Study Design for Investigating Auditory Feedback in Mixed-Reality Testing Environments

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Abstract

Technical systems emit sounds that convey information about operating states and interaction processes. However, systematic approaches for investigating different levels of such process-relevant auditory information in physically coupled mixed reality environments are scarce. This paper presents and pilots a study design addressing this gap. A robot-guided mixed reality drilling task is implemented with five auditory feedback conditions that vary in their informational content, including force-dependent sonification based on user interaction. We assess subjective and objective measures targeting presence, sense of agency, perceived auditory support, and drilling performance. A pilot study evaluates the feasibility of the proposed approach.

Keywords

Auditory Feedback, Mixed Reality, Presence, Performance

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1. Introduction

Increasing competitive pressure across industries has led to substantially shorter product development cycles. As a result, reducing product development time and accelerating time-to-market have become important objectives in modern product development [1]. To address these challenges, virtual prototyping approaches are used before physical prototypes are created [2]. However, the successful application of virtual prototyping depends on the extent to which user studies conducted can provide valid insights into real-world experiences and behavior [3]. This requires participants to experience interactions with virtual systems in a manner that adequately reflects the intended real-world use context. One approach to realizing such a mixed-reality testing environment is the Human-Machine Symbiosis Laboratory [4] , a Human-in-the-Loop environment designed for investigating adaptive human-machine collaboration. Within this setup, users interact with a physical object while process parameters generated during the interaction, such as applied force, are captured in real time and used to influence the virtual and physical representation as well as the auditory feedback.

To assess the experience during such interactions, sense of presence and sense of agency are frequently used to evaluate how participants perceive and experience virtual interactions, both of which can affect task performance. These constructs are shaped by multisensory feedback provided, including visual, haptic, and auditory stimuli [5]. While the importance of auditory feedback has been demonstrated [6, 7], implementations differ considerably in the amount of information they provide, ranging from simple sound stimuli to process-dependent or physically modeled sounds [5, 7–9]. This aspect is particularly relevant for virtual representations of technical systems in mixed reality testing environments, as sounds emitted by technical systems inherently contain information about their operating state [10]. In many power tools, acoustic characteristics are influenced by the ongoing interaction between human, tool, and workpiece. Drilling tasks are a representative example, as process variables such as material contact and applied feed force change continuously throughout task execution and may therefore be reflected in the generated auditory feedback. This raises the question of how much process-relevant information should be conveyed through auditory feedback in mixed reality testing environments. However, it remains unclear to what extent varying levels of process-related auditory information influence users' sense of presence, sense of agency, and task performance when interacting with virtual representations of technical systems in mixed reality testing environments. Systematic investigations of this issue are scarce, limiting the evidence-based design of mixed reality testing environments and the selection of appropriate simulation fidelity during early product development.

Investigating the role of process-relevant auditory information requires an experimental approach in which different levels of auditory information can be implemented and systematically varied under controlled conditions. Therefore, this paper develops and pilots a mixed reality study design featuring multiple auditory feedback conditions with varying informational content. The guiding research question is: To what degree can different levels of auditory feedback with process-relevant information be distinguished and investigated using a mixed reality testing environment?

The following chapter provides an overview of existing approaches to auditory feedback in virtual environments and subsequently introduces sense of presence and sense of agency as relevant evaluation criteria for mixed reality environments. Building on this foundation, a study design for investigating auditory feedback with different levels of informational content is presented and evaluated in a pilot study. Finally, the study findings and limitations are discussed.

2. Background and Related Work

Investigating the role of auditory information in mixed reality testing environments requires both an understanding of existing auditory feedback approaches and appropriate measures for evaluating their effects. Therefore, relevant work on auditory feedback is presented first, followed by an introduction to sense of presence and sense of agency as key evaluation criteria.

