Effect of Localization, Pitch, and Gain on Auditory Displacement for Pseudo-Force Feedback: An Exploratory Study

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Abstract

This paper reports on exploratory trials of an interactive virtual river system where sound simulates water pushing the user's hand, aiming to investigate the role of auditory cues on building displacement for pseudo-force feedback. Two trial sessions—one with restricted sound movement—were conducted during live demonstrations, using an embodiment questionnaire tailored for audio-only environments to collect user feedback. Analysis focused on patterns and contrasts across sessions rather than performance comparison, indicating that effective auditory displacement may rely on accurate sound localization—with variations in pitch (frequency) and gain (volume) enhancing the stimuli—when used in high-agency interactions. As expected in early-stage development, tactile responses were unclear, yet most participants still reported feeling some type of sensation, either tactile or interpreted as such. Ultimately, these insights advance sound-based pseudo-haptics as a step toward more accessible immersive environments for the visually impaired.

Keywords

Pseudo-haptics, Binaural sound, Accessibility

1. Introduction

Designing inclusive immersive environments demands multi-modal support tailored to user needs, especially for the visually impaired. As immersive technologies continue to evolve and expand, embedding accessibility into the design process is essential for creating inclusive experiences [1, 2]. Inclusive immersion requires thoughtful adaptation of content and interaction to suit diverse user needs and sensory modalities [1, 3]. This is particularly challenging when it comes to visually impaired users, who face major barriers due to the mainly visual nature of virtual reality, as discussed by Zhao et al. [4]. In this regard, literature on immersive technologies emphasizes the role of auditory and tactile modalities in overcoming such barriers [5, 3].

Audio-tactile interaction enables new haptic approaches to enhance accessibility for visually impaired users. In this context, pseudo-haptics uses cross-modal interaction to evoke tactile sensations by stimulating other senses, thus offering a simpler and more affordable alternative to traditional haptic devices [6, 7]. However, most pseudo-haptic designs rely on visual stimuli, making them inaccessible for visually impaired users [7, 8]. For this group, pseudo-haptics using sound presents a promising yet still underexplored alternative [6, 7], despite existing research on audio-tactile interaction [9, 10].

Recent research on sound-based pseudo-haptics reflects growing efforts to address this gap [11, 12, 13, 6]. Among these, Lopez et al. [11] explored the use of sound localization to induce force sensations, offering valuable technical insights and a comprehensive experimental setup. Building on their work, this paper reports on exploratory trials conducted using an improved version of that setup (see Fig. 1), analyzing system features and sound parameters through user feedback to uncover their role in the pseudo-haptic experience.

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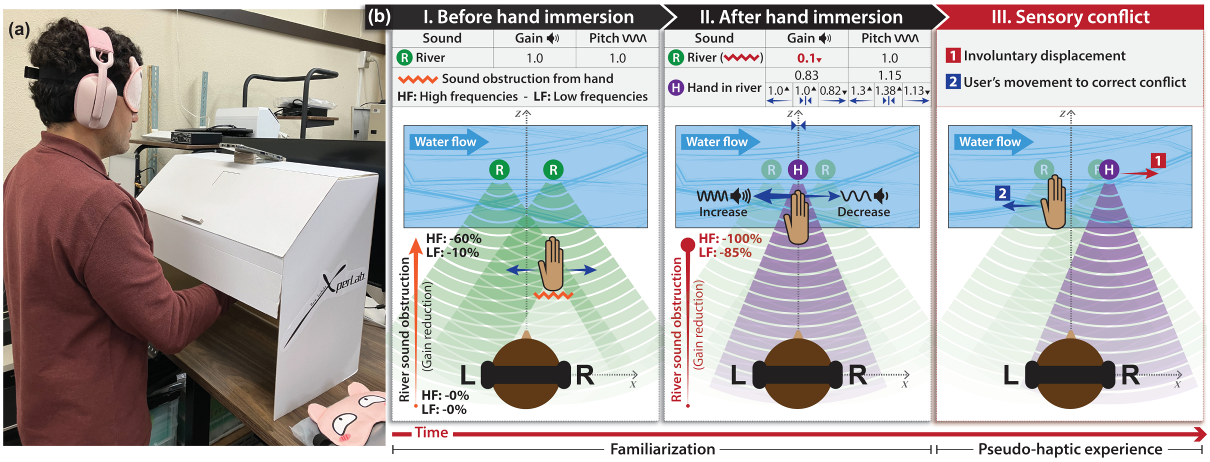

Figure 1: (a) System setup and (b) audio virtual environment, reproduced from [14]. **Environmental parameters:** listener's position ($[x, y, z] = [0, 0, 0]$) and orientation ($[x_{at}, y_{at}, z_{at}, x_{up}, y_{up}, z_{up}] = [0, 0, 1, 0, 1, 0]$); attenuation model (Inverse Clamped); reference distance (1.5); maximum distance (35.0). **Sound sources:** river (left: $[x, y, z] = [-3.75, 0, 8]$, right: $[x, y, z] = [3.75, 0, 8]$); hand-in-river ($[x, y, z] = [dynamic, 0, 8]$). **Custom features:** hand obstruction and hand-river interaction

2. Related Work

Despite limited research on sound-based pseudo-haptics, Lopez et al. [11] draw from prior work to propose a new design. Bosman et al. [12] found realistic sounds and hand ownership key for believability, while Kitagawa [9] showed that spatial sound cues can influence tactile and body perception. Building on this, Lopez et al. propose a pseudo-force feedback design based on sound localization, implemented across two water-stream scenarios. In the first, users keep their hand steady in a virtual river while sound simulates the flow of water pushing against it. In the second, they move their hand through a virtual water tank, with sounds indicating streams that either assist or resist the motion. Both scenarios omit visual cues and use binaural sound to simulate a pushing force through the displacement of the hand's perceived auditory position in virtual space, creating a conflict with its actual position.

