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Use of Psychoacoustics for Improved Interaction and Navigation Capabilities in Extended Reality

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Abstract

Extended Reality (XR) virtual environment (VE) development is heavily focused on visual models, artifacts and interactions. This reliance on visuals in augmented, virtual, or mixed reality (i.e., AR, VR, or MR) can reduce clarity and overload cognitive resources, especially for uses in education and training, for learners with diverse sensory needs. The next most straightforward sensory modality to add is sound, which is often limited to a passive background effect. However, with research minded implementation from the field of psychoacoustics, sound can be used as an effective interaction method in a VE, while simultaneously increasing effects such as presence and immersion. This research describes the development challenges and solutions encountered in building spatial audio as an active, instructional feedback tool in a STEM focused VR environment. The VE was designed to introduce middle and high school students to basic concepts of how the Internet functions (e.g., IP addresses, data packet routing). By embedding meaningful auditory cues and feedback, the system supports learners by reinforcing task completion and guiding attention. The sound design leverages psychoacoustic principles and spatialization techniques, which were iteratively refined with learner and expert input.

Introduction

Although there are several modes of delivery for gamified learning, Virtual Reality (VR) technologies have gained traction to provide immersive, interactive, and engaging environments for learners to advance knowledge. It has been widely adopted as a safe and effective tool within educational settings [1] [2]. Science, Technology, Engineering, and Mathematics (STEM) education in particular, benefits tremendously from the use of VR systems to teach concepts that are sometimes difficult to conceptualize, through “learning by doing” [3].VR environments primarily rely on visual cues through head-mounted displays (HMDs), causing learners to depend heavily on visual prompts to complete tasks. However, overreliance on visual feedback can limit both clarity and interaction in educational VR experiences, especially for: 1) learners with diverse sensory needs or 2) when multitasking strains the cognitive resources of the learner. These VEs can be very compelling and useful but could be more so with the incorporation of additional sensory modalities [4]. Currently, audio is present in educational and training VEs but mostly as ambient sounds without serving an active role in feedback or instructional reinforcement. Only leveraging sound in this manner leaves a significant opportunity untapped. Integrating interactive audio feedback that reinforces task completion and guides actions can provide faster confirmation, reduce errors, and create a more engaging learning environment.

This research focuses on the integration of spatial audio cues within an adventure-based VE developed to introduce cybersecurity concepts to students in rural communities. Drawing from the field of psychoacoustics, spatially aware audio sources were placed to help users perceive sound direction, distance, and task completion more accurately. This research bridges the gap between gamified learning, extended reality (XR) technologies, and Psychoacoustics and soundscapes to improve the retention of cybersecurity knowledge.

Background

The United States faces a growing cybersecurity workforce deficit, with the Government Accountability Office (GAO) report identifying critical gaps in the federal pipeline [5]. Game based and gamified learning approaches for STEM have emerged as promising introductions for technical workforce development. The use of game design elements in educational contexts has been studied extensively as a strategy to improve student engagement, motivation, and learning outcomes. Dicheva et al., conducted an early systematic review which demonstrated the growing adoption of gamified elements such as points, badges, and leaderboards across learning environments, noting that those elements promote improved learner attitudes and engagement [6]. In a more recent guided systematic review of 41 peer reviewed studies published between 2013 and 2023, it was confirmed that gamification fosters positive learning attitudes, though it is important to note that its effectiveness depends on the learning context and student characteristics.

From a theoretical point, Self-Determination Theory (SDT) provides a framework for understanding why gamification engages learners. Rutledge et al, argue that well designed game elements can satisfy the three core psychological needs: relatedness, autonomy, and competence which fosters intrinsic motivation that sustains long term engagement [7]. Building on SDT, Csikszentmihalyi’s flow theory identifies a state of heightened engagement that emerges when task challenges align with a learner’s skill level [8]. Game based approaches have shown promise in STEM and technical fields where traditional methods fail to sustain learner attention. A systematic literature review on gamification within cybersecurity curricula has demonstrated an improvement in students’ knowledge acquisition and engagement [9][10][11].

