, which also emits gunshot sounds when shooting. The scene has suspenseful background music. This scenario has four tools. The *left-right balance* (SA1) tool allows the user to shift all sounds in the game towards the left or right side. The *system frequency/volume adjustment* (PM1) tool allows adjustments of the volume and frequency of all sounds in the game. The *direction-based prioritization* (PT4) tool prioritizes the enemy sounds that the user is facing. The *shoulder localization helper* (SA2) tool tells the player when an enemy starts shooting and whether the enemy is on their left or right.

Scenario 4: Escape Room. This scenario is designed to evaluate our tool in a game where the task is to navigate a space and locate sound sources. The scene consists of three rooms: a tutorial room, a room where the user finds a speaker playing a sound clue, and a room with a maze leading to an active target sound source. The user can move around using their controller. There are four tools in this scenario. The *silence zone* (SA6) tool inserts a silence zone between ambient sounds in different rooms to reduce confusion when traversing. The *live listen helper* (SA5) tool lets users isolate the clue

[1] Though captions substitute sounds visually instead of sonically, we incorporated them since they are commonly used. Our tools are meant to enhance, not substitute other VR accessibility features.

sound source from other noises. The *sound distance assistance* (SA4) tool changes the pitch of the target of the navigation task as the player increases or decreases their distance to the target. The *shoulder localization helper* (SA2) tool tells the user whether the target is on their left or right when they press a button.

Scenario 5: Rhythm Movement. This scenario was designed to evaluate our tools for a music VR game where users move and receive system feedback. The game is designed similarly to the popular VR game, Beat Saber [60]. A music soundtrack accompanies the game. Colored cubes move towards the user in sync with music, prompting the user to cut them using the corresponding controller. The system plays a "correct feedback sound" for accurate moves and an "incorrect feedback sound" for errors. There are four tools in this scenario. The *system frequency/volume adjustment* (PM1) tool allows the user to change the volume and frequency of the music and feedback sounds. The *beat enhancement* (PM5) tool increases and decreases the music volume at the same pace as the beat of the music. The *custom feedback sound* (AS2) tool allows the user to choose correct and incorrect feedback, each with seven options. The *calming noise* (AS3) tool allows the player to add white noise, pink noise, or rain sound to this scenario.

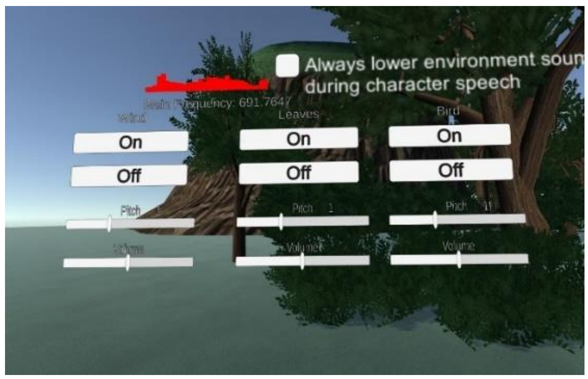


Figure 2: A screenshot of example UI for the scenarios. This image shows the UI for the *speech prioritization* (PT1) and *sound frequency/volume adjustment* (PM2) tools.

4.2 Participants

We recruited 10 DHH participants (P1-P10, six men and four women) through email lists, social media, and snowball sampling (Table 1). The participants were, on average, 40.10 years of age (*SD*=18.13 years). Eight participants identified as hard of hearing, one as deaf, and one as Deaf. Six participants had profound to severe hearing loss, two had moderate to moderately severe hearing loss, and two had unilateral hearing loss. Two participants have experienced VR before.

Table 1: Study 1 participant demographic. The hearing loss levels were self-identified. “LHLL” stands for “Left Ear Hearing Loss Level”; “RHLL” stands for “Right Ear Hearing Loss Level”; “PMoC w/DHH” stands for “Preferred Mode of Communication with DHH people”; “PMoC w/Hearing” denotes “Preferred Mode of Communication with Hearing people. “Exp w/ VR” is “Experience with using VR applications”.

