# Designing a Multimodal Feedback Component for VR Applications

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## ABSTRACT

Virtual Reality (VR) environments have shown great potential across a wide range of applications that benefit from interaction through touch and haptic feedback, such as entertainment, education, and rehabilitation. By simulating realistic tactile sensations, such as contact, texture, and pressure, VR systems can enhance user engagement, accessibility, and understanding of virtual worlds. In this context, haptic-enabled VR applications can play a fundamental role in diverse scenarios that demand precise object manipulation and spatial awareness. This paper presents a multimodal feedback system for VR applications to provide precision in object recognition using headset controllers and their collision with virtual objects. The proposed system generates haptic feedback regarding three types of collision: touch, stroke, and entering. It is intended to increase the user experience and sense of presence. In the evaluation, most users reported being satisfied with the application and stated that it provided a good sense of presence. They also found that, among the vibration patterns, the irregular one was the most successful in conveying the intended texture.

## KEYWORDS

Multimodal, Multisensory, Virtual Reality, Acessibility

## 1 INTRODUCTION

Virtual Reality (VR) refers to computer-generated, three-dimensional environments that allow users to interact with simulated worlds in real time. By leveraging visual, auditory, and haptic modalities, VR systems offer immersive experiences that can closely replicate real-life scenarios. VR solutions enable the simulation of real-world activities in interactive and immersive virtual environments. This technology is applied in various fields, including health [25] and sports [3, 11], to create realistic scenarios for study and practice.

Immersive Virtual Environments are examples of VR systems designed to simulate complex situations using multisensory feedback in order to promote a strong sense of presence within the simulated experience [7]. These environments are capable of engaging the user at perceptual, motor, and cognitive levels, making them suitable for applications that require realistic interaction, such as rehabilitation, training, education, and assistive technologies. In fact, VR has shown a positive impact of being closer to real environments. Studies such as [1] indicate that VR experiences are useful for spatial knowledge acquisition. This could make the activity of exploring virtual environment yield better results in the real world. It also allows easier multimodal feedback, with the ability to split vibrations and audio from left and right.

These environments achieve a greater degree of immersion and realism when the tactile feedback displays high precision in the reproduction of physical properties of objects. Studies by [12] demonstrate that subtle variations in intensity, frequency and duration of the vibration enable the user to discern sensations of weight, rigidity and texture with enough fidelity to engage the sensations of the user, increasing the subjective presence on the virtual environment. This level of tactile detail reinforce the coherence between vision, sound and touch, reducing conflicts of perception and strengthening the illusion of truly being there [12]

In applied cases, such as odontological simulators with haptic feedback, this precision became even more valuable after being combined with machine learning. Advanced techniques analyze subtle variations in force, velocity and trajectory of the movements of the interns, generating objective evaluations in real time of their performance[18]. Beyond reinforcing the sensation of presence, this detailing enables immediate ajusting of training parameters, either by the instructor or the system, reducing the learning curve without overwhelming the user.

An important interaction in these environments, especially when aiming to create accessible VR environments for people with disabilities, is the proper detection of collisions with objects and the generation of multimodal feedback suited to the user's profile (e.g., visual deformation of the object, sounds, vibrations, textures, haptic feedback). The literature present studies [4, 6, 8, 9, 12, 17, 20] that seek to provide better precision in object collision recognition as well as avoiding interactions that, *e.g.*, traverses an object [9]. Besides, [9] found better results when using force feedback in comparison to vibration feedback.

Considering the above scenario, this paper presents a multimodal feedback system for VR applications, we shall call throughout this paper as *virtual touch system (VTS)*. VTS seeks to provide precision in object recognition using headset controllers and their collision

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with virtual objects. It also provides multimodal feedback combining audio trails and different vibration patterns to help distinguish objects. With VTS we intend to answer the following research question: *How precision in object detection and multimodal feedback impact on user experience and sense of presence?*

The remainder of this paper is structured as follows. Section 2 presents studies that addresses similar issues as VTS. Section 3 describes previous research that has applied VR with a focus on the rehabilitation of blind individuals and how our work will extend these efforts. Section 4 described the Virtual Touch System (VTS). Section 5 presents the evaluation conducted with VTS. Finally, Section 6 concludes this paper and presents future work.