The design presented by Lopez et al. [11] employs the same pseudo-haptic technique as the HEMP system by Pusch et al. [15], but using a different sensory modality. The HEMP study presents an augmented reality experience via a video see-through HMD, where a virtual force field—rendered as a steam tube with flowing particles—displaces the hand's visual position upon immersion, creating a conflict with its real, kinesthetic position. In that sense, while both systems use spatial sensory conflict to create a pseudo-haptic effect, Pusch et al. rely on visual displacement, whereas Lopez et al. employ auditory displacement.

Displacement is a widely used pseudo-haptic technique, yet important aspects remain to be explored. Essentially, it involves applying translational or rotational movement to user input to produce a distorted output, leading to a sensory conflict that elicits a pseudo-haptic effect [7]. As discussed by Ujitoko et al. [7], displacement has been used in prior research to elicit various haptic properties, such as weight, compliance, friction, and even force. However, while its use with visual stimuli has been extensively explored, its application through auditory stimuli has received little attention (ibid). Given the distinct nature of auditory and visual modalities, further research is needed to understand how acoustic parameters—particularly sound localization—can support pseudo-force illusions.

3. System

The system used in this study—originally introduced in [14] and shown in Fig. 1—extends the work of Lopez et al. [11] to provide a more robust setup for studying pseudo-haptic force feedback using sound localization, reinforced by obstruction and variations in pitch (frequency) and gain (volume). It

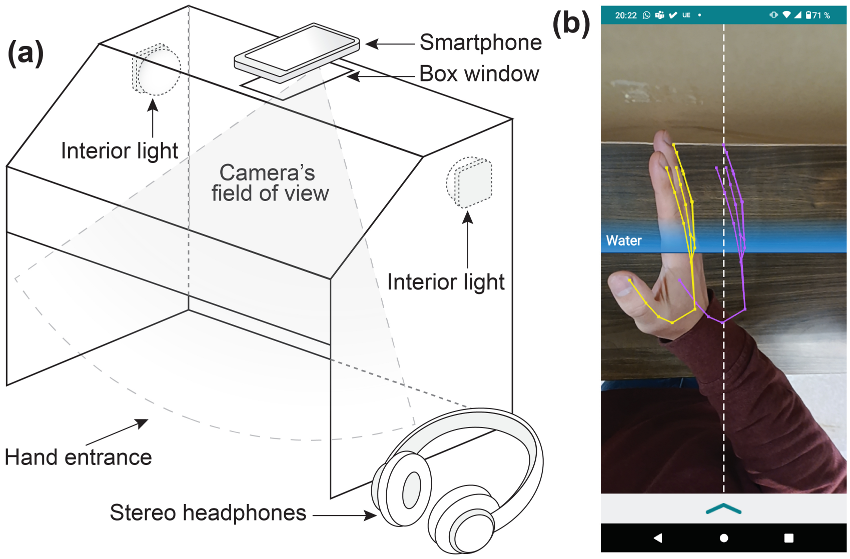

Figure 2: System Setup: (a) hardware and (b) software, reproduced from [14].

features a virtual river scenario where sound simulates water pushing the user's hand, while allowing free interaction by sweeping the hand through the environment.

3.1. Method

As mentioned earlier, the pseudo-haptic effect emerges from a conflict between the kinesthetic and auditory position of the hand. The auditory position consists of river-like sounds projecting the hand's real, kinesthetic position into the virtual environment through binaural localization. These spatial sound cues support hand ownership, and their displacement alters self-body perception (i.e., proprioception [16]), resulting in a sensory conflict that evokes a force sensation

The displacement involves a lateral shift of the hand's auditory position after immersion, emulating the dragging force of the river. It uses a stepwise function with acceleration and deceleration phases to provide a realistic approximation of the velocity and movement of the hand. First, the velocity increases exponentially from rest to match the river's velocity and direction, then decays exponentially towards zero as the hand, attached to the arm and body, resists the river's flow. These phases are described by the following formulas.

$$v_{\text{hand}}(t) = v_{\max}\,(1 - \exp(-k \cdot t)) \quad \boxed{\text{Acceleration Phase}} \tag{1}$$

$$v_{\text{hand}}(t) = v_{\max}\exp(-d \cdot (t - t_{\text{peak}})) \quad \boxed{\text{Deceleration Phase}} \tag{2}$$

Where:

- $v_{\text{hand}}(t)$: velocity of the hand at time t
- $v_{\max}$: maximum velocity (river's velocity)
- k: acceleration constant
- d: deceleration constant
- t: time
- t_{peak}: time at which the maximum velocity is reached

The displacement parameters were fine-tuned to create a noticeable sensory conflict while remaining subtle enough to build the illusion. These parameters—maximum velocity and acceleration/deceleration factors—control the displacement distance over time, and their optimal values were set through preliminary testing to achieve a noticeable yet believable effect (see Fig. 3). These values enable continuous