The use of ambient sounds in VR environments has been well documented over twenty years. Kern and Ellermeier demonstrated the effects that ambient nature soundscapes have on increasing presence, realism, and participant involvement in a virtual park simulation [15]. Further, audio in VR educational games has been shown to influence memory [14], confirming that ambient sounds can actively shape cognitive engagement and not just act as a neutral filter. Yet, while background ambience has been widely adopted, the application of spatial audio within VR games remains an emerging area. Spatial audio deepens the sense of immersion and presence in people using VR environments by delivering omnidirectional auditory cues that operate beyond the field of view, providing 360 sounds that standard mono sounds cannot provide. This takes the use of audio a step further by enabling users to localize sound sources with accuracy to improve performance. Hendrix and

Barfield found a 20% mean increase in presence from non-spatialized to spatialized audio in a 3D display environment [18]. Although spatial audio has been implemented and tested within VR games, these implementations are not grounded in psychoacoustic principles [13] [16]. Psychoacoustics study the relationship between physical sounds and how the brain interprets them [17]. The methods and principles within psychoacoustics would aid in the development of a standard that can be used across multiple instances of VR games. While current VR audio design relies heavily on intuition and case by case approaches, psychoacoustics principles provide guidelines for spatialization, loudness matching, and source separation.

Methodology

The initial STEM VR environment comprised of five interactive stations which relied heavily on text and visual cues for guidance. However, feedback from users and experts indicated that excessive text overwhelmed learners and they were uncertain about task requirements, completion status, and where to go next. Figure 1 shows two views of the environment.

Figure 1a

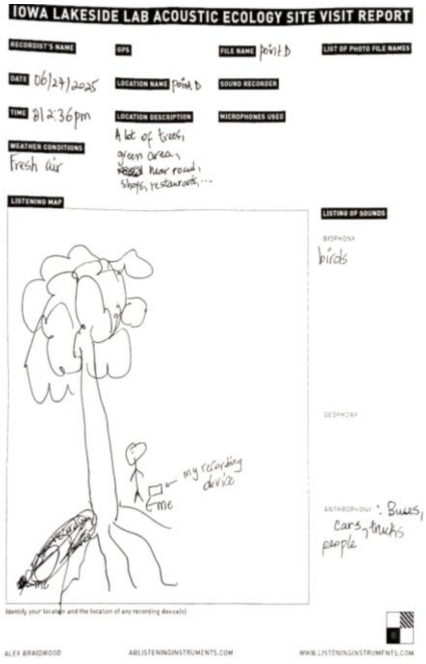
Figure 1b

Figure 1: *Screenshots of educational VR environment to engage middle and high school students in basic concepts of the Internet*

The top of the figure shows the training room where learners should go first to become acquainted. The bottom of the figure shows the next station. For example, after completing training as shown in Figure 1a, a user is supposed to navigate to the router station shown in the bottom Figure 1b to plug the virtual ethernet cable into the laptop. However, when plugging the cable in a user doesn't know if it was done correctly. The field of psychoacoustics informs that the "click" obtained in the real world is very satisfying and lets a user know that not only is the connection made, but it was performed correctly. The same correctness can be conveyed, and resulting satisfaction achieved, in a VE. Audio feedback was used to address this issue to provide clear, immediate confirmation of task success. Completing the action of plugging an Ethernet cable into a device triggers a distinct positive sound. The tone, pitch, and volume of the sound are also important. Psychoacoustics teaches that in the real-world high-pitched sounds tend to be associated with alarm or danger (i.e., fire alarms) whereas lower pitched sounds are often calming. The reverse is true in computer environments where lower pitched sounds are often associated with something being incorrect. For this research, higher pitched "pleasing sounds" were implemented to denote a task being done correctly.

A soundwalk, which is a technique within psychoacoustics used to understand a location and foster conscious listening of an environment, was conducted through Marston Hall, Campanile, Lake LaVerne, Lincoln Way sidewalk, and Helser Residence Hall at Iowa State University as seen in Figure 2.

Figure 2: Soundwalk Map around ISU Campus



IOWA LAKESIDE LAB ACOUSTIC ECOLOGY SITE VISIT REPORT

RECORDIST'S NAME

GPS

FILE NAME point D

LIST OF PHOTO FILE NAMES

DATE 06/27/2025

LOCATION NAME point D

SOUND RECORDER

TIME @12:36pm

LOCATION DESCRIPTION
A lot of trees,
green area,
near road,
shops, restaurants, ...