ID	Age	Gender	Identity	LHLL	RHLL	Onset Age	PMoC w/DHH	PMoC w/Hearing	Exp w/ VR
P1	66	Man	HoH	Severe	Severe	birth	Writing	Verbal	Never used
P2	65	Man	HoH	Severe	Severe	62 yrs	Writing	Verbal	Never used
P3	36	Woman	HoH	Profound	Severe	1.5 yrs	Verbal, Writing	Verbal	Tried a few times
P4	24	Woman	HoH	No loss	Moderately severe	birth	Verbal	Verbal	Never used
P5	21	Woman	HoH	Moderate	Moderately severe	6 yrs	Verbal	Verbal	Never used

P6	23	Man	HoH	Profound	Profound	5 yrs	Writing	Writing	Never used
P7	23	Man	HoH	Profound	No loss	8 yrs	Writing	Verbal	Tried a few times
P8	61	Man	HoH	Moderate	Moderately severe	43 yrs	Verbal	Verbal	Never used
P9	40	Man	Deaf	Profound	Profound	birth	Verbal	Verbal	Never used
P10	42	Woman	deaf	Profound	Profound	birth	Verbal	Verbal	Never used

4.3 Procedure

The user study, largely qualitative, took place in a university research lab and lasted about two hours. After obtaining consent, the researcher used a background form to collect participant demographics such as age, gender, and hearing level (Table 1). Then, the researcher introduced our idea of sound modification in VR and guided participants to experience our tools through the five simulated scenarios. For each scenario, the researcher described the scenario, detailed the tools used in the scenarios, and instructed participants on how to utilize the tools. The participants then donned the VR device (Meta Quest 2) and participated in the scenario implemented in Unity. Each scenario lasted five to 10 minutes. The order of scenarios was counterbalanced using the Balanced Latin Square method proposed by Bradley [9]. Since our study contained an odd number of scenarios (5) as conditions, we doubled the rows of the Latin square table from five to ten.

Participants were instructed to toggle each tool on and off at least once in a scenario using the tool configuration UI (Figure 2) and experience the tool's effects. After experiencing each scenario, the participants removed the VR device and completed a questionnaire, where they rated: (1) scenario immersiveness, sound information gained, and their overall experience in the scenario, and (2) their experience with individual tools. The rating scale for the former spanned -3 (much worse) - 0 (the same) +3 (much better) to compare participants' subjective experience in the scenario with and without the tools. The rating scale for the latter spanned 1 (very bad) - 3 (neutral) - 5 (very good) to determine the participants' subjective rating of each tool on their effectiveness in making the targeted sound or sound scene accessible. We also asked participants to provide reasoning for their ratings and collected their open-ended thoughts on the user interface of the tools, the overall experience with the tools, and any improvement suggestions. After experiencing scenarios, participants took part in a semi-structured interview containing questions about their overall toolkit experience including on tool aesthetics, any experienced distraction or discomfort, and thoughts about fairness in competitive gaming.

To support communication accessibility during the study, we made two accommodations. First, we recruited a real-time captioner to attend all sessions, and participants could additionally opt for a sign language interpreter if desired. Second, we implemented a text-based communication interface in Unity that allowed the researcher to communicate in real-time with the participants by displaying text typed from their keyboard. This was used to convey any needed instructions to answer any participant questions, eliminating the need for them to remove the VR device mid scenario.

4.4 Data Analysis

Our quantitative data consisted of responses to the questionnaires completed by participants after each scenario. We used descriptive statistics to summarize the data, which included calculating the mean and standard deviation for the per scenario ratings on immersion, sound information gained, and overall experience, as well as for the ratings of each tool. Additionally, we generated box plot distributions to interpret the data.

For interview responses, we retained the captioner's transcripts and used them to conduct a thematic analysis [22]. First, the first author familiarized herself with the data by skimming the transcripts and generated an initial codebook. She then assigned codes to the transcripts while simultaneously refining the codebook by adding, merging, or deleting codes. The final codebook contains 23 third-level codes, 9 second-level codes, and 4 first-level codes. Another researcher then independently assigned codes to all the transcripts using the final codebook. We calculated the inter-rater reliability using the ReCal2 package [72], yielding a Krippendorff's alpha [36] value of 0.88 (>0.80 is considered a good agreement) and a raw agreement of 93.8% between the two coders. The coders then resolved disagreements via consensus. Finally, we determined the significance of the themes by calculating the number of occurrences of included codes and formed our narrative.

4.5 Findings

We discuss relevant themes which include: the effect of our tools on VR sound accessibility, potential for information overload, need for further customization, need for subtleness, thoughts on combining tools, and implications of our tools for other media formats.

