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Enhancing Object Localization in VR: Tactile-Based HRTF and Vibration Headphones for Spatial Haptic Feedback

Detjon Brahimaj¹, Eric Vezzoli², Frédéric Giraud¹, Betty Semail¹

Abstract—Virtual reality (VR) technology offers an immersive experience, transporting users to simulated environments through specialized headsets. Advancements in haptic feedback using tactile sensations have been remarkable, but the area surrounding the ears, with high haptic sensitivity, has been underexplored. This paper delves into the effectiveness of vibration headphones (VH), specifically the Razer© Kraken V3 HyperSense, in providing directional information for object spatial localization in VR. The experiment examined haptic-only, audio-only, and audio-haptic conditions, comparing accuracy and completion time using a generic haptic-based Head Related Transfer Function (HRTF) developed by us. Participants (N=21) had to locate an invisible spheres using provided directional information based on feedback. Results revealed statistically significant differences in accuracy between audio-only and audio-haptic ($p = 0.00053$) and between haptic-only and audio-haptic ($p = 0.0315$). Interestingly, participants favored the haptic condition and ranked it as the most enjoyable while the completion time was similar for all our conditions. These findings highlight the potential of VH to provide directional information and the possibility to substitute the auditory channel for localization or navigation tasks. By focusing on the area surrounding the ears, developers can offer a new sense in VR.

Index Terms—HCI, Multimodal Systems, Tactile Devices, Virtual Reality, Human Performance

I. INTRODUCTION

VR is an immersive technology that transports users to simulated environments via specialized headsets. These headsets, thanks to advancements in computer graphics and sound synthesis, provide high-quality visual and auditory feedback, captivating the senses and enhancing the overall experience.

Many studies have utilized the auditory channel for directional information in VR, typically employing individual or generic Head-Related Transfer Functions (HRTFs) to render specialized sound. HRTF describes how the ear receives sound from a source. Berger et al. [1] demonstrated that generic HRTFs suffice for accurate auditory source localization, suggesting that individualized HRTFs may not be necessary. Furthermore, research by Ahrens et al. [2] highlighted that incorporating visual information, such as head position and environmental dimensions, improves localization performance compared to scenarios without visual cues. In recent years, haptic feedback has greatly enriched VR interactions as tactile

sensations can be used to convey information or simulate touch in virtual environments. This progress is largely attributed to innovative haptic devices like haptic surfaces, gloves, and wearable haptic devices [3]. The integration of haptic feedback holds great importance as it has the potential to substantially enhance VR experiences, boosting user interaction and immersion. Furthermore, it empowers designers not only to heighten the sense of touch but also to convey information through this novel channel, including directional cues, opening up exciting possibilities for creative design approaches.

Interestingly, our skin happens to be the largest sensory organ in our body, although the level of sensitivity varies across different regions [4]. Researchers have been intrigued by the potential to convey information through the sense of touch and they have investigated various body locations and experimented with different tactile signals. In an exemplary study, Paneels et al. [5] utilized a tactile bracelet capable of generating static and dynamic patterns to convey directional information. Their research showcased that dynamic patterns were recognized with greater accuracy in comparison to static patterns, revealing the fascinating phenomenon of phantom sensation, wherein multiple simulations are perceived as a unified stimulation.

Taking into account various tactile devices, Meier et al. [6] conducted an extensive investigation to assess the effectiveness of three vibrotactile devices (a belt, a wristband, and shoes) in a pedestrian navigation task. Their compelling findings indicated that, in less intricate geographical situations, vibrotactile feedback alone could suffice to facilitate accurate navigation. However, in more complex scenarios, the integration of additional guidance mechanisms might be imperative to ensure precise and reliable navigation.