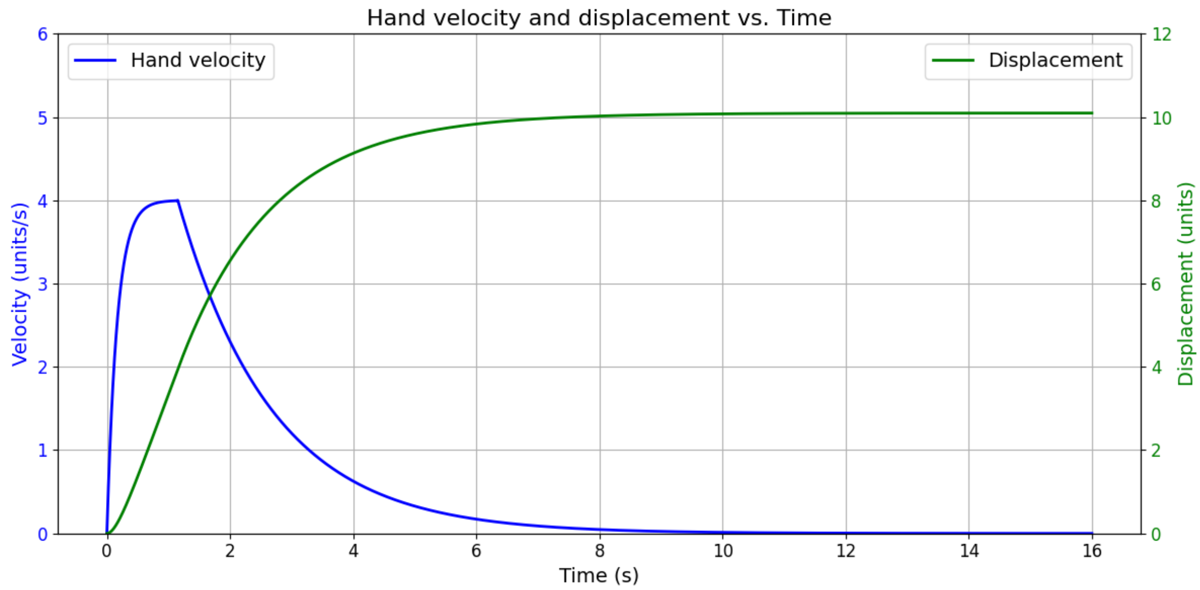

Figure 3: Hand velocity and displacement over time for producing the sensory conflict. Parameters set to $v_{\max} = 4$ units/s, $k = 6.0$, $d = 0.65$, resulting in a displacement of 10.1 units over a period of 10.4 seconds.

displacement with multiple feedback cycles before stopping, simulating the river persistently pushing the hand.

The perception of the hand being pushed leads to a corrective process that completes the pseudo-haptic experience. The auditory displacement alters proprioception, creating a conflict that the user is expected to resolve through a motor reaction. This involves muscle effort to maintain the original auditory position of the hand, helping to build the mental representation of force being exerted. Therefore, the user must be initially instructed to keep the hand steady in order to trigger this corrective process in response to displacement.

Finally, it is important to note that the sensory conflict occurs in a comprehensive auditory virtual environment, with sound obstruction and pitch-gain variations also resulting from user interaction. These sound cues are then leveraged to reinforce the sensory conflict by improving realism and expectation on the auditory displacement, thus making it more convincing.

3.2. Implementation

The system is implemented as an Augmented Reality application in Java, Kotlin, and C++, running on an Android smartphone, leveraging hand position as the primary input and binaural sound cues as the primary output. Hand position is captured from mid-air gestures via the smartphone's camera using the MediaPipe library, while binaural sound cues are rendered via Bluetooth stereo headphones using the OpenAL library. Additionally, to optimize hand tracking, the smartphone is mounted on a cardboard box that blocks external interference and includes internal light bulbs for extra illumination (see Fig. 2).

The audio virtual environment includes three feature layers: *environmental parameters* that govern global sound behavior—such as listener position and orientation, attenuation model, and reference and maximum distances—configured for realistic first-person interaction; *sound sources*, playing river-like sounds within those parameters, each with specific properties (gain, pitch, position); and *custom features*, which integrates the first two to enable system interactivity. Among these interactions, hand obstruction simulates how the hand muffles the river sound—as it approaches or enters the virtual river—by mainly reducing high frequencies based on its position, with asymmetrical effects in each ear. The hand–river interaction also features distinct sound cues based on contact and movement, including splash sounds on entry and exit, dynamic positioning of the hand-in-river sound based on lateral hand motion, and pitch and gain changes when moving against (left) or with the flow (right).

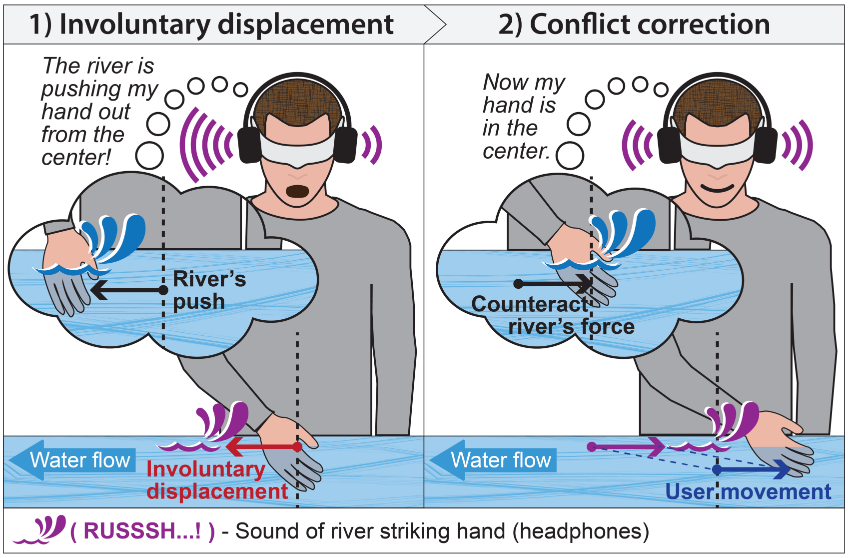

Figure 4: User perception of displacement, reproduced from [14].

