The Effect of Interaction Method and Vibrotactile Feedback on User Experience and Performance in the VR Games

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(ABSTRACT)

Recent hand tracking systems have contributed to enhancing user experience in the virtual environment (VE) due to its natural and intuitive interaction. In addition, wearable haptic devices are another approach to provide engaging and immersive experiences. However, controllers are still prevalent in VR (Virtual Reality) games as a main interaction device. Also, haptic devices are rare and not widely accepted by users because they get bulky to implement sophisticated haptic sensation. To overcome this issue, I conducted experiments (Study 1 and Study 2 of this Thesis) to investigate the effect of interaction method (controller and whole-hand interaction using hand tracking) and vibrotactile feedback on user experience in the VR game. In Study 1 of this Thesis, I recruited 36 participants and compared the user's sense of presence, engagement, usability, and task performance under three different conditions: (1) VR controllers, (2) hand tracking without vibrotactile feedback, and (3) hand tracking with vibrotactile feedback at fingertips through the gloves I developed. The gloves deliver vibrotactile feedback at each fingertip by vibration motors. I observed that whole-hand interaction using hand tracking enhanced the user's sense of presence, engagement, usability, and task performance. Further vibrotactile feedback increased the presence and engagement more clearly. Based on the participants' feedback, I could further modify the form factor to make it more usable in the VR game and comfortable to wear on a regular basis.

In this sense, in Study 2 of this Thesis, I developed a new thimble-shape device to deliver vibrotactile feedback only at one fingertip rather than ten fingertips. Further, social VR is an emerging VR platform where multiple users can interact with one another. However, most social VR applications have not provided a sense of touch. I recruited 24 participants and conducted an experiment that explored the effects of interaction method and fingertip vibrotactile feedback on the user's sense of social presence, presence, engagement, and task performance in a cooperative VR game under four different conditions: (1) VR controllers without vibrotactile feedback, (2) VR controllers with vibrotactile feedback, (3) hand tracking without vibrotactile feedback, and (4) hand tracking with vibrotactile feedback with the fingertip vibrotactile device. The results showed that whole-hand interaction using hand tracking increased the level of presence. In addition, multiple items in the presence questionnaire indicated that vibrotactile feedback enhanced the level of presence as well. However, I could not observe the significant difference in social presence due to the unique setting of this experiment. Unlike the previous studies, my task was sufficiently cooperative, and thus, the participants felt high level of social presence regardless the conditions, which led to the ceiling effect. I also observed that there was no significant difference in engagement. Controller conditions had higher performance than hand tracking due to the technological limitations in hand tracking. Results are discussed in terms of implications for the components of interaction in the VR with hands, a touch in social VR, cooperative VR game, and practical design guidelines.

The Effect of Interaction Method and Vibrotactile Feedback on User Experience and Performance in the VR Games

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(GENERAL AUDIENCE ABSTRACT)

Recent hand tracking systems have contributed to enhancing user experience in the virtual environment (VE) due to its natural and intuitive interaction. In addition, wearable haptic devices are another approach to provide engaging and immersive experiences. However, controllers are still widely used in VR (Virtual Reality) games. Also, haptic devices are rare and not widely accepted by users because they get bulky to implement sophisticated haptic sensation. To overcome this issue, I conducted two experiments to investigate the effect of interaction method and vibrotactile feedback on user experience in the VR game. In Study 1 of this Thesis, I recruited 36 participants and compared user experience and performance under three different conditions: (1) VR controllers, (2) hand tracking without vibrotactile feedback, and (3) hand tracking with vibrotactile feedback with the haptic gloves I developed. The gloves deliver vibrotactile feedback at each fingertip by vibration motors. I observed that hand tracking enhanced user experience and performance in the VR game. Further vibrotactile feedback also increased user experience more clearly. Based on the participants' feedback, I could further modify the haptic device to make it more usable in the VR game and comfortable to wear on a regular basis.

In this sense, in Study 2 of this Thesis, I developed a new thimble-shape device to deliver vibrotactile feedback only at one fingertip rather than ten fingertips. I recruited 24 participants and conducted an experiment that explored the effects of interaction method and fingertip vibrotactile feedback on the user experience and performance in a cooperative VR game under four different conditions: (1) VR controllers without vibrotactile feedback, (2) VR controllers with vibrotactile feedback, (3) hand tracking without vibrotactile feedback, and (4) hand tracking with vibrotactile feedback with the fingertip vibrotactile device. The results showed that hand tracking partially increased user experience. Unlike the previous studies, my task was sufficiently cooperative. Also the task was too complex to be affected by the limitation of current VR tracking technology. This led the result insignificant across the conditions. Results are discussed in terms of implications for the components of interaction in the VR with hands, a touch in social VR, cooperative VR game, and practical design guidelines.

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Study 1 of this Thesis was submitted to International Journal of Human Computer Interaction and received a minor revision request. Study 2 of this Thesis will be submitted to the Journal on Multimodal User Interfaces.

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Chapter 1

Introduction

Providing an immersive experience to virtual reality (VR) users has been a long-cherished wish for HCI researchers and developers for decades. Improvements in recent VR hardware with respect to display, sound, refresh rate, and mobility play a great role in improving immersive experience [17]. Along with technical advancements, delivering haptic feedback in the virtual environment (VE) is another approach to provide engaging and immersive experiences. Haptic sensation is important to perform quick and accurate interactions with our surroundings [64]. Without haptic feedback in real life, it is impossible to do any ordinary tasks we take for granted. Further, based on the Multiple Resource Theory [82], which assumes that adding vibrotactile feedback will increase the task performance in a multimodal task environment.

In this sense, numerous studies investigated the effects of haptic feedback on user experience in the VE [4, 14, 23, 24, 29, 34, 36, 37, 38, 43, 60, 62, 67, 68]. In spite of numerous research works, it is still rare to find the VR haptic devices that are successfully accepted by users. One reason is that the devices require a large amount of space for hardware to implement sophisticated force feedback or tactile feedback. This makes users fatigued and the device is cumbersome to wear on a regular basis. For example, HaptX [30] is one of the example devices that provides realistic and delicate haptic feedback with pneumatics, but the size of the device causes it to be extremely bulky to wear, and the user needs to carry a backpack all the time.

In addition to haptic feedback, interaction methods are another aspect that impacts on user experience in the VE [32]. Currently, controllers are the primary interaction method in most VR applications, by indirectly manipulating virtually rendered hands in the VR with buttons or triggers. For instance, an index finger is bent by interacting with the trigger, and a thumb movement are adjusted by a joystick. VR controllers are designed to provide simple and straightforward interactions, such as shooting with triggers or locomotion with joysticks. Recently, hand tracking technology and head mounted displays (HMDs) with a built-in camera enable gesture-based interactions to be a main method in the VR applications. An example of this is Oculus Quest 2 hand tracking, or the Leap Motion Controller. Whole-hand interaction using hand tracking might not be appropriate for specific situations, such as shooting or locomotion in which they can be easily implemented with triggers and joysticks. However, whole-hand interacting using hand tracking provides a natural and intuitive experience, consistency with real world interactions, and freedom from burdensome hardware [80], resulting in a more immersive user experience. Slater et al. also discussed how interaction mappings influenced a system's fidelity [76] which can affect users' subjective judgements.

Social VR is an emerging online social networking system where multiple users can interact with one another with HMDs in the VE [52]. Social VR is reframing the traditional online social communication. Commercial social VR applications such as VRChat, RecRoom, Microsoft AltSpace or Facebook Horizon let the users engage in online social relationships, explore the virtual places, experiment self representation [22], and enjoy immersive games [44]. Compared to traditional social applications, social VR provides immersive experiences and diverse interaction methods [81]. For example, in the traditional online concert, the audiences can only watch the live shows through the flat screen. On the other hand, social VR enables the users to place in the virtual space to interact with the performers and audiences in the same place. According to a psychologist, Ray Birdwhistell [53], non-verbal communications including gesture, body posture, facial expression, behavior and touch accounted for 60-70% of human communication. With the current VR technology, hand tracking, body tracking, and facial expression of a virtual avatar made the non-verbal communication possible which leads to enhancement in communication experience in social VR applications. However, most of existing social VR applications do not provide the feeling of touch, and it is more difficult to find in social VR games. In addition, according to Nowak and Biocca's work [58], the participants who interacted with high anthropomorphic agency felt higher levels of copresence and social presence, so having realistically rendered hands will lead to increased social presence. However, there is little research on social VR applications that implemented whole-hand interaction using hand tracking but used controller's buttons and triggers to control the hand pose.

To explore the effects of interaction methods and vibrotactile feedback on user experience in the VR game, in Study 1 of this Thesis, I recruited 36 participants and conducted a user study. I investigated the sense of presence, engagement, usability, and objective task performance under three different conditions: (1) VR controllers, (2) hand tracking without vibrotactile feedback, and (3) hand tracking with vibrotactile feedback. To deliver a vibrotactile feedback, I developed the haptic gloves that deliver vibration at the user's fingertips while hands are tracked by built-in cameras on a VR headset. I observed the results that whole-hand interaction using hand tracking significantly increased presence, engagement, and usability. Vibrotactile feedback enhanced presence and engagement more clearly as well as whole-hand interaction using hand tracking improved the task performance. I further noticed that comfort of wearing a haptic device can impact the user experience and performance. More specifically, the participants responded that wires and electronics within the gloves made the hands movement uncomfortable. Furthermore, due to safety regarding the COVID pandemic, I instructed the participants to wear additional plastic gloves underneath the vibrotactile gloves.

To explore the effect of comfort of wearing, I developed a new thimble-shape vibrotactile feedback device based on the participants' feedback and my observations from Study 1 of this Thesis. This device delivered vibrotactile feedback only at one fingertip rather than ten fingertips to provide better comfort of wearing by decreasing the amount of vibrotactile feedback at hands but providing enough vibrotactile cues to the user. Along with this device, I explored the effect of fingertip vibrotactile feedback on the user's sense of presence, engagement, usability, and task performance in a cooperative VR game. I investigated whether the fingertip vibrotactile feedback at one finger can make a significant difference on the user experience compared to the haptic gloves in Study 1 of this Thesis, conventional VR controllers or hand tracking which are primary interaction methods in current VR applications. Further, I explored the effect of vibrotactile feedback on the user's sense of social presence in a cooperative VR game. The cooperative game contained a sculpturing task that required two players to interact and collaborate with one another to build 3D artifacts. The results showed that whole-hand interaction using hand tracking increased the level of presence. In addition, multiple items in the presence questionnaire indicated that vibrotactile feedback increased the level of presence as well. However, I could not observe the significant difference in social presence since the task was too cooperative and interactive, so the participants felt a high level of social presence across the conditions. The participants were not familiar with a cooperative VR game which resulted in a novelty effect. I also observed that there was no significant difference in engagement. Based on my observation and feedback from the participants, the instability of the hand tracking weakened the significance of the level of engagement and task performance.