When it comes to providing haptic feedback, researchers have primarily focused on different body parts, with the hand being the most extensively studied region. The hands and face possess a higher density of tactile afferents, making them well-suited for haptic stimulation due to their heightened tactile sensitivity [7]. Dim et al. [8] investigated vibration feedback sensitivity across nine different body parts, including the ear, neck, chest, waist, wrist, hand, finger, ankle, and foot. Their study revealed that the ear, hand, and foot exhibited the highest sensitivity among the examined regions. Consequently, technologies such as haptic gloves and hand-based devices have been developed to stimulate the fingertips, palms, and hands, offering an enhanced haptic experience. However, with the increasing popularity of head-mounted displays (HMDs),

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researchers have turned their attention providing tactile stimuli directly to the head, where the haptic systems can be co-located with the display.

One simple approach has been to integrate vibrotactile actuators into HMDs, utilizing helmets, as demonstrated by Kaul et al. [9]. Similarly, Kerdegari et al. [10] integrated seven vibrotactile actuators into a firefighter helmet's forehead area to guide users in low-visibility environments. In a navigation task, the authors compared haptic and auditory feedback and found that haptic resulted in lower route deviation, highlighting its potential for improving navigation accuracy. Focusing on the face region, another avenue of exploration involves temperature displays, leveraging the relatively high density of thermoreceptors in the forehead [11]. These technologies have shown promise in increasing immersion and providing directional cues [12]. However, the author in [12] noted a significant difference in recognition between cold and hot stimuli, rendering thermal-directional systems less suitable for navigation purposes. Rietzler et al. [13] introduced airflow from various fans as a means of providing haptic feedback, thereby enhancing the user's sense of presence and realism by adding environmental information (such as wind) to the virtual experience.

Despite numerous studies investigating haptic systems that stimulate the face, hand, wrist, fingers, and other body regions, relatively little attention has been given to haptic feedback in the area surrounding the ears [14], which, as previously mentioned, exhibits a high degree of haptic sensitivity [7] [8].

Gil et al. [15] explored the use of a mid-air haptic device capable of providing ultrasonic tactile feedback to stimulate the user's face. They achieved a high recognition rate when targeting the center of the forehead. However, the authors opted not to use ultrasonic stimuli on the ears due to safety concerns. Another study by Lee et al. [16] involved the use of a compact ear-worn haptic device that could deliver information by stimulating three different locations in each ear's auricle. The authors successfully provided haptic feedback through the ears' auricles, emphasizing the potential of this approach. Nevertheless, they did not evaluate the accuracy of navigation scenarios in their research.

One promising method to convey directional information in VR is through the use of vibration headphones (VH). These commercially available headphones integrate vibrating motors inside each ear cup to deliver haptic feedback. This method may be a good solution for substituting directional information typically provided with auditory-based HRTF by a tactile-based HRTF. To the best of our knowledge, we are the first to investigate the application of these VH in a Virtual Environment (VE), examining their effectiveness in providing directional information in a localization task. Based on the findings in [1], we believe that a generic haptic-based HRTF may be sufficient to have comparable audio-based HRTF accuracy and comparable efficiency in providing directional information.

Through an extended exploration and adept implementation of haptic feedback within the realm of Virtual Reality (VR), our objective is to unveil novel avenues for conveying information. This haptic feedback holds the potential to

create captivating virtual experiences, including applications in navigation and beyond. Thus, the central query driving our research is: Can we substitute audio-based HRTF with its haptic-based counterpart for object localization, all while upholding accuracy? This inquiry is rooted in a comparative analysis of their performance.

II. EXPERIMENT

The primary objective of this research paper is to examine the efficacy of a commercially available vibration headphone, specifically the Razer© Kraken V3 HyperSense, in conveying directional information to facilitate accurate localization of non-visible objects within a VR environment. To achieve this, we conducted an experiment comprising three distinct conditions, enabling us to compare and contrast the outcomes of haptic-only feedback against auditory-only feedback and audio-tactile feedback.

Through a comprehensive analysis of the experiment's results, we sought to gain valuable insights into the effectiveness of the vibration headphone as a sensory modality for conveying directional information for object localization in VR scenarios. These findings contribute to the broader understanding of the applications and limitations of haptic, auditory, and combined audio-tactile feedback in virtual environments.

