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ADDRESSING ACOUSTIC SIMULATION PITFALLS IN VIRTUAL REALITY FOR OCCUPATIONAL SAFETY RESEARCH

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ABSTRACT

Virtual reality (VR) technologies are increasingly utilized in occupational safety research to simulate hazardous environments. Acoustic simulations within VR offer opportunities to study noise exposure impacts on behavior but also introduce challenges that can affect research validity. Ensuring virtual sound levels accurately reflect real-world conditions is essential for drawing meaningful conclusions about safety practices.

A collaboration between the University of Malaga, Spain, and Iowa State University, USA, has developed a VR-based approach to studying noise-related occupational risks. This approach integrates a high-fidelity Binaural Rendering Toolbox (BRT) to create immersive soundscapes simulating varying noise levels. The complexities of calibration, consistency across devices, and participant safety underscore the importance of careful design when implementing acoustic simulations.

This paper reflects on lessons learned during the framework's development, focusing on sound calibration, device consistency, and safety measures for participants exposed to high noise levels. Sharing best practices herein aims at guide researchers in overcoming acoustic simulation challenges in VR and ensure these technologies provide accurate and effective insights for improving workplace safety.

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Keywords: *binaural rendering toolbox***,** *spatial audio simulation, occupational hearing loss, virtual reality simulation, noise exposure assessment.*

1. INTRODUCTION

Virtual reality has transformed occupational safety research by enabling controlled, repeatable, and immersive environments for studying workplace hazards. Among these hazards, noise exposure is particularly challenging due to its long-term health implications and impact on worker performance. Noise-induced hearing loss (NIHL) remains a significant occupational health issue, affecting millions of workers exposed to hazardous noise levels daily. Traditional training methods lack the realism needed to prepare workers effectively for real-world noise hazards, whereas VR offers an opportunity to create immersive training experiences in a risk-free setting.

The accurate simulation of acoustic environments in VR is essential for ensuring valid research findings. Auditory hazards are inherently spatial and dynamic, requiring precise rendering to replicate real-world auditory experiences. This research collaboration between the University of Malaga and Iowa State University has integrated the Binaural Rendering Toolbox (BRT) [1], to enhance VR noise simulations using binaural spatial audio. BRT is an open-source binaural rendering engine [2] designed for precise spatial sound simulation, offering a high degree of experimental control. However, implementing realistic spatial audio in VR presents significant challenges, including sound calibration, device consistency, and ethical concerns related to exposing participants to high-intensity noise levels.

Although the substantial potential of VR-based noise research, significant methodological and technical hurdles remain. Calibration inconsistencies across different VR hardware and software platforms can introduce variability in perceived sound levels, potentially undermining the reliability of experimental findings. Ensuring that participants experience realistic soundscapes, particularly in simulations involving high-noise environments, requires careful validation and standardization of audio output. Furthermore, ethical considerations must be addressed when exposing participants to high-intensity noise in VR, particularly concerning potential discomfort and stress responses. Effective research in this field necessitates interdisciplinary collaboration between experts in acoustics, human factors, psychology, and occupational safety to refine experimental designs and enhance the applicability of VR-based findings to real-world settings.

This paper explores these challenges, detailing the technical solutions developed within BRT to ensure accurate, safe, and consistent acoustic simulations for occupational safety research.

2. THE ROLE OF ACOUSTIC SIMULATION IN OCCUPATIONAL SAFETY

Noise is recognized as a significant occupational hazard due to its potential to cause hearing loss, cognitive fatigue, and stress, ultimately influencing productivity and decision-making [3][4]. In settings such as manufacturing or emergency response, workers frequently operate under elevated noise levels that hinder communication and establishing proper situational awareness. VR technologies provide an avenue to study these conditions with higher ecological validity than traditional methods, offering immersive and interactive experiences that replicate the complexity of real-world noise exposure scenarios while preserving a controlled experimental environment.