## 2 RELATED WORK

This section presents related work regarding either the rendering of multimodal feedback to *virtual touch* in VR applications or the development of software components to better identify *virtual touch*. To find the related work we used the following search string:

*("virtual reality" OR "VR") AND ("haptic feedback" OR "tactile feedback" OR "multimodal feedback") AND ("collision detection" OR "object interaction" OR "touch feedback")*

A search conducted in Scopus in June 2025 resulted in six studies, and two additional publications were identified through snowballing.

### 2.1 Multimodal feedback

In particular, four investigations stood out for employing **multimodal feedback** in applications designed for people with disabilities. Kaplan and Pyayt [10] combined audio descriptions with haptic responses to provide users with information about two-dimensional environments. Sánchez and Mascaró [19] utilized three-dimensional environments and audio to simulate a virtual city and employed haptic feedback delivered through a haptic glove. Tzovaras et al. [22] developed a cane simulation using the *CyberGrasp* haptic device, which yielded positive results in real-scale environment navigation. Won et al. [24] investigated how tactile recognition altered the perception of sound intensity, highlighting the importance of multimodal feedback in scenarios lacking typical vision.

### 2.2 Perceptual latency and Multimodal synchronization

Perceptual latency between sensory channels is one of the main limitations of immersion. To evaluate this, Di Luca and Mahnan [6] measured visual-haptic synchronization limits in realistic touch tasks and concluded that vibration delays less than or equal to 50 milliseconds after visual contact are, on average, imperceptible. This threshold for vibrations preceding the visual stimulus, however, drops to 15 milliseconds. Similar to the above study, Smith [20] indicated that haptic delays should remain less than 100 milliseconds to avoid breaking the user's sense of presence in the virtual environment.

Additionally, Richard et al. [17] analyzed three configurations (force, vibration, and no feedback) in a fine drawing task, demonstrating that synchronized kinesthetic forces, which are the ability to feel and perceive the movement and position of the body in space, are essential to alert users, generating a greater sense of agency and reducing mental load compared to simple vibration. Results such as these reinforce the need to evaluate the accuracy of Meta Quest 2, the focus of the present work.

### 2.3 Haptic feedback and Object discrimination

The perception of virtual object properties depends on both the visual representation and the quality of the haptic feedback. Khosravi et al. [12] combined a physically based virtual hand with mass-proportional vibration to induce a sensation of weight and showed that the addition of vibration significantly improved mass discrimination between cubes. Ha et al. [9] proposed a physical model of the hand (palm, phalanges, and sides of the fingers) coupled with the *SenseGlove* glove, providing resistance forces and vibrations that prevented users from entering virtual objects besides providing sensation of rigidity.

Cui and Mousas [4] estimated thresholds for intensity, duration, and frequency of vibration in the Meta Quest 2 controller. In this study, minimum values were established for these three variables, which, if exceeded, allow users to perceive vibration variations. These values were essential for parameterizing the vibration patterns presented here.

Furmanek et al. [8] investigated how the size of collision detectors (representing virtual fingertips) affects reaching and grasping. After testing, they concluded that the size of the collider – a component that defines the geometric shape of a virtual object for physical interaction purposes, such as collision detection – and not the feedback modality (haptic or visual), affected the perception of the object's size and the user's motor planning, suggesting attention to the size of the colliders in hand modeling.

These studies demonstrate the importance of correctly modeling the application's haptic feedback to build the sensation of the properties of virtual objects; as in this present study, where we produce vibration patterns to create the sensation of textures for different virtual objects. To the best of our knowledge, no other work presented the use of different vibration patterns to indicate the texture of objects.

## 3 NAVIGABLE SPACES

### 3.1 Orientation and mobility (OM)

Orientation and mobility (OM) is a field of training and rehabilitation that seeks to enable visually impaired people to navigate their environment safely and independently [16]. It helps train skills related to space perception [15], analyzing tactile and audio cues to perform spatial tasks such as navigation, route planning, and localization [21]. The use of assistive technologies can help the practice of OM by creating immersive, engaging, and controllable experiences. Studies such as [2, 13, 21] indicate that virtual reality OM training yields comparable results to real-world ones. The use of virtual reality (VR) for OM training also provides a safe space for users to explore new situations.

