# Spatial Haptics: A Sensory Substitution Method for Distal Object Detection Using Tactile Cues


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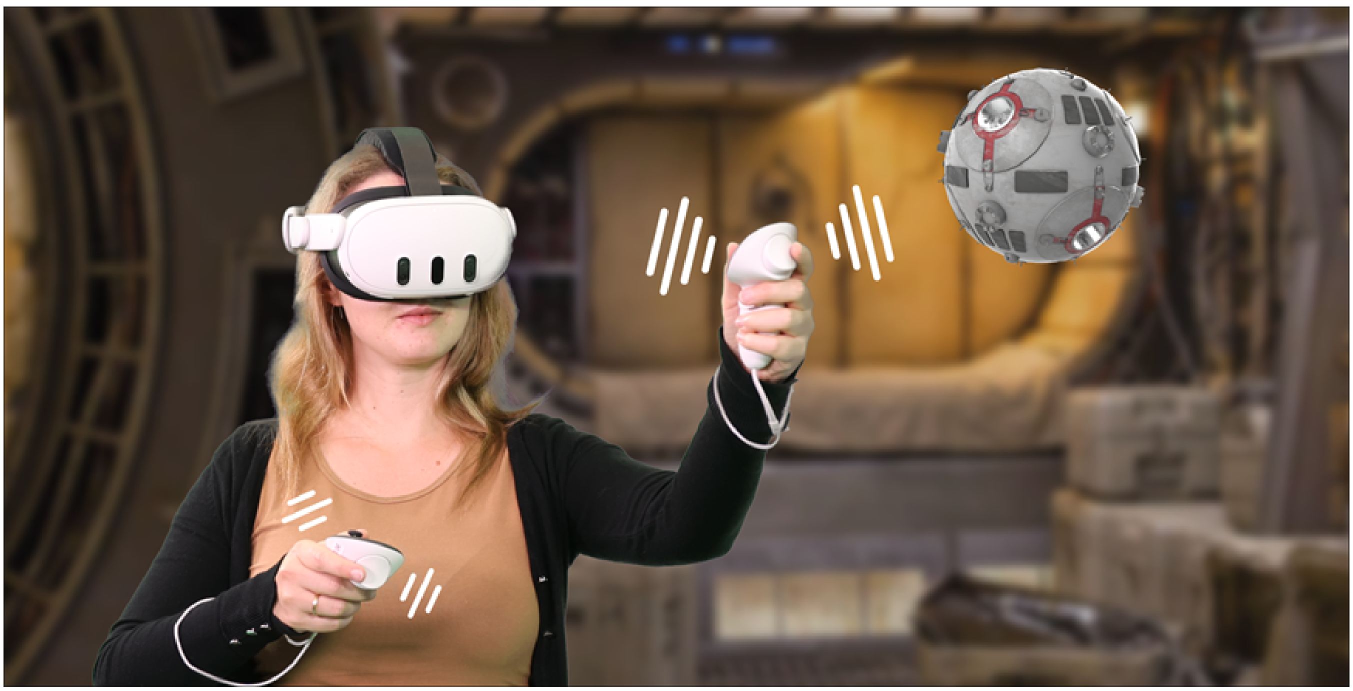

**Figure 1: A user wearing a VR head-mounted display utilizes handheld controllers with adaptive vibrotactile feedback to detect and locate a remote object in 3D space. The intensity of vibrations in each controller varies based on the object's relative position, mimicking auditory localization mechanisms to enhance spatial awareness.**


## Abstract

We present a sensory substitution-based method for representing locations of remote objects in 3D space via haptics. By imitating auditory localization processes, we enable vibrotactile localization abilities similar to those of some spiders, elephants, and other species. We evaluated this concept in virtual reality by modulating the vibration amplitude of two controllers depending on relative locations to a target. We developed two implementations applying this method


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using either ear or hand locations. A proof-of-concept study assessed localization performance and user experience, achieving under 30° differentiation between horizontal targets with no prior training. This unique approach enables localization by using only two actuators, requires low computational power, and could potentially assist users in gaining spatial awareness in challenging environments. We compare the implementations and discuss the use of hands as ears in motion, a novel technique not previously explored in the sensory substitution literature.

## CCS Concepts

• **Human-centered computing** → **Interaction techniques**; **Virtual reality**; • **Computing methodologies** → *Virtual reality*; *Perception.*

## Keywords

Haptic, Tactile, Sensory substitution, Spatial perception, Localization

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## 1 Introduction

Localization is the process of determining the spatial location of objects in our environment relative to oneself. This results from an extrapolation of objects' positions and locations, achieved primarily through a combination of visual and auditory cues. Localization of sound, for example, is crucial for our survival [18], recognizing threats and dangers such as a car rushing behind one's back, or a fierce opponent in a VR shooter game. But it is also crucial for orientation, as well as social interaction, by allowing one to localize and differentiate between voices. In practice, localization is a very basic and crucial ability that we possess. As such, it is a highly sought-after ability to enable localization for individuals experiencing difficulties with spatial localization. For example, people with hearing impairments or those situated in challenging environments, such as areas with excessive noise or virtual reality settings, may struggle with localization. In addition, the possibility of augmenting localization in entirely new ways is also a promising avenue.

Sensory substitution devices, that convey information from one modality through another, tap into the brain's inherent multisensory processing abilities to enable an intuitive and cognitively efficient perception of information. This can be especially helpful for reducing the load on vision or audition (which are commonly flooded with sensory input) via tactile cues [3, 24]. In this work, we employ a sensory substitution method based on the localization abilities provided by the human ears for allowing localization through touch, building on related work exploring these principles [4, 38, 83]. We developed a novel method that simulates the auditory localization system by touch, conveying spatial information through differences between two multifrequency actuators in a manner similar to the differences in frequency, latency, and amplitude between our two ears, creating an understanding of locations in three-dimensional space (See Figure 1).