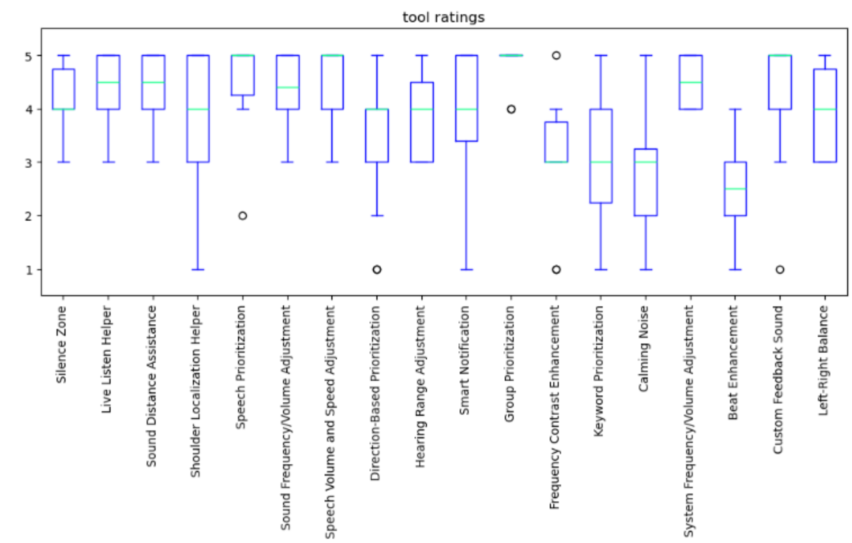
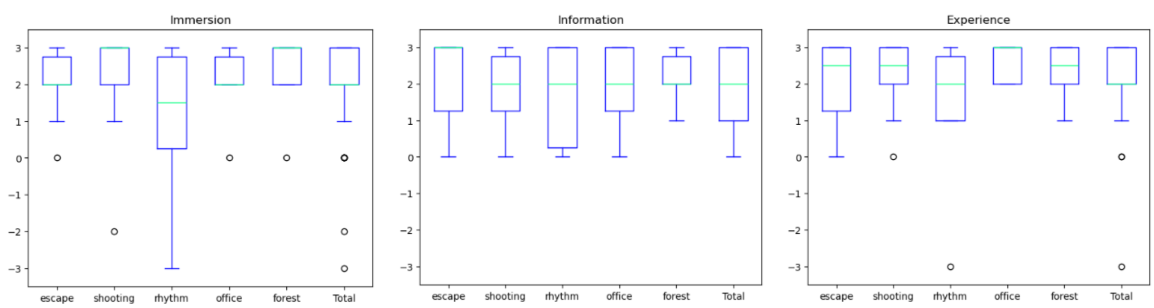


Figure 3: Boxplot distribution of the participant ratings for all 18 tools. The vertical axis shows the rating from 1 (Very Bad) - 3(Neutral) - 5(Very Good), and the horizontal axis shows the 18 different tools. The box spans from the first to the third quartile values, with the median represented by a line. Whiskers show the data range, while outliers are plotted as individual dots [84].



(a) (b) (c)

Figure 4: Boxplot distribution of the participant ratings for the five scenarios in terms of: (a) immersiveness (b) sound information gained, and (c) overall experience. The vertical axis shows the rating from -3 (Much Worse) - 0 (The same) - +3(Much Better), and the

horizontal axis shows the five different scenarios and the overall average. The box spans from the first to the third quartile values, with the median represented by a line. Whiskers show the data range, while outliers are plotted as individual dots [84].

4.5.1Effect on VR Sound Accessibility

On analyzing the ratings for individual tools, we found that most tools (14/18) were rated high (>=3.5 on a scale of 1-5, 5 being best). The four tools with low ratings include *keyword prioritization* (PT3) (*mean*=3.20, *SD*=1.32), *frequency contrast enhancement* (PM3) (*mean*=3.00, *SD*=1.25), *calming noise* (AS3) (*mean*=2.85, *SD*=1.39) and *beat enhancement* (PM5) (*mean*=2.50, *SD*=1.08). When asked for reasoning, participants commented that the *keyword prioritization* tool (PT3), while helping them focus on the conversation with the keyword, occasionally distracted them from the conversation they were originally listening to. In terms of the *frequency contrast enhancement* (PM3), some participants (*N*=6) found the relatively small magnitude of frequency change unnoticeable. The *calming noise* (AS3) tool on the other hand, increased the sound processing workload for participants, especially in sound-intensive environments. Finally, participants reported that although the *beat enhancement* tool (PM5) did "*pick up different parts of the beats*" (P5), the drastic change of music volume "*breaks the music up*" (P8). Figure 3 shows the box plot distribution of ratings for individual tools.

