Exploring Deaf And Hard of Hearing Peoples' Perspectives On Tasks In Augmented Reality: Interacting With 3D Objects And Instructional Comprehension

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Abstract

Tasks in augmented reality (AR), such as 3D interaction and instructional comprehension, are often designed for users with uniform sensory abilities. Such an approach, however, can overlook the more nuanced needs of Deaf and Hard of Hearing (DHH) users who might have reduced auditory perception. To better understand these challenges, our study utilized the single-player AR game *Angry Birds AR* as a probe to explore how 11 DHH participants and 15 hearing participants experienced AR interactions. Our findings highlight that DHH users prefer interaction based on context, effective haptic cues, audio cue substitutes, and clear instructional design. We, therefore, propose the following design recommendations to enhance the accessibility of AR for DHH users. This includes customizable UI options, modular feedback systems, and virtual avatars for sign language instructions.

CCS Concepts

• **Human-centered computing → Empirical studies in accessibility**.

Keywords

Deaf and Hard of Hearing; Augmented Reality; Accessibility; Accessible AR

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1 Introduction

With the rise of augmented reality (AR) in various research and application areas (i.e., education [78], healthcare [14, 81], training [47, 48], entertainment [29], etc.), the range of tasks that users can perform within these AR-based environments has expanded significantly. Tasks such as interacting with and manipulating 3D objects, as well as comprehending and following instructions in AR, are becoming increasingly prevalent, requiring users to position and adjust 3D objects within the physical environment [6] while adapting to real-time modifications of instructions [17, 18]. In short, tasks in AR are often sensory-intensive, requiring users to interpret visual, auditory, and haptic cues while adapting to changes in both the physical surroundings and the digital overlays. Additionally, users must maintain spatial awareness of the real environment while interacting with virtual elements. These tasks also seem to be predicated on the assumption that all users have a similar level of

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perception (visual, auditory, haptic, etc.). This assumption, however, may not hold true for Deaf and Hard of Hearing (DHH) people, who may rely more heavily on another sense (e.g., visual or haptic) due to hearing loss [20]. In addition, such tasks demand a high level of attention, requiring users to process multiple streams of information simultaneously, such as digital overlays, physical surroundings, and contextual cues.

Relying on fewer senses increases cognitive load [68], leading to distinct experiences for DHH users compared to their hearing peers in AR tasks. DHH people often encounter unique challenges when performing tasks that involve competing attention demands, such as observing someone sign in physical or digital settings, comprehending specific audio cues [80], relying more on visual and haptic cues [59], and maintaining spatial awareness [42]. DHH people may face similar or greater challenges in AR when interacting with 3D objects and understanding instructions, as AR combines the physical environment with virtual elements. Current research on AR and DHH users primarily focuses on two key areas. First, it addresses the facilitation of communication between DHH people and their hearing peers, who are often unfamiliar with visual languages [31, 55] like sign languages. Second, it explores ways to enhance situational awareness for DHH users [25, 64].

Though these areas are important, there is a lack of research on the experiences of DHH users and the challenges they face while performing tasks in AR environments. As a result, the under-explored experiences of users and the challenges they face could impact task performance and the comprehensive engagement of DHH users in various AR environments, including education, training, and entertainment. In other words, these challenges are not negligible. Fully understanding the experiences and identifying the challenges faced by DHH people in AR environments is crucial for the development of accessible multisensory experiences, which forms the exigency of this study. This is particularly important given that DHH people constitute over 5% (430 million) of the global population [61]. By recognizing and addressing these challenges, the risk of a digital divide can be minimised [75], which might otherwise marginalize the DHH user base, preventing these users from fully adopting and benefiting from sensory-rich technologies such as AR. Moreover, determining and resolving the challenges will pave the way for new opportunities in learning, training, entertainment, and employment that relate to AR-based technologies for the DHH community.

Our study explores the experiences of 11 DHH participants and 15 hearing participants while playing a single-player mobile AR game, *Angry Birds AR* , used as a research probe[1]. The comparative nature of our research enriched the contextual understanding of our findings. Seven DHH participants preferred spoken English, while four used American Sign Language (ASL), whereas all hearing participants used spoken English instructions. Participants played seven rounds of the game across both private and public settings.

Using reflexive thematic analysis (RTA) [9], we examined participants' lived experiences in relation to AR interaction designs. DHH participants provided crucial insights into challenges such as interacting with 3D objects and interpreting instructions. The inclusion of hearing participants helped to shed light on design decisions tailored for non-DHH users, thereby further highlighting the accessibility barriers faced by DHH people in AR. This approach allowed us to recognize the unique experiences of DHH players and inform a series of design recommendations to enhance AR accessibility.

Our research identified and contextualized the unique experiences and challenges that DHH users face in AR environments. These challenges are distinct from those of traditional digital interfaces, such as web and app interfaces on smartphones, tablets, and computers, as well as dashboard interfaces in vehicles. Unlike these systems, AR requires interaction with both physical and virtual elements, significantly increasing cognitive load for DHH users. In our study, DHH participants shifted focus between immersion and spatial awareness based on their surroundings, sought timely haptic feedback and audio substitutes, and faced difficulties with brief instructions and action outcomes. These findings offer insights for designing AR to meet DHH user needs. Future research could extend these insights to non-gaming applications, including education, entertainment, training, and industrial fields like construction and manufacturing.

The key contributions made by our work are as follows:

(1) An exploration of experiences and challenges DHH users face in AR while performing tasks related to interacting with and manipulating AR, and comprehending and following instructions. We specifically demonstrate:
   (a) The approaches DHH people prefer for interacting with and manipulating 3D objects in AR, and the factors influencing those preferences.
   (b) How haptic cues and background sound enhance AR immersion for DHH people, especially for those who have residual hearing and can process sound.
   (c) How DHH people perceive and prefer instructional guidance in AR.
   (d) The challenges DHH people face when understanding the outcomes of their actions after following instructions in AR.
(2) Design implications to address the identified challenges of DHH people. For example, customizable UI options, closed captions and multimodal feedback to enhance conveying the state of dynamic AR environments, modular feedback systems, virtual avatars to provide instructions through visual language, etc., to enhance accessibility, immersion, and task performance in AR.