A key benefit of VR-based acoustic simulation lies in its capacity to engage workers in dynamic, hands-on learning. Instead of passively watching instructional materials; in VR, participants become active agents, navigating virtual industrial settings where they must identify unsafe noise levels, consider protective equipment, and respond to realistic auditory cues. This experiential approach to training heightens hazard awareness fosters deeper retention of safe practices. Moreover, VR allows systematic manipulation of factors such as noise intensity, spatial distribution, or reverberation, enabling researchers to examine how various acoustic configurations influence worker stress, performance, and risk perception. Combining precise spatial audio rendering with interactive virtual environments, VR-based simulations thus offer a flexible and safe platform for studying occupational noise risks, laying the groundwork for evidence-based interventions and more effective hearing conservation strategies.

3. THE SONIC SAFE-VR TRAINING PLATFORM

SonicSafe-VR is a VR-based platform specifically designed to test and refine immersive noise simulations for occupational safety research and training.

The virtual environment simulates an industrial facility containing various pieces of machinery, each emitting characteristic noise that can sometimes indicate malfunction or poor maintenance. Participants navigate this environment while exposed to spatialized industrial sounds rendered via the BRT. The system allows them to visually identify machinery, perceive realistic noise levels, and make decisions regarding personal protective equipment (PPE) usage and deciding on noise safe zone. By implementing this training virtually, a safety limitation can be enforced to ensure that, at no point during exposure to the virtual environment, the user is subjected to noise levels exceeding a predefined safety threshold.

Within the simulation, participants navigate a workspace with noise-generating machines, each with distinct operational sound profiles. They are equipped with a virtual noise level meter, which allows them to assess noise intensity at different locations. Based on their assessments, they place safety cones to delineate hazardous areas where noise levels exceed safe thresholds. Additionally, participants evaluate machinery performance by recognizing noise cues indicative of maintenance needs and decide whether interventions are necessary.

A core feature of the platform is its interactive hearing protection system, allowing participants to wear and remove virtual earmuffs in response to changing noise conditions. This function simulates real-world protective behavior, offering insight into how workers adapt to hazardous noise environments. The system also tracks decision-making patterns, response times, and behavioral accuracy, providing researchers with quantifiable metrics on hazard recognition and risk mitigation strategies.

Figure 1 shows a simplified block diagram of SonicSafe-VR, illustrating the primary components: (1) audio rendering through BRT, (2) the industrial VR environment, (3) user's interaction (selecting PPE, positioning cones) and their *transform*, where *transform* refers to both position and orientation, and (4) data logging and monitoring. Communication between (1) and (2) is handled through OSC (Open Sound Control) commands, ensuring seamless integration and real-time data exchange between the virtual environment, the BRT rendering engine, and the control interface.

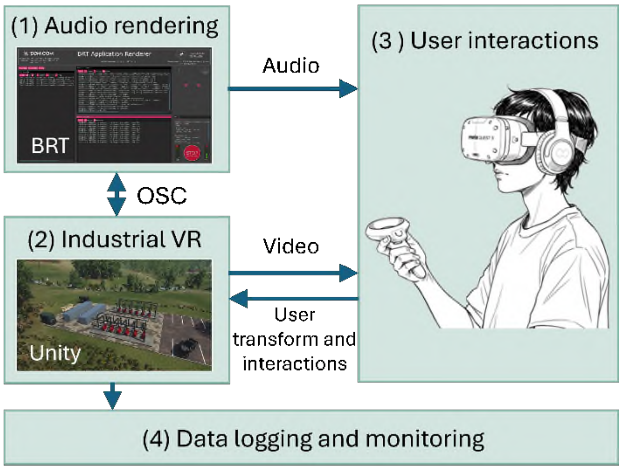

Figure 1. SonicSafe-VR primary components

The audio spatialization is handled by the BRT library, which is a continuation of the 3DTI-Toolkit [5] and provides flexible and high-quality real-time audio processing, making it particularly suited for applications that require accurate spatialization and experimental control over sound delivery [6]. In this simulator, BRT operates with a specific configuration, as shown in Figure 2. It performs real-time audio rendering for two types of listeners: a human listener, who perceives spatialized audio through headphones, and a virtual sound level meter, which captures sound for measurement purposes. The signal delivered to each listener is simulated through a distinct processing path. For the human listener, a listener model is used to process the sound, where spatialization is achieved using HRTF-based algorithms [7], incorporating near-field effects [8]. The system also models the environment as a free field, including distance attenuation and propagation delay. Additionally, a binaural filtering stage simulates the attenuation effects of earmuffs, followed by a sound level limiter. For the virtual sound level meter, the renderer simulates a separate listener. In this case, the listener model simulates an omnidirectional monophonic listener, which perceives sound uniformly from all directions without spatial cues. The environment model for the free-field simulation includes distance attenuation and propagation delay rendering. The tracker of both listeners feed the models, as spatialization and distance simulation primarily depends on the relative position between the listener and the sound source.