To achieve tactile localization, we developed a two-actuator implementation utilizing standard VR controllers. We explore two methods to the realization of this concept: ear-based localization (EBL), in which feedback is determined based on the relative locations of the ears to a target; and hand-based localization (HBL), in which feedback is determined based on the relative locations of the hands to a target. In EBL users can move their heads to acquire a better understanding of the location through the vibration in their hands, similar to localizing sound, while in HBL, the user's hands allow them to freely explore the space to understand the represented location.

Our two methods were evaluated in a psychophysical study investigating the detection thresholds, as well as in subjective measures, for evaluating user performance and experience.

## 2 Related Work

Our novel approach for enabling localization through tactile cues builds upon related work in spatial haptic feedback and sensory substitution.

### 2.1 Spatial Haptic Feedback

Spatial haptic feedback has been shown to be beneficial for multiple purposes in virtual and physical reality. These include navigation, interaction with the environment, manipulation of objects, and more [10, 11, 28–31, 34, 62].

Representation of spatial information through haptics has previously mainly focused on navigation rather than the indication of an object's location in space [11]. Several works explored localization mostly on the body itself using multiple actuators, often applying well-known haptic illusions or numerous actuators working together to represent locations between them and increase resolution [15, 52, 54, 55, 78, 91]. Another somewhat relevant application is the development of controllers that are used to interact with objects in space [23, 25]. These also commonly use multiple actuators to simulate the feeling of one object touching another and interacting with the environment in different directions [54, 55, 78].

In contrast, in this work we suggest employing a sensory substitution approach, using the substitution of auditory to tactile information to enable natural perception of locations in space using only two actuators. This approach fits the popular means of providing haptic information currently prominent in VR, by bootstrapping onto existing game controllers. This cost-effective method also utilizes the tactile acuity of the fingers [9, 11].

### 2.2 Sensory Substitution for Tactile Spatial Perception

Sensory substitution systems are widely employed for research, but also for pragmatic applications, leveraging the demonstrated ability to achieve sensory-like perception through alternative senses following training [5–8, 13, 21, 42, 44, 61, 76, 77, 85, 86, 89]. Such systems present potential advantages for people with sensory impairments, could help regulate sensory load, improve perception of information, and more.

Much of the early seminal work in the field has focused on enabling visual and spatial perception for the blind [6, 56, 66, 77]. A pioneering example of such technology is the TVSS sensory substitution system, which conveyed visual information through tactile cues, spatially distributed on the body [5–8]. It was developed by Paul Bach Y-Rita, known as the founder of sensory substitution. He later also developed the tongue display unit, another early example of a spatial-tactile solution that represents the visual field using electrotactile stimulation on the tongue [20, 48, 80]. The EyeCane is a later device designed to help blind people navigate and orient themselves in virtual and real-world environments [57, 58]. The device uses vibration and auditory cues at different intensities to represent the distance from the person to the object at which it is pointed. The same principle was applied in other systems, implemented in wristbands, gloves and belts, and expanded to convey information from multiple points as well as elevation angle [17, 32, 50, 75].

### 2.3 Sensory Substitution for Augmenting Tactile Spatial Perception

Nowadays, there is a growing awareness and interest in the potential of auditory-to-tactile sensory substitution systems. These are believed to be effective due to similarities between the auditory and tactile systems, their joint evolution, receptor types, and shared brain mechanisms [79, 82, 90, 92, 93]. Historically, most of these systems have been developed as accessibility aids for the hearing impaired [33, 35–37, 71, 74]. Yet it is now becoming more and more common to employ these methods for other purposes, including extension or augmentation of sensory capabilities. In this context, it is particularly relevant to note that numerous members of the animal kingdom have the ability to localize via vibrotactile cues. Examples include elephants, some moles, kangaroo rats, and spiders [51, 69, 72, 73]. We aim to imitate this ability in humans, extending tactile sensory abilities outside of their natural range through sensory substitution.

One practical motivation for enabling spatial localization through tactile cues stems from the multiple-resource theory, which proposes that conveying information via the tactile sense, can decrease cognitive and perceptual overload from the often overloaded visual and auditory senses [3, 24].

Previous applications of devices that substitute or augment spatial information to tactile information have taken numerous approaches and form factors, from head mounted tactile displays [19, 27], to gloves that represent different intensities as distances [50]. They have been utilized for various use cases, from increasing the spatial awareness of drivers [68], to firefighters in low-light conditions [2].

As mentioned above, the algorithm we used for the representation of location in 3D space is inspired by previous work. More specifically, Fletcher et al. [38] successfully improved users' ability to localize sounds in space by delivering a synthesized version of the signal received in each ear to the corresponding hand using a wristband. In a different work, an algorithm based on manipulating the amplitude dependent on azimuth differences was used to represent horizontal locations through vibration to the fingers, using four actuators with a 90° angle between adjacent fingers [4, 83]. This work inspired us to consider a vector-based intensity calculation, and specifically one that considers the location of the actuator itself as the sensing point. By using simple calculations and consumer grade hardware, our implementation suggests a practical solution obtainable in the very near future that could address some of the needs raised.