The pseudo-haptic effect relies on an involuntary sound displacement. Users are first asked to keep their hand's auditory position centered, causing the pitch and gain of the hand-in-river sound to increase—simulating resistance against the water and priming the upcoming shift. Then, the sound moves to the right (with the flow), simulating the river's force pushing the hand (see Fig. 4).

4. Exploratory trials

Before moving on to more rigorous testing, eventually engaging visually impaired users, an exploratory phase with an open pool of participants is essential for gathering initial insights to refine the system. Exploratory trials were conducted during two public demonstration events—SIGGRAPH Asia 2024 (*Session A*) and Augmented Humans 2025 (*Session B*)—where participants engaged freely with the system in naturalistic conditions (see Figures 5 and 6). The format of the events limited demographic data collection but allowed for spontaneous user feedback and valuable observations for early-stage evaluation of the role of sound cues in the pseudo-haptic experience.

Both sessions used the same setup, but *Session B* added a water-resistance feature for deeper exploration. This feature creates a drag effect restricting leftward movement (against flow) of the hand's auditory position, triggering audio-tactile interaction to adjust proprioception and reinforce the sensory conflict. This effect mirrors the stepwise function from Section 3, integrated with respect to time to produce dragging distance instead of velocity (since velocity now depends on user movement), with the hand's real position as the controlling variable. Moreover, the parameters were adjusted to ensure a perceivable restricting effect (see Fig. 7).

The trials followed a two-phase protocol—familiarization and pseudo-haptic experience—with participants blindfolded throughout to eliminate visual input. During *familiarization*, users moved their hands through the virtual environment, while auditory feedback helped them grasp the interaction dynamics and foster a sense of hand ownership. In the *pseudo-haptic experience*, they were asked to keep their hand's auditory position centered in the river, triggering the priming cues and the involuntary displacement described earlier.

After each trial, participants filled out a questionnaire assessing usability, embodiment, and first impressions of the pseudo-haptic experience. The questionnaire was adapted from Gonzalez-Franco and Peck's Embodiment Questionnaire [17] to better suit an audio-only virtual environment (see Fig. 8). It included Likert-scale items ranging from −3 (strongly disagree) to +3 (strongly agree), assessing Usability (Q1); Body Ownership (Q2); Body Location (Q3, Q4); Agency and Motor Control (Q5, Q6); Tactile Sensations (Q7, Q8, Q9); and Response to External Stimuli (Q10–Q14). It also contained one

Figure 5: Public demonstration at SIGGRAPH Asia 2024 conference (Tokyo, Japan).

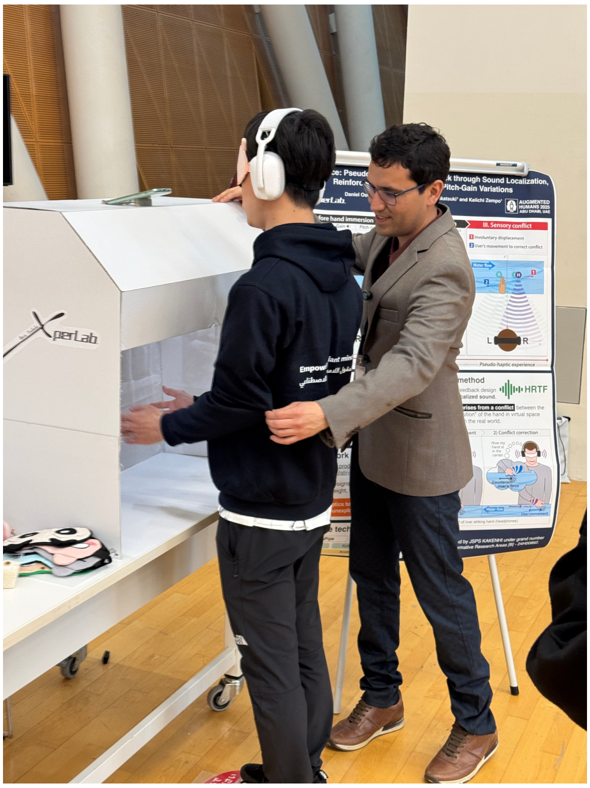

Figure 6: Public demonstration at Augmented Humans 2025 conference (Abu Dhabi, UAE).

multiple-select item on events triggering tactile sensation (Q15, Fig. 9), and four open-ended questions for qualitative feedback on the overall experience and system improvements.

5. Results

Data were collected from 30 participants—17 in *Session A* and 13 in *Session B*. One participant from *Session B* was excluded due to hand tracking issues, and three participants did not answer all questions. These exclusions have minimal impact, as most analyses are conducted on a per-question basis using the available sample size. Results are reported descriptively based on question category.

Participants consistently rated the system as easy to understand. The usability question (Q1) scored high in *Session A* (M = 1.82, SD = 0.73), and even higher in *Session B* (M = 2.08, SD = 1.51).

Body ownership and location were strongly perceived. The feeling that the heard hand was one's own (Q2) was rated highly, especially in *Session B* (M = 2.50, SD = 0.67) compared to *Session A* (M = 1.71, SD = 0.47). Perception of the hand's location in the river (Q3) showed moderate agreement in both sessions (*Session A*: M = 1.65, SD = 0.86; *Session B*: M = 1.67, SD = 1.37). Participants also agreed that the sound helped position the hand at the river's center (Q4), with higher ratings in *Session B* (M = 2.33, SD = 0.89) compared to *Session A* (M = 1.47, SD = 1.23).