Based on the Study 1 and Study 2 of this Thesis, I was able to observe the effect of two different interaction methods (controllers and whole-hand interaction) and vibrotactile feedback on user experience and performance in the VR games. My findings supported the existing studies that natural and intuitive control of the pose of virtual hands using hand tracking can improve the levels of presence and engagement compared to interfaces where controllers are used to control the virtual hand pose. In addition, providing vibrotactile feedback may help enhance the level of presence and engagement in the VR games.

Chapter 2

Literature Review

In this chapter, the terms and definitions used in the present Thesis are identified. Also, the relevant literature was analyzed and compared to identify the existing research gap to guide directions for my studies.

2.1 Haptic in VR

Current VR devices are largely dependent on visual and auditory sensations due to technical and practical issues. VR devices with haptic feedback are rare because of difficulty implementing realistic and satisfactory haptic sensations in the proper size at an affordable price. However, several studies have demonstrated the effects of haptic feedback on user experience and task performance in the VE. In [62], the authors investigated the effect of multiple sensory stimuli by adding the haptic (thermal and wind) and olfactory stimuli to the traditional visual-auditory VR hardware. They found that adding the haptic stimuli increased the sense of presence. A study [29] demonstrated the impact of different sensory stimuli on presence in credible VEs. The study indicated that there was a significant increase in the involvement subscale when passive haptic, vibration, and other sensory stimuli were delivered. Another study [14] examined the effect of substitute multisensory feedback on task performance and the sense of presence in the VR. The study showed that there were significant main effects from use of tactile feedback on task performance and the participants' subjective ratings. In [68], the authors presented the experiments in which two participants passed the objects in the VE with and without haptic feedback. The result indicated that haptic feedback increased perceived virtual presence, social presence, and perceived performance. Based on these studies, I can expect that adding vibrotactile feedback will increase presence, engagement, other subjective measurements, and performance in the VR.

2.2 Wearable Haptic Devices

In order to deliver the haptic feedback to the users in accordance with the VE, it is necessary to implement wearable or mounting hardware. The haptic gloves or the fingertip haptic devices are a form of apparatus that delivers haptic feedback to the user. Many researchers implemented and investigated the user experience of gloves and fingertip type devices. In [7], researchers developed the force feedback gloves to provide a better user experience with haptic feedback. A study [37] inspected different types of haptic feedback influencing the task-based presence and performance in the VR. Results demonstrated that vibrotactile haptic feedback outperformed force feedback and non-haptic feedback conditions. In [39, 66], the researchers designed the pneumatic force feedback gloves to provide the haptic sensation. These gloves provide the haptic feedback as well as track the hands movement for gesture interactions in the VR. In [19, 35], researchers developed the data gloves that track hands movement in six Degree of Freedom (DoF) which enabled gesture-based interactions in a VE. Schorr and Okamura [71] developed a pair of finger-mounted haptic feedback devices for virtual object manipulation and exploration. The result demonstrated that the device provided a compelling haptic experience for object manipulation in VE. Girard et al. [27] developed a haptic device called HapTip that delivered 2 DoF force on the fingertip for 3D interactions. The result showed that the participants were able to discriminate the directions of the 2 DoF stimulation as well as perceived weight differences of virtual objects. The numerous wearable haptic devices [13, 25, 41, 42, 54, 61, 78] have been invented for diverse research and functional purposes. In spite of the advantages of haptic feedback on user experience, a haptic device has not been widely accepted by researchers and users due to its bulkiness, tracking issue, and high price.

2.3 Hand Tracking

Whole-hand interaction tracks the hands movement so that the hands are able to be rendered in the VR. Whole-hand interaction became available with advances in computer vision and VR/AR technology. It is becoming more prevalent to use hand tracking in VR games and applications using devices such as Oculus Quest 2. Many researchers have investigated the effect of hand tracking-based interaction or the influence of different interaction methods on user experience under the VE. In [1], the authors developed the cyber-gloves that track hands and fingers movement. They examined how the different interaction methods in the VE affect the sense of presence and performance in door opening tasks. The participants felt more presence and had better performance with the cyber-gloves. However, this study was seeking the impact of interaction methods without haptic feedback. A study [79] investigated the effect of interaction methods on user experience. They instructed the participants to perform grabbing and typing tasks and compared emotional arousal, presence, and usability under controllers and hand tracking conditions. This study is similar to Study 1 of this thesis, but it did not explore the effect of vibrotactile feedback and did not provide objective performance results. Oskouie et al. [60] designed the task of typing on a virtual keyboard in the VR and compared the usability and performance between HTC VIVE controllers and passive haptic feedback with bare hands. They observed that bare hands with passive haptic feedback had better performance and usability than HTC VIVE controllers where passive haptic was collectively said to be a feeling by holding or touching a physical object linked to the VR system [73]. However, their focus was passive haptic feedback which is different from my experimental setup that focuses on vibrotactile feedback. Additionally, they did not examine presence, engagement or other subjective evaluations. Maereg et al. [43] designed a wearable vibrotactile haptic device for stiffness discrimination in a VE. They put vibrotactile actuators at the fingertips and compared the discrimination of stiffness on virtual linear spring in three sensory modalities: haptic only, visual only and both. Results showed that vibrotactile haptic feedback enhanced the perception of stiffness. However, their experiment settings focused on adding vibrotactile feedback, and there was no comparison of interaction methods between hands and controllers. Moreover, they did not investigate user experience during the experiment. Kim et al. [36] developed a wearable haptic device that provides the heat and vibrotactile haptic feedback at the thumb and index fingertips. They investigated the sense of presence in three conditions: bare-hand, vibrotactile, and heat. Results showed that vibrotactile and heat conditions provided higher presence than the bare-hand condition. This experiment is also similar to Study 1 of this Thesis, but their research questions were not highlighted on comparing controllers and hand tracking-based interaction. Furthermore, they did not measure any objective performance metrics. Based on these studies, I can expect that adding vibrotactile feedback will increase user experience and performance in the VR. However, these studies were conducted under task-oriented contexts. There are still questions unanswered, such as "how would an experiment conducted under a game context lead to different outcomes?". In addition, adding the haptic feedback can be done with diverse form factors of the haptic devices. I can still pose a question, "how can different form factors of the haptic devices affect user experience and performance?".

2.4 Social Presence

Social presence is collectively defined as 'the sense of being together' [6] or 'the sense of being with another' [18]. However, social presence was defined in many different ways. According to Biocca et al.'s review of social presence [6], the definition of social presence can be classified into three categories: co-presence, psychological involvement, and behavioral engagement. Sensory awareness of the embodied other [28] is one explanation of the co-presence in which Goffman identified each sensory channel as a way to experience social presence. Several researchers argued that social presence is a notion of being in the same location, space, or room [46, 49, 69]. In addition, mutual awareness which is referred to as "being aware of each other" is another definition of co-presence. Psychological involvement is another approach to define social presence. This approach contains a sense of access to intelligence [5], salience of the interpersonal relationship [74], intimacy and immediacy [63], and mutual understanding [70]. Last, the definition of social presence includes implicit or explicit behavioral engagement in which the virtual environment or computer games have large potentials for this behavioral interaction [6]. As demonstrated, social presence could be defined in several perspectives. In this Thesis, I am focusing on co-presence to explore how people feel being in the same location, space, or room. To measure the social presence, I utilized the social presence questionnaire (SPQ) from Harms & Biocca [31] in which I selectively used the subsection of co-presence.

2.5 Social and Cooperative VR

Social presence is important in social or cooperative VR games and applications since social presence has a positive correlation to enjoyment [59]. To evaluate social and cooperative game experience, social presence is an important measurement to be considered. In this sense, numerous social and cooperative VR applications have attempted to increase the level of social presence by utilizing the benefits of immersive experience and diverse interaction methods from the VR. Maureira [47] investigated the impact of co-located play on the game experience and social presence. The study compared two conditions: 1) playing in the same physical space while directly communicating between players, and 2) playing in separated rooms, communicating via intercom. The results showed that there was no significant difference between two conditions which can tell that the VR can facilitate the experience as if it were played co-located. Giannopoulos et al. [26] investigated the effect of haptic feedback on basic social interaction within shared VEs. An experiment was conducted using a shared desktop based VE where 10 pairs of couples solved the jigsaw puzzles together. The results showed that basic haptic feedback increased the sense of social presence. Fermoselle et al. [21] developed a web-based VR communication platform with a haptic component to simulate the touch. The purpose of this platform was to enhance the VR communication experience and increase social cues exchange between the users in the VR. The results showed that among 119 participants, 78% of the participants responded that touch increased the quality of the VR experience. Although this study was confined to communication scenario, it demonstrated that haptic feedback can improve the social VR experience. Bailenson and Yee [2] examined the ways in which people touch the virtual avatar of human compared to touch the non-human virtual object. Results showed that the participants used less force when touching people than nonhuman objects, and that the participants touched the face with less force than the torso area. The authors discussed that this results converged towards an implicit, behavioral measure of co-presence. People interact with the virtual people in a measurably different manner from other nonhuman objects. To the best of my knowledge, there is no existing study that measures social presence in terms of interaction method and vibrotactile feedback. In addition, listed studies were conducted in task-oriented setup, whereas experiments of this Thesis were conducted in a game context in which I can collect the participants' responses associated with the game.

2.6 Unique Contribution

Study 1 and Study 2 of this Thesis differ from existing works in several aspects. First, my studies systematically compared both subjective user evaluations and objective task performance under different interaction methods (controllers and whole-hand interaction using hand tracking). I can find how the different interaction method affect the level of presence, engagement, and task performance in the VR games. Additionally, I investigated the effects of vibrotactile feedback with hand tracking. There is little research on comparing subjective and objective evaluations under different conditions (hand tracking and vibrotactile feedback). My studies can provide the meaningful insights adding the vibrotactile feedback impact the level of presence, engagement, and task performance in the VR games. In addition, I investigated the level of social presence in terms of different interaction methods and vibrotactile feedback under a cooperative VR game scenario. My studies can contribute to identify how the different interaction methods affect the level of social presence in the VR game. In addition, I can find whether adding the vibrotactile feedback can impact the social presence and other subjective ratings in a social VR context. Further, my studies were conducted within the VR game environment. The VR games have the biggest portion of the current VR VR industry, I anticipate that my findings would be beneficial for those who practice in the VR game, VR hardware development or software development. Unlike other task-oriented experiments, my experimental task focuses on playing a game in the VE which allowed me to gather the user experience associated with the game. Task-oriented experiments have the pure goal to complete the given tasks. However, in game context, the objective is to complete the given tasks, but the ultimate goal is to enjoy the game while completing the given task. I expect that different goals would impact the user's responses on subjective ratings such as presence or engagement. Last, I developed the prototype vibrotactile devices (the haptic gloves in Study 1 and the fingertip vibrotactile device in Study 2 of this Thesis) and measured the usability. These prototypes can be possible guidelines for the engineers and developers to design the VR contents and platforms that enable the users more engaged and immersed in the VR with haptic feedback.