2 Background and Related Work

2.1 Tasks in AR

Manipulating and interacting with 3D objects is a widely performed task in AR. Prior work related to manipulating and interacting with 3D objects focuses on optimizing intuitive interactions across various contexts. For instance, tangible user interfaces [6] and hand gesture-based interaction methods [45] were found to be more natural and precise for manipulating 3D objects in AR, as compared to traditional input devices. Intuitive interaction methods [63] and context-awareness [63] in AR can significantly enhance productivity in industrial maintenance, where workers interact with 3D

[1]Here we refer to a probe as a tool for collecting data [7].

models of machinery parts. Similarly, AR has effectively supported teaching complex concepts in education [65].

The usability and effectiveness of AR applications require the users to comprehend and follow instructions in AR. Being able to use AR applications effectively is essential for various application areas, which can focus on navigation, training, maintenance, and education. AR can transform traditional learning environments by improving instruction with interactive and engaging content, making it more intuitive and accessible [17, 18]. In industrial-based tasks, AR instructions improve the accuracy and speed of assembly processes by reducing cognitive load and minimizing errors [28]. Additionally, AR documentation has been proposed to improve instruction clarity in industrial settings [23].

While the research discussed in Section 2.1 offers valuable insight into AR tasks, they presumed uniform sensory capabilities, such as visual, auditory, haptic, etc., among users and did not consider DHH users as their demographic. However, DHH participants, relying more on visual or haptic senses due to hearing loss, may experience tasks differently and face access barriers. Accordingly, there is a pressing need for further scholarly attention to the experiences and challenges of DHH users in AR.

2.2 DHH-Focused Interaction Designs

DHH people often require or prefer assistive environments and features while interacting with or using digital media or technology. Deaf signers, for instance, prefer using sign language but often face challenges with video content due to the lack of captions in signed videos [52]. To address this issue, design elements such as improved captioning practices, visual communication tools like emojis, GIFs, and ASL-specific enhancements have been identified as effective solutions. Additionally, DHH users desire detailed information about non-speech sounds [36], however, require a balance to avoid potential distractions [3]. Proposed design strategies include multimodal captions with text and graphics, context-aware systems, and user-centric designs prioritizing accessibility. Additionally, DHH users prefer device-specific feedback, such as haptic feedback on wearables and visual feedback on smartphones, emphasizing the need for feedback systems tailored to each device [20].

Prior research has explored accommodating DHH requirements across media, including smartphones, web applications, smartwatches, and HMDs. Studies have substituted sounds in VR with visual and haptic feedback [35] and refined mobile sound recognition systems for diverse environments [15, 34]. Combining visual and haptic feedback on wearables like smartwatches has effectively conveyed sound direction, loudness, and identity [24]. HMD visualizations help DHH users locate sounds spatially [32], while haptics in VR aid in identifying sound direction [54].

Researchers have addressed accessibility in collaborative environments like teleconferences, requiring features beyond captions and interpreters [43]. Design recommendations include multimodal options such as captioning, interpreters, transcripts, and simplified interfaces to reduce cognitive load. Studies involving DHH users emphasized visual hierarchy and fixed visual cues to enhance accessibility in video conferencing [40]. Additionally, HMD captions in mobile contexts, such as walking, improved communication access and attentional balance [33].

Similarly, research on e-learning platforms for DHH users recommends features like automated video recording and seamless integration of sign language interpreters [12]. Efforts to improve web accessibility have focused on sign language incorporation, multimodal feedback, and user-centered, customizable interfaces [13, 37]. Accessibility enhancements have also been explored for museums [39] and live theaters [72]. These studies highlight the importance of multimodal feedback, user-centric designs, and reducing the cognitive load to support DHH users effectively.

Due to reduced auditory access, DHH people experience and perform tasks differently across physical and virtual environments. Previous research has sought to understand their unique challenges and needs, aiming to make these environments more accessible. Across these diverse contexts, the recurring themes of adaptability, multimodal designs, and cognitive simplicity form the foundation for accessible solutions tailored to the needs of DHH people. However, AR remains under explored regarding DHH experiences, particularly concerning 3D interaction and instructional comprehension tasks. This oversight risks alienating the DHH community in the design of AR environments.

2.3 AR for DHH Users

AR has effectively developed assistive environments for DHH users, improving their awareness of their surroundings and real time interactions in diverse contexts like entertainment [76], education [30, 51, 71, 79], vocational training [60], etc. Additionally, AR has facilitated communication between DHH people and hearing peers who are not proficient in visual languages such as sign language. As a result, real-time captioning using AR has emerged as a prominent trend in the current literature on AR for DHH users. For example, AR integrated with automatic speech recognition (ASR) and text-to-speech synthesis (TTS) can provide live captions in real-time for DHH users [55]. Recent studies have focused on delivering real-time captioning for users utilizing AR [31, 70], with features such as customizable shapes, numbers, and placement of captions in 3D space. Some of these studies involved DHH users in co-designing systems to optimize content length, sequence, and visualization of speech from different speakers, even when out of view [64]. Additionally, certain studies have explored classifying and visualizing sound identity and location alongside speech transcription [4, 25], aiming to enhance the spatial awareness of DHH users.

Moreover, using virtual agents [38, 51, 76] within the user's field of view represents another effort to create accommodating environments for DHH users. Depending on the context, these agents function as real-time speech-to-sign language translators. Research has increasingly focused on modes of interpretation, user-preferred customization options, implementation, design, and the accuracy of these systems. Furthermore, existing studies have explored the potential of AR to facilitate accessible communication for DHH users. These investigations have ranged from utilizing smart speakers in home settings [53] to fostering collaboration among DHH people with diverse hearing abilities and communication methods within AR environments [50] AR has also been employed to develop a multi-modal communication system that integrates sign language translation, speech recognition, and shared object manipulation in a mobile AR environment [46].

Task Scenerios	In-game Actions
Interacting With and Manipulating 3D Objects	Players can either physically move around the AR structure or use on-screen UI buttons to rotate it and view it from various angles. By moving closer or farther from the AR structure, they can zoom in or out for different perspectives. To target pigs on the tower, players tap the screen to pull the AR slingshot (Figure 1). The game engages players with a combination of visual, audio, and haptic feedback throughout the gameplay.
Comprehending and Following Instructions	The game offers players a few textual instructions, such as how to place the AR structure (Figure 2a, 2b, and 2c), how to use UI elements to manipulate the view (Figure 2d), and introduce new game elements as they appear (Figure 2e and 2f). Additionally, the game provides visual instructions, like indicating where the bird might land with a dotted path when pulling the slingshot and prompting the player to tap on the screen when idle for a certain period. These instructions assist players in better understanding the game mechanics and elements.