2.1. Auditory Feedback in Virtual Environments

Auditory feedback represents an important component of multisensory virtual environments and can complement visual information by conveying system states, directing attention, and supporting interaction processes. A systematic review by Apostolou et al. found that multisensory virtual reality systems generally provide benefits over traditional audiovisual systems with respect to presence, user experience, environmental perception, and task performance [5]. Their review further indicates that sensory cues that are congruent with the virtual environment contribute positively to sense of presence and that increasing the fidelity of individual sensory components can improve task performance.

Several studies have demonstrated the contribution of auditory feedback to the experience in virtual environments. In a VR wheel-change task, Cooper et al. [6] manipulated visual, auditory, and haptic cues indicating critical task events. Their results showed that providing these cues across multiple sensory modalities reduced task completion times and increased subjective presence ratings, with auditory and haptic cues exerting significant positive effects on both performance and experience. In this context, auditory cues informed users about relevant system states, such as the successful tightening of a bolt, thereby supporting task execution.

The relevance of multisensory feedback becomes particularly evident in mixed reality testing environments involving hand-held technical tools and interactive systems. Grant et al. [8] investigated a virtual drilling task and compared auditory feedback with combined audiohaptic feedback. Participants in the audiohaptic condition demonstrated more accurate drilling behavior and reported higher levels of realism, suggesting that additional sensory information can improve both objective and subjective outcomes. Similarly, McAnally et al. [7] examined auditory contact feedback and error feedback during interaction with a virtual touchscreen. Their results indicate that such auditory feedback can improve task accuracy and interaction efficiency and may partially compensate for missing tactile and proprioceptive information in virtual environments.

Overall, existing research demonstrates that auditory feedback can enhance overall experience and task performance, particularly when integrated into multisensory interaction concepts [5, 6]. However, most studies focus on the presence or absence of auditory feedback or on comparisons between different sensory modalities. Comparatively little attention has been given to the amount and type of information conveyed by auditory feedback itself, leaving it unclear how different levels of auditory information influence presence, sense of agency, and task performance in mixed reality testing environments for technical systems. This gap motivates the study design presented in the following chapter.

2.2. Sense of Presence and Sense of Agency as Evaluation Criteria in Mixed Reality

To evaluate the experience in mixed reality environments, the concepts of sense of presence and sense of agency are frequently investigated. Both constructs capture complementary aspects of how users perceive and interact with immersive systems and are therefore valuable for assessing immersive experiences [11–13].

Sense of presence is commonly understood as the subjective feeling of being located within the virtual environment rather than merely observing a simulation [14]. According to Slater [15], this experience can be described through two complementary components: the feeling of being situated in the virtual environment (place illusion) and the perception that the events occurring within the environment are believable and meaningful (plausibility illusion). When both components are sufficiently supported, humans tend to respond to virtual environments in a manner similar to real-world situations [15]. Presence is commonly assessed using self-report instruments such as the Igroup Presence Questionnaire (IPQ) [16], which captures dimensions including spatial presence, involvement, and experienced realism. However, challenges regarding the conceptualization and measurement of presence remain an ongoing topic of discussion [17].

Another important construct in immersive experiences is the sense of agency, referring to the experience of being the initiator and controller of one's actions and their consequences [18]. It can be measured using the Sense of Agency Scale (SoAS) [19], which differentiates between positive and negative experiences of control. Recent findings suggest that feedback characteristics shape agency in virtual reality. Positive feedback has been found to increase perceived control and improve subsequent task performance, possibly by enhancing participants’ confidence [20]. More embodied visual feedback, such as a virtual hand rather than a cursor, has been associated with stronger agency and faster sensorimotor adaptation in virtual reality tasks [21].

3. Study Design

To investigate the proposed research question, a study design for assessing auditory feedback in a mixed reality testing environment is developed. Figure 1 provides an overview of the proposed study design, including the auditory feedback conditions, the mixed reality drilling task, and the outcome measures used for evaluation. The individual components of the study design and the procedure applied in the pilot study are described in detail in the following sections.