## 3 Spatial Haptics Implementation

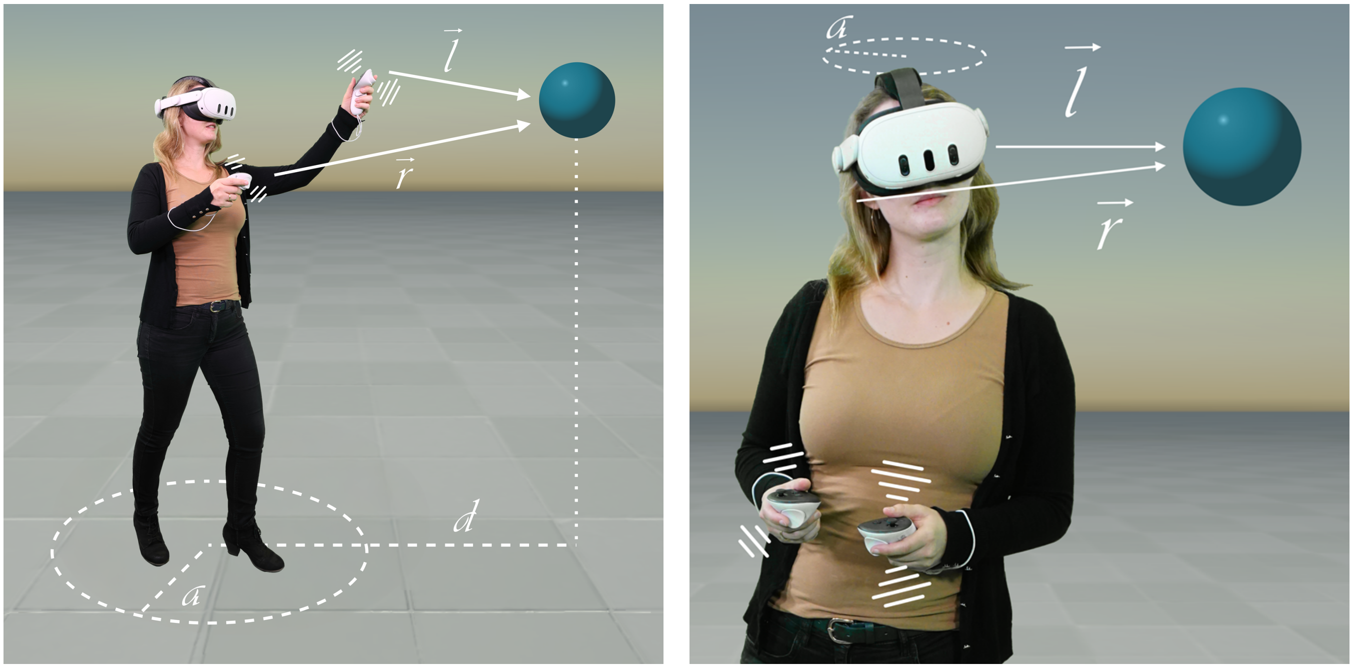
To enable spatial haptic localization, our approach implements a simplified Interaural Level Difference (ILD) through vibration to the user's hands. This is one of the basic mechanisms that allows the localization of sound, based on the difference in amplitude of the signals reaching the two ears. The second important principle applied is the ability of dynamic movement to improve object localization by continuously "sampling" more data points.

Our implementation builds on the close connection between the auditory and tactile systems. It assumes that when using the palms of the hands as sensory organs for auditory-like cues, the sensory substitution would allow for performing spatial localization. In this way, we can use the dynamic ability by moving the hands to "sample more data points" than by using the ears, as well as for localizing without needing to change one's gaze. Illustrated in Figure 2, we developed two implementations of our concept:

- **Ear-Based Localization (EBL):** Vibration levels in the user's hands are determined by the relative positions of the ears to the target object. For example, when the user's right ear is directed towards the target, the user's right hand will receive vibrations at maximum amplitude while the left hand will not receive vibrations. This implementation directly translates the approach of auditory localization to haptics.
- **Hand-Based Localization (HBL):** Vibration levels in the user's hands are determined by the relative positions of the hands to the target object. For example, when the user's right hand reaches towards the target object, the right hand will receive vibrations with maximum amplitude. The vibration range is calibrated in a circle around the user with radius defined by the user's arm length. This implementation explores the possibility that one could use their hands as sensing organs for spatial location, metaphorically having ears in their hands.

We defined a vector-based algorithm that calculates a gain multiplier value between 0 and 1 based on the distance between the target object and either the user's ears or hands. This value is set using an exponential scale to mimic the way sound intensity decreases logarithmically in distance, also emphasizing the differences between distances closer to the target due to the steeper gain curve. This resonates with Weber's law, which determines that perceptual sensitivity is proportional to relative changes in stimulus intensity [40] (see Figure 3). We apply the following equations:

$$\begin{cases} m_r = (1 - \dfrac{|\vec{r}| - (d - a)}{2a})^2 \\ m_l = (1 - \dfrac{|\vec{l}| - (d - a)}{2a})^2 \end{cases}$$




**(a) Hand-based Localization Method (HBL)**

**(b) Ear-based Localization Method (EBL)**

**Figure 2: Spatial Haptic Localization Methods: (a) Hand-based Localization Method: Vibration intensity varies according to the distance vectors ($\vec{l}$ and $\vec{r}$) from the controllers to the object in space. The user is positioned within a circle of radius $r$, and $d$ denotes the distance to the spherical object; (b) Ear-based Localization Method: Vibration intensity varies according to the distance vectors ($\vec{l}$ and $\vec{r}$) from the ear positions to the object in space. Each vector respectively determines the intensity of the left and right controllers.**

where $a$ is the user's arm length for HBL and head radius for EBL, and $d$ is the distance to the target object. This vector-based algorithm approach enables real-time calculation, requiring lower computational power compared to complex spatial audio algorithms, making it an efficient and applicable way for conveying location of virtual objects using vibrations.