Table 1: In-game actions that are mapped with our selected tasks

Several of the studies mentioned in section 2.3 require DHH users to engage in tasks involving interaction with 3D elements [25, 46, 64]. Although these studies successfully created accommodating environments for DHH people, researchers did not specifically focus on the experiences of DHH participants or identify their challenges while performing these tasks.

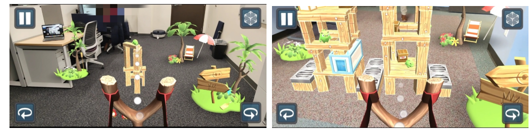
3 Method

3.1 Data Collection

We divided our study into two segments: (i) gameplay, followed by short interviews, and (ii) one-on-one interviews. For the gameplay segment, we used "*Angry Birds AR*" [67] as the probe, a single-player AR game with a first-person perspective. We selected this game particularly for its simplicity and suitability for players with audio-related access requirements, as it does not rely on sound cues to convey critical information. Given that a portion of our participants were DHH, it was crucial to use a game that did not rely heavily on audio cues, which could have hindered their ability to participate fully. While the game involves relatively simple tasks, this choice allowed all participants to focus on the AR interaction, minimizing the potential confound of varying audio accessibility and ensuring inclusive participation. The game starts by instructing the player to find a flat surface to position the AR island. The player has to use a slingshot to launch birds at wooden towers inhabited by pigs, aiming to topple all the pigs. Each level gives players three birds, and players win by eliminating all the pigs.

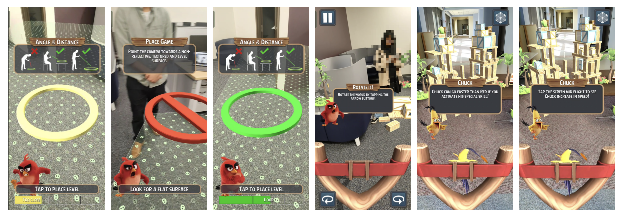
The player must complete the current level before progressing to the next level. Table 1 represents our task scenarios mapped with the in-game actions.

3.1.1 Participants. We promoted our study by distributing flyers at a local college and sending emails to students and staffs. Interested people were directed to complete an online "Participant Registration" form (see Supplementary Materials, Section 1). We aimed



(a) **(b)**

Figure 1: Player is holding the slingshot with a bird to shoot in (a) private setting, and (b) public setting. The white dots show projectile paths where the bird might land. Two UI elements (buttons) in the bottom with directional arrows indicating which way (left and right) it can rotate the structure.



(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 2: Interfaces of *Angry Birds AR* providing instructions to the player. The game instructs the player (a) to look for a space in a further position, (b) to look for a flat space, and (c) the space is good enough for AR placement, (d) about UI elements to manipulate 3D view, (e) about new game element (yellow bird), and (f) about how to use (tap to increase speed) the new element.

to recruit an equal number of DHH and hearing participants to ensure balanced representation. Initially, we received responses from 20 DHH people (self-identified) and 31 hearing persons. To maintain balance, we contacted the first 20 hearing respondents and all 20 DHH respondents to confirm their availability for the study. Despite our best efforts, only nine DHH and 15 hearing people confirmed their participation initially. Recognizing the importance of a robust DHH sample, we re-contacted the remaining 11 DHH respondents who had expressed initial interest but had not yet confirmed availability. Our additional outreach resulted in two more DHH participants joining the study. While we prioritized inclusive recruitment, the final sample was shaped by the availability and willingness of participants. The difference in participant numbers arose from recruitment challenges, particularly in reaching DHH people who were both interested and available to participate.

A total of 26 participants, consisting of 11 DHH and 15 hearing people aged 18 to 59, took part in our study. Of the DHH participants, eight were hard of hearing and three were deaf. Seven DHH participants preferred spoken English, while four preferred American Sign Language (ASL). All of the hearing participants preferred spoken English as their primary mode of communication. In post-gameplay interviews, we discovered that while all participants were familiar with the 2D version of the selected game, none had prior experience with its AR version. Participants' AR expertise varied from novice to expert, as indicated in their registration responses.

For further details on participant demographics, please refer to Appendix A.

3.1.2 Procedure. For our study, we employed contextual inquiry [41], where the participants gained firsthand experience through gameplay, followed by a brief structured interview [1] and an extended semi-structured interview [22]. In the interviews we asked them about their gameplay experiences and challenges.

Participants were provided with an Android device (smartphone, Realme 8 Pro (RMX3081) with a 6.4-inch screen) with *Angry Birds AR* installed, and they played seven levels of the game. The default settings of the game, including sound, music, and vibration, were enabled and participants could adjust them according to their requirements. They had the freedom to explore the levels and strategize as they wished. For participants who preferred ASL, we arranged for an interpreter to facilitate communication between the researchers and the participants, informing the participants beforehand of the interpreter's presence. We obtained verbal consent from participants to video and audio record their gameplay, and the short and long interviews. We implemented the think-aloud method [19] during the gameplay, where we instructed the participants to speak loudly or sign their in-game actions while playing. This approach allowed us to gain a clearer understanding of their immediate reactions and in-game decisions. In addition, they were asked to record the screen of their devices during the game.

The first three rounds took place in a private lab setting. There were few pieces of furniture and the space was artificially lit. The next four levels took place in a public indoor hallway, with few pieces of furniture. However, the second space was wider compared to the first one and was naturally lit. We decided to conduct the study in two locations, including a public hallway, to simulate realistic environments where users commonly engage with mobile AR games [62, 66]. Public spaces were chosen to reflect typical user behavior, as many players often play mobile games in outdoor or semi-public areas where secluded environments are not accessible [2, 26]. We documented their actions during the gameplay for later observational analysis. After each participant completed their gameplay session, the game progress was reset to ensure that the next player would receive all instructions from the beginning.

It is important to note that, while all participants completed the seven levels of the game, their experiences varied in terms of ease of use and accessibility. We intentionally chose this game as our probe as it had relatively simple tasks and mechanics to ensure inclusivity, however, this did not mean that every participant found each level equally straightforward. Certain levels introduced new features, instructions, and interaction methods, which occasionally required participants to adapt and learn. To support participants and allow them to fully engage with the game, we provided the flexibility to replay levels as needed. This ensured they could progress at their own pace without feeling rushed, allowing them to overcome any challenges they faced. Although we did not track the exact number of times participants replayed levels, this approach enabled them to fully experience and complete all levels, regardless of any initial difficulties. Including this flexibility helped us gather richer data on user interaction and accessibility without imposing time constraints or pressure, aligning with the study's focus on understanding user experience comprehensively. This context provides a fuller understanding of participants' ease of use perceptions and how they navigated the game's challenges.