For scenario ratings, when compared to the same scenario with tools turned off, we observed an average increase (on a scale of -3 to 3, where -3 indicates much worse and 3 indicates much better) of 1.96 (*SD*=1.32) for immersion, 1.98 (*SD*=1.04) for the sound information gained, and 2.16 (*SD*=1.13) for the overall VR experience. Figure 4 visualizes the box plot distributions. These ratings show that, despite the low ratings of a few individual tools, overall our tools increased the participants' sense of immersion, made sound information more accessible, and enhanced the overall VR experience.

Subjective comments from the participants support these ratings. Indeed, participants highly favored our tools, with nine out of 10 mentioning that the tools helped them access important sound information from the scenes. For example, P7 said: "*when you turn [the speech prioritization (PT1) feature] on, it is much easier to hear what [the tour guide] is saying*". Similarly, P6, who has high-frequency hearing loss, explained:

> *"For the bird [sound], [...] I had a hard time hearing because it was high pitched so I moved it over [to a lower range using the sound frequency/volume adjustment SP2 tool] and it's really easy to hear".*

Being able to effectively hear sounds contributed to the feelings of immersion in VR, with P1 commenting, "*when you hear the environment, you feel [as if you] were there*".

Besides information access, eight participants explicitly disclosed that the tools helped them focus better and direct their attention to important sound sources. For example, on the *smart notification* (AS1) tool, which plays an accessible notification at the source of the sound, P4 said:

> *"it takes me a second longer to hear something, and then it's a bit frustrating to miss the first few words," and our tool helped to "redirect [...] attention".*

Similarly, the *keyword prioritization* (PT3) tool provided notifications of keyword occurrences, which enabled P5 to "*focus on one conversation instead of hearing everyone else talk about whatever they're talking about*".

Beyond just directing attention, the tools also helped participants effectively identify the location of sound sources (*N*=6). For instance, P5 found the *sound distance assistance* (SA4) tool very helpful, saying he "*wasn't entirely able to locate where the alarm was coming from by myself without [the tool] telling me*". Similarly, a participant with better hearing ability on his right side noticed how the *left-right balance* (SA1) tool helped him locate spatial sounds:

> *"I usually rely on my right side more. [...] If I put it (left-right balance) more on the right side, it helps me find where the footsteps (are)" (P6).*

4.5.2Potential for Information Overload

Despite the overall positive experience, almost all participants (*N*=9) expressed concerns that the tools could become distracting or overwhelming. For example, when commenting on the *keyword prioritization* (PT3) tool, P7 mentioned, "*I heard a notification, and [it] caught me off guard*". Similarly, P4 pointed out that "*if you use this (keyword prioritization) on the daily, [...] it would make a lot of sense. But in this quick experience, it was more so distracting*". Participants also expressed being overwhelmed at times, particularly with tools that provide multiple options. For example, the *custom feedback sounds* (AS2) tool provides seven custom notification options for each type of user action, and P5 commented, "*I was a little bit overwhelmed by how many choices there were. I think maybe only having three or four would be enough*".

Naturally, participants provided suggestions to avoid distraction or overload. To reduce distraction from additional sounds introduced by our tools, some participants (*N*=2) recommended using less intrusive alerts, such as employing "*alert sounds rather than alert words*" (P2) for the *shoulder localization helper* (SA2). Additionally, participants suggested dynamically alerting tools according to the user's focus. For example, P4 explained that the *keyword prioritization* (PT3) tool should not release a notification if the user is already focused on the conversation containing the keyword.

4.5.3Need for Further Customization

Several comments from participants indicated the need to further customize the tools in terms of configuring the targeted volume, frequency changes and the tool's spatial locations.

In terms of volume, some participants (*N*=2) reported that the volume changes performed by some tools were too drastic and jarring. For example, although the *speech prioritization* (PT1) tool helped make speech more prominent, P4 commented that it made "*the background noise [...] too far gone,*" and "*the feeling of immersion*" was compromised. P7 said that the *direction-based prioritization* (PT4) tool made the gunshot sounds in the shooting game scenario so much louder that "*it caught me really off guard*". In contrast to P7's comment, P6 found the tool's changes soft or unnoticeable, commenting that, "*when I try to switch directions, it's like really hard to see if it's a difference*". This indicates the need for customization of volume change to accommodate the diverse preferences and hearing ranges of DHH people.