A. Participants

We recruited a total of twenty-three participants. Two participants withdraw the experiment due to motion sickness provoked by the Virtual Environment. Twenty-one healthy volunteers participated in these experiments (15 males and 6 females, aged $M = 26.4, 2$ and $SD = 5.23$). None of the participants declared problems of hearing loss or tactile numbness on the area surrounding the ears. Each participant took part in the experiments voluntarily and signed the informed consent before the start of the experiment, and the ethical committee of Lille University approved the experiment.

B. Stimuli and Setup

Setup

The delivery of haptic and auditory stimuli for this experiment relies on the utilization of the Razer© Kraken V3 HyperSense vibration headphones. The entire experiment is developed and implemented using the Unity3D game engine, specifically version 2020.3.20f1 [17]. To provide the immersive virtual experience, we employ the commercial Oculus Quest 2 headset [18].

Within the virtual scene, a sphere is defined as both the haptic source and audio source. This sphere object is positioned in a random angular position in relation to the user's head, while maintaining a consistent distance. The generation of audio and haptic stimuli is contingent upon the position of the sphere object and the specific experimental conditions being investigated. The experiment comprises three distinct conditions: Haptic-only, audio-only, and audio-haptic. By delineating the specific stimuli employed, we can effectively investigate the impact and effectiveness of haptic-only, audio-only, and audio-haptic feedback in the context of object localization within the VR environment.

Mechanical Characterization

Prior to utilizing the VH (vibration headphone), it is essential to characterize its mechanical behavior. By conducting this characterization process, we obtain vital information for understanding the VH’s capabilities and limitations, ultimately contributing to the overall understanding of its performance during the subsequent experiments. To achieve this, we employed a sweep frequency signal spanning the range of 1 Hz to 200 Hz as the input stimulus. The vibrations generated by the VH in response to this input signal were recorded using a single-axis piezoelectric shear accelerometer (ACCELEROMETER, ICP® Model 352A24) with a sensitivity of $10.07 \text{ mV}/(\text{m}/\text{s}^2)$ (or $98.7\text{mV}/g$). The input signal followed a linear time/frequency relationship, with the frequency increasing at a rate of approximately $21.35 \text{ Hz}/\text{s}$.

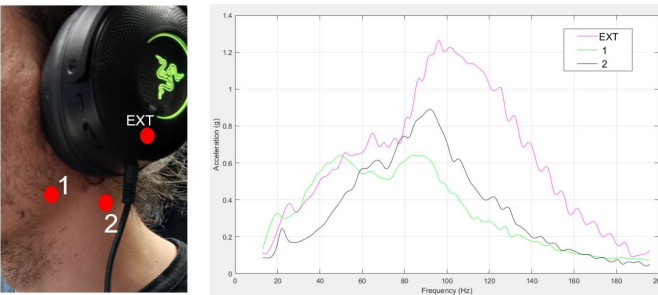


Fig. 1. **Left** Illustration of the measuring points. One point is on the external part of the VH’s cup, two points are on the body: mandible and neck, about two cm right below the ear cup. **Right** Measured output of the accelerometer plotted as frequency vs acceleration (m/s^2).

In order to assess the damping effect of vibrations and the amplitude loss in the input signal, we conducted measurements at various points (see Fig. 1): one point on the VH itself, one on the mandible, and another on the neck. The recorded vibrations were then translated from mV to gravitational unit g (m/s^2).

Analyzing the data from Fig. 1, we observed a resonance peaks in the actuator’s frequency response ($\sim 96\text{Hz}$). With this frequency we observed a damping effect of 36.5% and 60.21% at point 1 and 2 respectively. Although this frequency corresponded to the strongest vibration within the measured range, it exhibited inefficiency from an energetic perspective and generated audible noise, which was not desirable for our experimental setup. Around the frequency of 60 Hz , we observed a lower damping effect of 13.85% at point 2 and 16.92% at point 1. We aimed to strike a balance between perceptible vibrations and minimizing any potential auditory feedback, ensuring an optimal experience for participants in our experiment. Therefore, we decided to work with a frequency of 60 Hz , as it provided easily perceptible vibrations even if still being slightly audible. The audible component will be masked using a pink noise during the experiment.