After the gameplay, the participants returned to the lab and participated in a short structured interview, during which we asked them about their first impression of the game, which space they preferred and why, features of the game they liked and why, and features they wanted to change or add and why (see, Supplementary Materials, section 2). Participants joined a longer semi-structured interview at a later time which was conducted online over Zoom [82]. During this session, we asked more about their gameplay experiences, the challenges they encountered, and their suggestions for overcoming these challenges (see, Supplementary Materials, section 3). We constructed a semi-structured interview that we tailored according to our observational notes of each participant during gameplay, screen recordings of the game, audio and video recordings of the participants, and their responses during the short structured interview. An interpreter was also present for ASL users (4/26) during this session. Participants were compensated with a $50 e-gift card for their time.

3.2 Data Analysis

In our data analysis, we used data triangulation [73] by integrating data from gameplay sessions, screen recordings, interview recordings, and observational notes. The primary source of our qualitative data was the cleaned interview data, both the short and long ones.

We conducted short structured interviews, lasting approximately five to ten minutes, immediately following gameplay to gather participants' immediate reactions to specific gameplay scenarios (as detailed in Table 1). The timing of these interviews was crucial to minimize the risk of participants forgetting key details about their experience, interactions, or environmental influences on gameplay. By focusing on task-specific feedback, such as ease of interaction, preferences for game features, and environmental effects, these interviews provided context-rich, detailed data while the experience was still fresh in participants' minds. The structured nature of these interviews further ensured consistency in capturing task-specific insights across participants.

In contrast, the long semi-structured interviews were conducted at a later time to allow participants deeper reflection on their overall gaming experience, as stepping away from an activity fosters greater introspection, enabling more thoughtful and comprehensive insights [74]. This timing allowed participants to move beyond the immediacy of task-specific details and consider broader themes, such as their general impressions of AR technology, accessibility challenges, and recommendations for improving AR interfaces. These interviews, which were significantly longer in duration (40 to 60 minutes), provided a flexible and open-ended format, encouraging participants to unpack their experiences in greater depth. This approach enabled us, as researchers, to gain a more holistic understanding of their perspectives, capturing nuances that might not have surfaced in the immediate post-gameplay context.

We conducted reflexive thematic analysis (RTA) using NVivo [49], integrating both semantic and latent approaches. Semantic codes were derived directly from participants' explicit responses in both interview formats. For instance, short interviews yielded task-specific codes like "preference for rotation feature on UI" or "suggestions for appropriately placed haptic cues," while long interviews provided broader themes such as "confusion in understanding instructions" or "need for sound-independent feedback."

We developed the latent codes by analyzing observational notes, gameplay recordings, and screen recordings with participants' explicit responses, capturing deeper insights and underlying patterns not immediately apparent from verbal data alone. This triangulation allowed us to identify gaps in participants' perceptions and actual gameplay dynamics. For instance, a few DHH participants reported believing that their actions had no consequences in the final level of the game. However, our analysis of screen recordings showed that consequences were present but were subtly conveyed through audio and visual cues.

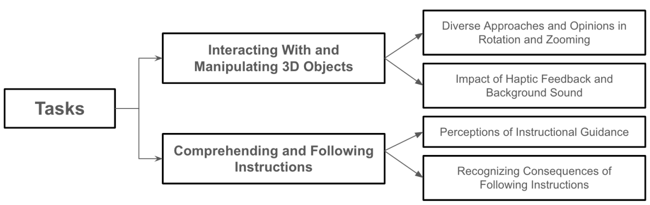


Figure 3: Thematic map derived from analysis of acquired data.

Initially, we generated 279 codes across both types of interviews. After several iterations, we refined these codes to 174, forming the basis of our thematic map (Figure 3).

4 Findings

4.1 Interacting With and Manipulating 3D Objects

4.1.1 Diverse Approaches and Opinions in Rotation and Zooming. Participants could physically move around the AR structures in the game to get a 3D view of it and rotate the AR structure using UI buttons present on the interface, which were introduced with textual instruction after the first two levels of the game. They could also use the slingshot to shoot the birds from any position. A white-dotted projectile path would appear to show the player a possible space where the bird might land. Additionally, the game did not have any UI options for zooming in to the 3D objects, and the player has to physically move back and forth to zoom in or out of the AR view.

Initially, researchers let participants know that they could move around the AR structure to have a 3D view. When they started playing the game in the private lab setting, all of them (26/26) physically moved around the AR structures to have views of them from different angles. They also moved back and forth to achieve the desired level of zoomed-in or out views. DHH (8/11) and hearing (12/15) participants appreciated that the AR environment gave them a sense of immersion. For instance, P09 (DHH) stated,

> "It was a lot like VR and I felt the characters are real." [P09, DHH]

P16 (non-DHH) further stated,

> "I felt that I was in the game and I even tried to touch the island at one point" [P16, non-DHH]

When the rotate feature was introduced, most of them (19/26; 7/11 DHH, 13/15 non-DHH) used it. We also observed that both DHH and hearing participants used a mixed approach of moving around AR structures and using the UI buttons. When asked about the reason for using the combination of physical movement and UI options, they stated that they wanted to try the newly introduced feature, along with the immersive experience. P26 (DHH) explained,

> "I think the options [physically moving and UI buttons] are really cool. When it [rotation feature] came up, I wanted to see what it did. But I still really liked that you can walk around island [AR structures]." [P26, DHH]

P11 (non-DHH) further stated,

> "I noticed those buttons on the screen from the beginning of the game but didn't know what to do with them. But when I got what they were meant for, I used them for the next levels. [...] But I wouldn't give up the walk-and-see [physically moving around AR] version either because it gives you the 3D effect." [P11, non-DHH]

While they had to fix their position or move back and forth in this phase as well to zoom in or out of the AR structures, participants did not mention anything special about it.