Targeting at helping OM practice, our research teams developed a three-dimensional navigable space with audio cues. Those spaces are rendered by the ENA (Navigable Space) tool according to maps created by OM instructors where audio cues help users find a set of objects placed on those maps. The goal is to introduce unfamiliar environments or concepts for visually impaired people before they engage with them in real life. Figure 1 illustrates the virtual navigable space created with ENA.

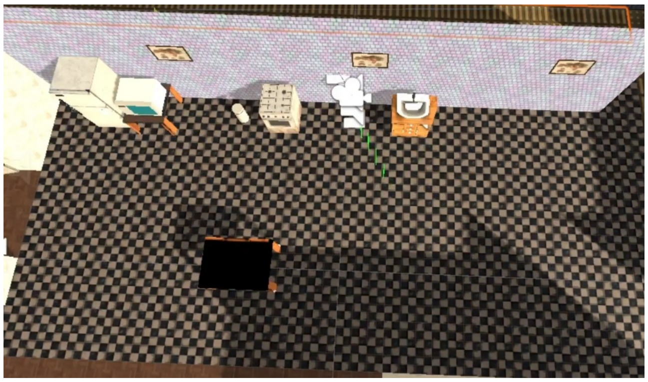

**Figure 1: ENA's three-dimensional navigable space example.**

### 3.2 Navigable Spaces initial versions

ENA was initially developed for mobile devices using headphones and a Bluetooth controller. It was developed in Unity using the engine features for rendering 2D and 3D audio cues. It presents different step sounds considering the type of floor and sounds for interactive objects, *i.e.*, the ones to be found by the user. Given its use of a controller for movement, the player movement in ENA provides only $90^{o}$ left/right turns.

While refactoring it to VR several new features where included in ENA. One of the biggest challenges was to create a movement system that remains faithful to real life, while maintaining the basic laws of VR movement to prevent motion sickness. The choice was a controller system that uses the joystick to move the player in a set pace and length, directly simulating the act of walking. The direction of walking is set according to the player body direction, thus enabling turns in every angle. Figure 2 depicts the controller scheme.

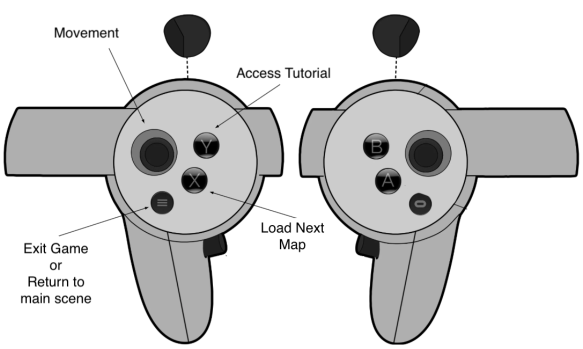


**Figure 2: ENA VR's Controller Scheme. Each VR controller button is associated to a predefined action.**

To prevent the player from going through walls or having the virtual representation of the player diverging from its position, the movement system employs *raycats*, which work as lasers invisible to the player, that detect objects in the virtual environment of the application. It is worth mentioning that this application employs raycasts in other areas, so their operation will be detailed further in this article.

Thus, if an object that would obstruct the player's movement is detected, a sound will be emitted from the place where the object is located, and the player cannot move there.

Given the availability of haptic feedback in VR controllers, ENA VR uses the controller position detection functionality to simulate the use of hands while navigating the virtual ambient. To further improve accessibility of ENA VR, crucial functions such as changing maps, accessing the tutorial, or exiting the application are accessible via controller buttons.

In this paper, we focus on the feedback system provided by ENA VR. Feedback is associated to different types of collision as will be discussed in the next section.

## 4 VIRTUAL TOUCH SYSTEM

Given the importance of touch for the acquisition of knowledge about the environment in OM tasks [5] and the realism it brings to VR applications [22], this paper presents a study that seeks to provide precision in object recognition using headset controllers and their collision with virtual objects. Although devices such as haptic gloves are the main choice in studies such as [22], our work intends to use default headset controllers, thus easing the access to applications.

The Virtual Touch System (VTS) proposed here, is responsible for two main tasks: *(i)* recognize the collision of controllers with virtual objects in the virtual environment, and *(ii)* provide multimodal feedback according to the type of collision detected. The following sections detail those two main features.