Participants showed a clear sense of agency and motion control. They strongly agreed that their movements affected the river's sound (Q5), with high scores in both sessions (*Session A*: M = 2.71, SD = 0.47; *Session B*: M = 2.42, SD = 0.90). Agreement was slightly lower, but still positive, regarding the river's sound influencing their movements (Q6), with *Session A* scoring M = 1.65 (SD = 1.41) and *Session B* scoring M = 1.67 (SD = 1.15).

Perceived tactile qualities were more varied. The sensation of touching the river (Q7) received low to moderate agreement (*Session A*: M = 1.00, SD = 0.94; *Session B*: M = 0.58, SD = 1.31). The distinction between moving with or against the flow (Q8) was moderately perceived (*Session A*: M = 1.35, SD = 1.41; *Session B*: M = 1.42, SD = 1.08). Finally, the feeling of pushing against a force while relocating the hand

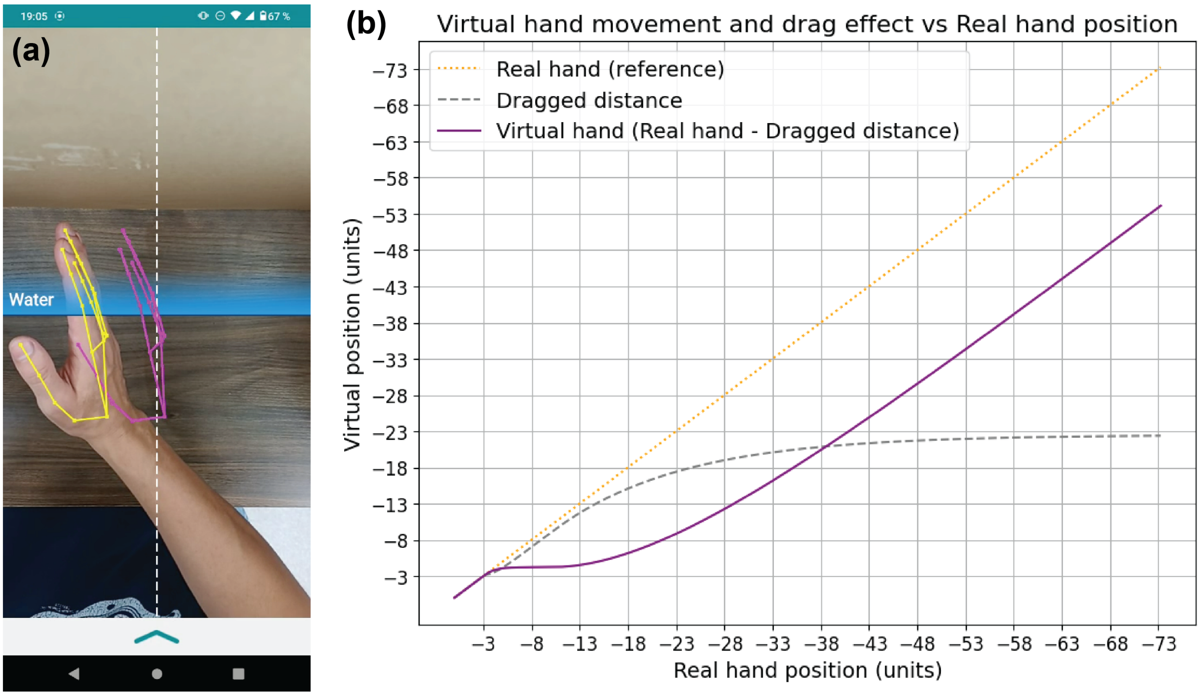

Figure 7: Restricted leftward movement in *Session B*: a) Software, b) Plot of virtual hand movement and drag. The drag effect starts at $x = -3.25$ and continues along the negative X-axis up to $x = -71.6$, with parameters $v_{\max} = 1$ units/s, $k = 1.0$, $d = 0.075$, resulting in a total drag distance of 19.1 units.

(Q9) was notably weak in both sessions (*Session A*: M = 0.00, SD = 1.37; *Session B*: M = 0.11, SD = 1.76).

Participants showed mixed responses to external stimuli. The need to resist the water's force while the hand was centered (Q10), ranged from low in *Session A* (M = 0.29, SD = 1.26) to moderate in *Session B* (M = 0.75, SD = 1.36). The sensation of something about to happen due to the sound (Q11) was generally weaker, barely above neutral (*Session A*: M = 0.59, SD = 1.42; *Session B*: M = 0.50, SD = 1.45). The tactile response to the involuntary rightward-moving sound (Q12) was even weaker, especially in *Session B* (M = -0.17, SD = 1.53) compared to *Session A* (M = 0.41, SD = 1.06). Similarly, the feeling of being pushed by the river (Q14) was barely perceived in both sessions (*Session A*: M = 0.29, SD = 1.36; *Session B*: M = 0.00, SD = 1.87). However, the instinct to correct the hand's position when the sound moved rightward (Q13) was noticeably stronger (*Session A*: M = 0.94, SD = 1.52; *Session B*: M = 1.22, SD = 1.92).

Regarding events triggering tactile sensations (Q15), results varied across sessions (see Fig. 5). In *Session A*, the most frequent sensations were linked to the hand drifting left (18%), drifting right (16%), or involuntarily shifting right while centered (16%). Others resulted from the hand hitting the water (14%) and a leftward correction toward center (11%). Only 9% reported no tactile sensation, and all other responses were less than 8% each. In *Session B*, the most common sensation was triggered by the hand hitting the water (28%), followed by the hand being centered (17%) or exiting the water (17%). A sensation linked to the hand moving right was less frequent (11%), and all other responses, including absence of tactile feedback, were 6% or fewer. Percentages are rounded for clarity.