Chapter 3

Research Questions

I investigated the existing studies that researched the effect of haptic feedback and the hand tracking in the VR. However, there are still unresolved questions: how does different interaction method and vibrotactile feedback affect the user experience and task performance under the VR rhythm game environment?, how does the vibrotactile feedback influence the user's sense of social presence in a cooperative VR game?, and how does the comfort of wearing of the haptic device impact user experience in the VE?. In this regard, I present the research questions as follows:

1. How do different interaction methods (controllers and hand tracking) in the VR rhythm game influence user experience and task performance? (Study 1)

2. How does adding vibrotactile feedback in hand tracking influence user experience and task performance in the VR rhythm game? (Study 1)

3. How does adding the vibrotactile feedback in the cooperative VR game influence the user's sense of social presence? (Study 2)

4. How does the fingertip vibrotactile feedback (only at one fingertip) influence user experience and task performance in the cooperative VR game? (Study 2)

RQ1 and RQ2 were answered by Study 1, and RQ3 and RQ4 were answered by Study 2. Based on the results and feedback from Study 1, I conducted Study 2 to complement the

Study 1 and further investigated the effect of interaction method and fingertip vibrotactile feedback on the user's sense of social presence.

Chapter 4

Study 1

In this study, I investigated the effect of interaction method and vibrotactile feedback on the user's sense of presence, engagement, usability, and objective task performance under the VR rhythm game environment.

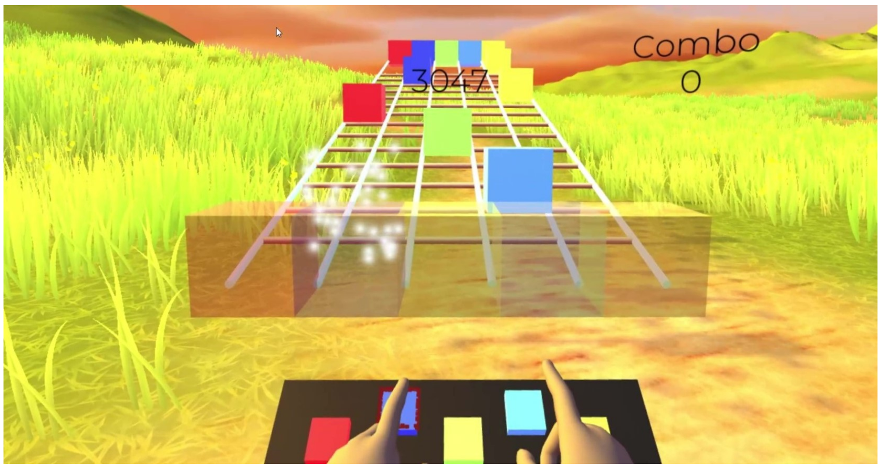


Figure 4.1: Gameplay of Study 1.

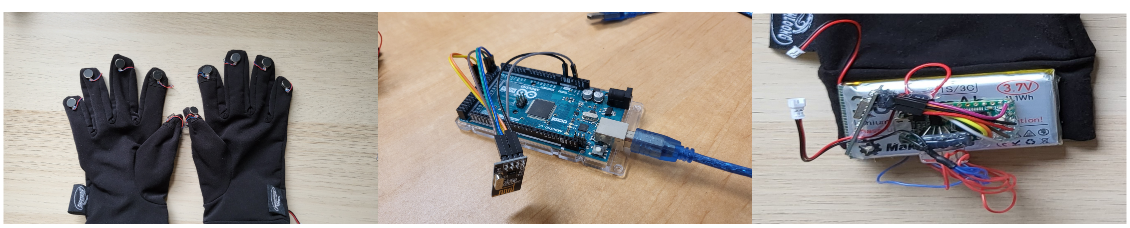
4.1 Participants

For this experiment, 36 participants were recruited. Fifteen participants were female (age $M = 26.67$, $SD = 2.98$) and 21 were male (age $M = 26.76$, $SD = 4.29$). The participants were asked subjectively, on a scale from one to ten, how familiar with the VR they felt they were ($M = 4.28$, $SD = 2.31$). Approval for the study was given by the Institutional Review

Board (IRB). All participants gave written consent before the beginning of the study.

4.2 Experiment Setup

For the study, Oculus Quest 2 HMD was used to place the participants within a VE. Vibrotactile gloves, I developed, were used to deliver vibrotactile feedback. These gloves were made using thin fabric gloves that have ten vibration motors at the end of each finger. The vibration motors run in 3V DC, 85mA at 12000 rpm. Motors were controlled by the Teensy 3.2 microcontroller and Arduino Mega (Fig. 4.2b.) via three nRF24L01 modules which allow wireless communication (Fig. 4.3.). One was installed on the PC to work as a base station, and the other two were mounted on left and right gloves (Fig. 4.2.). Thin coated wire circuits were connected between the microcontroller and the motors inside the gloves. Vibrotactile feedback was delivered with the maximum (3V, 85mA) power output when the participants hit the buttons. Vibration sustained for 0.3 seconds for each time the motor was activated from hitting the buttons.



(a) Gloves palm side (b) Base station (c) Electronics on the gloves

Figure 4.2: Vibrotactile feedback gloves and peripheral electronics for wireless communication.

Experimental environment was developed using Unity version 2021.1 (Fig. 4.4.). In the environment, there was a height adjustable panel with five differently-colored buttons in front of the initial position of the participant. There was a sloped track where cubes are scrolling downward from the top with the music. The participant had to hit the same colored

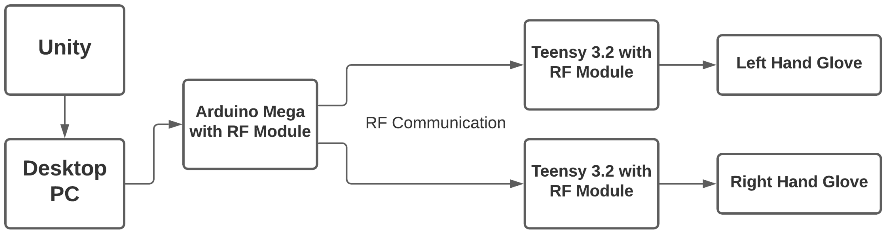


Figure 4.3: Hardware setup diagram.

button when the cubes passed over a set of transparent cubes at the bottom.

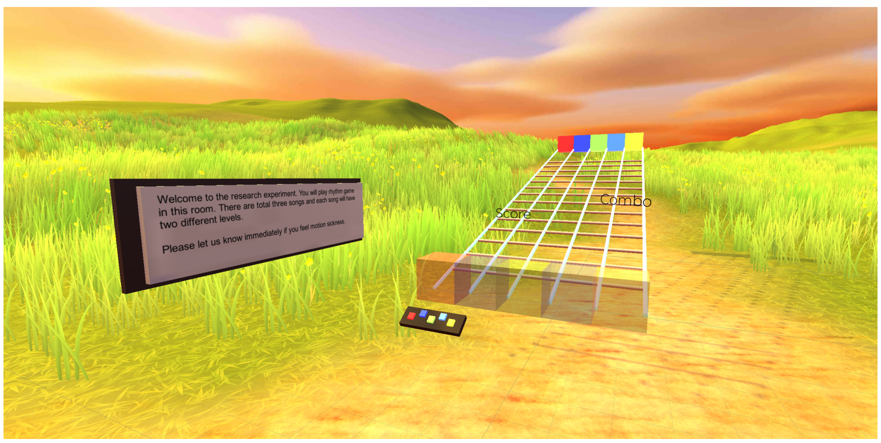


Figure 4.4: Virtual environment implemented with Unity game engine.

4.3 Experiment Design

To investigate the effects of interaction method and vibrotactile feedback, the study used a within-subjects design. The participants were instructed to play the VR rhythm game under three different conditions:

- `Controllers`: the participants used the Oculus Quest 2 controllers to play the VR rhythm game. No vibrotactile feedback was provided in this condition (Fig. 4.5a.).

Figure 4.5: Three different conditions for the experimental task.

- `Hand Tracking (Hands)`: the participants used the Oculus Quest 2 hand tracking system with no additional hardware to play the VR rhythm game. No vibrotactile feedback was provided in this condition (Fig. 4.5b.).

- `Hand Tracking with Vibrotactile Feedback (Gloves)`: the participants used the Oculus Quest 2 hand tracking system with the vibrotactile feedback gloves to play the VR rhythm game. Vibrotactile feedback was delivered to the participants' fingertips (Fig. 4.5c.).

I prepared four different songs for the rhythm game where one song was used for a tutorial purpose and the other three songs were used for experimental tasks. A tutorial song (Faded - Alan Walker) was chosen based on the popularity for the participants to get familiar with the experimental task and environment. Other three songs were chosen from the YouTube Audio Library. I chose songs that have the same BPM and comparatively similar lengths. All three songs had different genres to diversify the task trials. All songs except the tutorial had two different difficulty levels, and the number of cubes, level design, and timing were designed by researchers. The order of conditions along with the order of songs were counterbalanced across the participants. Further information about songs are described in Table 4.1.

Table 4.1: Song Information

Song Name / Author	Genre	Length (s)	Total Cubes (Easy/Difficult)	BPM
Natural / Endless Love	Pop	79	56/82	90
Juno In The Space Maze / Loopo	Dance & Electronics	92	118/153	90
Greaser / TrackTribe	Country & Blues	92	67/123	90

4.4 Task

The task of this experiment was playing a rhythm game in the VE. The gameplay required the participants to hit the five differently-colored buttons corresponding with the cubes that appeared on the sloped tracked. During the gameplay, cubes scrolled downward from the top of the sloped track accordance with the music and passed over a set of transparent cubes at the bottom (denoted as the target area). When the scrolling cubes overlapped the transparent cubes, the participants must hit the corresponding buttons. The participants were given a score which was calculated based on the accuracy of hitting buttons. A higher score was attained when the participants successfully hit the buttons in time with the music.

4.5 Measurement

To examine the effects of interaction method and vibrotactile feedback on the user experience, I collected subjective evaluations of presence, engagement, usability, and objective performance (accuracy and deviation).

4.5.1 Presence

Researchers in VR and HCI fields are often confused by the terms, presence and immersion even though they have distinct definitions. Slater et al. defined presence as “a sense of being there” and defined immersion as “something that can be objectively assessed” [75]. More specifically, it can be referred to as ”the environment in which the sense of being there can be objectively assessed”. Presence is a user’s psychological evaluation to the virtual environment, whereas immersion is the objective level of fidelity the VR systems contain. The authors further discussed that “presence is a human reaction to immersion”. In this Thesis, I am focusing on the term “presence” since my work focuses on the user’s subjective experience (human reaction) from my experimental setup (immersion).

To measure the levels of presence, I administered a modified Witmer Presence Questionnaire (PQ) [83, 84]. Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. The questions of modified PQ are listed as follows:

1. How responsive was the environment to actions that you initiated (or performed)?
2. How natural did your interactions with the environment seem?
3. How much did your experiences in the virtual environment seem consistent with your real world experiences?
4. How involved were you in the virtual environment experience?
5. How quickly did you adjust to the virtual environment experience?
6. How much did the control devices interfere with the performance of assigned tasks or with other activities?
7. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
8. How completely were your senses engaged in this experience?
9. Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
10. How easily did you adjust to the control devices used to interact with the virtual environment?