Tactile Stimuli

The haptic stimuli in our experiment consist of a pulse signal with a frequency of 60 Hz and a duration of one second. The amplitude of the haptic signal is dynamically adjusted in

real time based on the orientation of the user’s head in the virtual environment (VE). Among different possible functions for intensity tuning, we choose to use a method that mimic a simple HRTF for specialized audio in 3D space with the objective of making the haptic feedback easy to understand and use. Therefore, to determine the amplitude for each side of the VH, we employ a generic HRTF as depicted below:

$$L = N * (1 + \sin(\alpha))/2 \quad 0 \leq \alpha < 360^\circ$$

$$R = N * (1 - \sin(\alpha))/2 \quad 0 \leq \alpha < 360^\circ$$

Here, N represents the number of vibration levels, and α denotes the angular position of the haptic source object relative to the user’s head. The variables L and R indicate the vibration intensities applied to the left and right sides of the VH, respectively. As an example, when $\alpha = 0^\circ$ (indicating that the object is in front of the user), the vibration intensity on both sides of the VH is equal ($L = R = N/2$). As α increases (indicating that the object is rotating on the user’s right side), the intensity on the right side of the VH increase and reaches its maximum at 90° ($R = N$), while the intensity on the left side decreases, reaching its minimum (i.e., $L = 0$).

To provide a visual representation of these angular positions and the associated haptic stimuli, refer to Fig. 2. The figure illustrates the user’s head at the center and the Haptic Source (the object with a vibration component) at five different angular positions. This visualization helps demonstrate how the amplitude of the vibrations varies based on the relative angular position of the haptic source object with respect to the user’s head, thus illustrating the logic behind our HRTF.

To ensure that participants rely solely on their somatosensory ability during the task, we introduce a pink noise background audio in the haptic-only condition. By incorporating this auditory stimulus, we effectively mask any slight audible cues that may arise from the haptic signal, guaranteeing that participants focus exclusively on the tactile feedback.

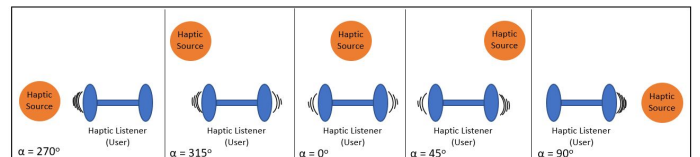


Fig. 2. Representation VH feedback with different intensities for the left and right sides, depending on the angular position of the haptic source. The first and last schemas show only one side vibrating, the third schema ($\alpha = 0^\circ$) shows both sides vibrating equally, and the intermediate schemas ($\alpha = 315^\circ$ and $\alpha = 45^\circ$) show one side vibrating more than the other.

Auditory Stimuli

In both the audio-only and audio-haptic conditions, the auditory stimuli consist of pink noise. To implement the audio component, the sphere object, which serves as the haptic source, is equipped with a Unity Audio Source component. To achieve a 3D sound simulation, we will utilize the Unity Audio Spatializer HRTF SDK [19], configuring the Spatial Blend parameter to 3D. This setting enables us to play the audio stimuli, creating the perception of sound originating from specific positions in virtual space.

The implementation of the 3D sound simulation involves reducing the audio to a single channel and then applying attenuation (altering the volume) based on the distance and position of the listener, which in this case is the user's head. As the distance between the audio source and the user remains fixed, the audio sound will only change in response to the angular position of the object relative to the user's head. Furthermore, there is no implementation of the Doppler effect of the audio source. The HRTF of the audio in the 3D space closely aligns with the haptic stimuli's HRTF within the virtual environment, as depicted in Figure 2.

C. Procedure

In the experimental setup, participants were comfortably seated in chairs and equipped with the Meta Oculus 2 headset connected to a PC running the simulation. Before the experiment, participants were given an explanation of how the stimuli behaved in relation to the position of a sphere. Participants familiarized themselves with the haptic, audio, or audio-haptic feedback by moving their heads from side to side. We intentionally excluded preliminary training to assess participants' performance without any prior guidance.