Besides volume, some participants (*N*=4) requested customizable frequency ranges for some tools. For example, to accommodate their high-frequency hearing loss, P6, P7, and P9 all proposed allowing users to redefine the range within which the *sound distance assistance* (SA4) tool interpolates sound frequency. For the *frequency contrast enhancement* (PM3) tool that increases the frequency difference between close sources, P8 suggested allowing adjustments of the frequency contrast to make it more noticeable.

Additionally, some participants (*N*=6) desired the ability to customize the spatial locations of some tools. For example, P7, who has unilateral hearing, suggested that the *shoulder localization helper* (SA2) tool would be more helpful if it allowed users to reposition it – for example, to the "*better hearing*" side. Moreover, P3 expressed moving the tool so she could better see the captions during a tense scenario like a shooting game.

4.5.4Need for Subtleness

Some participants (*N*=3) stressed the importance of tools being subtle to enhance user engagement. Noticeably, when comparing the *sound distance assistance* (SA4) tool, which provides more intuitive and subtle guidance through pitch change, to the *shoulder localization helper* (SA2) tool, which provides more direct verbal hints, P7 said, *"[Shoulder localization helper] is more of [the] game trying to help me out [which is not as engaging as] the game giving me the information that I need […] [With sound distance assistance,] I can figure out myself where it was coming from. I didn't have a hint, right? I could walk around and could find my way out".*

P4 also discussed the importance of fitting the tool's design into the aesthetics of the original app. For example, she pointed out that it would be a bad user experience "*if there is a game that's like Zelda and you're like in a valley on a horse and suddenly there's ping ping ping [sound notification]*". She urged to ensure that sound accessibility tools align with an app's aesthetic and interaction style, emphasizing that "*it's not [just] access, but also [...] access with artistry*".

4.5.5Combining Tools

Another interesting idea suggested by participants is to support combining tools to enable new functionalities. For example, one participant suggested combining the *keyword prioritization* (PT3) tool and the *shoulder localization helper* (SA2) tool to simultaneously direct her attention and help her locate the sound source. She said,

"When I hit a keyword like 'weather', it would have been helpful for me to be like, OK, which conversation are you supposed to join? [The shoulder localization helper would tell me to] Turn left or middle or right." (P3).

P5 suggested that the *keyword prioritization* (PT3) tool should have different notifications for different speakers, which can be achieved by combining it with the *custom feedback sound* (AS2) tool. Similarly, P6 suggested using *calming noise* (AS3) to blur the background sounds when the user is trying to focus on a single sound source using the *live listen helper* (SA5) tool. These suggestions imply that the tools should be designed to support integration–for example, by allowing one tool to evoke the functionality of another.

4.5.6Implications for Other Media Formats

Some participants (*N*=4) compared our tools with existing technology in other media formats such as PC games and phone apps. Although there has been research about sound modification and customization in other media (*e.g.*, [46, 54, 64]), its application is not universal. One participant said, "*I'd like to see this tool in many of the apps I normally use on my phone and my computer*" (P6). One participant mentioned how the mechanics of the *sound distance assistance* (SA4) tool would be useful in a game he could not play because of the lack of sound accessibility:

"There was a game I played a few years ago when there was something similar. [...] Your character is blind, and they're supposed to use sound to guide you so I was stuck on that level because I couldn't make out where the sound was coming from. So, I had to turn the game (brightness) all the way up to be able to see something and walk around to figure it out. Something like this (sound distance assistance) [...] would have been helpful in that kind of situation." (P7).

These comments highlight the possibility of applying SoundModVR tools to other media formats and to potentially support other sensory disabilities.

5 STUDY 2: PRELIMINARY EVALUATION WITH VR DEVELOPERS

To understand how VR developers may use our tools in their apps, we compiled a Unity toolkit with our tools and conducted a usability study with six experienced Unity VR developers.

5.1 SoundModVR Toolkit Design and Documentation

We have developed 18 tools–a number difficult to evaluate comprehensively in a developer-focused study. Since our focus was on testing developers' ability to integrate tools in their apps rather than each tool's specific functionalities, we chose to evaluate only half of them—nine out of the 18 tools. However, we note that our released toolkit includes all 18 tools: github.com/AccessibilityLab/SoundModVR.

To select the nine tools, we sorted the tool ratings from Study 1 and selected the top-rated one to two tools in each of the four categories. We also included two low-rated tools: *shoulder localization helper* (SA2) for its versatility across scenarios, and *keyword prioritization* tool (PT3), which works in conjunction with the highly-rated *group prioritization* tool (PT2).