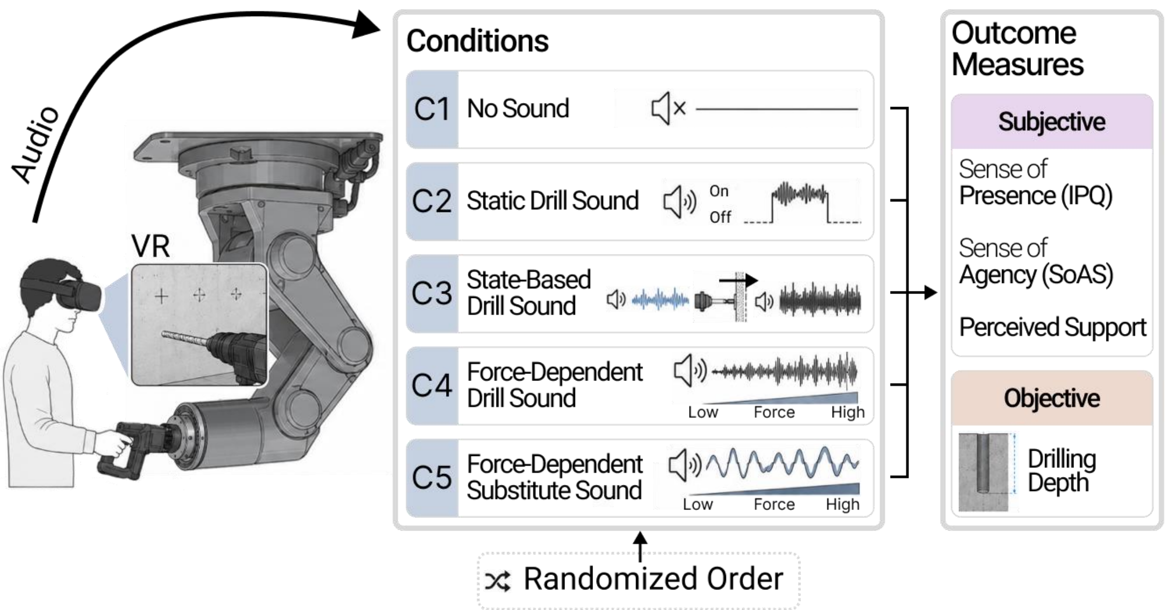

Figure 1: Schematic representation of the study design (created by the author, partially with the aid of AI).

3.1. Experimental Setup

The study is conducted in the Human-Machine Symbiosis Laboratory [4] using a mixed reality setup that combines immersive visual feedback with physical interaction capabilities. The laboratory consists of a six-axis industrial robot whose end effector can be equipped with interchangeable handles representing different technical systems The robot is equipped with a six-axis force-torque sensor that enables force-velocity control. This allows participants to guide the robot freely while the system reproduces the movement dynamics and response characteristics of the simulated application. The position and orientation of the robot's end effector can be continuously recorded during task execution.

A Unity-based virtual environment is displayed through a Meta Quest 3 (Meta Platforms, Inc., California, USA) head-mounted display. The study employs the mixed reality testing environment described by Saurbier et al. [22]. To ensure spatial alignment between the physical and virtual worlds, both the human and the robotic system are tracked using a Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, United Kingdom), allowing the pose of the robot's end effector to be continuously transferred to a corresponding virtual tool.

For the present study, the robot's end effector is equipped with the housing of a rotary hammer (Figure 1) that shares the same pose as its virtual counterpart. As a result, participants can simultaneously see and physically interact with the tool at its virtual representation. Interaction with the tool is realized through natural hand movements and trigger input, while the robotic system provides force feedback during tool operation. Together, these components create a mixed reality testing environment that combines co-located visual and haptic feedback for the investigation of technical systems.

3.2. Auditory Feedback Conditions

Five auditory feedback conditions are implemented. To ensure a consistent presentation of auditory feedback across all conditions, sounds are spatially integrated into the virtual environment using Unity's audio system. The virtual sound source is attached to the virtual rotary hammer, enabling participants to perceive the sound as originating from the tool itself. To maintain verbal communication between participants and the experimenter during the study, auditory feedback is presented through the integrated speakers of the headset rather than through acoustically isolating headphones.