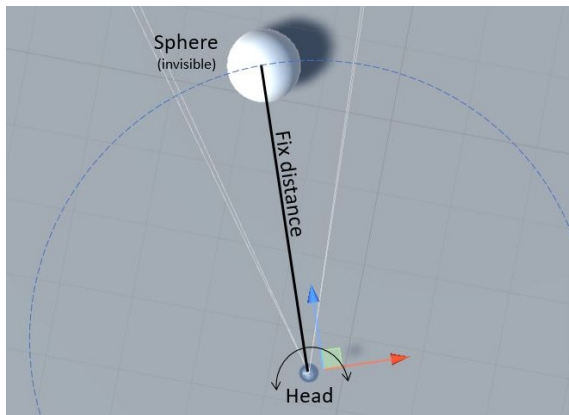


Fig. 3. Top view of the experimental setup during a trial. Participants rotated their heads to locate the invisible sphere (visible in the picture), which was positioned at a fixed distance and a randomized angular position. White lines represent the participants' field of view.

Participants searched for an invisible sphere randomly positioned around them, maintaining a fixed distance. They rotated their heads and relied on the stimuli (haptic-only, audio-only, or audio-haptic) to locate the sphere. When they found it, they pressed a button on the Oculus controller. The sphere became visible, allowing them to verify their location. A 3-second pause occurred before each trial, with stimuli turned off. This prevented vibration desensitization, as prolonged vibration exposure can increase tactile threshold and reduce sensitivity [20].

Participants performed 30 trials for each of the three experimental conditions, in a counterbalanced order. A 3-minute break was provided after each condition to reduce fatigue. The experiment lasted approximately 30 minutes per participant.

D. Data Analyses

In the course of the experiment, we meticulously gathered data on the angular position of the sphere and the corre-

sponding angular error, which denotes the disparity between the sphere's position and the participant's head rotation. These measurements were utilized to ascertain the accuracy of participants across the various experimental conditions. Moreover, we took also completion time for each condition and participant to evaluate possible differences.

To gauge participants' perceptions and subjective experiences within each condition, participants were asked to provide ratings based on the following criteria: Difficulty, Preference and Enjoyment. Furthermore, we invited participants to provide additional comments. This open-ended question allowed participants to offer their thoughts, insights, and suggestions, providing valuable qualitative feedback that complemented the quantitative data collection.

III. RESULTS

For each trial and condition across all subjects, we recorded the angular error (difference between the forward direction of the head and the angular position of the source object) and the sphere's angular position. In total, we collected 1890 data points, consisting of 30x3 angular error-position pairs. To visualize the results for all participants and conditions, we present a polar plot showing the distributions of sphere position and angular error in Fig. 4. The distribution of trials between the left and right sides appears to be well balanced for each participant (difference < 5%).

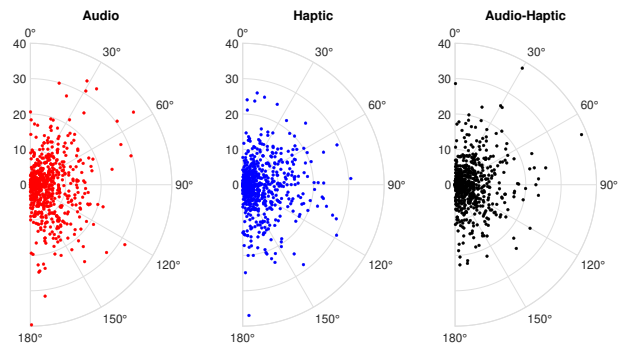


Fig. 4. Polar plot of the three experimental conditions for all participants. The angle represents the sphere's position in each trial, with angles less than 90° on the left side of the participants' head and angles greater than 90° on the right. The y-axis represents the angular error, or how far off the participants were from the sphere's actual position.

The box plot displayed in Fig. 5 presents the angular error for each experimental condition across all participants. The median angular error was 6.547° for condition A, 5.910° for condition H, and 5.511° for condition AH. These results indicate that, overall, participants achieved lower errors in the AH condition, followed by the H and A condition.