We also made two other adjustments. First, we combined the *system frequency/volume adjustment* (PM1) and *sound volume/frequency adjustment* (PM2) into one tool, *frequency/volume adjustment* (PM6), because of their similar underlying functionality. Second, the *speech prioritization* (PT1) tool was renamed to *sound prioritization* (PT5) to expand its functionality to prioritize specific non-speech sounds as well. This suggestion was given by P7 in Study 1.

Our nine-tool toolkit included each tool's scripts and Unity audio mixer integration, an example unity scene implementing the tool's functionality, and documentation on each tool. This documentation provided an overview of the tools, usage recommendations, script(s) interface, implementation steps, and a demo video showing each tool's functionality. The toolkit was shared with developers on GitHub. Table 2 shows the details of each tool in the toolkit and the reimagined categories.

Table 2: The tools included in the Study 2 toolkit. The first row is the category; each row contains the corresponding tools.

Prioritization (PT)	**Parameter Modification (PM)**	**Spatial Assistance (SA)**	**Additional Sounds (AS)**
Group Prioritization (PT2)	Speech Speed Adjust (PM4)	Shoulder Localization Helper (SA2)	Smart Notifications (AS1)
Keyword Prioritization (PT3)	Frequency/Volume Adjust (PM6)	Live Listen Helper (SA5)	Custom Feedback Sound (AS2)
Sound Prioritization (PT5)			

5.2 Participants

We recruited six VR Developers (D1-D6, three men, two women, one non-binary) through word-of-mouth, email lists, and social media posts. The participants were 24.33 years old on average (*SD*=1.75). All participants were graduate students with an average Unity VR development experience of 3.58 years (*SD*=2.18). Only one participant had prior experience integrating accessibility in VR.

5.3 Procedure

The preliminary evaluation was conducted remotely and asynchronously by sharing written instructions with the developers and lasted about 60 to 90 minutes. The developers were instructed to download the toolkit, implement it in two of their personal Unity VR projects, and then complete a study questionnaire to rate their experience and respond to free-response questions. The rating questions covered the technical difficulty of implementing tools into projects (on a scale of 1-5, 5 being the hardest), difficulty with integrating toolkit into the conceptual design of the app (*e.g.*, what tools to use with what sounds) (1-5, 5 being the hardest), experience with debugging and testing (1-5, 5 being best), and the overall experience (1-5, 5 being best). The free-response questions asked about developer's tool choices for their apps, attitudes toward different tools, improvement suggestions, and thoughts about aesthetics, cognitive load, and fairness. To ensure that developers followed the study instructions, they were asked to record their screens during the implementation process.

5.4 Data Analysis

Our quantitative data consists of ratings in the study questionnaire completed by the participants. We used descriptive statistics to summarize the data, which included calculating the mean and standard deviation for the ratings regarding difficulty, debugging and testing, and experience.

To analyze the free-form responses, we followed Braun and Clarke's thematic analysis approach similar to Study 1 with a team of two coders [22]. One researcher skimmed the transcripts, generated the initial codebook, and coded the data while refining the codebook. Another researcher then used the final codebook to independently assign codes to the data. The average Krippendorff's alpha [36] was 0.92, and the raw agreement was 96.3%. Disagreements were resolved using mutual consensus. The final codebook contains 18 third-level codes, 6 second-level codes, and 2 first-level codes.

5.5 Findings

Our preliminary findings show that the participants found the nine-tool toolkit easy to use, but also suggested improvements such as modularization and better documentation. We also report on participants' considerations while implementing tools into their apps, such as tool choices, UI design, tool combinations, and approach towards fairness when using our accessibility tools.

5.5.1Technical Implementation of the Toolkit

The ratings show that the technical difficulty of implementing toolkits was low (average 1.83 on a scale of 1-5, 5 being the hardest). The participants also reported positive experiences with debugging, and had a good overall experience using the toolkit (average 3.83 and 4.33. respectively, on a scale of 1-5, 5 being best). Subjective comments from participants echo these high ratings. For example, P2 concluded the toolkit was "*pretty quick to learn how to use, and the documentation was very thorough*". Furthermore, five of the six participants indicated they would consider using the toolkit in future projects, while one participant expressed mixed feelings because of the increased workload.

Despite the positive reviews, participants expressed concerns about the toolkit's implementation workload. For instance, two participants mentioned that the tools increased the cognitive load during development. To enhance this aspect, most participants (*N*=5) said the toolkit could benefit from further modularization, including packaging tools into Unity prefabs [61] and providing visual elements like default UI inside the prefab.