## 4 Evaluation

The evaluation was set out as a proof-of-concept for our approach to representing location in space through tactile cues, and exploring the differences between the two implementations.

### 4.1 Participants

We recruited 16 participants (4 identified as female, 12 as male), with a mean age of 24.21 years (SD = 4.12, min = 19, max = 34). They reported that, to the best of their knowledge, they do not have uncorrected disorders of vision or haptic perception. This study received ethical approval from the University Ethical Review Board (ERB). Two participants were deemed extreme outliers (2SD from the mean), and excluded from further analysis.

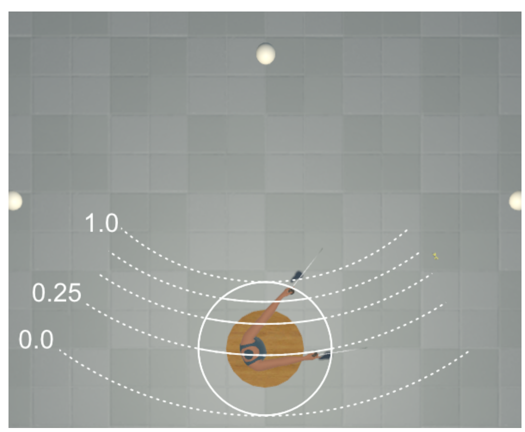
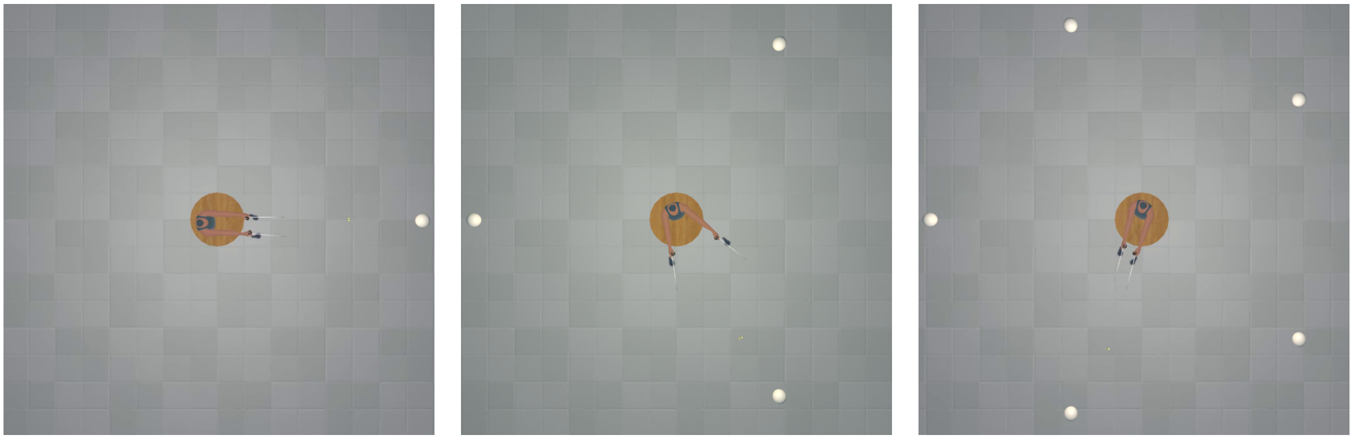



**Figure 3: Algorithm visualization of the vibration feedback mechanism: Vibration is "emitted" from the target object (at the top of the image). Intensity decreases with distance exponentially, with the maximum, 1.0 value when a controller is closest to the object and decreases down to 0 at the furthest distance from the target within the user's reach, providing spatial feedback to the user based on proximity to the target.**



(a) Single sphere (starting condition) (b) Three spheres (every 120°) (c) Five spheres (every 72°)

**Figure 4: Multiple-Object Evaluation: A staircase inspired procedure to determine the amount of spheres present in the scene to which the user can reliably identify the target object communicated through haptic cues. For each localization method, the procedure started with one sphere and could increase up to a maximum of 51. Correct responses added two spheres, while incorrect indications removed one. Figures (a) to (c) portray two consecutive correct responses. Each new target was randomly chosen at a distance of at least 90° away from the previous target. The procedure concluded after six reversals, i.e., answers where the correctness differed from the previous response. Thresholds were calculated using the last four reversal points.**

## 4.2 Experimental Design

The experiment took place in a virtual environment with tiled floor patterns to enable depth perception. The study included two evaluation phases: (1) A multiple-object evaluation, and (2) a single-object evaluation. We implemented a within-participants design, with the localization method (EBL, HBL) as the independent variable, and as the dependent variable, in the multiple-object stage - the number of objects to which users can reliably distinguish the target object using spatial vibrations, and in the single-object stage - the offset threshold in degrees between a visual target and spatial vibrations where the user still experiences the vibrations as originating from the visual target. All targets were of 0.2m radius and positioned on the horizontal plane at eye level and at a distance of 3m.

*4.2.1 Multiple-Object Evaluation.* In the scene, participants were surrounded by equally distributed, visually identical spheres in a circle. Participants were instructed to locate a single target sphere, indicated only via spatial haptic localization. To confirm their selection, they aimed a yellow crosshair at the center of their view at the target, and pressed one of the thumb buttons. Upon selection, the crosshair briefly turned blue for a correct response, or red for an incorrect response.