Three basic audio signals are used to realize the experimental conditions. Two recordings originate from a DUSS P26C combi hammer (Friedrich DUSS Maschinenfabrik GmbH & Co. KG, Bietigheim-Bissingen, Germany) equipped with a D20 drill bit and capture the sound of the tool operating either in free air or while drilling into concrete. In addition, a synthetic square-wave signal generated in MATLAB (The MathWorks, Inc., Natick, MA, USA) is used as an abstract auditory stimulus.

The five auditory feedback conditions (C1 – C5), shown in Figure 1, were designed to systematically vary both the amount of information conveyed through sound and the acoustic plausibility of the presented feedback. The informational content increases progressively across the conditions, ranging from no auditory information to binary feedback indicating tool activation, state-dependent feedback communicating wall contact, and finally continuous feedback conveying the applied feed force. The two sonification conditions (C4 and C5) implement identical force-dependent mappings while differing only in the underlying sound source. This allows the influence of acoustic plausibility to be investigated independently of the amount of information communicated by the auditory feedback.

- C1 serves as a baseline and provides no auditory feedback.
- C2 implements a simple auditory icon by continuously looping a recording of the drill operating in concrete whenever the trigger is pressed. This condition communicates only whether the tool is active.
- C3 increases the amount of information conveyed by the sound. Here, auditory feedback distinguishes between idle operation and active drilling. When the trigger is pressed while the drill is outside the wall, a looping idle sound is played. As soon as the drill enters the wall, the system switches to the concrete-drilling recording. The auditory feedback therefore communicates both tool activation and drilling state.
- C4 implements parameter-mapping sonification. Similar to the previous condition, idle and drilling sounds indicate the current drilling state. In addition, characteristics of the drilling sound are continuously modified based on the applied feed force measured by the robot's force-torque sensor. Feed force was selected because it constitutes a continuously varying interaction variable that reflects the ongoing drilling process and is directly influenced by the participants. This allows the auditory feedback to convey not only whether drilling occurs but also information about the current interaction dynamics.
- C5 also employs parameter-mapping sonification, but replaces the realistic drill recordings with a synthetic square-wave signal. The same force-dependent parameter mappings used in C4 are applied. During wall contact, the acoustic parameters are modulated according to the measured feed force, whereas outside the wall a constant baseline value is maintained. By preserving the same force-dependent information while changing the underlying sound source, the condition isolates acoustic realism from informational content.

For the two sonification conditions (C4 and C5), a continuous audio loop forms the basis of the generated feedback. An acoustic analysis of reference recordings obtained under different feed force levels was conducted to identify force-dependent sound characteristics. Based on this analysis, loudness, spectral composition, and temporal-rhythmic properties were selected as relevant parameters and continuously modulated in real time according to the measured feed force.

3.3. Measures and Procedure

For the present study, a drilling task is implemented within a mixed reality environment. Participants are required to drill holes of varying target depths into a virtual wall. Since target depth varies across trials, participants cannot rely on a single, predefined movement to complete each drilling accurately and instead needed to adjust their movement to the current target. To perform the task, participants use the virtual rotary hammer described in the previous section.

The study follows a within-subject design in which each participant completes the drilling task under all five auditory feedback conditions. To minimize order effects, the conditions are presented in a randomized order.

At the beginning of the study, participants receive an introduction to the experiment, provide informed consent, and complete a short questionnaire on demographic characteristics and prior experience with virtual reality systems and power tools. Participants then receive an introduction to the experimental setup and the drilling task, including an explanation of the mixed reality environment and relevant safety instructions. To familiarize participants with the robotic interaction device and the virtual environment, two training trials are conducted before the actual experiment begins. The first training trial is completed without the VR environment, allowing participants to become accustomed to handling the robot-guided tool. The second training trial is performed in VR and familiarizes participants with the virtual workspace and interaction mechanics.