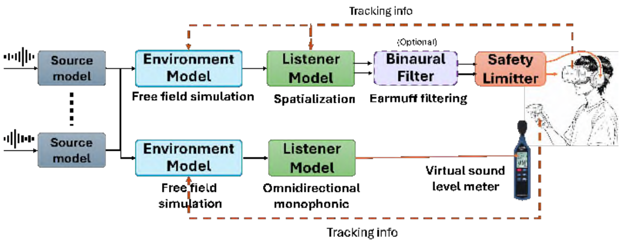

Figure 2. BRT architecture

In the current experimental setting, participants are assigned to different noise exposure conditions, ranging from mild (70 dB) to moderate (85 dB) to high-intensity (100 dB) levels, replicating common workplace hazards. The controlled VR environment ensures that no participant is subjected to unsafe real-world noise exposure while still allowing researchers to examine cognitive and behavioral responses under varying conditions.

SonicSafe-VR integrates realistic acoustic cues with interactive elements to deliver an engaging and instructive experience in occupational noise awareness and management. By integrating BRT-based simulations in SonicSafe-VR, the project team gained insight into the practical demands of calibrating, limiting, and verifying noise exposures in VR. The following sections detail the technical challenges encountered and the solutions devised to ensure accurate, safe, and consistent acoustic experiences.

4. TECHNICAL CHALLENGES IN VR-BASED SPATIAL AUDIO RENDERING. IMPLEMENTATION IN THE BINAURAL RENDERING TOOLBOX

In this section, we focus on the technical challenges of VR-based spatial audio rendering for occupational safety training and noise exposure assessment. Unlike conventional, general-purpose VR simulators, these training applications require specialized technical features that are not typically available, particularly in sound simulation. Standard VR platforms often lack precise control over spatialized audio rendering, real-time binaural processing with dynamic head tracking, and the ability to simulate realistic room acoustics. In addition, these limitations make it difficult to create accurate and immersive auditory environments necessary for safety training and noise exposure assessment.

Moreover, training simulations for noise exposure introduce even more specific requirements regarding the sound levels delivered to users. Unlike general VR applications, where audio is primarily designed for immersion and spatial awareness, these training systems must ensure precise control over the intensity of sound exposure to accurately replicate real-world noise conditions while maintaining user safety. This includes the ability to calibrate absolute sound levels, enforce exposure limits in accordance with occupational safety regulations, and dynamically adjust playback to reflect realistic variations in noise environments.

To meet these requirements, we have used the BRT, which provides precise manipulation of spatial audio rendering, ensuring accurate and reproducible auditory conditions. For this application, we have extended its functionality to offer full control over the delivered sound levels and their proper calibration. This allows the system to maintain the spatial accuracy required for realistic training simulations and enforce strict safety constraints on noise exposure, ensuring compliance with occupational health standards. Additionally, the ability to monitor and quantify sound levels at any point within the virtual environment is essential, which is why we also incorporated the capability to implement a virtual sound level meter that provides real-time feedback on the auditory conditions experienced by the user.

4.1 Hardware Requirements for Sound Delivery

Achieving accurate sound reproduction in VR-based noise exposure training requires a carefully designed hardware setup. One of the main challenges is delivering sound levels that can reach at least 100 to 105 dB without introducing unwanted distortions. Standard consumer-grade headphones are often not capable of maintaining this level of output while preserving audio fidelity, as they may exhibit nonlinear distortions when driven beyond their optimal operating range.