MICROPHONES USED

WEATHER CONDITIONS
Fresh air

LISTENING MAP

Identify your location and the location of any recording device(s)

LISTING OF SOUNDS

BIOPHONY
birds

GEOPHONY

ANTHROPHONY : Buses, cars, trucks, people

ALEX BRAIDWOOD

ABLISTENINGINSTRUMENTS.COM

WWW.LISTENINGINSTRUMENTS.COM

Figure 3: Lakeside lab acoustic ecology report

Figure 4: Ambisonic Mic (H3-VR Field Recorder)

The location was chosen due to proximity and was meant to shift perception from passive to critical observation of the natural environment. As the walk was conducted, notes were documented on the Lakeside Lab acoustic ecology report, Figure 3, which is a common method to note details about a location in psychoacoustics and soundscapes. To effectively capture and simulate spatial audio, an ambisonics microphone was used, Figure 4. This type of microphone can convert standard A format sounds to a binaural B format using a 4-channel output. This enables a separation between layers such as the background ambience and foreground distinct and localized sounds. Use of this method was specifically due to the capacity to decode captured sounds and render them spatially within the VE. The sounds captured would be similar to what was found in real world scenarios and enables sound localization based on head position.

Once stations are connected by a user, they send data back to a virtual router. A visual effect shows waves "beaming" from the stations (i.e., laptop, mobile phone) to the router to signify the connection, but confusion (i.e., visual and/or cognitive overload) would result when multiple connections had been made. To address this spatial audio was used. A pulsing sound lets a user know when data is traveling to the router. In addition, by spatializing the audio, a user moving around the VE knows if they are approaching an already connected station (i.e., sound growing louder) or a station they still need to connect (i.e., no sound) through unique sound marks attached to stations Figure 5.

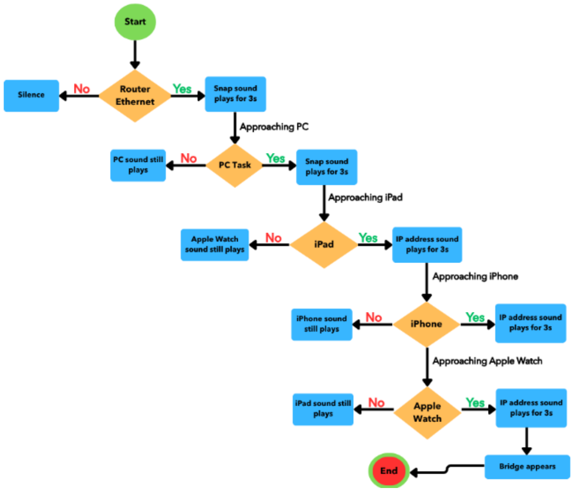


Figure 5: Flowchart of the sound integration process

In the VE sounds were processed using Steam Audio features such as air absorption and occlusion, ensuring cues responded naturally to environmental factors and learner movement. In addition, Steam Audio allows audio spatialization as described earlier. The application was developed in Unity and deployed on the Meta Quest 3 via Meta Quest Link. Learners experienced the environment through the Meta Quest 3 headset paired with BOSE QuietComfort 35 headphones for high-quality audio delivery. In addition to the sound walk, mechanical sounds were sourced from online repositories like freesound.org. Iterative testing across three sessions compared participant reactions to the environment with and without sound, involving learners and experts to refine sound choices and placement. This feedback-driven process resulted in enhanced guidance and task reinforcement within the VR learning environment.

Evaluation

The findings demonstrate that integrating calibrated audio cues with tasks enhances clarity of instructions in the VR environment through increasing presence and engagement. The frame rate remained stable and did not influence the experience when audio was added. Initial users and experts also responded positively to the placement of sounds. Iterative refinements to audio volume, timing, and positioning resolved initial issues with jarring or mismatched sounds, which created a more natural setting as seen in Figures 6 and 7.