The multiple-object stage used an "up-down" procedure inspired by staircase approaches in psychophysics, as detailed in Figure 4. The amount of spheres presented in a circle around the user served as the measured stimuli. The threshold aimed at determining the accuracy of each localization method in terms of the amount of spheres present where participants were still able to determine the target object through spatial vibrations.

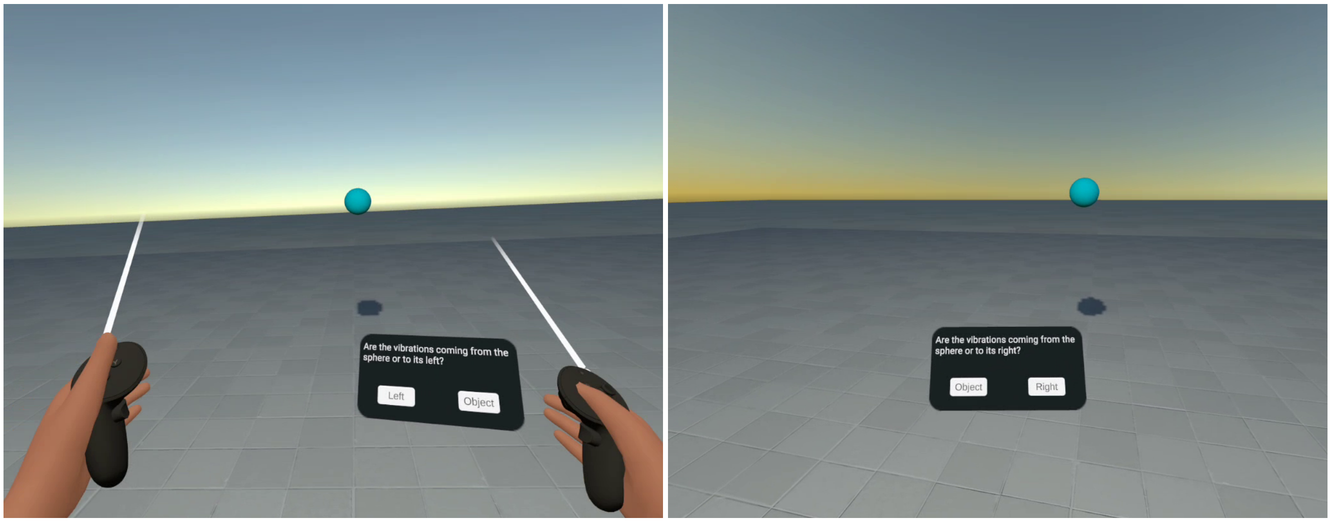
*4.2.2 Single-Object Evaluation.* In the scene, a single visible sphere appeared at a random location around the participant, and an invisible vibrating sphere appeared at changing distances from it. Participants were asked to indicate whether the vibration was coming directly from the sphere itself or not from the sphere, but rather from either its right or left side in an alternating fashion. After each answer, the sphere relocated.

The single-object stage focused on determining the accuracy of spatial localization through haptic cues, as detailed in Figure 5. We used an interleaved staircase procedure to determine the threshold defined by the angular offset (stimulus) of a visual target and spatial vibrations generated from a hidden target to which participants still experienced the vibrations as originating from the visual target.

## 4.3 Measurements

In addition to threshold values for determining the accuracy of localization, we collected the following measurements:

- *Short User Experience Questionnaire (SUEQ)*: We used the SUEQ for evaluating the usability, efficiency, clarity, and overall enjoyment of the task [81].
- *Skill level assessment*: We evaluated users' confidence in performing the different tasks using a single scale, based on the "skill" evaluation of the UX in IVE questionnaire [87].
- *Experience consequence assessment*: We used 6 questions based on the possible negative consequences section of the UX in IVE questionnaire [87] after each stage of the experiment to assess cyber-sickness related effects.
- *Experience reflection questionnaire*: We used custom questions to evaluate subjective performance and method preference, as well as several open ended questions to collect qualitative insights. Participants were asked to describe the differences between methods, how they used them, if either felt more natural, in which they felt that they performed better, and which they preferred.




**(a) Vibration coming from the left of the visible sphere**

**(b) Vibration coming from the right of the visible sphere**

**Figure 5: Single-Object Evaluation: Two staircase procedures were interleaved, each with two sequences – one starting at 45° offset, one at 1° – approaching the threshold for either direction (left side and right side). A 1-alternative forced choice (1AFC) question was used to assess if they noticed the stimulus or not. Participants answered either *left* (a)/*right* (b) or *object* to the question 'Are the vibrations coming from the sphere or to its left (a)/right (b)?'. Answering *object* indicated that the stimulus was not noticed, while *left* or *right* indicated that the stimulus was noticed. Three different step sizes were used, i.e., an early step size (< 2 reversals) with 8° increases and 5° decreases, a late step size (< 4 reversals) with 5° increases and 3° decreases, and a final step size with 3° increases and 1° decreases. Each sequence concluded after eight total reversals, with thresholds calculated using the last four reversals. The final thresholds were calculated by averaging the thresholds of the individual sequences. With the final step sizes, we targeted to obtain the conservative 75%-correct threshold for reliably distinguishing spatial vibrations from visual targets with an offset.**

## 4.4 Procedure

Participants provided informed consent and confirmed they do not fall under the experiment exclusion criteria. They completed a demographic survey indicating their age, gender, and handedness, after which they were introduced to the VR environment and the upcoming course of events.

The experiment consisted of three stages - introduction, multiple-object stage, and single-object stage. The introduction included a system calibration and an onboarding that took an average of 2.04min (SD = 0.58), where users were asked to perform simple tasks to familiarize themselves with the experiment and localization methods. For HBL, they were asked to move the controllers and feel the change in vibrations; for EBL they were asked to rotate their head and feel the change in vibrations. Following each of these tasks, participants indicated their perceived performance using the skill level assessment. Afterwards, participants completed the experience consequence assessment.