Interestingly, when participants played the game in the public hallway, we observed differences in the gameplay interactions between our DHH and hearing participants. We observed that most of the DHH (9/11) participants remained in one place and used the rotation feature on the UI to look around the AR structures to look for targets. However, they were seen fixing their positions and moving their upper body and hand to achieve desired zoomed-in or out views of AR. As the reason for their choice, they stated that staying stationary gave them a better view of their surroundings, especially in a public setting where people were moving around them. P12 (DHH) stated,

> "I am generally mindful of others' presence when I am outside. The rotation option let me play without moving and so I did that. It wasn't the same as when I was walking around it [AR structure]. [...] I could also see if people were coming my way or not." [P12, DHH]

Moreover, most of the hearing participants (10/15) were seen utilizing a combination of both physical movement and rotation features as they did in the private setting. We also observed one hearing participant using physical movement even after colliding with a non-player. When we wanted to know the reason behind their choice, they explained that they preferred the immersive nature of the game in AR, rather than the stationary gameplay. P06 (non-DHH) further explained,

> "Isn't that the point of AR? I mean I had the option to not move, but that would just make it like any other game. I used the buttons [rotation feature] and I liked it, but the option for moving around made it more real for me." [P06, non-DHH]

We further asked the DHH participants who preferred using UI options rather than physical movement in public space whether they would prefer a complete stationary AR experience, which was not possible due to the games' nature as they had to move for zoomed in or out views. We found varying opinions where a few (3/11) wanted UI options for the zooming mechanism; others (3/11) felt it would clutter the screen, make the UI more complex, and expressed they were satisfied with the current zooming mechanism; while a few other (2/11) thought there should be customizable options for how many UI elements the user want to cater to the specific users' requirement.

Moreover, a few hearing participants(4/15) preferred complete stationary gameplay in both private and public settings as they are generally used to being stationary while playing games. They even expressed frustration when they had to move to achieve the desired level of zoom or focus and felt the necessity of UI elements for the zooming feature. We also observed opposing opinions stating concerns about potential "clutter on the screen" (P20, non-DHH) or perceived "cheating" (P11, non-DHH) if zooming capabilities were introduced on UI.

4.1.2 Impact of Haptic Feedback and Background Sound. While participants shot birds with a slingshot, all the participants (26/26) could feel the pull force of the slingshot through haptic feedback (vibration) as they tapped on the screen to pull it. The game did not have any other haptic feedback in any place apart from the mentioned one. However, few of the DHH participants (5/11) raised concerns about placements of haptic feedback. For instance, P26 (DHH) expressed that they did not feel any vibration during gameplay,

> "I remember seeing a vibration option in the setting, and it was turned on. But now that I think about it, I don't remember if I felt any vibration at any point." [P26, DHH]

A similar sentiment was shared by P01 (DHH), who stated,

> "I don't think I felt any vibration at any point. [...] If I could choose the placement [of vibration], I would place them [vibration] when the tower falls down." [P01, DHH]

However, upon reviewing the screen recordings of both P01 and P26, it was confirmed that all default settings, including sound, music, and vibration, were enabled. Additionally, P24 (DHH) pointed out concerns about the placement of vibrations,

> "I felt the vibration but they did not have any [vibration] when the tower crashed, or I shoot the birds. I think those are some places where they could have some [vibration]." [P24, DHH]

Similarly, P09 (DHH) noted,

> "I felt a faint vibration when I pulled the bird [with slingshot], but the bird hits the pigs, there aren't any [vibration]. If there is a buzz [vibration] when the bird hits the pigs, I can feel I am doing a good job in the game." [P09, DHH]

We did not observe any significant challenges among hearing participants regarding haptic cues. However, few of them (5/15) noted that vibration could add a new dimension to the gaming experience, making task feedback more impactful and immersive.

A portion of the participants (11/26), both DHH (4/11) and non-DHH (7/15) participants, described the positive impact of background sound in enhancing their task experience, sense of immersion, and engagement within the AR environment. Audio cues, such as the sound of pulling back the bird in a slingshot, targets (pigs) falling down, etc., provided valuable feedback and guidance, reinforcing correct actions and contributing to the overall immersive experience. For instance, P17 (DHH) stated his reliance on subtle audio cues,

> "I think it (audio cues) was important. Cause I'm a hard of hearing student, so I rely on these little cues a lot. Like the bricks falling down or the birds making noise. I think it really improved the gameplay" [P17, DHH]

Moreover, a portion of the participants (8/26; 3/11 DHH, 5/15 non-DHH), stated audio cues did not play any significant role in enhancing their experience. Unsurprisingly, those DHH participants had little to no residual hearing, and thus, they could not perceive audio cues at all. On the other hand, hearing participants reported they either "did not pay much attention to it" [P18, non-DHH] or "did not find them important," [P21, non-DHH] which suggests the necessity of more impactful audio cues.

4.2 Comprehending and Following Instructions

4.2.1 Perceptions of Instructional Guidance. Participants in the study were presented with instructions throughout the game of *Angry Birds AR* predominantly in textual format. Instructions were given at several key stages: before the game commenced to guide players on placing the AR structure, after the second round to introduce the rotate function, and before the seventh and final round to introduce a new game element.

These instructions were perceived positively by a majority of both DHH (7/11) and hearing (11/15) participants, who described them as "sufficient" (1/7 DHH, 2/11 hearing), "helpful" (3/7 DHH, 4/11 hearing), and "easy to follow" (2/7 DHH, 4/11 hearing). These participants acknowledged that the instructions were prominently displayed and facilitated their progress through the game. However, some participants (7/16; 3/11 DHH, 4/15 non-DHH) expressed that the game lacked necessary instructions and those that were included, were not prominent enough for them to notice. For instance, the game lacked explicit instructions about physical movement, although researchers informed participants that they could move around AR objects to view them from different angles. Regarding the lack of instructions about physical movements, P10 (non-DHH) stated,

> "I didn't understand at first that I could walk around the structure to see all sides of it, because there [in the game] were nothing about it. But then you [researchers] told me about it." [P10, non-DHH]

P15 (DHH) further stated,

> "I am not too familiar with AR, and without you [researchers] telling me, I probably wouldn't have noticed that." [P15, DHH]

Moreover, P01 (DHH) stated about not noticing any instruction throughout the game,

> "I don't think I remember seeing any instructions apart from the beginning. [...] Maybe they disappeared too quickly before I noticed." [P01, DHH]

Subsequent analysis of participants' screen recordings further indicated that instructions, while present, were displayed only briefly, often when participants were deeply engaged in gameplay.

4.2.2 Recognizing Consequences of Following Instructions. Before the final round a new game element [new bird] is introduced and the player is instructed to double-tap on the screen to make the bird go faster. As the bird goes faster, it emits a subtle auditory cue (i.e., a "whoosh" sound) and a visual cue (i.e., a vapor trail) indicating increased speed.