### 4.1 Collision Detection

Default Unity's collision detection system, essentially, registers a collision when two colliders meet. Colliders provides shapes to represent the boundary of virtual objects. Basic shapes, such as cubes, spheres and capsules, enables one to detect both when objects touch each other and if one is inside the other. This, however, is not true for complex shapes that matches an object mesh.

Figure 3 depicts the three different types of collision detected by VTS. In the figure, the solid vertical line represents the boundary of a virtual object that represents an obstacle to be detected. The arrows next to the controller represent the direction of the controller movement (either perpendicular or tangential to the obstacle). Finally, red lines represent *raycast* rays. Raycasts are a Unity component that function like a virtual ray of light, more accurately, like a laser; they do not exist in real life, only the application, and are not visible to the player. They can be represented as lines that detect collisions, as you can see in Figure 3.

VTS is constructed on top of Unity's default collision system. For the intents of this work, the collisions that we are interested in are those of the headset controllers with the virtual environment. Therefore, whenever the controller collides with an object, VTS identifies it as a touch. Touch is depicted on top of Figure 3 and is related to moving the controller and reaching an object.

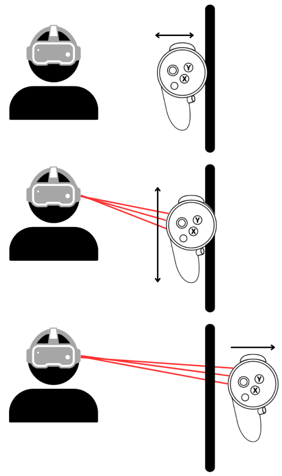


**Figure 3: The three types of collision detected by the system. The vertical line represents an object boundary, while arrows represent the direction of the controller movement and red lines represent *raycast* rays.**

Provided the controller stays on the surface of an object in unity and it keeps moving on this surface, the application considers this continuous collision to be a stroke. Stroke is represented in the middle of Figure 3 and is related to moving the controller tangentially to the object boundary.

To distinguish a stroke from the controller entering the object, VTS utilizes *raycasts*. While a collision is happening, VTS will send *raycasts* from the position of the player to the position of the controller every 0.05 seconds.

The system functions on a simple premise. When the *raycast* is sent, it expects to find the controller. If the controller is not found as the first thing the *raycast* hits, that means that there is an object in between the player and the controller. Therefore, the controller is inside an object, and it is considered an entering collision. This is represented on the bottom of Figure 3 and is related to moving the controller beyond the object boundary.

## 4.2 Multimodal Feedback

For each type of collision, a corresponding form of feedback is delivered. Audio feedback is associated exclusively with touch collisions, whereas haptic feedback is applied to all three collision types (touch, stroke, and entering), as detailed in the following sections.

*4.2.1 Audio Feedback.* Audio feedback associates audio trails to each virtual object. In this work, an audio trail contains three audios. Two of them reflect what the object is, *e.g.*, a microwave with its usual hum and metallic doors to reflect what the object is, and another audio that directly describes what the object is, by saying its name. Audio trails are meant to guide the user into associating what the object is through audio cues, albeit with the answer still being there so that the user does not become lost or overwhelmed.

The audio feedback system uses Unity's spatial audio, which is essentially binaural audio, also considering its distance to the user. The audio source that provides the spatial audio originates from the direct point from which the user interacted with the given object. The goal behind that is to avoid disorientation from the sound coming from a totally different place where the touch happened.

*4.2.2 Haptic Feedback.* Haptic feedback associates pulse and vibration patterns to each virtual object. Those (possibly) different patterns are associated to stroke collisions to help differentiate by giving an illusion of texture. Besides, vibration is performed in the exact controller that is colliding (left or right).

When a touch collision is detected, a pulse vibration is executed. Different pulses are associated to different objects in order to differentiate *e.g.*, rigid/soft materials. Figure 4 depicts the idea. Intensity $i_{max}$ and pulse duration $\delta_t$ are defined by the object type. Time $t_d$ represents the moment the collision is detected. After the pulse duration the vibration intensity diminishes to a minimum intensity $i_{min}$ designed to help users distinguish they are still in contact with the object.