To conduct a more detailed analysis on our participant population, we requested them to self-identify as either gamers or non-gamers. This information was gathered using the following definition: a gamer is someone who spends an average of at least 8 hours per week playing video games.

Interestingly, when dividing the participants into gamers (14/21) and non-gamers (7/21), a slightly different pattern emerges. In our results, gamers showed similar accuracy for conditions A and H (6.394°) but had lower errors in the

AH condition (5.445°). In contrast, non-gamers demonstrated better accuracy in the H condition (5.126°), followed by the AH (5.589°), and A condition (7.092°).

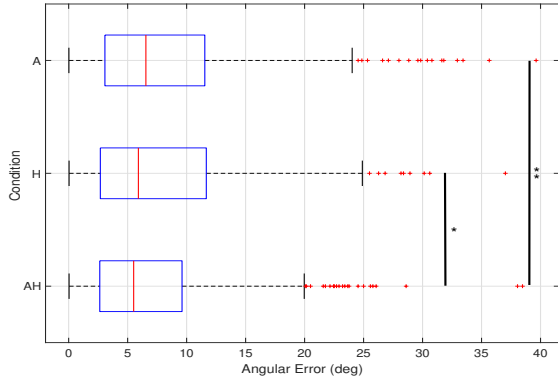


Fig. 5. Boxplot visualization illustrating the distribution of data across the experimental conditions: Audio(A), Haptic(H) and Audio-Haptic(AH). Each box represents the interquartile range (IQR) with the median indicated by the red vertical line. The whiskers extend to the most extreme non-outlier data points within 1.5 times the IQR, while any outliers are shown as individual points (red cross) beyond the whiskers.
* $p < 0.05$, ** $p \leq 0.0005$

A. Statistical Analysis

To analyze the effects of the three experimental conditions (A, H, AH) on accuracy, measured as angular error, a one-way ANOVA was conducted. The results revealed statistically significant differences in accuracy between the Audio and Audio-Haptic conditions ($F = 12.09$, $p = 0.00053$) and between the Haptic and Audio-Haptic conditions ($F = 4.64$, $p = 0.0315$). However, no statistically significant difference was found between the Audio and Haptic conditions.

Additionally, the data underwent further analysis by dividing participants into gamers and non-gamers. While the statistically significant differences in the gamers’ sub-group remained consistent with the previous analysis, the ANOVA results for non-gamers revealed significant differences in accuracy between H and A ($F = 5.31$, $p = 0.0222$) and between A and AH ($F = 6.42$, $p = 0.012$). However, no statistically significant difference was found between the H and AH conditions in the non-gamers’ group. Nevertheless, it’s essential to note that the sample size of the non-gamers group was relatively small ($N = 7$). Therefore, the statistical analysis relative to gamer and not gamer should be interpreted with caution.

To ensure the robustness of our analysis and account for potential outliers, we followed a method described by Halldestam [21], which examines the influence of extreme data points on the type-I error probability, potentially leading to false positives. Outliers were identified and removed from our dataset before conducting the ANOVA again. Remarkably, we consistently obtained significant differences in accuracy among the experimental conditions, reaffirming the robustness of our findings.

However, it’s important to acknowledge that the p-values from the second analysis appeared to be smaller by a factor of ten compared to the initial analysis.

B. Completion Time

In relation to completion time, we recorded the duration for each participant and condition as illustrated in table I.

TABLE I
MEAN AND STANDARD DEVIATION COMPLETION TIME PER CONDITION

	Completion Time		
	Session	Singular Trial	STD
Audio	5 min 54 s (354.3 s)	11.81 s	2.02
Haptic	6 min 20 s (380 s)	12.6 s	2.17
Audio-Haptic	6 min 14 s (374.2 s)	12.47 s	1.78

Overall, our participants took an additional 20 s to complete the audio-haptic condition and 26 s longer for the haptic-alone condition, both compared to the audio-alone condition. Performing a one-way ANOVA did not reveal any statistical significant difference for completion time among our experimental conditions. Therefore, completion time was not influenced by the experimental conditions.