Notably, some DHH participants (4/11) reported following the explicit instruction to double-tap the bird to make it fly faster in the final round but could not grasp the impact of this action. P26 (DHH) noted,

> "The 2D version has a third-person view and you can see the bird flying faster. But in this game, it didn't look like it was going faster." [P26, DHH]

However, we confirmed from the screen recordings that the auditory and visual cues from the bird were indeed present. We further asked these participants what they thought might be the reason behind not catching the consequences of their actions in AR, and all of them stated they did not notice the visual cue or the sound effect. P24 was surprised and said,

> "They [visual and sound cue] were [present]? I definitely couldn't tell. [...] Also maybe they were on the screen for very shortly." [P24, DHH]

When we asked non-DHH participants about the same phenomena, most of them (11/15) agreed they could recognize the impact of their actions. P05 stated,

> "You can't directly see if it's going fast, but I got it because it left smoke as it was going and I noticed a very low sound." [P05, non-DHH]

Responses from DHH participants made it more clear that visual cues articulating the consequences of their actions did not remain long enough on the screen for them to recognize. Moreover, similar to the scenario mentioned in Section 4.1.2, these DHH participants might have faced challenges in perceiving audio cues in this context as well. Furthermore, we also observed that a few of these participants (2/4) did not use the double tap method at all when they were shooting their very last bird.

5 Discussion

5.1 Mobile vs. Stationary AR Interactions

The design of the AR probe we used intentionally encouraged physical interactions, such as moving around AR structures to gain a 3D perspective and adjusting positions to zoom in or out. This design choice was intended to enhance the sense of immersion, a goal of AR [57] that was largely achieved, as evidenced by both DHH and hearing participants' appreciation for the immersive experience. Notably, DHH participants highlighted the game's immersive quality as comparable to VR, emphasizing the potential of AR to offer rich, multisensory experiences without relying on auditory cues. This finding reinforces the importance of physical interaction as an accessible method for enhancing immersion, particularly for users who may not benefit from auditory feedback. By leveraging spatial movement, AR can create inclusive environments where all users feel equally engaged.

Our study identified distinct interaction preferences influenced by the context of play. In private settings, both DHH and hearing participants actively used physical movement to explore AR environments. However, in public spaces, DHH participants favored UI rotation for navigating AR structures, prioritizing spatial awareness and safety. Conversely, hearing participants in public continued combining physical movement and UI rotation, valuing the immersive aspects of AR despite occasional collisions. These findings draw attention to how public environments shape interaction styles, with DHH users focusing on situational awareness and hearing users prioritizing immersion.

The introduction of the UI rotation feature offered an alternative means of interaction, complementing physical movement. This feature was well-received, demonstrating that users appreciate having multiple interaction options. However, the absence of a UI-based zooming mechanism caused mixed reactions. While some DHH participants expressed a preference for such a feature, particularly in public settings, others raised concerns about screen clutter and increased complexity. These divergent opinions underscore the need for customizable UI elements in AR games. Offering users the flexibility to enable or disable certain features based on their preferences and context of use could enhance both usability and accessibility. This approach aligns with the broader trend of user-centric design, which prioritizes adaptability to cater to diverse needs [10].

5.2 Requirement For Effective Haptic Cues and Audio Substitutes

The AR game's haptic feedback, intended to simulate the physical force of the slingshot, received mixed responses. While it enhanced the tactile experience for some participants, others—particularly among the DHH group—reported inconsistencies. Some DHH participants noted that they either did not feel the vibration or found its placement inadequate, especially during key game moments like the tower crashing or bird launches. It is important to note that these inconsistencies were not caused by the limitations of the device, which is capable of robust haptic feedback, but by how the game was programmed to use this feature. This highlights the need for robust, strategically placed haptic cues, especially for users relying on non-auditory feedback. Future AR systems could adopt dynamic haptic mechanisms, like variable intensity or pattern-based vibrations, to better simulate in-game events. Such tailored feedback has been shown to enhance user experience and immersion, particularly for individuals with limited hearing [24, 35, 54].

Auditory cues enhanced immersion for hearing participants, though their impact varied; some found them valuable, while others overlooked them, suggesting room for design improvement. For

DHH participants with residual hearing, subtle sounds, like slingshot tension or falling objects, provided added immersion and guidance. This supports previous research indicating that DHH users want detailed information about non-speech sounds [36]. However, participants without residual hearing lacked access to these cues, underscoring the need for alternative sensory feedback. Future AR systems should integrate customizable haptic options [35] and enhanced visual cues [4], such as dynamic effects synchronized with key events, to better support non-auditory users. In addition, auditory feedback should be thoughtfully designed to ensure impact and seamless integration.

Our findings on interaction feedback highlight the potential for AR applications beyond gaming. Prior research suggests that incorporating multimodal feedback, such as haptic and auditory cues, can improve engagement in interactive learning environments [5] and rehabilitation tasks in healthcare [58]. Similarly, in industrial training, real-time sensory feedback has been shown to enhance task performance and safety [77]. These insights suggest that adapting AR design principles to diverse contexts can improve accessibility and user experience.

5.3 Improving Instructional Prominence

The predominantly textual format of the instructions was generally well-received, with a majority of participants from both groups describing them as "sufficient," "helpful," and "easy to follow." This suggests that the clear and prominent display of textual instructions effectively supported participants in progressing through the game. However, the experiences of those who found the instructions lacking or insufficiently noticeable reveal important insights into the interaction dynamics within AR environments, particularly in relation to DHH users.

For DHH participants, who often rely more heavily on visual information due to the absence or limitation of auditory cues, the clarity and prominence of instructions are crucial. The experiences of DHH participants underscore the importance of ensuring that the instructions are not only clear but also persist long enough to be fully processed. This need is amplified in AR environments, where users must divide their attention between interacting with virtual elements and maintaining awareness of their physical surroundings. The brief display of instructions observed in the current AR probe may have inadvertently contributed to cognitive overload, particularly for DHH users, who may require additional time to absorb and act upon textual information, as seen in other digital environments [13, 37].

Another critical aspect of the findings is the gap in instructional content regarding physical movement. Despite the game's reliance on physical interaction with AR objects, explicit instructions on how to move around and view these objects from different angles were missing. This gap was noted by participants across both groups, expressing initial confusion about the ability to walk around the structure. The lack of such instructions could disproportionately affect DHH participants, who may already face challenges in integrating spatial and visual information without auditory guidance. Ensuring that all necessary instructions are included and clearly communicated is essential for supporting the immersive experience that AR aims to deliver.