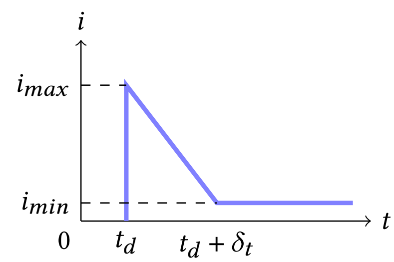


**Figure 4: VTS pulse vibration scheme.**

When a stroke collision is detected, a vibration pattern is executed. Different patterns are associated to different objects in order to differentiate their texture. Those patterns are represented by a vector of vibration intensities, where each index of the vector is associated to a fixed controller displacement. Figure 5 depicts the idea.

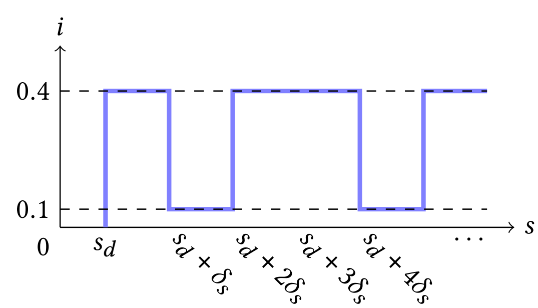


**Figure 5: VTS vibration pattern scheme. In the example a vector** $[0.4, 0.1, 0.4]$ **is considered.**

The vibration pattern cycles through the intensity vector to simulate a texture. In the example presented in Figure 5, a vector with pattern $[0.4, 0.1, 0.4]$ is presented. Spatial coordinate $s_d$ represents the location where the touch collision was first detected.

As the controller moves tangentially the object boundary, this causes the controller to vibrate in different intensities according to the vibration pattern vector. If the controller is moving large distances between the intervals that detect the position, the vibration will change rapidly, because the controller is changing position often, with smaller distances the vibration changes less frequently. Therefore, a threshold $\delta_s$ defines the amount of movement is necessary for the system to move to the next index of the vector as indicated in Figure 5. Finally, when the controller is detected to not be moving, the vibration goes back to a regular touch and decreases along time.

For entering collisions, the vibration intensity increases linearly to 1 to indicate the user is moving their hands in the wrong direction. Figure 6 depicts this idea.

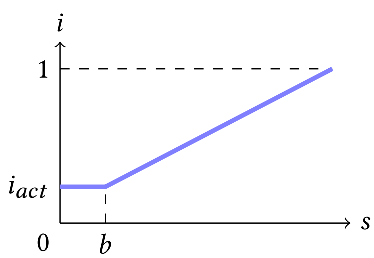


**Figure 6: VTS entering vibration scheme.**

In the figure, $b$ represents the object boundary and as position moves to the right in $s$ axis the more the controller enters the object. The vibration intensity than changes from its current value ($i_{act}$) to the maximum value 1.

## 5 VTS EVALUATION

This section presents the evaluation conducted with VTS. It details the participants sample, the instruments used, the evaluation procedure, and ethical concerns. The primary objective of this evaluation was to assess whether the haptic feedback system was immersive and capable of providing a credible and realistic experience to users. Specifically, we sought to answer the research question: does the precision in object detection and multimodal feedback impact user experience and sense of presence? Through systematic evaluation, we aimed to determine if VTS could effectively simulate tactile sensations that enhance user engagement and spatial awareness within virtual environments, particularly focusing on the system's ability to convey texture information through vibration patterns.

### 5.1 Sample

Ten undergraduate computer science students participated in the evaluation. Participants were invited via academic mailing lists. Five out of the ten participants were unfamiliar with virtual reality.

### 5.2 Instruments

Test results were gathered in two ways. The objective measurement was gathered through a standard User Experience Questionnaire (UEQ) [14] and a standard Presence Questionnaire (PQ) [23]. The subjective measurements were gathered through voice recordings done while the participants utilized the test application.

Both UEQ and PQ use a seven-point Likert scale. The values were contextual, such that some question might have seven as the best possible value while others as the worst possible value. UEQ combines the responses into six scales: attractiveness, perspicuity, efficiency, dependability, stimulation and novelty.

In the voice recordings, participants were asked to give descriptions of how they interacted with the VTS. We were not judging how close the participants were to the expected results, just how they felt.

### 5.3 Procedure

*5.3.1 Pre-test.* At the pre-test stage, a brief description of the evaluation goals were presented and the participants consent were collected. The participant was seated and the HMD Meta Quest 2 was then adjusted for the participant. Before the main tests, participants were given a simple scene to explore basic functionalities of the application and familiarize themselves with it.