4.5.2 Engagement

The subjective gameplay experience can be evaluated in existing metrics and questionnaires. In this Thesis, I used engagement and flow. The definition of engagement has been characterized by many aspects including immersion, presence, flow [15], effort [20], and enjoyment [48]. Flow represents the feelings of complete focus in an activity with a high level of enjoyment that is derived from a balance between skill and challenge being achieved in the process of performing an activity [55, 56]. Csikszentmihalyi's research [16] identified eight major components of flow including: 1) complete concentration on the task, 2) clear goals and rewards, and immediate feedback, 3) an altered sense of time, 4) a intrinsically rewarding experience, 5) an effortless involvement, 6) a balance between challenge and skills, 7) a loss of self-consciousness, and 8) a sense of control. The combination of these elements results in higher levels of flow experience and enjoyment [12, 77]. A questionnaire is widely used method to evaluate the user's level of engagement. IJsselsteijn et al. developed the game experience questionnaire (GexpQ) [33] that is applicable to investigating a player's experience in a video game. In the questionnaire, there are seven different subcomponents: competence, sensory and imaginative immersion, flow, tension/annoyance, challenge, negative affect, and positive affect out of 33 items. Brockmyer et al. developed the game engagement questionnaire (GengQ) [9] to evaluate the negative issue of video game violence. The motivation of the questionnaire is different from GexpQ, however, GengQ is widely used by many researchers and still a valid measure of engagement [57]. In this Thesis, I used the GengQ since the questionnaire items in GenQ were more relevant to my experimental setting than GexpQ.

Similarly, to evaluate engagement, I adopted a modified Game Engagement Questionnaire (GEQ) [9]. Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. The questions of modified GEQ are listed as follows:

1. I lose track of time.
2. Things seem to happen automatically.
3. I feel different.
4. The game feels real.
5. I get wound up (excited).
6. Time seems to kind of stand still or stop.
7. I feel spaced out.
8. I can't tell that I'm getting tired.
9. Playing seems automatic.
10. I lose track of where I am.
11. I play without thinking about how to play.
12. Playing makes me feel calm.
13. I really get into the game.
14. I feel like I just can't stop playing.

4.5.3 Usability

To measure usability, I used the System Usability Scale (SUS) [10, 11]. Questionnaires were presented after each condition. Responses were collected with one of five responses that range from Strongly Agree to Strongly disagree in following ten questions:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.

3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

4.5.4 Performance

I measured two objective task performance metrics: accuracy and deviation. Accuracy was measured in a binary sense, counted as a hit or a miss. Then, I calculated by dividing the number of hits by total cubes for each song and difficulty level. Accuracy scores have a range of 0 to 1. Deviation was measured in centimeters by calculating the distance between scrolling cube and target cube when the button was pressed by the participants. Therefore, this deviation indicates how well the participants hit the buttons at the right time.

4.6 Procedure

When the participants arrived outside the lab building, their temperature was first taken. If the temperature showed no signs of fever, they were brought into the lab. Once the participants were brought into the experiment space, they filled out questionnaires about presenting symptoms of COVID-19, signed the IRB consent form, and COVID addendum for the study. Next, the participants completed the first part of a motion sickness questionnaire to create a baseline for subjective measures such as feeling tired, disoriented, or lightheaded before wearing the Quest 2 HMD. Only participants who had not experienced motion sickness continued the experiment.

After completing the motion sickness screening, the participants was instructed how to interact in VE with Oculus Quest 2 controllers and hand tracking. The participants started each of three conditions by playing the tutorial song (Alan Walker - Faded) to have practice with each condition before completing the rest of the songs and levels. After the tutorial, the participants were instructed to remove the HMD and complete the SUS questionnaire. Once completed, the participants were instructed to wear the HMD and play six different trials, each of which was designed from one of three different songs at an easy or difficult level. As the participants completed all songs, Unity was programmed to collect accuracy and deviation data for further analysis. After the six trials, the participants removed the HMD and completed the PQ and GEQ for the associated condition. After completing the survey, the participants put on the equipment for the next condition, for which the order was predetermined to be counterbalanced, and the participants restarted the procedure by playing the tutorial song again. After all the conditions were completed, the participants filled out a subjective feedback questionnaire which allowed us to collect comments regarding the participants' experience with the songs or equipment within the study. The participants were compensated with $10 and the study concluded. The study took around 60 minutes.

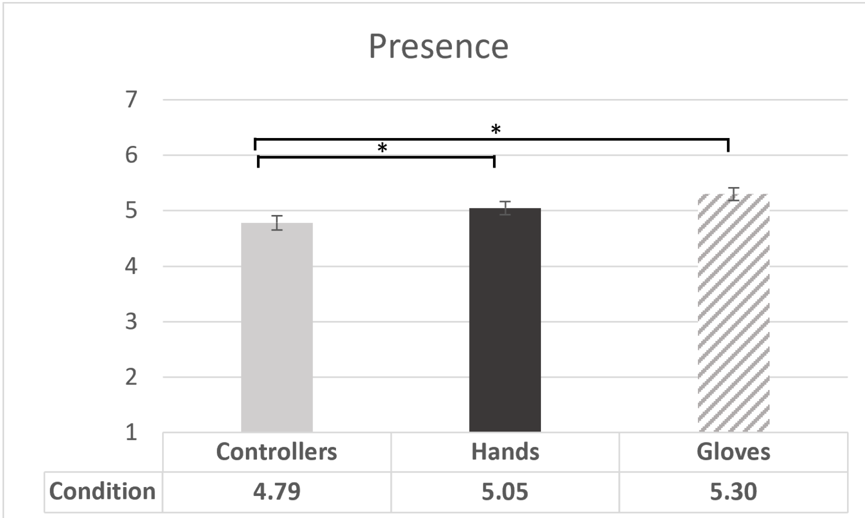


Figure 4.6: Average of all PQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

4.7 Results

4.7.1 Presence

For presence, I averaged all questionnaire items and performed a one-way repeated measures analysis of variance (ANOVA), using three conditions as an independent variables and the mean score of the presence questionnaire as a dependent variable. For PQ 6 (How much did the control devices interfere with the performance of assigned tasks or with other activities?) and PQ 9 (Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?), I reversed the score which indicated that higher score means higher presence. There was a statistically significant difference among the three conditions [$F(2,105) = 4.52$, $p < 0.05$]. For the multiple comparisons among the conditions, I conducted paired-samples t-tests. All pairwise comparisons in the present study applied a Bonferroni adjustment to control for Type-I error, which meant that I used a more conservative alpha level (0.0167). Gloves condition was significantly higher ($M = 5.3$, $SD =$

0.68) than controllers condition (M = 4.79, SD = 0.77), [t(35) = -3.86, $p < 0.0167$]. Hands condition (M = 5.05, SD = 0.73) was also significantly higher than controllers condition [t(35) = -2.59, $p < 0.0167$].

4.7.2 Engagement

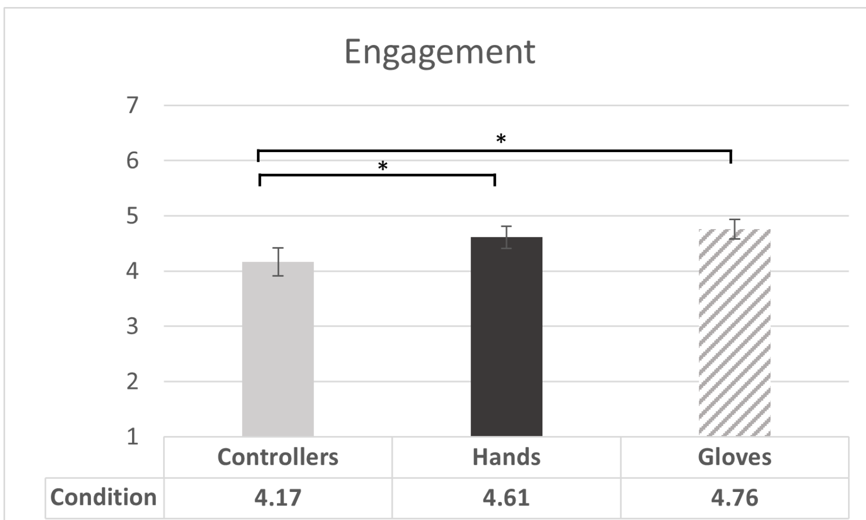


Figure 4.7: Average of all GEQ questionnaires across the conditions. Error bars indicate standard error of the mean. *$p < .0167$.

For engagement, I averaged all questionnaire items and performed another one-way repeated measures ANOVA. It was determined that different conditions had a significant effect on modified GEQ score [F(2,105) = 3.36, $p < 0.05$]. Paired-samples t-tests showed that gloves condition (M = 4.76, SD = 1.00) engaged participants significantly more than controllers condition (M = 4.17, SD = 1.08) [t(35) = -5.77, $p < 0.0167$]. Similarly, hands condition (M = 4.61, SD = 0.95) had a significantly higher score than controllers (M = 4.17, SD = 1.08) condition [t(35) = -3.86, $p < 0.0167$].

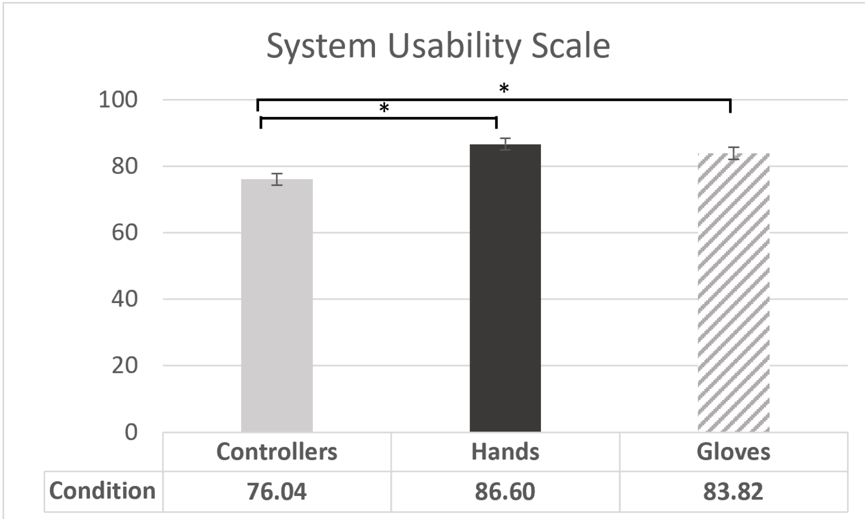


Figure 4.8: Average of all SUS questionnaires across the conditions. Error bars indicate standard error of the mean. *$p < .0167$.