Finally, participants in both sessions shared mixed impressions and suggestions, which are included in the Discussion to better contextualize the analysis.

6. Discussion

This study examined how sound parameters—particularly localization—can produce auditory displacement to evoke pseudo-force sensations. Therefore, the results were analyzed for patterns and contrasts between sessions to extract useful insights instead of determining superiority.

The system was consistently perceived as easy to understand, even though auditory displacement

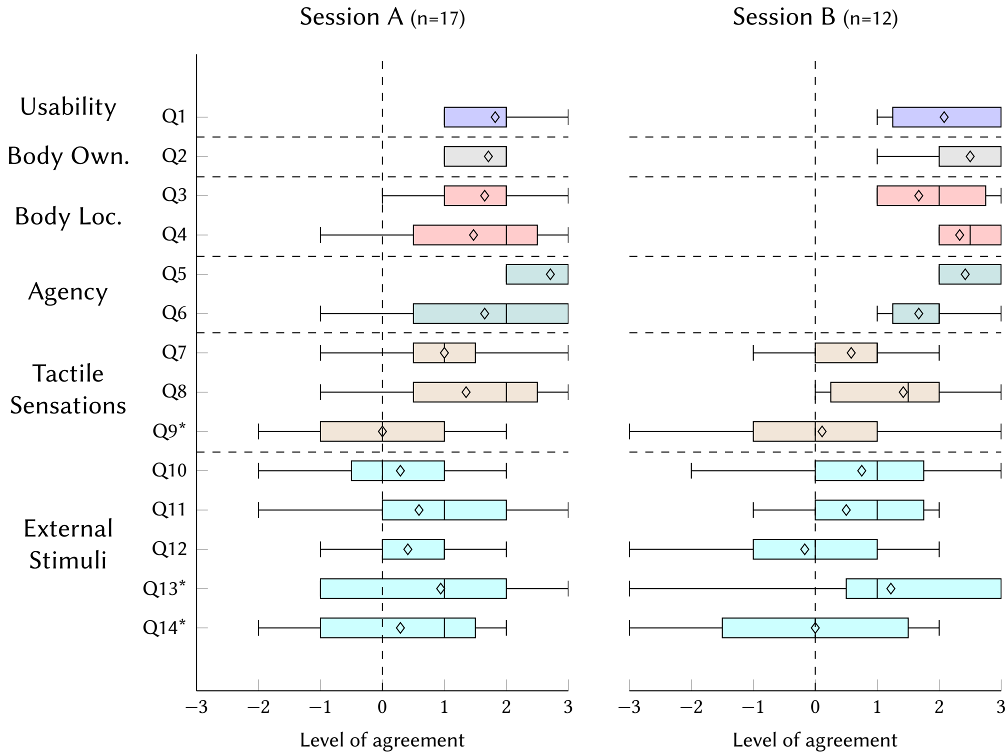

Figure 8: Agreement on Likert-scale items (−3: strongly disagree, +3: strongly agree) per session, by category. **Q1:** *I thought that the system's behavior was easy to understand, even with my eyes closed.* **Q2:** *It felt like the hand I heard interacting with the river was my own hand.* **Q3:** *I felt as if my hand was located where the river's sound reacted.* **Q4:** *The sound helped me locate the center of the river and position my hand there.* **Q5:** *The changes in the river's sound were caused by my movements.* **Q6:** *I felt as if the sounds of my hand in the river were influencing the way I moved my hand.* **Q7:** *It seemed as if my hand was touching the river.* **Q8:** *Moving my hand left (against the flow) felt distinct from moving my hand right (with the flow).* **Q9:** *When moving my hand to the opposite direction (left) to relocate it at the center I felt like I was pushing against a force.* **Q10:** *I felt as if I needed to exert some effort to resist the force of the water while my hand was centered.* **Q11:** *The sound of keeping my hand centered made me feel like something was about to happen.* **Q12:** *I felt a tactile sensation in my hand as I heard the sound moving right from its centered position.* **Q13:** *When I heard the sound of my hand moving (right) from its centered position, I felt the instinct to correct the position by moving my hand to the opposite direction (left).* **Q14:** *I felt as if my hand had been pushed.* (Outliers kept in data but not shown in plot for exploration.)
* Question with smaller sample size in Session B (n=9)

may disrupt perceptual coherence. This likely reflects the design rationale in [14], which enables audio augmentation while preserving realism, thereby providing a reliable setup for auditory displacement.

Body ownership and location were clearly perceived; while ownership aids in building a coherent virtual model [12], body location seems to be a factor directly shaping the pseudo-haptic effect. Precise body localization was achievable using sound cues alone, but their contribution appears tied to responses to involuntary displacement (see Q4 and Q13, Fig. 8). This suggests that accurate sound localization may be key for effective auditory displacement. As one participant recommended, *"Transition sound can be smoother."* Since localization can be affected by factors like motion, distance, and reverberation [18, 14], it is important to carefully adjust sound parameters and system features to maximize accuracy.