Before each experimental condition begins, the robotic system automatically returns the tool to a predefined starting position to ensure consistent initial conditions across participants and conditions. During each trial, participants drill four holes into the virtual wall, with holes one and two requiring a depth of 15 cm and holes three and four requiring a depth of 20 cm. Throughout each trial, the end effector position of the robot is continuously recorded along the three spatial axes. These data are used to determine the achieved drilling depth and thereby provide an objective measure of task performance. The vertical position of the drilling targets is adapted to the participant's VR headset height to maintain a consistent relative working position.

After completing each trial, participants complete a questionnaire assessing the dependent variables of the study. Sense of presence is measured using the Igroup Presence Questionnaire (IPQ) [16]. Sense of agency is assessed using selected, adapted items (Table 1) from the Sense of Agency Scale (SoAS) [19]. In addition, participants complete study-specific items (Table 2) assessing the perceived support provided by the auditory feedback during task execution. These items evaluate the extent to which the respective auditory feedback condition supports participants in performing the drilling task. For all subjective measures, responses were collected using seven-point Likert scales.

Table 1: Selected and adapted SoAS items with original German wording and English translation.

Items (German)	**Items (English translation)**
Ich hatte während der Interaktion die volle Kontrolle darüber, was ich getan habe.	Throughout the interaction, I had complete control over what I was doing.
Ich konnte den Bohrhammer genauso bewegen, wie ich es wollte, als würde er meinem Willen gehorchen.	I could move the hammer drill exactly as I wanted, as if it were obeying my will.
Ich hatte das Gefühl, die Bewegungen des Bohrhammers zu kontrollieren.	I felt as though I were controlling the hammer drill’s movements.
Es fühlte sich so an, als würde ich die Bewegungen, die ich beim Bohrhammer gesehen habe, selbst verursachen.	It felt as if I were causing the movements I saw in the hammer drill myself.
Es fühlte sich so an, als würde das Geräusch durch meine eigene Handlung entstehen.	It felt as if the noise were being produced by my own actions.
Das Geräusch hat sich passend zu meiner Handlung beim Bohren angefühlt.	The noise felt appropriate for my actions while drilling.

Table 2: Study-specific items assessing the perceived support provided by auditory feedback.

Items (German)	**Items (English translation)**
Das Geräusch hat mir geholfen, die gewünschte Bohrtiefe zu erreichen.	The sound helped me achieve the desired drilling depth.
Anhand des Geräuschs konnte ich einschätzen, wie tief ich bereits gebohrt hatte.	Based on the sound, I was able to estimate how deep I had already drilled.
Ich war mir sicher, wann ich die Zieltiefe erreicht hatte.	I was confident that I had reached the target depth.

4. Pilot Study Results

To evaluate the feasibility of the proposed study design, a pilot study was conducted with three participants. All participants completed the experimental procedure and were subsequently invited to provide qualitative feedback regarding the task, auditory feedback conditions, questionnaires, and the overall mixed reality setup.

Overall, participants were able to complete the drilling task and distinguish between the implemented auditory feedback conditions. All three participants reported being able to distinguish between the implemented auditory feedback conditions. Changes in the auditory feedback were generally perceived; however, participants reported difficulties identifying the specific information conveyed by the sound variations. Observations made during the pilot study indicated that participants frequently positioned the drill at the target location before pressing the trigger. As a result, the idle sound implemented in the third auditory feedback condition was encountered only infrequently during task execution. This reduced the practical distinction between the second and third auditory feedback conditions during task execution.

Several practical challenges were identified during the pilot study. Participants reported difficulties interpreting items of the Igroup Presence Questionnaire (IPQ) due to the alternation of positively and negatively phrased statements. This occasionally led to uncertainty when completing the questionnaire. Also, the calibration of the Vicon tracking system proved to be a critical procedural step. Due to the vibration sensitivity of the Vicon camera system, recalibration was required during pilot testing. Another observation concerned participants' difficulties in determining the exact moment at which the virtual drill entered the wall. The most frequently discussed issue concerned the interaction device itself. Participants noted that the behavior of the robotic system during movements between drilling locations felt less natural than the drilling process itself. In particular, repositioning the tool between holes was perceived as distracting and negatively affected the feeling of presence.