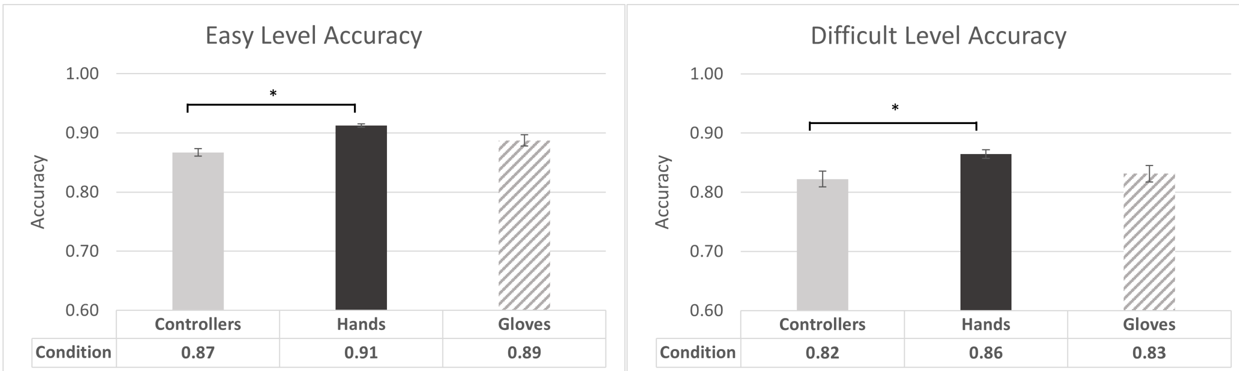
4.7.3 Usability

I evaluated usability using the SUS questionnaire [10]. To analyze the data, I used a one-way repeated measures ANOVA, using three conditions as an independent variables and SUS score as a dependent variable. I found that there was a significant main effect of different conditions [F (2,105) = 9.5, $p < 0.001$]. For the multiple comparisons, paired-samples t-tests were conducted. Hands (M = 86.6, SD = 10.23) and gloves (M = 83.82, SD = 11.06) conditions had significantly higher score than controllers condition (M = 76.04, SD = 10.65) [$t(35)$ = -5.24, $p < 0.0167$], [$t(35)$ = -3.70, $p < 0.0167$], but there was no significant difference between gloves and hands conditions [$t(35)$ = 1.57, p = 0.12].

4.7.4 Performance

To evaluate the performance, I averaged the three different trials (songs) by difficulty levels.

Accuracy



(a) Easy Level Accuracy

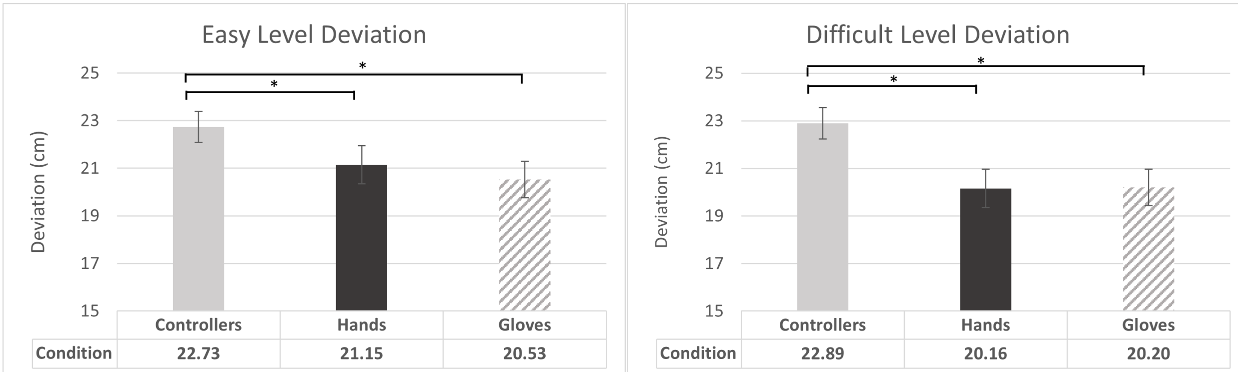
(b) Difficult Level Accuracy

Figure 4.9: Average of all cubes' accuracy across the conditions. Error bars indicate standard error of the mean. *$p < .0167$.

I performed two-way repeated measures ANOVA and determined that both difficulty levels [$F(1, 210) = 13.6$, $p < 0.001$] and conditions [$F(2, 210) = 3.69$, $p < 0.05$] had significant effects on accuracy. Hands condition ($M = 0.91$, $SD = 0.009$) had higher accuracy than controllers condition ($M = 0.87$, $SD = 0.013$) for an easy level [$t(35) = -3.64$, $p < 0.0167$]. Likewise, hands condition ($M = 0.86$, $SD = 0.014$) had higher accuracy than controllers condition ($M = 0.82$, $SD = 0.019$) for a difficult level [$t(35) = -2.72$, $p < 0.0167$]. I did not observe any significant interaction effect [$F(2, 210) = 0.06$, $p = 0.94$].

Deviation

Similarly, I performed two-way repeated measures ANOVA and determined that there was a significant main effect with respect to conditions [$F(2, 210) = 7.95$, $p < 0.001$]. Controllers condition ($M = 22.73$, $SD = 3.90$) had higher deviation than hands condition ($M = 21.15$, $SD = 4.83$) and gloves condition ($M = 20.53$, $SD = 4.60$) for an easy level [$t(35) = 2.78$, $p < 0.0167$], [$t(35) = 3.76$, $p < 0.0167$]. Similarly, in a difficult level, controllers condition ($M = 22.89$, $SD = 3.91$) had higher deviation than hands condition ($M = 20.16$, $SD = 4.00$)



(a) Easy Level Deviation

(b) Difficult Level Deviation

Figure 4.10: Average of all cubes' deviation across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

and gloves condition (M = 20.20, SD = 4.62), [$t(35)$ = 3.86, p < 0.0167], [$t(35)$ = 3.40, p < 0.0167]. However, there was no significant main effect on a difficulty level [$F(1, 210)$ = 0.88, p = 0.35] nor interaction effect [$F(2, 210)$ = 0.223, p = 0.89].

4.8 Discussion

To investigate the effects of interaction methods and vibrotactile feedback on user experience in the VR game, I compared results including subjective metrics, task performance, and feedback from the participants. I observed that hand tracking enhanced the subjective judgements as well as task performance. Based on the results, I outlined four inferences from the experiment:

1. Hand tracking significantly increased presence, engagement, and usability.

2. Vibrotactile feedback enhanced presence and engagement more clearly.

3. Hand tracking improved task performance in terms of accuracy and deviation.

4. Comfort of wearing can impact the user experience and performance.

4.8.1 Presence

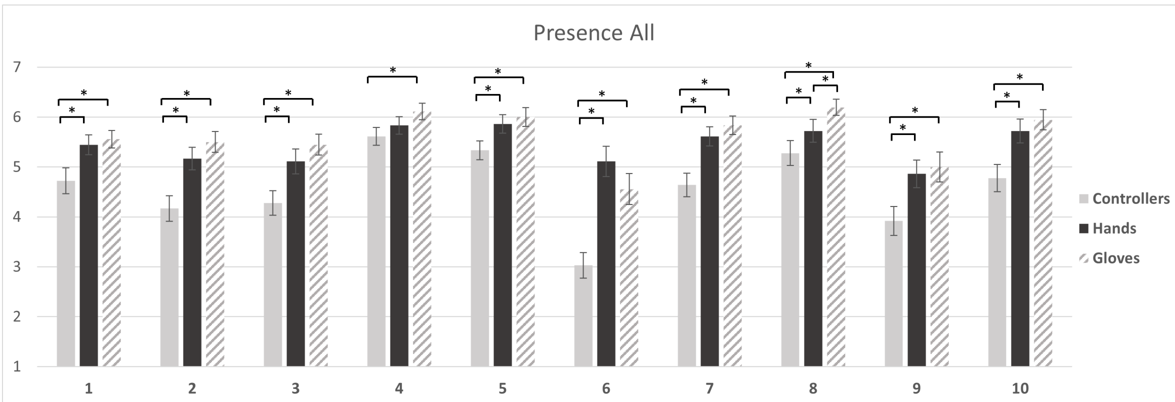


Figure 4.11: Average of individual PQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

A lesson I took from the experiment is that the participants felt more presence when they were using whole-hand interaction in the VR game than using controllers. Whole-hand interaction using hand tracking provided more natural and intuitive hand manipulation since users did not need to learn how to interact with the system but simply moving their hands as they would do in the real world. In contrast, controllers need more time and effort to learn how to manipulate the virtual hands with buttons and triggers on controllers. PQ 2 (How natural did your interactions with the environment seem?) and PQ 3 (How much did your experiences in the virtual environment seem consistent with your real world experiences?) supported that the participants felt more natural, intuitive experiences as well as felt consistent with the real world on hand manipulation. Furthermore, controllers cannot implement accurate hands movement. With the controllers, fingers are bending only in one-dimensional axes corresponding to the triggers, and each joint's movement are limited by system default values. This concurs with the hypothesis that realistically rendered hands lead to high levels of presence [8, 72]. Additionally, given the fact that task's focus was on the hand interaction method, my observation supports the previous finding that the sense of presence was influenced by interaction mechanisms [17].

Another observation I made was, the participants felt that controllers interfered with their experiences in the VE. Learning and utilizing how to use controllers made the participants feel less presence in the VE. I also observed from the participants that controllers in both hands were colliding with each other when they made their hands close together. PQ 6 (How much did the control devices interfere with the performance of assigned tasks or with other activities?) results further explained that controller condition interfered with the participants' sense of presence significantly more than hand tracking (hands and gloves conditions).

To my interest, I found evidence that vibrotactile feedback impacted the levels of presence that were not represented in overall PQ rating. PQ 4 (How involved were you in the virtual environment experience?) indicated that the participants felt significantly more involved in gloves condition than controllers condition while there was no significant difference between hands and controllers conditions. It can be inferred that vibrotactile feedback may increase the user's sense of presence. I also noted in PQ 8 (How completely were your senses engaged in this experience?) that they felt their senses are significantly more engaged in gloves condition than both controllers and hands conditions.

4.8.2 Engagement

I discovered that whole-hand interaction using hand tracking significantly engaged the participants in the VE than controllers. Along with PQ 8 (How completely were your senses engaged in this experience?), GEQ 13 (I really get into the game) clearly represented that the participants were more engaged in the VR game with hand tracking. When I scrutinized the individual items in modified GEQ 9 (Playing seems automatic) and GEQ 11 (I

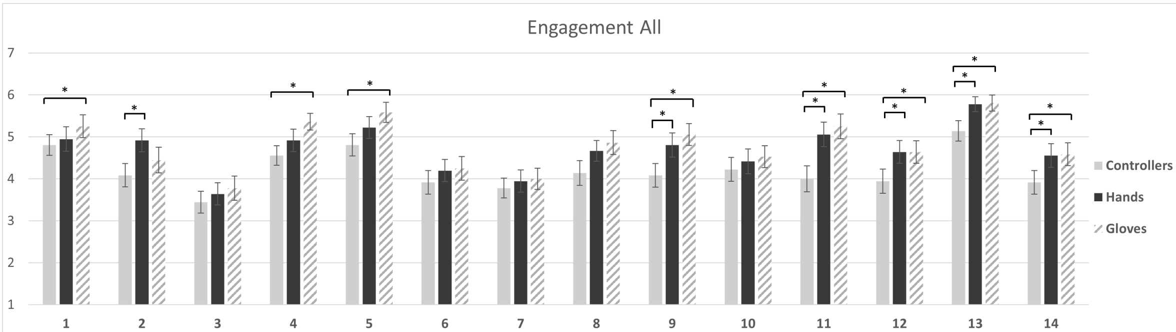


Figure 4.12: Average of individual GEQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$

play without thinking about how to play), the participants responded that hand tracking is more realistic, automated, and easy to use. According to [51], higher interaction fidelity is derived from the exact capture and measure of the user's action as well as consistency of body movement and interactions between real and virtual worlds. In this case, hand tracking had higher interaction fidelity than controllers. My finding can further support the existing study that high interaction fidelity increases the engagement in the VE [65]. Further, my result is consistent with previous studies [50] that higher interaction fidelity and natural interaction [8, 45] increased the sense of engagement and presence in the VE.