In the tests, the participant got a more detailed description of what they were supposed to do, and described in the following sections. Two researchers were alongside the participants providing any additional information.

*5.3.2 Task One.* In task one the participant has a simple cube in front of them. Using a controller button the participant could vary the size of the collider. The objective is to choose which collider size the participant feels is the most precise. Once the participant made a choice, they pressed the trigger button on the controller when they feel the vibration. Once that is done, a sound bite plays, indicating the successful conclusion of the task. The application generates a `csv` file containing five different fields of data: the current date time, the amount of time the player has spent on this test, the time spent colliding, the status of the test and the size of the collider. The objective is to determine the accuracy of the basic haptic system.

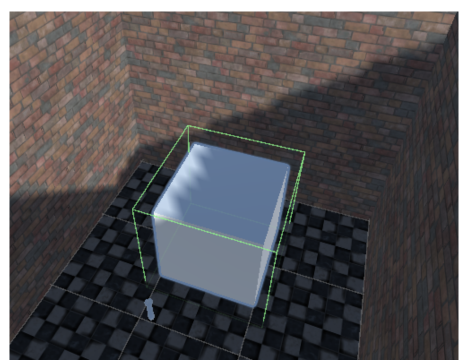

**Figure 7: Task one cube and its collider**

In Figure 7, we observe how the size of the collider differs from how the object looks in the scene. In the figure, the green lines represent the collider size, while the white cube is the object itself. In the task, the collider varies from 80% to 120% of its original size (which is the size of the cube object), in intervals of 5% that can be reduced or increased based on the participants preference.

*5.3.3 Task Two.* At task two, participants had three walls in front of them, A, B, and C, as depicted in Figure 8. The walls were designed to offer the least amount of bias possible.

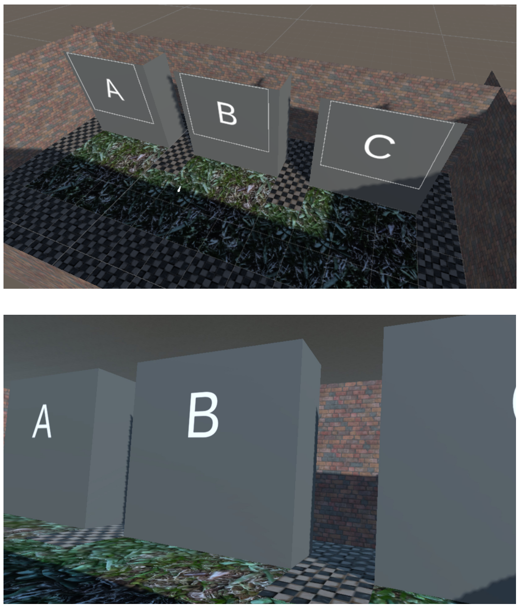


**Figure 8: Test two**

Each wall has a different vibration pattern associated to it. Table 1 describes the vibration patterns of each wall. The patterns were defined empirically after tests. Essentially, each value is meant to simulate a type of real life wall. Wall A would be simulating a regular brick or wood wall. Wall B simulates something like tiles or a painted wall. Finally, wall C would simulate an irregular brick or stone wall. They are identified in the table as rough, smooth, and irregular, respectively.

| Wall | Pattern | Description |
|---|---|---|
| A | [0.2, 0.6] | Rough |
| B | [0.2, 0.25] | Smooth |
| C | [0.1, 0.3, 0.5, 0.2, 0.3, 0.4] | Irregular |

**Table 1: Walls and their patterns with description**

The participants are not informed about what types of patterns they must find, nor which patterns are in each wall. Participants were invited to touch/stroke each wall and describe their perception of the texture. The participant could go back and forth between the three walls and test them multiple times, as much as necessary for them to develop their conclusions.

*5.3.4 Post-test.* At the post-test stage, participants were asked to fill both UEQ and PQ[1] and participated on a non-structured interview.

[1]The questionnaires are available at https://docs.google.com/forms/d/e/1FAIpQLSd5klCLf_szFj5jMeNADXeW9z-sq6rna6XrpVklOpcMUZDkmA/viewform

## 5.4 Ethical concerns

For conducting this evaluation, the following ethical considerations were taken. The inclusion criteria for the evaluation was participants with 18 years-old or more. Exclusion criteria were: persons with hearing or motor disabilities that affect the use of the HMD controller; persons with a history of motion sickness while using VR; participants that present difficulties in using VR in the pre-test training.