C. Subjective Evaluation

Following the experimental session, participants were asked to provide their subjective evaluations of the various experimental conditions, including Difficulty, Preference, and Enjoyment (see Fig. 6).

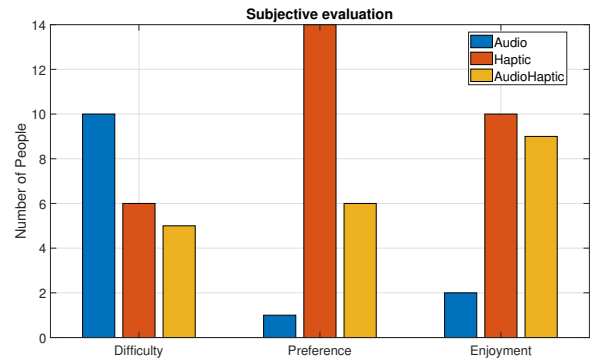


Fig. 6. Participants’ subjective evaluation on Difficulty, Preference and Enjoyment criteria for the experimental conditions.

From the bar plot, it is evident that participants generally perceived the audio-alone condition as the most challenging (10/21), followed by the haptic condition (6/21), and then the audio-haptic condition (5/21). Regarding preference, the Haptic alone condition received the highest rating (14/21), followed by the audio-haptic condition (6/21), and lastly, the audio-alone condition (1/21). When it comes to enjoyment, the haptic alone condition ranked the highest (10/21), closely followed by the audio-haptic condition (9/21), while the audio-alone condition received the lowest rating (2/21).

IV. DISCUSSION

From our analysis the audio-haptic condition shows a statistically significant difference in in terms of accuracy compared to audio-only and haptic-only conditions. Even if in general

our participants had lower errors in the haptic-only condition compared to the audio-only condition, this difference was not statistically significant. However, our results shows that auditory channel can be substituted with the tactile channel when conveying directional information. Moreover, haptic can be used also to reinforce directional information provided by the auditory channel. Indeed, our results suggests that combining haptic and auditory cues provides a more accurate sense of object localization, probably due to the reinforcement of directional information provided by the two sensory channels. Nevertheless, these results confirm the idea that multimodal integration leads to better performances [22].

On the subjective evaluation, participants perceived the haptic-only condition as the most enjoyable and preferred feedback method, indicating a preference for tactile sensations. Although the audio-only condition was perceived as more challenging, the addition of haptic feedback led to a more enjoyable experience for participants, likely due to the increased immersion and engagement. The fact that the audio-only condition was rated as preferred by only one participant and by two for the enjoyment may be due to the type of audio feedback we choose for the experiment (pink noise).

Interestingly, the completion times for the three conditions were relatively similar, with participants taking an average of approximately 12 seconds for each trial. While the audio-only condition had the shortest completion time, the slight differences among conditions do not appear to significantly impact task performance.

Upon analyzing participants' additional comments, we observed that they found the haptic-based HRTF method to be easily understandable and user-friendly. Some participant used term as 'easy adaptation' or 'intuitive' when referring to the haptic feedback. The feeling was 'like someone was guiding me to find the object' a participant stated while an other says that 'haptic feedback was like someone was pushing me in the object direction'. Some participant talk about a 'barrier showing them were the object was'. Interestingly, six participant expressed that they was using audio at first to find an approximation of the object position then focusing more on haptic to 'be more precise' on the audio-haptic condition.

Overall, our haptic-based HRTF method for conveying directional information for object localization in VR was appreciated by the participants which shows and state positive feedback during the open-ended question at the end of the experiential session.

V. CONCLUSION

Our experiment shows that VH can convey directional information for object localization in VR, using a generic haptic-based HRTF. Our haptic feedback was easy to use and accurate without requiring training, and participants preferred it over audio-alone.

Future work should explore variations in VH configurations and their impact on user experience, to improve the design and implementation of haptic feedback systems in VR.

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