In addition, my observation indicated that there was significantly higher level of flow experiences with hands and gloves conditions than controllers condition. GEQ 4 (The game feels real), GEQ 5 (I get wound up (excited)), GEQ 9 (Playing seems automatic), GEQ 11 (I play without thinking about how to play), and GEQ 12 (Playing makes me feel calm) which fell into the flow group of GEQ [9] demonstrated my observation. Flow represents the feelings of complete focus in an activity with a high level of enjoyment that is derived from a balance between skill and challenge being achieved in the process of performing an activity [55, 56]. Csikszentmihalyi's research [16] identified eight major components of flow including direct and immediate feedback, sense of control, and effortless concentration on the task. In my study, hand tracking has higher levels in listed components than controllers due to whole-hand's natural, intuitive, and effortless interactions. The combination of following elements results in higher levels of flow experience and enjoyment [12, 77].

Individual GEQ questionnaires showed that the vibrotactile feedback may enhance the levels of engagement more clearly. The participants responded in GEQ 1 (I lose track of time), GEQ 4 (The game feels real), and GEQ 5 (I get wound up (excited)) that they were losing tracking of time and could not tell that they were getting tired only when the vibrotactile feedback was delivered. The participants also felt the game was real when they played a game with vibrotactile feedback gloves. For these three GEQ questionnaires (GEQ 1, 4, 5), I found that there was a significant difference only between gloves and controller conditions which demonstrated that providing the additional vibrotactile feedback in hand tracking contributed to increasing the engagement.

I received the feedback from a couple of participants that they did not like the feeling of vibrotactile feedback at hands which may lead to insignificant outcomes in terms of vibrotactile feedback. However, most of the participants responded that adding vibrotactile makes the game more fun. Further, most of the participants responded that they prefer to play with whole-hand interaction than controllers. They responded after gameplay that controller often collided each other when they hit the buttons in the middle at the same time.

4.8.3 Usability

For usability, hands and gloves conditions had a higher SUS score than controllers condition. Both hands and gloves conditions are considered as excellent, and controllers condition is considered as good [3]. Although all three conditions are above the average, hands and glove conditions are significantly more usable than controllers in my experiment. However, there was no significant difference between hands and gloves conditions.

4.8.4 Performance

I found that whole-hand interaction using hand tracking showed higher accuracy than controllers among both difficulty levels. My result is consistent with the case studies [51] that task performance increases as interaction fidelity increases from moderate (controllers) to high (hand tracking) levels. I also discovered that hand tracking outperformed the controllers condition with respect to deviation. Controllers condition had significantly higher deviation than the other two conditions among all difficulty levels. I think there are two reasons that hand tracking increased task performance. First, hand tracking can implement lateral movement of the fingers whereas controllers cannot. More control of hand pose may help increase the performance in hand tracking conditions. The other reason is, when the participants hit the button using hand tracking, they can bend their fingers as much as they want based on their hand position. However, it was hard for the participants to control precise finger movement with the index triggers. It made the participants to move the entire controller to hit the buttons. The amount of movement also may impact the task performance. Lastly, I saw that there was no significant statistical difference between hands and gloves conditions which tells us that both conditions have similar performance.

4.9 Limitations

In spite of my attempts to minimize the size of gloves and increase the comfort of wearing, I still observed and received feedback that a few participants felt uncomfortable with vibrotactile gloves. More specifically, they responded that wires and electronics within the gloves made the hands movement uncomfortable. Furthermore, due to safety regarding the COVID pandemic, I instructed the participants to wear additional plastic gloves underneath the vibrotactile gloves. I assumed that uncomfortable experience could possibly neutralize the significance between hands and gloves conditions in terms of task performance. Nevertheless, I found that adding the vibrotactile feedback enhanced individual ratings in questionnaires.

In the discussion, I scrutinized the individual items of PQ and GEQ and analyzed them. These questionnaires were designed to be used as a whole set, and it may not be appropriate to analyze them individually. However, it is still meaningful to observe how the individual items of questionnaires make the significant differences across the conditions.

This study did not compare all the existing VR controllers such as Valve Index or HTC VIVE controllers which have different shapes from Oculus Quest 2. It is possible that performance and subjective ratings could differ from the current outcomes when adopting different controllers. However, most popular VR hardware like PlayStation VR, Oculus Quest 2, HP Reverb G2, and Valve Index controllers have the same number of buttons, triggers, and their arrangements which might demonstrate that my approach was legitimate.

Chapter 5

Study 2

To answer the rest of the research questions (RQ3 How does adding the vibrotactile feedback in a cooperative VR game influence the user's sense of social presence?, RQ4 How does the fingertip vibrotactile feedback (only at one fingertip) influence user experience and task performance in the VR game?), I conducted another experiment. First, I investigated the effect of the fingertip vibrotactile feedback and interaction method on the user's sense of social presence in a cooperative VR game. Also, the limitations I found in the Study 1 of this Thesis was from the form factor of the vibrotactile device and comfort of wearing it. I could reasonably infer that the comfort of wearing can impact user experience and task performance. In this experiment, I minimized the size and weight of the vibrotactile device but maximized the comfort of wearing by adding vibrotactile feedback only at one fingertip which still provided enough vibrotactile cues. I examined whether this fingertip vibrotactile feedback can still make significant differences compared to the conventional VR controllers and hand tracking without any vibrotactile feedback.

5.1 Participants

For this experiment, 24 participants were recruited. Fifteen participants were male and 9 were female (age $M = 23.16$, $SD = 4.05$). Only right-handedness participants were recruited to collect the unbiased data based on the task design. Approval for the study was given by the Institutional Review Board (IRB). All participants gave written consent before the beginning of the study.

5.2 Experiment Setup

To conduct the experiment, Oculus Quest 2 HMD was used. To deliver the vibrotactile feedback only at one fingertip, I developed the thimble-shape vibrotactile device (Fig. 5.1) that the participants can easily put it on their index fingertip. The vibration motors run in 3V DC, 85mA at 12000 rpm. Motors were controlled by the Teensy 3.2 microcontroller via nRF24L01 modules which allowed wireless communication. Similar to Study 1 of this Thesis, one RF module was installed on the PC to work as a base station, and the other module was mounted on the prototype device.

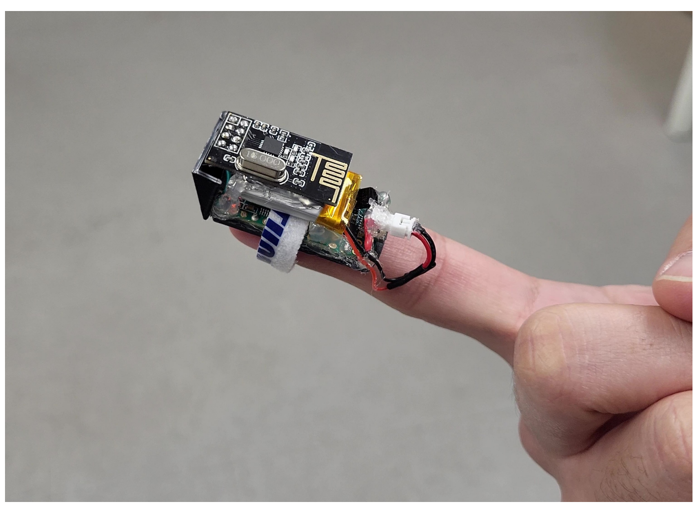


Figure 5.1: Fingertip vibrotactile device.

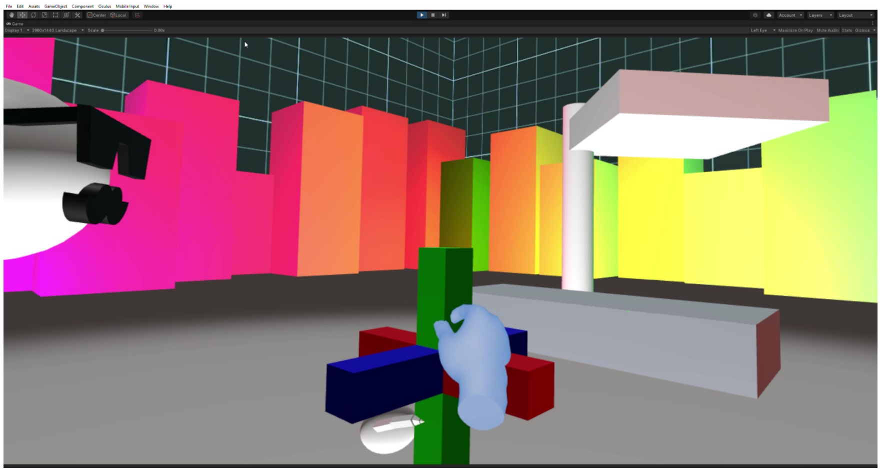


Figure 5.2: Virtual environment implemented with Unity game engine.

5.3 Experimental Design

To investigate the effects of interaction method and vibrotactile feedback, Study 2 this Thesis used a within-subjects design. The participants were instructed to play a cooperative VR game under four different conditions:

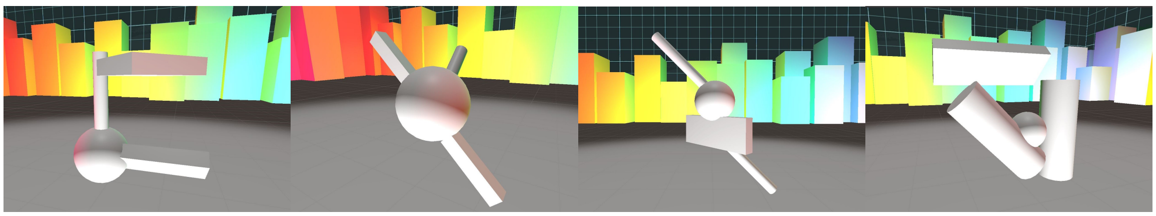
- `Controllers with No Vibrotactile feedback (CNV)`: the participants used Oculus Quest 2 controllers to play a cooperative VR game. No vibrotactile feedback was provided in this condition.

- `Controllers with Vibrotactile feedback (CV)`: the participants used Oculus Quest 2 controllers to play a cooperative VR game. Vibrotactile feedback was provided in this condition.