5. Discussion, Limitation and Conclusion

The pilot study suggests that auditory feedback conditions representing different levels of process-relevant information can be distinguished and investigated to a meaningful degree within the proposed mixed reality testing environment. However, it also revealed factors that may have reduced the practical separation of individual information levels during task execution and should therefore be addressed before conducting a larger-scale evaluation. In particular, participants frequently positioned the drill at the target location before activating the tool. As a result, the idle sound intended to distinguish C3 from C2 was encountered only infrequently during task execution. Participants also reported that characteristics of the interaction device, particularly during tool repositioning, demanded attention that might otherwise have been directed toward the auditory feedback, potentially affecting the perception of differences between conditions. Together, these observations indicate that different levels of process-relevant auditory information can generally be distinguished and investigated within the proposed mixed reality testing environment, while also highlighting several design aspects that should be refined before conducting a larger-scale evaluation.

The findings should also be considered in the context of existing research on auditory feedback in virtual environments. Previous studies have largely focused on comparing sensory modalities or examining the effects of adding auditory cues to virtual interactions [7–9]. In contrast, the proposed study design enables the systematic investigation of informational content within the auditory modality itself. In this respect, the proposed approach extends existing research on auditory feedback beyond conventional modality comparisons.

Beyond the perceptibility of the implemented auditory manipulations, the pilot study also demonstrated the technical feasibility of the proposed approach. All participants were able to complete the drilling task and interact with the mixed reality system. Moreover, the pilot study confirmed the feasibility of combining a robotic interaction device, a virtual drilling task, and configurable auditory feedback within a controlled mixed reality testing environment. Together, these observations indicate that the proposed study design provides a suitable foundation for a larger-scale investigation of process-relevant auditory information in mixed reality testing environments. At the same time, the pilot study revealed opportunities for improving the interaction design. While the drilling process itself was generally perceived as plausible, participants described the movement of the tool between drilling locations as less natural. In particular, repositioning the drill required participants to move the physical handle attached to the robotic system, which differed from their expectations of operating a conventional rotary hammer. This observation suggests that further refinement of the force model and interaction dynamics may improve the overall realism of the experience. Future iterations of the setup should therefore focus not only on the representation of the drilling process itself but also on the transitions between different interaction phases.

It should be noted that the pilot study was not intended to evaluate the effectiveness of the selected sonification mappings or the suitability of feed force as an auditory parameter. Rather, the implemented mappings served as one possible operationalization of continuous process-related information. The pilot nevertheless provided valuable methodological insights for refining the experimental procedure, including improvements to questionnaire administration, motion-tracking calibration, and drill-wall contact detection.

The findings presented in this work should be interpreted in light of several limitations. Most importantly, the pilot study involved only three participants and was intended solely to evaluate the feasibility of the proposed study design. Accordingly, the observations reported here are qualitative in nature and do not allow conclusions regarding the effectiveness of the individual auditory feedback conditions.

In conclusion, this work contributes a study design for investigating auditory feedback in mixed reality testing environments, together with an operationalization of five auditory feedback conditions representing different levels of informational content. The pilot study confirmed the technical feasibility of the proposed approach and demonstrated that the implemented auditory feedback conditions were perceptible and generally distinguishable during task execution. At the same time, several opportunities for improving the interaction design and experimental procedure were identified. Building on these findings, future work can employ the proposed study design to investigate which level of auditory information most effectively supports presence, sense of agency, and task performance in mixed reality testing environments during early product development.

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Declaration of Generative AI Use in the Writing Process

Copilot was used to improve writing and language skills. The authors reviewed, revised, and validated all generated content and take full responsibility for the final manuscript.

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