Agency appears to play a key role in shaping effective auditory displacement. Stronger feelings of control over the environment (Q5) were linked to higher tactile responses in high-agency interactions (e.g., moving the hand left and right—Q8), while lower feelings of environmental influence (Q6) correspond to weaker responses during low-agency actions (e.g., keeping the hand steady—Q10, Q11, Q12; small hand movements—Q9). Excluding the stronger responses during the low-agency involuntary displacement (Q13)—likely driven by the *centering* task than by a felt force, as reflected in Q9, Q12, Q14—this suggests

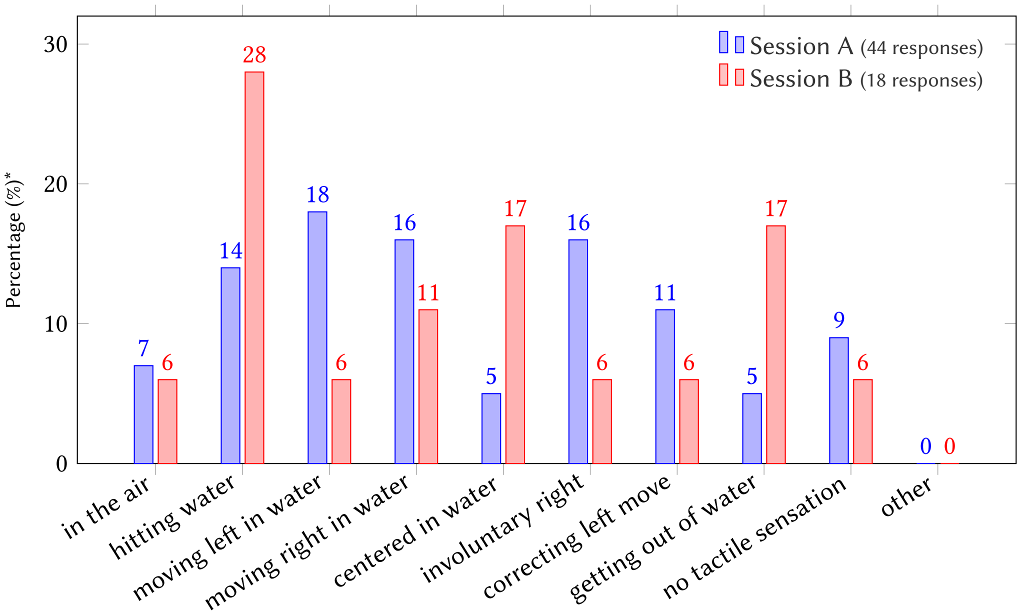

Figure 9: Response distributions per session for the multiple-select question (Q15): *"I felt a tactile sensation in my hand when I heard the sound of (my hand)..."*
* Percentages rounded for clarity; totals may slightly differ from 100% due to rounding.

that fostering a strong sense of agency during displacement, or employing high-agency interactions, may enhance its effect.

Focusing on interactions with consistent tactile responses across sessions allows for a deeper analysis of the sound cues contributing to the displacement. While tactile responses were generally weak (Q7, Q9, Q12, Q14) even with a clear perception of displacement (Q13), stronger sensations were reported during left/right hand movements (Q8). Lateral hand movements involved pitch-gain variations affecting sound localization in both sessions, while localization was dynamically restricted only in *Session B* (see Section 4). This suggests that pitch-gain variations may contribute meaningfully on producing displacement. Although displacement was defined as a spatial shift (see Section 2), sound-based pseudo-haptics may call for a broader model of sensory conflict.

Overall, effective auditory displacement may rely on accurate localization and strategic pitch and gain use to enrich stimuli, especially in high-agency contexts.

Finally, participants did not report clear tactile feedback (see Q7–Q14, Fig. 8), yet most linked certain events to touch (Q15, Fig. 9)—suggesting implicit interpretation. As one participant noted: *"I didn't feel like I was pushing it, but I immediately knew that the movement of my hand had a sound and an effect."* That said, strong agreement was found for sensations during hand immersion and rightward movement in water—both tied to high agency, accurate localization, and pitch-gain variation. In contrast, leftward movement showed mixed results; despite high agency and pitch-gain changes, restricted sound movement in *Session B* may have reduced its effect. Low-agency events—like keeping the hand centered, involuntary displacement, or small leftward corrections—also gave inconsistent outcomes. Exiting the water showed mixed results—though pitch-gain variation was present, it typically marked the end of interaction. Ultimately, in-air hand motion evoked minimal sensations—as intended.

7. Conclusion

This paper explored how sound properties and interactions support auditory displacement for pseudo-force sensations, offering insights toward accessible immersive environments for the visually impaired. To this end, two trial sessions—one with restricted sound movement—were conducted using an interactive virtual river system where sound simulated water pushing the user's hand. These sessions were held during live demonstrations, with user feedback collected via an embodiment questionnaire—adapted for audio-only environments—to analyze the pseudo-haptic effects of sound cues across various aspects of user experience.

As an exploratory study, analysis focused on patterns and differences across sessions to gain insights rather than assert superiority. Findings suggest that the system offers a robust platform for exploring sound-based pseudo-force feedback, balancing realism with audio augmentation. In this context, sound localization appears a reliable cue for displacement—though enhancing its precision could improve effectiveness—while pitch and gain variations can be applied strategically to reinforce the stimuli. Moreover, fostering a strong sense of agency during displacement—or using high-agency interactions for it—seems key for enhancing its effect. Finally, tactile responses were not consistent—as expected in early-stage development—yet most participants reported perceiving sensations that may have been tactile or interpreted that way.

Although the study involved uncontrolled conditions—such as ambient noise, flexible procedures, and open participation—these suited its exploratory goals. Future research should address these limitations, including targeted recruitment of visually impaired users—who may be harder to engage—to enable rigorous testing and conclusive results. The system should also adapt to these findings for further testing, and scale to broader uses, like emulating force from solid objects.