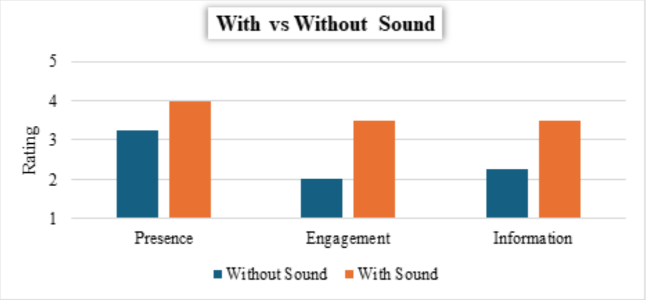


Figure 6: Users' presence, engagement, and information depth based on with and without sound

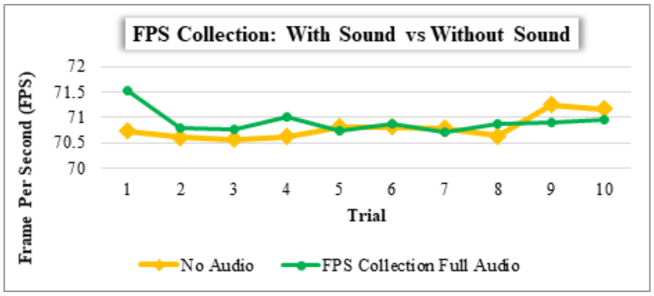


Figure 7: Frames per second (FPS) with and without sound

The approach described in the paper demonstrates the integration of psychoacoustic informed spatial audio into an educational virtual environment to support task clarity, navigation, and user engagement. Directional audio cues were used to confirm task completion and guide learners through a sequence of interactive stations, reducing reliance on textual prompts that had previously contributed to confusion and visual overload. The initial assessment suggests that these cues can be added without degrading system performance and with generally positive learner and expert responses. Over the course of the iterative design process, refinements to volume, timing, and positioning of sound sources led to improvements in perceived realism and user satisfaction. Early feedback indicated that some sounds were either too jarring or did not match the visual context, which prompted adjustments that ultimately contributed to a more natural and immersive environment. A notable trend was observed in the second iteration, where users reported the highest engagement levels. This may be due to a convergence of sound placement, task design, and novelty, suggesting that a balance between interaction complexity and sensory feedback can heighten engagement.

Conclusion

This paper presents the design and development of a sound-integrated educational VE aimed at supporting task clarity and navigation in a cybersecurity learning context. Psychoacoustic informed spatial audio was incorporated as a core interaction mechanism to provide confirmation of task completion and directional guidance within the environment. The work demonstrated how iterative sound design can be embedded into VR development workflows to address recurring user uncertainty without increasing visual complexity or compromising system performance.

Although the system was demonstrated within a cybersecurity learning module, the audio design strategy is not limited to this domain. The same principles can be applied to instructional and exploratory VR environments where users must interpret task state, locate points of interaction, and maintain orientation within complex spaces. By treating sound as a functional component of interaction rather than a purely aesthetic addition, this work highlights the role of audio in shaping user experience and supporting intuitive navigation in virtual environments.

A limitation of this study research is the reliance on pre-recorded audio sourced from online libraries. Without systematically examining specific sound parameters such as frequency, spatial fidelity, or source directivity, it is difficult to determine how variations in audio quality may influence user metrics. Additionally, the pilot assessment was limited to a small sample size of nine participants, which constrains the generalizability of the findings.

Future Work

Future work will expand upon the current system by exploring more formal and controlled evaluation methods. Further, studies could incorporate objective physiological measurements, such as data from wearable sensors (e.g., EmotiBit) or electroencephalography (EEG), to better understand how sound influences engagement, attention, and cognitive load. In addition, future iterations could investigate the effects of customized, context-specific audio recordings with varying acoustic properties. Examining sound parameters such as frequency content, spatial fidelity, and source directivity would provide deeper insight into how audio quality influences both performance metrics and user experience. Introducing performance-based measures, including task completion time and accuracy, would further clarify how sound affects user behavior in instructional VR settings. With the goal of presenting a generalizable tool that can be used to assess the engagement of spatial audio in multiple VEs.

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