To ensure precise control over the delivered sound level, the hardware configuration must include high-performance headphones capable of handling elevated sound pressure levels without degradation. Additionally, the audio chain must incorporate an amplifier that can drive the selected headphones without introducing distortion or limiting dynamic range. The amplifier must be chosen to match the impedance and sensitivity of the headphones, ensuring that the system can provide the necessary acoustic power while maintaining an accurate frequency response.

In this context, a dedicated hardware setup is essential to guarantee both the required output levels and the preservation of spatial audio cues. Any deviation in the reproduction chain, whether from driver limitations, amplifier saturation, or non-linear response, could compromise the accuracy of the training simulation.

For our setup, we selected the Audio-Technica ATH-M50x headphones, which offer high sensitivity and relatively low impedance, making them suitable for reaching the required sound levels with moderate amplification. While this configuration allows for efficient power handling using a standard audio interface (Focusrite Scarlet 2i2 4th Gen was used in our setup), evaluating distortion at high output levels remains a critical factor in ensuring accurate and controlled sound reproduction. In our tests, we confirmed that no audible distortion was present at output levels of 100 dB. Additionally, the measured sound level matched the expected value, suggesting that no distortion was affecting the output. Given that the sounds used in these simulations typically consist of broadband industrial machinery noise, naturally less sensitive to distortion artifacts, this verification method aligns with the requirements of our application, where ensuring accurate sound level delivery is a key aspect.

4.2 Calibration Procedure for Accurate Sound Level Delivery

After addressing the challenge of delivering high sound pressure levels, we focused on ensuring that a precise target level is consistently achieved. To accomplish this, we implemented a calibration system entirely managed from the software side. This calibration process consists of two key phases:

The first phase establishes the relationship between the digital signal level in dBFS (Decibels Full Scale) and the actual sound pressure level (SPL) in dB SPL as delivered through the headphones. To ensure that this mapping is accurate and unaffected by any potential distortion in the audio chain, the calibration begins with a moderate or low signal level. A known digital signal level of pink noise—a broadband signal with a wide frequency spectrum—is played back, and the user is asked to measure the corresponding SPL using a sound level meter at the headphones' output. By collecting this measurement, the system determines the precise correspondence between dBFS and dB SPL, effectively calibrating the setup.

Once this mapping is established, the second phase serves as a verification step. The system instructs the user to measure the maximum intended output level (100 dB SPL in our case). Since the calibration already defines the required digital level to achieve this SPL, the system applies the appropriate signal and asks the user to confirm that the measured output indeed reaches 100 dB SPL. This final check also ensures that the audio chain is free from distortion. If distortion, such as clipping or any other non-linearity, were present, it would artificially lower the measured SPL due to signal alteration, indicating that adjustments are needed before proceeding with training simulations.

4.3 Safety Limits for Noise Exposure

In applications where users are exposed to elevated noise levels, ensuring their safety is a critical concern. Prolonged exposure to high-intensity sound can lead to hearing damage, making it essential to establish clear safeguards. Beyond the technical aspects, this issue has ethical implications, as any experiment or training simulation involving potentially harmful sound levels must comply with ethical guidelines and obtain approval from institutional review boards or ethics committees. To align with these standards, exposure duration must be carefully controlled based on established safety thresholds.

The noise exposure limits in this study are based on the U.S. Occupational Safety and Health Administration (OSHA) Occupational Noise Exposure Standard 1910.95 [9]. This standard, among other information, defines permissible noise exposure durations to minimize the risk of noise-induced hearing loss.

Figure 3 illustrates the OSHA noise exposure limits, detailing the maximum allowable exposure time for various noise levels. In the SonicSafe-VR simulation, the highest noise level participants may encounter is 100 dB, which, according to OSHA guidelines, corresponds to a permissible exposure duration of 2 hours. To ensure a conservative safety margin, SonicSafe-VR is designed to automatically cease the simulation after 30 minutes, providing ample protection while still allowing for meaningful data collection and training effectiveness.