We also learned that the documentation of certain tools may cause confusion. For example, D1 misunderstood the purpose of *frequency/volume adjustment* (PM6) and commented that he could "*already adjust the volume and pitch of audio sources and groups through code*", while the tool aims to enable end-user adjustment (not on the developer's end). D3 found it hard to determine the keywords for *keyword prioritization* (PT3) because they didn't know "*which words would be especially important for accessibility reasons*". Participants suggested documentation improvements such as beginner guidance, scenario-specific tool recommendations, and accessibility guidelines to alleviate these confusions.

5.5.2Integrating the Toolkit into App Design

Apart from technical implementation, participants also found it easy to incorporate the toolkit into the conceptual design of existing apps (*e.g.*, what tools to use with what sounds) (average 2.00 on a scale of 1-5, 5 being the hardest). D6 pointed out that "*the toolkit is simple to understand and implement and covered most parts of the audio [...]. Therefore, it is pretty well-rounded*".

Participants commented on how different tools improved specific applications. For instance, D4 highlighted that *keyword prioritization* (PT3) improved learning efficiency in his educational apps, while *group prioritization* (PT2) could benefit multi-user online chats. One participant mentioned that the *sound prioritization* (PT5) tool allowed him to have more variety in his background sound choice, saying,

> *"I always worry that when I mix the sounds together they won't fit. I've usually gotten around this by just making background sounds significantly less loud than effect sounds, or by turning off the background noise at certain times. I feel like the sound prioritization would give me more options for sound levels, and it feels like a cleaner solution than outright turning off sounds at certain times."*

In terms of the UI design of the tools, participants discussed methods to ensure usability. Many participants (*N*=4) believed that the UI needs to be simple and non-invasive. This means that both visual components like the buttons of the tools (Figure 2) and audio components like the tool notifications need to fit into the original app's design aesthetics. As D1 argued, "*It's important that the accessibility features feel like part of the app*". Some participants also suggested combining existing visual and haptic accessibility tools like audio description and vibration with our sound modification tools to further enhance the user experience.

Similar to DHH people in Study 1, participants also mention the possibility of combining tools to achieve expanded functionality. For example, D2 suggested that *frequency/volume adjustment* (PM6) could enable users to customize the volume change caused by *sound prioritization* (PT5). She also mentioned that developers could use the *sound prioritization* (PT5) tool to prioritize *shoulder localization helper* (SA2) hints.

Another consideration is how accessibility tools affect fairness in competitive apps. Some participants believed that the tools would not cause significant advantages. Others provided a different perspective, saying that other users could also benefit from the tools, like blind and low-vision people, or just about anyone. One participant emphasized getting feedback from a diverse user base. Another proposed enhancing developer awareness by including competitive advantage scenarios in the documentation. Overall, the participants mentioned diverse perspectives that could inform future accessibility technology design.

6 DISCUSSION

In a 2019 position paper, Mott *et al.* emphasized that virtual reality technology was in a critical position of emerging and near maturity, making it crucial to integrate cross-industry accessibility standards and guidelines to achieve "accessible by design" instead of leaving them as an afterthought [48]. The successful recent releases of commercial Mixed Reality products like Meta Quest 3 [85] and Apple Vision Pro [86] showcased VR's increasing popularity, further highlighting the need for comprehensive VR accessibility standards and toolkits. Previous work in VR sound accessibility has covered visual and haptic substitutions of sounds [27, 40, 44]. In this work, we explored using sound modification for VR sound accessibility. Some VR games and applications include sound accessibility features [68, 74, 75], but these are one-off efforts. We offered a more scalable approach by developing a toolkit that can be integrated into any VR app.

To our knowledge, this is the first toolkit that allows users and developers to modify sounds in VR to fit users with partial hearing. Our contributions include: (1) a set of 18 VR tools to manipulate and customize sounds in VR, (2) findings from a study with 10 DHH people across five common VR scenarios, and (3) preliminary insights from a study with six VR developers. Below, we reflect on further implications, key study limitations, and future work.

6.1 Combination of the Tools

In both Study 1 and Study 2, participants wanted to combine the tools for expanded functionality. Some tool functionalities might also overlap. This opens a new avenue for exploration. Expanding on our study findings, we suggest exploring the following methods of combining the tools:

One tool evokes another: This involves using one tool to trigger another that adds to the functionality of the first one. This rule will combine two tools in different categories. For example, having a *keyword prioritization* (PT3) notification trigger the *shoulder localization helper* (SA2) to reveal the keyword's sound source location, or having a *shoulder localization helper* (SA2) hint trigger the *sound prioritization* (PT5) functionality to prioritize the hint.