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Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT and Gemini in order to: Grammar and spelling check, Paraphrase and reword. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

References

[1] J. Dudley, L. Yin, V. Garaj, P. O. Kristensson, Inclusive immersion: a review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse, Virtual Real. 27 (2023) 2989–3020. URL: https://doi.org/10.1007/s10055-023-00850-8. doi:10.1007/s10055-023-00850-8.

[2] M. Mott, E. Cutrell, M. Gonzalez Franco, C. Holz, E. Ofek, R. Stoakley, M. Ringel Morris, Accessible by design: An opportunity for virtual reality, in: 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), 2019, pp. 451–454. doi:10.1109/ISMAR-Adjunct.2019.00122.

[3] W3C, Xr accessibility user requirements, 2021. URL: https://www.w3.org/TR/xaur/.

[4] Y. Zhao, C. L. Bennett, H. Benko, E. Cutrell, C. Holz, M. R. Morris, M. Sinclair, Enabling people with visual impairments to navigate virtual reality with a haptic and auditory cane simulation, in: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI '18, Association for Computing Machinery, New York, NY, USA, 2018, p. 1–14. URL: https://doi.org/10.1145/3173574.3173690. doi:10.1145/3173574.3173690.

[5] C. Creed, M. Al-Kalbani, A. Theil, S. Sarcar, I. Williams, Inclusive ar/vr: accessibility barriers for immersive technologies, Universal Access in the Information Society 23 (2024) 59–73. URL: https://doi.org/10.1007/s10209-023-00969-0. doi:10.1007/s10209-023-00969-0.

[6] M. Melaisi, D. Rojas, B. Kapralos, A. Uribe-Quevedo, K. Collins, Multimodal interaction of contextual and non-contextual sound and haptics in virtual simulations, Informatics 5 (2018). URL: https://www.mdpi.com/2227-9709/5/4/43. doi:10.3390/informatics5040043.

[7] Y. Ujitoko, Y. Ban, Survey of pseudo-haptics: Haptic feedback design and application proposals, IEEE Transactions on Haptics 14 (2021) 699–711. doi:10.1109/TOH.2021.3077619.

[8] A. Pusch, A. Lécuyer, Pseudo-haptics: from the theoretical foundations to practical system design guidelines, in: Proceedings of the 13th International Conference on Multimodal Interfaces, ICMI '11, Association for Computing Machinery, New York, NY, USA, 2011, p. 57–64. URL: https://doi.org/10.1145/2070481.2070494. doi:10.1145/2070481.2070494.
[9] N. Kitagawa, Link between hearing and bodily sensations, NTT Technical Review 11 (2013) 30–33.
[10] N. KITAGAWA, C. SPENCE, Audiotactile multisensory interactions in human information processing, Japanese Psychological Research 48 (2006) 158–173. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1468-5884.2006.00317.x. doi:https://doi.org/10.1111/j.1468-5884.2006.00317.x. arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1468-5884.2006.00317.x.
[11] D. Lopez, N. Wakatsuki, K. Zempo, Auditory ar system to induce pseudo-haptic force feedback for lateral hand movements using spatially localized sound stimuli, in: SIGGRAPH Asia 2024 Posters, SA '24, Association for Computing Machinery, New York, NY, USA, 2024. URL: https://doi.org/10.1145/3681756.3697955. doi:10.1145/3681756.3697955.
[12] I. d. V. Bosman, K. De Beer, T. J. D. Bothma, Creating pseudo-tactile feedback in virtual reality using shared crossmodal properties of audio and tactile feedback, S. Afr. Comput. J. 33 (2021).
[13] E. Frid, J. Moll, R. Bresin, E.-L. Sallnäs Pysander, Haptic feedback combined with movement sonification using a friction sound improves task performance in a virtual throwing task, J. Multimodal User Interfaces 13 (2019) 279–290.
[14] D. Lopez, N. Wakatsuki, K. Zempo, Audio-force: Pseudo-haptic force feedback through sound localization, reinforced by obstruction and pitch-gain variations, in: Augmented Humans 2025 Demos, AHs '25, Association for Computing Machinery, New York, NY, USA, 2025. URL: https://doi.org/10.1145/3745900.3746115. doi:10.1145/3745900.3746115, in press.
[15] A. Pusch, O. Martin, S. Coquillart, Hemp—hand-displacement-based pseudo-haptics: A study of a force field application and a behavioural analysis, International Journal of Human-Computer Studies 67 (2009) 256–268. URL: https://www.sciencedirect.com/science/article/pii/S1071581908001328. doi:https://doi.org/10.1016/j.ijhcs.2008.09.015, current trends in 3D user interface research.
[16] D. Martin, S. Malpica, D. Gutierrez, B. Masia, A. Serrano, Multimodality in vr: A survey, ACM Comput. Surv. 54 (2022). URL: https://doi.org/10.1145/3508361. doi:10.1145/3508361.
[17] M. Gonzalez-Franco, T. C. Peck, Avatar embodiment. towards a standardized questionnaire, Frontiers in Robotics and AI Volume 5 - 2018 (2018). URL: https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2018.00074. doi:10.3389/frobt.2018.00074.
[18] O. S. Rummukainen, S. J. Schlecht, E. A. P. Habets, Self-translation induced minimum audible angle, The Journal of the Acoustical Society of America 144 (2018) EL340–EL345. URL: https://doi.org/10.1121/1.5064957. doi:10.1121/1.5064957. arXiv:https://pubs.aip.org/asa/jasa/article-pdf/144/4/EL340/15336993/el340_1_online.pdf.