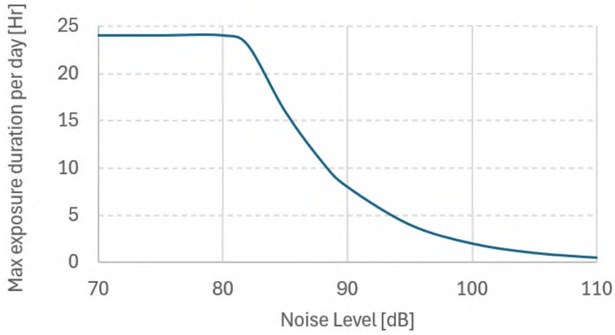

Figure 3. Maximum exposure duration based on the US OSHA.

On top of the safety feature above, we have ensured that our system includes built-in safety measures at the application level. From a software perspective, it is essential to implement safeguards that prevent excessive sound exposure. To address this, we incorporated a programmable sound level limiter within the BRT (see Figure 2). This feature ensures that if an application requests a sound level exceeding the predefined safety threshold, the render engine automatically limits the output to the maximum allowed level. Additionally, to maintain transparency in experimental control, the system communicates this event back, notifying the application that the requested level has been capped. This prevents the application from assuming that it is delivering a higher intensity than what is actually being played back, ensuring both safety and accurate monitoring of the auditory conditions within the simulation.

4.4 Virtual Sound Level Meter Simulation

In this type of research and training, users must become proficient in the use of sound level meters-handheld devices that allow them to measure noise levels at any location and time in the virtual environment. Proper handling of these instruments is important for assessing occupational noise exposure accurately. To simulate this functionality within the virtual environment, our BRT includes a multi-listener capability, enabling the simulation of multiple simultaneous auditory perspectives.

For this application, we have used this functionality to implement a virtual sound level meter within the simulation. The system employs two distinct listeners: a binaural listener that delivers the spatialized audio to the user through headphones and a second, omnidirectional monophonic listener positioned at the location of the virtual sound level meter within the VR world (see Figure 2). This secondary listener simulates how a real microphone would capture sound at that specific point in space. Additionally, it calculates the root mean square (RMS) value of the incoming sound, allowing it to provide standardized noise level readings using fast or slow response settings, in accordance with conventional sound level meter specifications [10].

A key aspect of this simulation is that the sound level measured at the virtual microphone is not necessarily the same as what the user perceives binaurally. If the user moves the virtual sound level meter closer to a noise source, the measured level will increase due to the reduced distance, even though their own auditory perception remains unchanged. In some cases, the device may even be positioned far from the user, providing independent readings at a different location in the environment. This makes the virtual implementation of a sound level meter particularly valuable in training scenarios, allowing users to develop practical skills in noise assessment under realistic and controlled conditions.

4.5 Simulation of Hearing Protection Devices

An essential aspect of noise exposure research and training is the simulation of personal protective equipment, specifically hearing protection devices. In our case, we leverage a feature provided by the BRT that allows the application of binaural filters after spatialization has been computed. These post-spatialization filters are applied to the left and right audio channels before being delivered to the user, enabling the simulation of the acoustic effects introduced by hearing protectors.

To replicate the noise reduction rate (NRR) effect of earmuffs, we implemented a pair of IIR filters designed to mimic the typical frequency response of these protective devices. Earmuffs generally attenuate high frequencies more than low frequencies, altering the spectral balance of the incoming sound. By applying these filters directly to the binaural signal before playback, we ensure that the attenuation follows the appropriate frequency profile, accurately simulating the effect of hearing protection on the user's auditory experience (see Figure 4. for an example of a simulated hearing protection device).

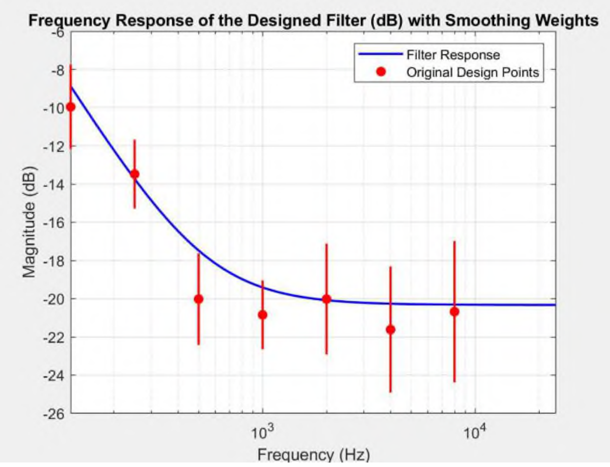

Figure 4. Filter response of a simulated earmuff specified by a ser of points describing it attenuation profile.