The second stage consisted of the multiple-object evaluation using both localization methods in a counterbalanced fashion. Following each of the trials, users completed the skill level assessment, the SUEQ, and the experience consequence assessment.

The third stage consisted of the single-object evaluation using both localization methods in the same order as the previous stage. The stage ended with the skill level assessment and the final experience consequence assessment.

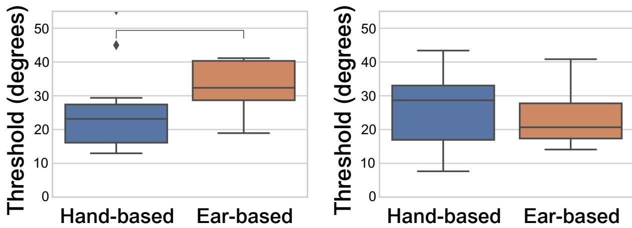
Finally, participants completed the subjective experience reflection questionnaire.

## 4.5 Apparatus

We developed a Unity3D (2022.03.32f1) application deployed on the Quest 3 VR Headset. The hardware was chosen specifically as its controllers use voice coil actuators that support a wide band of frequencies and complex signals. We chose a constant 125Hz frequency signal as previous research indicated that for hand-transmitted vibration, specifically grip, sensitivity peaks around this frequency [43]. To determine the value for the frequency parameter in the Meta Haptic SDK, we modeled a function mapping the parametric frequency value (0-1) to the physical frequency (Hz). This was done by sampling the controller's resonant frequency at different frequency levels using a high resolution USB microphone. Sampling was done using the spectrum analyser of RoomEqWizard[1] for 5sec per sample. The matching value for the 125Hz frequency was found to be 0.485.

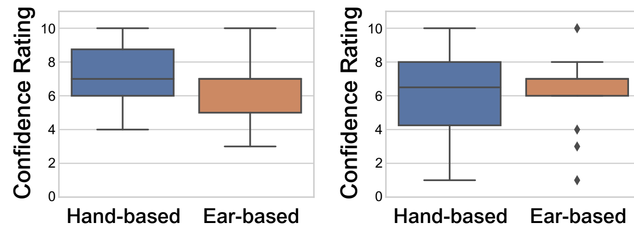
We narrowed the scope of our evaluation to a constant distance of 3m, and evaluated accuracy on the horizontal scale. We optimized the implementation for this distance, where the multiplier value is set to 1 when the controller is at a $3m - r$ distance from the target and 0 at $3m + 2r$, with $r$ the user's arm length. This suggests that if

[1] RoomEqWizard – http://roomeqwizard.com/




(a) Multiple-Object Evaluation (b) Single-Object Evaluation

**Figure 6: Threshold results of our study with $n = 16$ participants, comparing the two methods (hand-based and ear-based) for object localization in the two evaluation scenarios: (a) multiple-object and (b) single-object.**




(a) Multiple-Object Evaluation (b) Single-Object Evaluation

**Figure 7: Confidence ratings results of our study with $n = 16$ participants, comparing the two methods (hand-based and ear-based) for object localization in the two evaluation scenarios: (a) multiple-object and (b) single-object.**

**Table 1: Localization performance and subjective confidence per localization method.**

| | EBL | | HBL | |
|---|---|---|---|---|
| | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| Multiple-Object Performance | 37.53° | 17.11° | 25.20° | 12.06° |
| Single-Object Performance | 23.07° | 7.77° | 26.56° | 10.94° |
| Multiple-Object Confidence | 6.28 | 2.09 | 7.07 | 1.82 |
| Single-Object Confidence | 6.14 | 2.21 | 6.07 | 2.53 |

this implementation was used also for locating further objects, they would be represented with lower amplitude, as well as by a more uniform distribution of the amplitude across the space, similar to the case with sound.

The staircase procedure was implemented using the Unity Staircase Procedure Toolkit [94]. All data was stored on the Meta Quest device and retrieved after the study. Batteries in the controllers were replaced between participants to ensure identical starting conditions, despite no observable decrease in performance due to battery depletion.

# 5 Results

For our analysis, we considered localization performance, user experience and qualitative subjective reports. Performance evaluation was based on the objective performance and subjective confidence for each localization method, and user experience was based on the SUEQ and cyber-sickness evaluations.

## 5.1 Localization Performance

For the multiple-object stage, we computed the threshold in degrees by dividing 360° by the obtained threshold in terms of amount of objects. For each stage, we considered performance in terms of localization threshold in degrees, and subjective confidence (see Table 1).Statistical comparisons were made using Wilcoxon signed-rank tests.

*Objective performance.* During the multiple-object stage, HBL resulted in a significantly lower threshold than EBL ($W = 1$, $Z = -3.23$, $p < .01$) (see Figure 6). The distribution of error angles by method can be seen in Figure 8. No significant difference in thresholds was found during the single-object stage ($W = 33$, $Z = -1.22$, $p = .22$).

*Confidence.* For both phases, we did not find a statistically significant difference in subjective confidence between approaches (multiple-object: $W = 9$, $Z = -2.73$, $p = .20$; single-object: $W = 33$, $Z = -1.22$, $p = 1$) (see Figure 7).

## 5.2 User Experience

*SUEQ.* The localization methods were overall positively evaluated (see Figure 9). Compared to the benchmark by Schrepp et al. [45, 81], HBL was ranked above average on all parameters, while EBL was ranked below average on the Pragmatic scale, above average on the Hedonic scale and overall.