Ensuring accessible instructional content in AR can extend beyond gaming, particularly in education and workforce training. Studies indicate that well-designed AR instructions can improve learning outcomes for students with diverse hearing abilities [30, 71, 79] and enhance comprehension of complex tasks in industrial training, benefiting DHH employees [60]. These findings reinforce the need for inclusive AR design across multiple domains.

5.4 Sensory Disparities in Feedback Mechanism

The AR probe used a combination of visual and auditory cues to communicate the consequences of players' actions. While these cues were effective for hearing participants, who could leverage both sensory modalities to interpret the feedback, the experiences of DHH participants highlighted significant challenges in this design. Many DHH participants faced challenges recognizing the impact of their actions, despite following the instructions. Their responses pointed to two key issues: the fleeting nature of visual cues and the inaccessibility of auditory feedback. For DHH participants, the visual cues often disappeared too quickly or were not prominent enough, making it difficult to notice the changes intended to convey the effects of their actions. Additionally, the auditory cues—integral to the feedback loop—were inherently less accessible, further compounding the challenge. These findings emphasize the need for AR systems to implement inclusive feedback mechanisms, enabling full engagement for users of all sensory abilities.

These findings reveal a broader challenge in AR design: the overreliance on auditory cues as a core feedback component. For AR environments to be truly inclusive, visual feedback mechanisms must be independently sufficient to convey critical information. This includes ensuring that visual cues are not only prominent but also persistent and easily distinguishable. Enhanced visual feedback, such as longer-lasting visual trails or more distinct animations, could improve the experience for users who cannot rely on auditory signals. The observation that some DHH participants chose not to use the double-tap function during their final attempts further underscores the need for more effective feedback loops. This suggests that AR systems should offer multiple types of feedback and ensure each—visual, auditory, or haptic—is strong enough to independently convey essential information.

Moreover, multimodal feedback mechanisms that are independently effective as stand-alone systems hold significant potential for enhancing accessibility across diverse AR applications. For example, the exclusive use of visual cues in AR has proven effective in supporting real-time interactions [55, 70], fostering educational inclusion [30], and improving accessibility in vocational training environments [60].

5.5 Design Implications Based On Our Analysis

Drawing from the findings of our study, this section presents practical solutions aimed at enhancing accessibility and inclusivity in AR. This section focuses on tasks involving AR manipulation and interaction, as well as the ability of DHH users to follow and understand instructions. We translate the key insights of our study into actionable recommendations, offering specific interface enhancements, modifications, and adjustments tailored to their unique needs.

5.5.1 Providing Customizable UI Options. AR environments should offer multiple interaction modes, allowing users to choose between physical movement and customizable UI-based options depending on their preferences and the context in which they are playing. For DHH participants, the ability to engage fully with the AR environment without relying on auditory cues is crucial, and designers should prioritize visual and physical interaction mechanisms to ensure accessibility. Moreover, AR should take into account the social context of use. Features enabling stationary gameplay are particularly useful in public spaces, where physical movement may be impractical. This is especially important for DHH participants, allowing them to maintain spatial awareness while engaging in the immersive AR experience.

5.5.2 Substitution For Audio Cues. AR environments often rely heavily on sound cues, such as background music and subtle noises from AR elements, to create a sense of immersion. For DHH users, classifying and visualizing the identity and location of sounds [25] can effectively convey these auditory cues. To this end, we recommend closed captions that describe the AR environment state as an effective and straightforward method to convey dynamic environmental information. This approach can help DHH users understand changes and interactions within the AR setting. Furthermore, to address the challenge of subtle audio cues, AR systems should incorporate adaptive, multi-modal feedback mechanisms. For instance, haptic feedback could signal the presence of off-screen targets, with intensity varying based on proximity. This tactile information can guide users toward relevant AR elements, ensuring they do not miss important cues that would typically be conveyed through sound. Moreover, to integrate additional customizable audio settings without overwhelming the user interface, AR designs could adopt a modular approach, allowing users to enable or disable specific feedback mechanisms based on their individual needs.

5.5.3 Optimizing Haptic Feedback. Haptic feedback can significantly enhance immersion for DHH users by providing additional layers of sensory input [35, 54]. However, we recommend placing haptic feedback appropriately to enhance spatial awareness without causing distractions or redirecting attention away from critical AR elements. This aligns with the preferences expressed by DHH users in prior studies [3]. Designers should explore multimodal interaction techniques, combining visual, haptic, and gesture-based interactions [24]. This holistic approach compensates for the lack of auditory feedback and creates a more immersive and intuitive experience for DHH users. By integrating these methods, AR environments can become more accessible and engaging for DHH users. Additionally, offering customizable feedback options allows users the ability to tailor the AR experience to their preferences, or to choose between different types of sensory cues, further enhancing usability and immersion.

5.5.4 Improving Comprehension of Instructions. While textual instructions were generally well-received by both hearing and DHH participants, we recommend additional enhancements. Firstly, explicit instructions related to physical movements for navigating AR objects should be included and remain visible for an adequate duration, especially for DHH users. Because DHH users may require more time to process information due to divided attention between the physical and virtual environments and a potential preference for textual information over audio cues. Furthermore, designers should consider implementing multi-modal instructional delivery that combines textual, visual, and possibly haptic cues to cater to diverse user needs. For instance, using visual symbols [40] or brief animations [8] to complement textual instructions could enhance comprehension and retention of AR environment. Moreover, instructions can be conveyed through sign language utilizing virtual agents [38, 51, 76] in AR for the signing DHH users preferring sign language as their primary mode of communication [52]. In addition, AR applications should allow users to revisit instructions as needed, ensuring they have access to guidance to complete tasks confidently.

5.5.5 Effective Feedback Mechanism. The feedback of following instructions need clearer communication, especially in dynamic environments where brief visual cues alone might not suffice for DHH users. To address this issue, AR systems should employ alternative or complementary methods to ensure immediate and clear feedback. Persistent on-screen notifications can provide continuous guidance to clarify action outcomes [50]. Additionally, exploring the use of haptic cues can offer immediate tactile feedback, which can be particularly effective for DHH users in conveying the impact of their actions without relying on audio cues. By integrating these methods, AR environments can improve accessibility and intuitiveness for DHH users, enhancing their engagement and overall experience.

6 Limitations and Future Work

Our study offers valuable insights regarding the challenges of DHH users with AR tasks that were different to those experienced by hearing users. Below, we recognize the limitations of our research. As researchers, we acknowledge our position as outsiders to the DHH community. Although our affiliation with a local Deaf institution facilitated the participation of DHH students in our research, our interpretation of the results may be biased due to our position as hearing individuals. Although our study is an initial exploration of the experiences and challenges DHH users face with AR tasks, we aim to offer valuable insights based on their feedback and experiences. We welcome critical evaluation and feedback from the DHH community to improve future research.