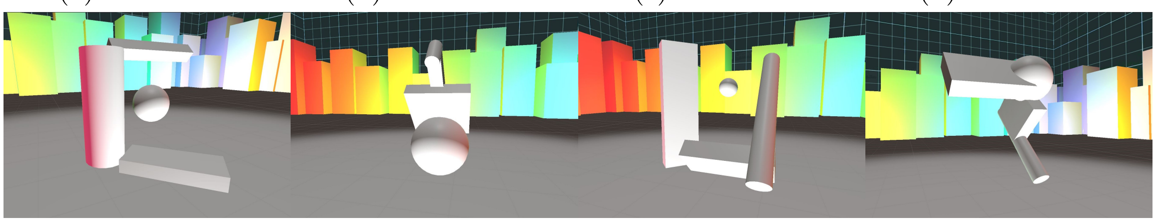
- `Hand tracking with No Vibrotactile feedback (HNV)`: the participants used Oculus Quest 2 hand tracking system to play a cooperative VR game. No vibrotactile feedback was provided in this condition.

- `Hand tracking with Vibrotactile feedback (HV)`: the participants used Oculus Quest 2 hand tracking system with the fingertip vibrotactile device to play a cooperative VR game. Vibrotactile feedback was delivered to the participants' index fingertip.

5.4 Task



(a) Artifact 1. (b) Artifact 2. (c) Artifact 3. (d) Artifact 4.

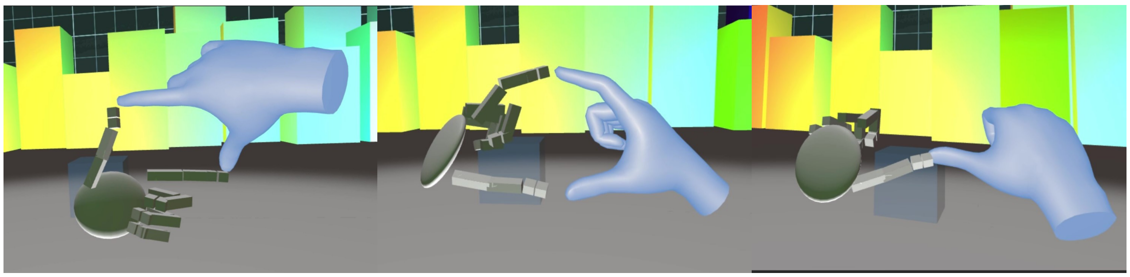


(e) Artifact 5. (f) Artifact 6. (g) Artifact 7. (h) Artifact 8.

Figure 5.3: Eight different artifacts.

The task was a cooperative sculpturing that requires two players. One player was a participant, and the other player was a researcher who conducted the experiment. In order to do sculpturing, the participants were instructed to manipulate the simple 3D objects: a cube, a sphere, and a cylinder. By combining and manipulating the simple 3D objects, players were able to create completely new artifacts (Fig. 5.3). The object manipulation consisted of four steps in following order: creating (Fig. 5.4), scaling (Fig. 5.5), rotating (Fig. 5.6), and positioning (Fig. 5.7). These object manipulations were performed by hand gestures which required two hands. Each player was limited to use one hand (the participants used a right hand, and the researcher used a left hand). Therefore, in order to create the artifacts, two players needed to cooperate their each hand to manipulate the simple 3D objects.

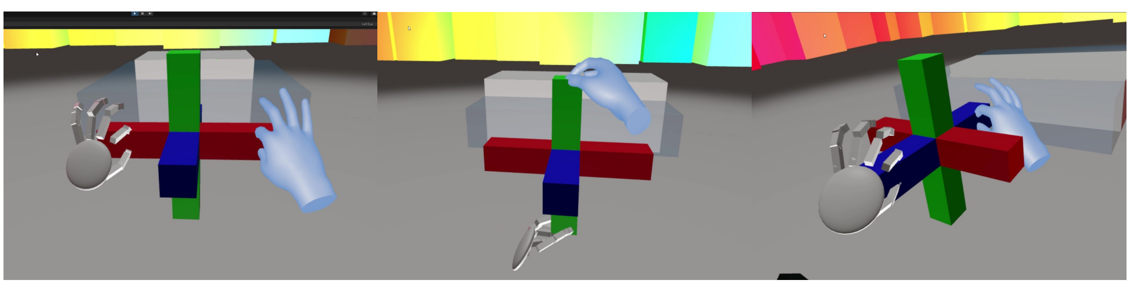
The participants were instructed to create two different artifacts (Fig. 5.3) for each condition. A transparent guide object was given in the VE, so the players were able to get the information about how to adjust the size and locate 3D objects. Each artifact consisted of four different simple 3D objects, and each simple 3D object had four different steps of manipulation.



(a) Creating a cube. (b) Creating a sphere. (c) Creating a cylinder.

Figure 5.4: Creating objects.

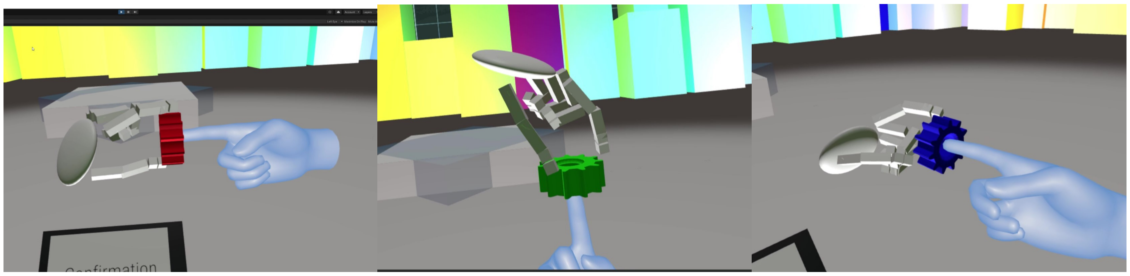
The first step was creating an object. To create a cube, each player made 'L' hand shape and combined together to make a square (Fig. 5.4a). To create a sphere, each player made 'O' shape together with index an finger and a thumb (Fig. 5.4b). To create a cylinder, each player made thumb up and touched the partner's thumb together (Fig. 5.4c).



(a) Scaling in X-axis. (b) Scaling in Y-axis. (c) Scaling in Z-axis.

Figure 5.5: Scaling objects.

The second step was scaling an object. To scale an object, each player pinched the end of each axis and stretched or shrunk the shape together based on the axis which the object needed to be scaled on.



(a) Rotating in X-axis. (b) Rotating in Y-axis. (c) Rotating in Z-axis.

Figure 5.6: Rotating objects.

The third step was rotating an object. To rotate an object, one player's hand became a knob, and the other player rotated a knob based on the axis which the object needed to be rotated on.

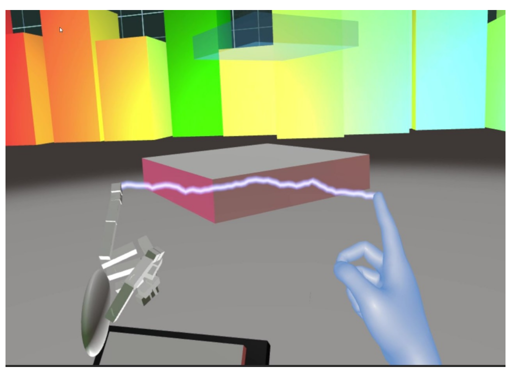


Figure 5.7: Positioning an object.

The last step was positioning an object. To position an object, first, two players' hands got close together. Once they were close to each other, a light string appeared between two index fingers. Once the light string appeared, the right hand player could move the hand to the direction where the object needed to be moved. The center position to control the object was set where the light string was enabled at the moment. For example, to move the object forward, the participants moved the right hand forward while the light string was enabled. After each step of the manipulation, the participants hit the confirmation button together to proceed to the next step. If the object was not identical to the transparent guide, players

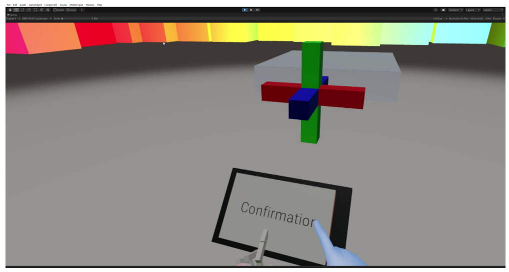


Figure 5.8: Gameplay scene.

could not proceed to next step.

Gesture recognition worked based on the touch of thumb and index fingers. For example, to create a cube or a cylinder, the gestures were recognized when the fingers on each hand touched together. It was the same for pinching in the scaling step where the pinching gesture was recognized when the index and thumb were contacted. The interactions with the controller conditions used the same VR hands, however, the hand gestures were performed by the buttons and triggers. For example, to make 'L' shape, the participants needed to press the middle finger trigger and release the thumb button and index trigger. To make the pinching gesture, the participants needed to press the index trigger and thumb button, and release the middle finger trigger. This implementation was identical to the default setting of Quest 2 controller setting. Two players were located in the same room and they were able to communicate verbally. However, they were separated by the partition, so they were remote in the physical world.

There were two different vibration patterns based on the interaction during the gameplay. The first pattern was monotonous vibration when the participants touched the other player's hand with the index finger. For instance, the participant were able to feel the vibration when they were creating the cube (Fig. 5.4a) or rotating (Fig. 5.6). The other pattern was provided when the light string was enabled during the positioning step (Fig. 5.7). The amplitude and the frequency of vibration were changing randomly so that the pattern mimicked the chaotic pattern of the light string. These two vibration patterns were provided in both controller and hand tracking conditions identically.

5.5 Measurement

5.5.1 Social Presence

To measure the level of social presence, I utilized and modified social presence questionnaire (SPQ) from Harms & Biocca [31]. I used the subsection of co-presence of the questionnaire set which was appropriate to this experiment setting. Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. The questions of modified SPQ are listed as follows:

1. I noticed (my partner).
2. (My partner) noticed me.
3. (My partner's) presence was obvious to me.
4. My presence was obvious to (my partner).
5. (My partner) caught my attention.
6. I caught (my partner's) attention.

5.5.2 Presence

To measure the level of presence, I administered a modified Witmer Presence Questionnaire (PQ) [83, 84] which is identical to Study 1 of this Thesis presence questionnaire but included one more item (PQ 4). Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. The questions of modified PQ are listed as follows:

1. How responsive was the environment to actions that you initiated (or performed)?
2. How natural did your interactions with the environment seem?
3. How much did your experiences in the virtual environment seem consistent with your real world experiences?
4. How well could you actively survey or search the virtual environment using touch?
5. How involved were you in the virtual environment experience?
6. How quickly did you adjust to the virtual environment experience?
7. How much did the control devices interfere with the performance of assigned tasks or with other activities?
8. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
9. How completely were your senses engaged in this experience?
10. Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
11. How easily did you adjust to the control devices used to interact with the virtual environment?

5.5.3 Engagement

Similarly, to evaluate engagement, I adopted a modified Game Engagement Questionnaire (GEQ) [9] which is identical to Study 1 of this Thesis. Responses were collected using the seven-point Likert scales.