*Negative consequences.* We assessed the results of the negative consequences ratings using Friedman tests. We found a significant difference between the single-object stage and the introduction ($T = 4.67$, $p < .001$), and the multiple-object stage ($T = 3.65$, $p = .001$). No difference was found between the multiple-object stage stage and the introduction ($T = 1.02$, $p = .32$).

## 5.3 Subjective Data

Six people indicated they preferred HBL, five preferred EBL, and three felt they were the same. Seven participants felt they performed better in HBL and six EBL. One stated they performed the same in both. Six participants reported that EBL felt more natural, five chose HBL, while three felt they were the same.

When asked about their strategy in using HBL, seven stated techniques that use the comparison between both hands, with statements such as "going from the left and right simultaneously and guessing the middle" [P5], "I point my hands to the center of the sphere and then slowly separate them and check which one loses its vibration first" [P13], or "I moved in a circle till the vibrating comes from both hand in the same intensity" [P11], while only two described searching for the location where the vibration is strongest [P2, P7].

# 6 Discussion

We presented a novel sensory substitution-based approach for representing spatial location via tactile cues, and two methods for its implementation. Through this proof-of-concept, we demonstrated

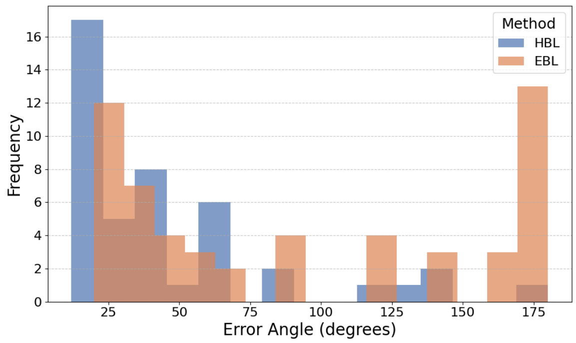



**Figure 8: Multiple-object stage distribution of error angles by method, in 15° buckets.**

that after a single session, users could reach an average accuracy better than 30° based on haptic cues alone, employing either localization method, with positive usability ratings for practicality and pleasure of use.

## 6.1 Significance and Use Cases

To contextualize our findings and their relevance, we examine previous spatial haptic representations and their use cases, demonstrating the generalizability and significance of our results compared to previous work, as well as relevant use cases in which it could be applied. A range of tactile devices were developed for navigation and orientation, both for blind and sighted users. The vast majority of these settle for orientation in two (180°) to four (90°) directions [53, 65, 88], giving our proposed method a relative advantage. These would normally use four or more actuators, while some increase the resolution by increasing the number of actuators. One example is the Feelspace belt which orients users to the north by using up to 16 actuators, resulting in a 22.5° accuracy [12]. This is in comparison to our implementations which enabled similar results using only two actuators using a pre-existing system. A similar approach was used in the design of several tactile torso displays. However, resolution cannot be infinitely increased with more actuators, but is rather limited by the sensory ability to differentiate between actuators [47].

Similarly, tactile devices are used for navigation and alerts in transportation, where haptics, as well as directional audio are used for parking orientation, warnings and more [41]. Most of these applications are also limited to 90° or even just front and back [16, 41, 46], indicating a possible advantage for our proposed approach also in this domain.

Another common use case is for enhancing or enabling auditory localization. Most often, this is studied for assisting the hearing impaired, whose ability to localize sound is usually limited. Users of single-sided cochlear implants (CI), comprising about 95% of the CI population, generally have little to no access to binaural auditory localization cues [38]. This is a crucial ability for interaction in the environment, finding things that emit sounds such as phones or pets, communicating effectively, and keeping safe in public spaces [18]. One auditory to tactile conversion system using bracelets [38] designed for speech, enabled similar performance to a bilateral hearing aid user of 28° after calibration to the individual user. Simpler, more mobile systems, also settled for a resolution of 90° [67]. One specifically relevant recent study used actuators on the head in different configurations for assisting in localization of sound-producing objects in VR. The system tested successfully for 45°, with their two actuator implementation enabling a lower success rate of approximately 50% for this resolution [22]. In comparison, our method enables similar or better performance than the systems mentioned, with a lower-complexity implementation. Furthermore, our method achieved this performance not only for supporting audio localization, but also for replacing it completely, without necessitating matching auditory signals. The challenge of auditory localization is not limited to the hearing impaired. Spatial 360° information in XR is recognized as especially important, as demonstrated by the growing use of spatial audio in these environments [49]. However, virtual 3D audio systems face challenges with respect to auditory localization performance [84].

The above leads us to feel confident in saying that our presented implementation offers an accessible tool for enabling a vast majority of currently explored applications already at the proof-of-concept stage. It is important to note that the measurement methods detailed in much of this previous research differ from those used to evaluate our method, which is conceptually different and relies on dynamic movement and relative interaction with the target object. Our results show that users can reach an accuracy comparable to related systems, using only two actuators and low-complexity calculations. The simplicity of the method and the ability to implement it even in available commercial systems, could lend itself to integration in real-world applications using existing or new systems, both in virtual and non-virtual settings.

*Hands as spatial sensors.* One particularly novel aspect explored in this work is that of using the hands as sensory objects for spatial perception, previously described as "ears in the hands". Participants were able to perform comparably using our method in both implementations. Furthermore, it was insightful to see that the use patterns adopted when using the hand-based method predominantly relied on comparative use of the two hands, similar to the use of ears, or animal limbs in tactile-based localization. These may indicate the possibility of further exploring this approach for both its basic science implications and for other practical applications.