To assess potential motion sickness susceptibility, participants were asked prior to testing about their previous experience with VR technology and any history of motion sickness or discomfort with movement-related activities. This pre-screening questionnaire helped identify individuals who might be more prone to motion-related discomfort during the VR experience.

The questionnaires contained a TCLE (Termo de Consentimento Livre e Esclarecido - Written Informed Consent Form) ensuring that participants were fully informed about the research procedures, risks, benefits, and their rights, and provided their voluntary consent to participate in the study.

To ensure compliance with LGPD (Lei Geral de Proteção de Dados - Brazilian General Data Protection Law), all personal data were anonymized and sensitive information was securely stored with appropriate safeguards to protect participant privacy and confidentiality.

For avoiding fatigue and motion sickness due to the use of VR, each task was limited to a duration of 20 min and a 5 minute interval was done after using the HMD for 20 minutes.

## 5.5 Objective Results

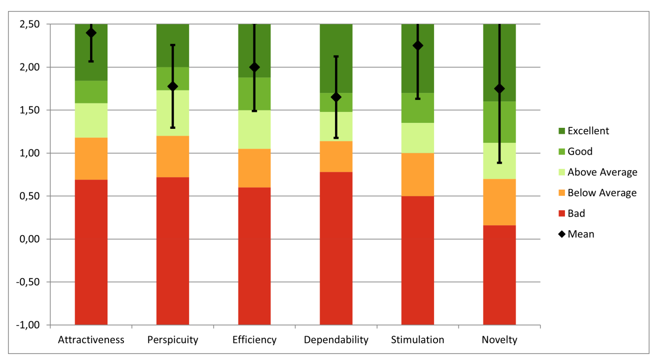


**Figure 9: UEQ results in its six scales. Results are presented considering a baseline provided for each scale.**

Figure 9 presents the results regarding UEQ questions according to its six scales. The value for each scale is presented together with its 95% confidence interval and compared against a baseline provided by UEQ.

According to the results presented in Figure 9, VTS presents excellent *attractiveness* and *stimulation*. Together both scales indicate that participants liked and felt VTS exciting to use. VTS also presents good to excellent *efficiency*, indicating no effort was necessary for using it. Finally, scales *perspicuity* and *dependability* were evaluated above average indicating that participants found VTS easy to understand and felt in control of its use. Although also presenting an above average result, the *novelty* scale has the greater confidence interval, indicating that not all participants found it innovative.

**Table 2: Most important questions**

| Number | Question |
|---|---|
| 7 | Were you able to inspect and search the virtual ambient through touch? |
| 13 | To what measure the quality of the image distracted or interfered in doing the proposed tasks? |
| 14 | To what measure the controllers interfered or distracted you in the process of doing the tasks? |
| 15 | How involved were your senses in the experience? |

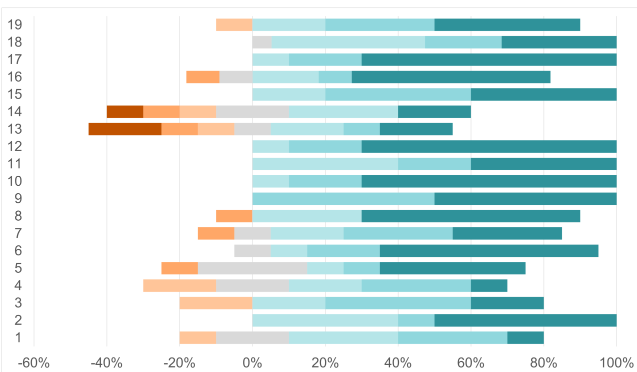


**Figure 10: PQ results in each question. As you can see the results were mostly positive**

Figure 10 presents the results regarding the PQ questions, and Table 2 shows the questions that we view as the most crucial to explain for the purposes of this article. As one can observe, participants in general reported a positive sense of presence. In the figure, green bars indicate positive answers (neutral-positive, positive, completely-positive), being the darkest green the most positive. Red bars indicate negative answers (neutral-negative, negative, completely-negative), being the darkest red the most negative. Finally, gray bars represent neutral answers.