Our study involved a sample size consisting exclusively of participants from a local college (students and staff). While this might limit the generalizability of our findings, the sample size is consistent with similar exploratory studies in the field [69]. In addition, this aligns with our aim of conducting an exploratory study rather than making broad generalizations.

Moreover, employing an AR game featuring more complex tasks and interactions could potentially lead to different outcomes. For this study, however, we intentionally selected a simpler game-based AR environment to focus on 3D interaction and instructional comprehension, minimizing potential confounding variables associated with task complexity. We acknowledge that the gamified tasks, with their structured interactions and clear goals, may have influenced participants' behavior and attention differently from real-world AR applications.

However, this approach was well-suited to our exploratory objectives. Specifically, it allowed us to isolate and analyze key elements of user interaction without the additional cognitive load introduced by more complex tasks or settings. Although this choice limits the generalizability of our findings to non-gamified or utilitarian AR applications, it does not detract from our study’s contribution to understanding foundational interactions within AR environments.

In addition, our participants were familiar with the 2D version of the probe, which could have influenced their interaction and understanding of the task mechanics and biased their opinions. Participants unfamiliar with this specific probe or AR environment might have produced different findings.

Despite these limitations, we explored the unique experiences and identified challenges of DHH people, that are likely relevant across different AR contexts. Future research should build on these experiences and challenges by validating and expanding the findings across a range of AR applications. Involving the DHH community in participatory design processes is essential to ensure that AR systems are tailored to their specific needs. Additionally, conducting longitudinal studies using qualitative methods (e.g., focus groups [56], case studies [21], narrative inquiry [11], etc.) and quantitative methods (e.g., surveys [16], correlational studies [44], time series analysis [27], etc.) in real-world settings can yield deeper insights. These insights can enable the development of more inclusive and effective AR systems that address the unique requirements of DHH users across diverse contexts.

In the future, we aim to use AR probes with more complex tasks and recruit participants from diverse backgrounds, encompassing different ages, occupations, and levels of AR knowledge. By doing so, we can ensure a balanced representation of diverse demographic groups. Our current study showcases challenges and design implications, specifically within the gaming context. However, we intend to extend our focus to AR environments across various contexts, such as education, training, and collaboration. We anticipate uncovering both context-specific and general challenges that DHH participants encounter in AR settings. In future iterations of this study, we will extend our investigation to encompass more intricate mobile AR games characterized by multifaceted objectives and a higher degree of task complexity. These environments will likely necessitate more sophisticated 3D manipulation tasks, and interactions with AR elements, as well as comprehension and execution of potentially convoluted instructions. By exploring user behavior within these high-attention environments, where the cognitive load is demonstrably increased through multitasking demands, we hope to achieve deeper insights into the generalizability of our current findings and refinement of our design recommendations, ensuring their applicability across a broader spectrum of AR contexts.

7 Conclusion

Our study examined the experiences and challenges encountered by DHH people in AR environments, paying specific attention to the context of interacting with and manipulating 3D objects and following task-related instructions. For this purpose, we employed *Angry Birds AR* , a single-player AR game, as a probe to collect data, involving 11 DHH participants with varying levels of hearing ability and 15 hearing participants. Participants played seven rounds of the game in both a private lab setting and a public hallway, followed by short structured interviews immediately after gameplay. We conducted a longer interview at a later time, which provided the participants with more time to reflect on their key experiences. By exploring the lived experiences of both DHH and hearing participants, we investigated how the design choices of the AR probe influenced interaction and engagement, particularly among DHH participants. Our findings revealed several unique experiences and challenges encountered by DHH participants, such as the need for UI elements tailored for stationary AR experiences, the requirement for audio cue substitutions to enhance immersion, more prominent instructions, and effective feedback mechanisms. We proposed design implications to enhance their experience and address these challenges to improve AR accessibility for DHH users. However, our study has limitations, including the simplicity of the AR tasks used in the probe and potential demographic biases. Future research will involve more complex AR environments to validate and generalize our findings across various fields such as education, entertainment, training, and industry, as well as designing and developing more accessible and inclusive AR environments for all users.

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A Demographic Information of the Participants

Players' Pseudo Name	Gender	Age	Experience Using AR	Identity	Preferred Mode of Communication
P01	Male	21	Limited experience	HoH	Spoken English, Written English
P02	Male	20	Limited experience	HoH	Spoken English, Written English, American Sign Language (ASL)
P03	Male	20	Limited experience	Hearing	Spoken English, Written English
P04	Male	20	Professional in AR	Hearing	Spoken English, Written English
P05	Female	21	Limited experience	Hearing	Spoken English, Written English
P06	Male	19	Limited experience	Hearing	Spoken English, Written English
P07	Male	20	Limited experience	Hearing	Spoken English, Written English
P08	Female	22	Professional in AR	Hearing	Spoken English, Written English
P09	Female	22	Heard of it but never had any experience with it	HoH	Spoken English, Written English, American Sign Language (ASL)
P10	Female	59	Heard of it but never had any experience with it	Hearing	Spoken English, Written English
P11	Male	20	Limited experience	Hearing	Spoken English, Written English
P12	Male	19	Professional in AR	Deaf	Written English, American Sign Language (ASL
P13	Male	19	Heard of it but never had any experience with it	Hearing	Spoken English, Written English
P14	Female	21	Limited experience	Hearing	Spoken English
P15	Male	21	Limited experience	HoH	Spoken English, Written English
P16	Female	19	Limited experience	Hearing	Spoken English, Written English
P17	Male	20	Heard of it but never had any experience with it	HoH	Spoken English, Written English
P18	Female	18	Heard of it but never had any experience with it	Hearing	Spoken English, Written English
P19	Male	28	Professional in AR	HoH	Written English, American Sign Language (ASL)
P20	Male	19	Limited experience	Hearing	Spoken English, Written English
P21	Male	21	Limited experience	Hearing	Spoken English
P22	Male	22	Limited experience	HoH	Spoken English, Written English
P23	Male	23	Limited experience	Hearing	Spoken English, Written English
P24	Male	20	Limited experience	HoH	Spoken English, Written English, American Sign Language (ASL)
P25	Female	23	Limited experience	Deaf	American Sign Language (ASL)
P26	Female	19	Limited experience	Deaf	American Sign Language (ASL)

Table 2: Participants' Demographic Information.