Our results are especially meaningful in the context of front-back confusion – a well-known challenge for auditory localization, in which it is not clear whether a sound comes from directly in front or directly in the back of an individual [63]. Examining the error angle distribution from the multiple-object stage (see Figure 8), it is apparent that front-back confusion was almost completely avoided when using HBL, with 24.6% of the errors made using EBL (13 of 55) being clear front-back confusions (180deg error) compared to 2.3% for HBL (1 of 44). This relates to the statistically significant advantage in performance using HBL in this stage, which might also be reflected in the above-average rating on the pragmatic scale reported in the UEQ compared to the EBL that ranked below average on this parameter (compared to the benchmark dataset). This is likely because the hands are free-moving and not maintained in the same relation to the front and the back. This can be extremely important

| Metric | EBL | HBL |
|---|---|---|
| | $\bar{x}$ | $\bar{x}$ |
| Pragmatic Quality | 0.91 | 1.25 |
| Hedonic Quality | 1.14 | 0.89 |
| Overall | 1.03 | 1.07 |

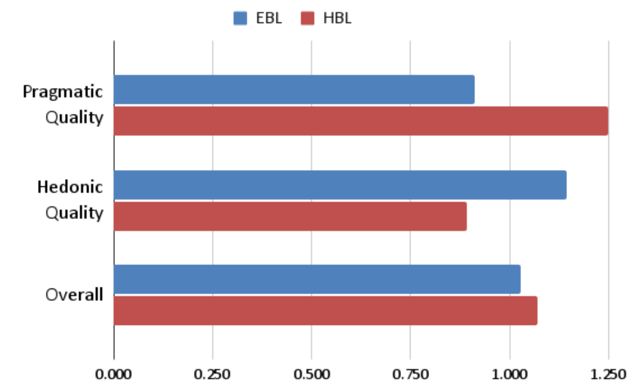



**Figure 9: Results obtained from the SUEQ evaluation for each localization method.**

for applications such as warnings in transportation, where small-angle mistakes are inconsequential, while mistakes in orientation could be critical.

## 6.2 Future Directions

Our results have several implications for future research.

*Perceptual learning.* An important aspect of the sensory substitution approach is that it is correlated with perceptual learning, increasing sensory capabilities through extended use, ultimately leading to automaticity [61, 89]. Following these known fundamentals of sensory substitution and perceptual learning, it is likely that users' performance using our system could implicitly improve with extended use, or be trained for better accuracy [1, 5, 6, 8, 12, 14, 26, 59–61, 64, 70]. For example, users of the hearing impairment-focused system mentioned above, improved in accuracy following only 5 hours of training, from 28° to 25° [38]. As such, future studies could employ training programs to test the system's full potential. Such explicit training could also enhance users' ability to perceive increasingly complex stimuli, higher resolutions, or allow them to simultaneously perceive multiple targets.

*HBL for latitude.* Latitude recognition in audio localization is considered difficult, as both ears are located at the same height, causing minimal differentiation between the signals reaching both ears. As this is similar to the front-back-confusion problem, it is likely that HBL would be more effective in latitude recognition.

*Expansion to complex signals.* One advantage of our approach lies in its diversity. Just like humans are not limited to listening only to one sound, our approach doesn't rely on a specific signal but rather on modifying the signal to simulate localization. Different signals could be used to represent different targets, also simultaneously, and could be associated with other signals in the environment. For example, associating vibrations with a sound could help differentiate it from other auditory signals. This is especially relevant for speech or voice where it could also help improve comprehension [37, 39]. Using complex signals can also enable the addition of other localization features borrowed from hearing. Specifically, similar to how we used Interaural Level Difference (ILD), it would be possible to use Interaural Time Difference (ITD), using differences in signal delay to represent location. Another mechanism that could be explored is modulation of pitch for representing latitude, as used in some sensory substitution systems [59, 60]. It is important to note that for this use, wide-range frequency actuators are required, as seen in recent work utilizing the technique for some of these purposes [22]. Fortunately these are becoming more commonly used in consumer systems such as the Meta Quest 3.

## 6.3 Limitations

The current system evaluation is limited to the representation of angular location and specifically horizontal localization. It was also calibrated to be optimized for a 3m distance. This was done for the purpose of simplification, considering that horizontal localization is generally the most basic and important feature of localization and specifically auditory localization. The system could still be extended using the same setup and method for representing locations in the entire 3D space, and as explained above, could potentially have some advantages over auditory localization. As such, evaluations in the full 3D space are necessary for understanding the potential and limitations of the system.

Another limitation of the system is the masking of other haptic signals. The effect of this masking should be further evaluated in relevant use cases. The use of different complex signals could help overcome this challenge, yet the extent to which complex signals could be distinguished when activated simultaneously should be further studied.

A limitation of the study is that it focused on evaluating attainable accuracy, and did not evaluate the time required for localization. This aspect should be addressed in future work, also considering training.

Finally, an increase in negative consequences was noted in the later stage of the experiment, which may have impacted performance.

# 7 Conclusion

We propose a novel approach for spatial localization through the tactile sense. We developed two implementations, and evaluated them in a user study, demonstrating the effectiveness of our sensory substitution approach. The concept and its implementations can be applied in existing and future systems with relatively low complexity, spanning a wide range of applications. Particularly, where maintaining visual or auditory attention is required for other tasks, or for assisting individuals with visual or hearing impairments. The feasibility of applying the concept of hands as ears in motion has been demonstrated, also revealing an advantage in front-back confusion, showing promise for future innovative applications and basic scientific research. Future work should go beyond this initial proof-of-concept to explore the complete potential of this approach.

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