One tool is used to adjust another tool: A tool could be used to adjust the sound elements of another tool. For example, *frequency/volume adjustment* (PM6) can be used to change volume/frequency in any other tool that uses sounds, and the *custom feedback sound* (AS2) tool could be used to change the notification sounds in *keyword prioritization* (PT3).

Tools that counteract each other: If a scene incorporates multiple prioritization or notification tools, they should be combined into a hierarchical system. Careful design is needed to prevent conflict. For example, the volume of a sound in an unselected group could be suppressed by *group prioritization* (PT2), but *smart notification* (AS1) would revert its volume to the original if the developer deems it important.

6.2 Customization of the Tools

One of the main ideas of our sound modification tools is to give DHH users the power to modify and customize the sounds they experience in VR. However, participants in both the DHH user study and the developer study expressed the desire to customize the tools even further. For DHH users, this would mean customizing the amount of volume change used in the prioritization tools, ensuring an accessible frequency range for automatic or dynamic frequency-modifying tools like *sound distance assistance* (SA4), or changing the location of notification tools. For the developers, the customization mainly focuses on aesthetics and UI changes to fit the accessibility features seamlessly into the application. These suggestions point to further questions in customizing sound modification tools: (1) what are the dimensions of customization for these tools? (2) how to achieve balance between tool customization and simplicity of the interface? (3) how could customization of tools interfere with the design of the original application?

6.3 Selection of the Tools

The sounds that a developer, especially a hearing developer, considers important might not necessarily be important for a DHH person. For example, while the developer of the Rhythm Movement scenario in Study 1 considered the music to be vital in a rhythm movement game, the DHH users did not find the music to be an important part, but irrelevant or distracting. While developers are recommended to add a limited number of tools into an app to reduce confusion and overload, at the same time, they should understand which tools to choose for their app. Recognize that the actual experiences are unique to each app, we attempt to provide suggestions on the suitability of each tool for different situations in the toolkit description.

6.4 Artistry in Accessible Game Design

In terms of sound accessibility in VR games, as one participant put it, "*It's important to not just consider access, but [...] access with artistry*". It is crucial to provide accessible sounds, while also making the game still enjoyable. Study 1 findings provided some suggestions. For example, some DHH users compared the *sound distance assistance* (SA4) tool, which changes the pitch of the sound as the user moves closer to the source, and the *shoulder localization helper* (SA2), where the user is given hints of the location of the sound with an assistant voice saying "to your left" or "to your right". The two tools are trying to achieve similar goals of helping with navigation, but the results of the tool ratings and qualitative interview showed that *sound distance assistance* (SA4) is preferred because "*the [sound] distance assistance was giving [...] all the information that [shoulder] localization [helper] is giving [...] in a way that was more fun*" (P7).

6.5 Limitations and Future Work

We acknowledge not all DHH people will benefit from enhanced sounds, including people with profound hearing loss and people who are reluctant to use sound information. Nevertheless, based on the diversity of the community [11] and the experience of our hard-of-hearing coauthor, we argue that many DHH users could benefit from our work. Nevertheless, future work should continue to study our toolkit with the larger DHH population to further refine and consider diverse perspectives.

Furthermore, although our VR scenarios covered a wide range of applications, we do not claim that they are exhaustive. Indeed, some VR app genres (*e.g.*, educational and meditation) are not included in our scenarios. We welcome future work to extend the idea of VR sound modification into more diverse scenarios.

While our study 1 findings revealed diverse patterns and suggestions, we conducted a lab evaluation and only with 10 participants. Future research could expand on our work and conduct a before-and-after study with our system as well as a longitudinal qualitative evaluation to better validate and extend our findings.

Lastly, we identify Study 2 as a preliminary evaluation due to its remote nature and small participant sample (6 developers). Future work should further expand our toolkit and evaluate it through real-world studies with a greater range of VR developers.

7 CONCLUSION

Our work contributes to the first study of sound modification techniques to help sound accessibility in VR environments. The evaluation of our 18 tools in different genres of VR applications shows this method improves the VR experience for DHH users. The evaluation of the Unity toolkit that consists of select tools shows that the toolkit is easy to use, test, debug, and integrate. As DHH users revealed in our interviews, the sound accessibility technology currently is very generalized, and the ability to modify sounds to personalize the experience would lead to better user experiences for DHH as well as users with other disabilities, not only for VR contexts, but also for other media such as PC games and phone apps.

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