Additionally, to fully replicate the perceptual changes introduced by wearing earmuffs, it is necessary to modify the HRTF used for spatialization. Since earmuffs cover the outer ears, they block the natural interaction between sound waves and the pinna, significantly altering spatial hearing cues. To reflect this effect, we replace the user’s standard HRTF with a spherical head model, which lacks the detailed spectral filtering associated with pinna-based localization. This change reduces the user's ability to accurately determine the direction of sounds, increasing front-back confusions and leaving only interaural differences as the primary localization cues for sounds that are strong enough to penetrate the hearing protection.

This approach allows for a more comprehensive and realistic evidence-based understanding of noise-induced behaviors and developing proper mitigation training experiences to ensure users experience the physical attenuation of noise as well as the spatial perception challenges introduced by hearing protectors in real-world conditions.

5. DISCUSSION & LESSONS LEARNED

Designing and integrating the BRT into the VR platform was not a task for the faint-hearted. This careful and diligent process required overcoming numerous technical hurdles, but ultimately it yielded a robust acoustic simulation framework that delivers reliable, realistic noise conditions for occupational and behavioural noise-induced research and training.

The pilot study [11] results validate this approach, as it is shown in Figure 5. For example, SonicSafe-VR's meticulous design allowed for effectively differentiate task performance levels between safety professionals and other workers. Notably, safety professionals improved their performance as noise levels increased, reflecting their adaptability to high-noise environments. In contrast, other workers' performance began to deteriorate once noise levels exceeded 100 dBA, underscoring the detrimental impact of excessive noise on untrained individuals.

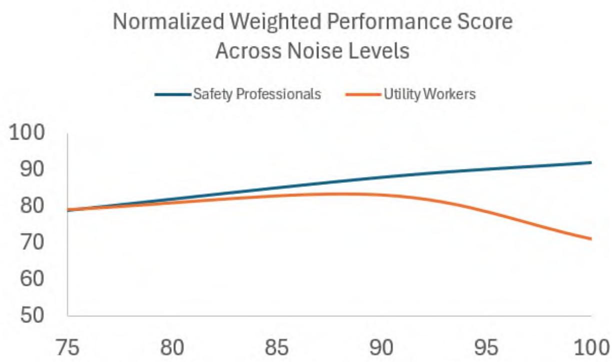

Figure 5. Results from a pilot study

Overall, these findings illustrate that the significant effort invested in acoustic simulation integration was worthwhile. The resulting VR platform not only achieves its safety and realism goals but also provides meaningful insights into user performance under noise stress. Those insights constitute key lessons that will guide future occupational safety research.

6. CONCLUSION & FUTURE WORK

This paper has outlined key challenges and technical solutions for implementing high-fidelity spatial audio in VR-based occupational noise exposure training. By addressing sound calibration, hardware consistency, and participant safety, BRT provides a reliable framework for studying noise hazards in controlled yet realistic settings.

The integration of the high-fidelity acoustic simulation with immersive typical industrial-based settings and tasks, allow SonicSafe-VR to offer a versatile research and training tool for understanding behavioral phenomena under various noise levels and improving occupational safety practices. In summary, the system facilitates empirical investigations into noise-related risks as well as serving as a foundation for developing evidence-based hearing conservation training programs that enhance worker awareness and adherence to safety protocols.

Ongoing research aims to further improve the robustness of these simulations by refining hardware adaptation methods and expanding the capabilities of real-time SPL monitoring. These advancements will contribute to the broader application of VR in occupational safety training and research.

As future lines of research, several enhancements to the sound level meter simulation should be considered. First, Curves A and C should be incorporated into the simulation, as the sound level meter not only measures the RMS but also applies a filter using either Curve A or Curve C, which represent the human perceptual response. Additionally, occlusion effects should be addressed, particularly in the context of a handheld sound level meter. The simulation should take into account the occlusion caused by the person holding the device, as it would attenuate the sound as perceived by the meter.

7. ACKNOWLEDGMENTS

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