Questions thirteen and fourteen, respectively about visual quality and controller interference, presented neutral results. Together they indicate that participants were neutral regarding the ambient visual quality and the use of controllers for performing the tasks.

A particularly positive result for VTS is seen in questions seven and fifteen. 80% of the participants liked using VTS for exploring the ambient through touch (question seven) and all participants felt all their senses were involved wile using VTS (question fifteen).

Summing up, participants answers indicate that most were satisfied with the application and felt it provided a good sense of presence. Image quality was probably one of the biggest complaints, but given the test ambient was fairly simple to avoid bias, that is not a big concern.

## 5.6 Open Comments

Table 3 summarizes participants comments about their perception of walls A, B, and C textures regarding the vibration pattern.

During task two, participants were able to feel the haptic feedback in all cases. They were able to identify that vibration patterns were different, although not being able to describe the pattern in some cases.

No two participants provided identical interpretations, although some offered reasonably accurate descriptions of what the vibration patterns were intended to simulate. Nonetheless, there was some common ground, as shown in Table 3, where bold comments indicate those that aligned with the intended design. Overall, 40% of the participants provided descriptions consistent with the design.

It is important to notice, however, that 60% of the participants were not able to distinguish wall A as rougher than wall B, even though the vibration pattern of the first presents a bigger contrast in intensity vibration than the second. Paradoxically, three participants described wall A as "weakest", "smooth", or "smoother than the others". This indicate that the contrast between the vibration values in itself may not be insufficient to generate a clear sensation of roughness.

Wall C proved most effective in conveying its intended texture. Participants offered accurate descriptions that captured the essence of the irregularity: one user described the temporal pattern as "weak-strong-weak-strong", while another identified "irregularity/pauses". Material associations were particularly rich, including "stone wall", "rough texture", and "very old concrete", demonstrating that users were able to relate the vibration pattern to familiar real-world textures.

# 6 FINAL CONSIDERATIONS

This paper presented the Virtual Touch System (VTS), a multimodal feedback component for VR applications designed to improve object recognition and user experience through precise collision detection and multimodal feedback. VTS enables applications to provide different feedback for interaction with virtual objects using the controller. It distinguishes between touching, stroking and entering objects. The system combines spatial audio with customizable vibration patterns to simulate textures, seeking to enhance the sense of presence and immersion.

Evaluation results indicate that participants found VTS both attractive and stimulating. Participants also felt engaged and involved in the virtual environment. Regarding the subjective evaluation of vibration patterns, while some participants struggled to differentiate walls A and B textures, the irregular vibration pattern of wall C proved highly effective in conveying the intended texture. This seems to indicate that a more complex pattern is necessary to improve realism. Further testing, however, is necessary to confirm such behavior.

Nevertheless, the study has limitations that should be considered. The small sample size and homogeneous group reduce the generalization of results, and the laboratory setting may not fully reflect real-world conditions. The short exposure time may also limit the

**Table 3: Player descriptions about walls texture regarding vibration patterns**

| Participant | Wall A | Wall B | Wall C |
|---|---|---|---|
| 1 | Weakest | Intermediary | "Smaller" vibration |
| 2 | Different, but unsure | Black board (through sound) | Brick wall |
| 3 | Smoother than the others | Concrete/Rougher than A | Close to B |
| 4 | **Cement/Stronger wall** | **Living room wall** | Wood planks |
| 5 | Different, but unsure | Different, but unsure | Different, but unsure |
| 6 | Smooth and constant | Intermediary | **Stone wall** (changing vibration) |
| 7 | **Less continuous than B** | Stronger than C / Continuous | **Felt irregularities** |
| 8 | **Rougher than B** | **Wavy, smoother than the others** | **Harsher, with a lot of variation** |
| 9 | **Harshest** | **Smoother texture** | Weaker than A |
| 10 | Similar to B | **Smooth brick wall** | **Old Concrete wall** |

detection of long-term usability issues. Internal validity may have been influenced by the novelty effect for participants without prior VR experience, potentially inflating positive ratings. In addition, the limited number of texture patterns and the subjective nature of tactile recognition could affect construct validity, while inconsistent interpretations of vibration patterns suggest potential reliability issues.

Future work includes refining vibration patterns for better texture discrimination, and evaluating the impact of sound to reinforce the texture perception. An important future work is to evaluate VTS with visually impaired users in real-world OM training scenarios.

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