5.5.4 Usability

To measure usability of the fingertip vibrotactile device, I used the System Usability Scale (SUS) [10, 11] which is identical to Study 1 of this Thesis. Questionnaires were presented only after HV condition.

5.5.5 Performance

To measure the performance, I collected the completion time of each artifact and averaged them among trials.

5.6 Procedure

When the participants arrived outside the lab building, their temperature was first taken. If the temperature showed no signs of fever, they were brought into the lab. Once the participants were brought into the experiment space, they filled out questionnaires about presenting symptoms of COVID-19, signed the IRB consent form, and COVID addendum for the study. Next, the participants completed the first part of a motion sickness questionnaire to create a baseline for subjective measures such as feeling tired, disoriented, or lightheaded before wearing the Quest 2 HMD. Only the participants who had not experienced motion sickness continued the experiment.

After completing the motion sickness screening, the participants were instructed about how to interact in VE with Oculus Quest 2 controllers and hand tracking. The participants started with the tutorial about how to manipulate the objects and play the game with hand gestures. After the tutorial, the participant was instructed to play eight different trials, each of which was making one artifact. As the participants completed the trials, Unity was programmed to collect completion time for further analysis. After the each condition, the participants removed the HMD and completed the SPQ, PQ, and GEQ. SUS was only given to HV condition. After completing the survey, the participants put on the equipment for the next condition, for which the order was predetermined to be counterbalanced. After all the conditions were completed, the participant were compensated with $10 and the study concluded. The study took around 60 minutes.

5.7 Results

5.7.1 Social Presence

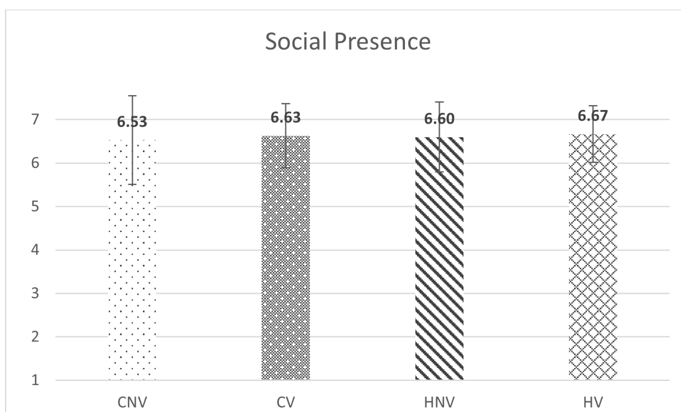


Figure 5.9: Average of all SPQ across the conditions. Error bars indicate standard error of the mean.

For social presence, I averaged all questionnaire items and performed two-way repeated measures ANOVA, using interaction method and vibrotactile feedback as independent variables and the mean scores of social presence as a dependent variable. There was no significant difference in terms of interaction methods [$F(1, 92) = 0.11$, $p = 0.74$], vibrotactile feedback [$F(1, 92) = 0.26$, $p = 0.61$], or interaction effect [$F(1, 92) = 0.01$, $p = 0.93$].

5.7.2 Presence

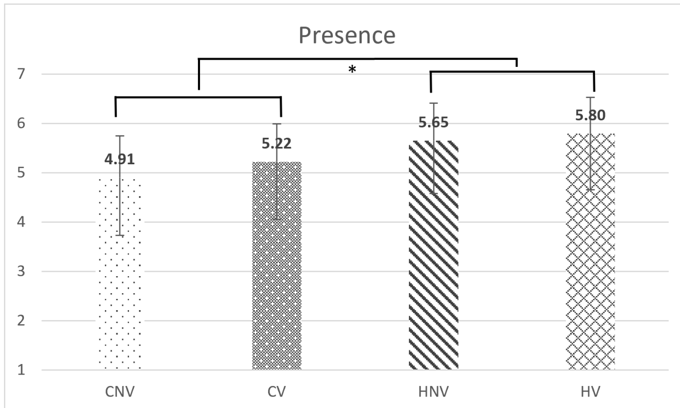


Figure 5.10: Average of all PQ across the conditions. Error bars indicate standard error of the mean. $*p < .05$.

For presence, I averaged all questionnaire items and performed two-way repeated measures ANOVA, using interaction method and vibrotactile feedback as independent variables and the mean scores of presence as a dependent variable. For PQ 7 (How much did the control devices interfere with the performance of assigned tasks or with other activities?) and PQ 10 (Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?), I reversed the score which indicated that higher score means higher presence. There was a statistically significant difference in terms of interaction methods. Hand tracking conditions had significantly higher level of presence than controller conditions [$F(1, 92) = 17.05$, $p < 0.001$]. There was no significant difference in terms of vibrotactile feedback [$F(1, 92) = 2.20$, $p = 0.14$] or interaction effect [$F(1, 92) = 0.27$, $p = 0.60$].

5.7.3 Engagement

For engagement, I averaged all GEQ items and performed two-way repeated measures ANOVA, using interaction method and vibrotactile feedback as independent variables and

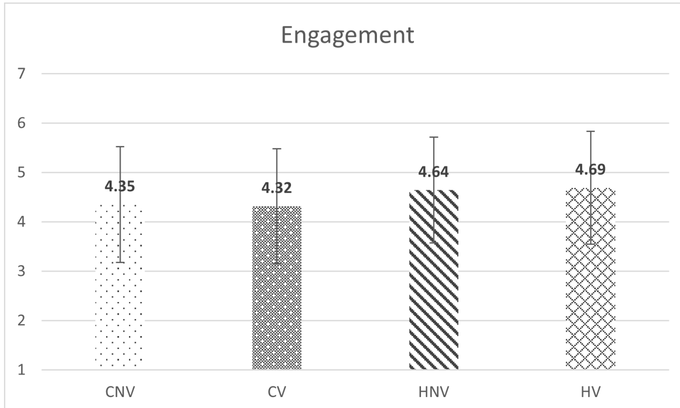


Figure 5.11: Average of all GEQ across the conditions. Error bars indicate standard error of the mean.

the mean scores of engagement as a dependent variable. There was no significant difference in terms of interaction method [$F(1,\ 92) = 1.98$, $p = 0.16$], vibrotactile feedback [$F(1,\ 92) = 0.0001$, $p = 0.98$], or interaction effect [$F(1,\ 92) = 0.02$, $p = 0.87$].

5.7.4 Usability

I evaluated the usability of the fingertip vibrotactile device using the SUS questionnaire. The SUS score of the prototype device was 78.6 [$SD = 13.47$].

5.7.5 Performance

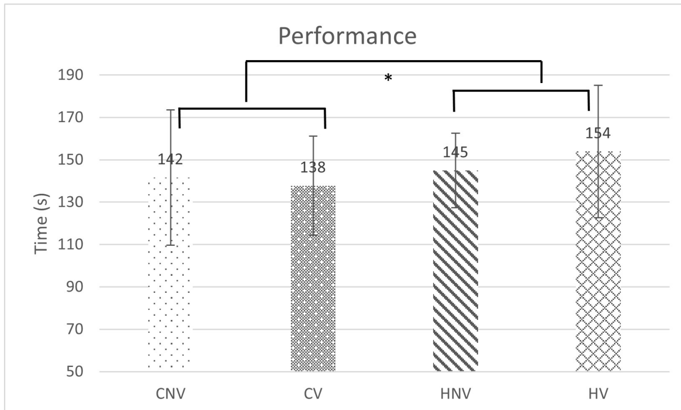


Figure 5.12: Average of completion time across all conditions. Error bars indicate standard error of the mean. $*p < .05$.

I performed two-way repeated measures ANOVA, and observed that there was a significant difference in terms of interaction method. Controller conditions had higher performance (lower completion time) than hand tracking conditions [$F(1, 188) = 6.40$, $p < 0.05$]. There was no significant difference in terms of vibrotactile feedback [$F(1, 188) = 0.45$, $p = 0.50$] or interaction effect [$F(1, 188) = 2.77$, $p = 0.09$].

5.8 Discussion

To investigate the effects of interaction methods and vibrotactile feedback on user experience in a cooperative VR game, I compared subjective metrics and task performance as well as analyzed feedback from the participants. I observed that hand tracking enhanced the level of presence. Based on the results, I outlined three inferences from the experiment:

1. Hand tracking significantly increased the level of presence.

2. Controller improved task performance.

3. Stability of the technology affected the user experience and task performance.

5.8.1 Social Presence

There was no significant difference among conditions and there was a ceiling effect on the level of social presence. Based on the observation and feedback from the participants, I could infer several possible reasons. First, this experiment was a cooperative game that required collaborative interactions with their each hand to manipulate the object together. This intimate cooperation and realistic representation of hands overrode the effect of the interaction methods and vibrotactile feedback, and the participants responded that they felt high level of social presence regardless of the conditions. There are several existing experiments support that haptic feedback increased social presence in the VE, but the experimental setting is quite different from this study. Lee et al. [40] explored the level of social presence while vibrotactile feedback was provided at footsteps when a virtual avatar got closer to the user in the VE. In this setting, there was no cooperative interaction, verbal or non-verbal communication with the avatar in the VE. Giannopoulos et al. [26] investigated the effect of haptic feedback on social interaction within shared the VE. In this setting, there was a cooperative interaction with two people to perform a task, however, it was a desktop based setting so they were not using any immersive display and user could not see the mediated virtual representation of the other partner through the display.

Another reason might be that most of the participants have not experienced in social VR applications, not to mention to a cooperative game that allows hand gestures to manipulate and create artifacts together. I received comments and feedback from the participants during and after the experiment that they have not experienced in hand tracking or hand gesture based cooperative multiplayer VR game before. This unusual experience might lead to the ceiling effect on the level of social presence.

5.8.2 Presence

Similar to Study 1 of this Thesis, the participants felt more presence with whole-hand interaction using hand tracking than controller conditions. PQ 6 (How quickly did you adjust to the virtual environment experience?) [$F(1, 92) = 9.37$, $p < 0.05$], PQ 8 (How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?) [$F(1, 92) = 8.18$, $p < 0.05$], PQ 10 (Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?) [$F(1, 92) = 16.58$, $p < 0.05$], and PQ 11 (How easily did you adjust to the control devices used to interact with the virtual environment?) [$F(1, 92) = 24.98$, $p < 0.05$] had consistent outcomes with Study 1 of this Thesis that the natural and intuitive interaction allowed the participants to adjust and focus on the VE, and thus increased the level of presence.

Other individual items of PQ showed that vibrotactile feedback increased the level of presence in a cooperative VR game. PQ 1 (How responsive was the environment to actions that you initiated (or performed)?) [$F(1, 92) = 7.67$, $p < 0.05$], PQ 4 (How well could you actively survey or search the virtual environment using touch?) [$F(1, 92) = 5.27$, $p < 0.05$], and PQ 9 (How completely were your senses engaged in this experience?) [$F(1, 92) = 4.37$, $p < 0.05$] indicated that vibrotactile feedback significantly increased the level of presence. These findings are consistent to the outcomes of Study 1 of this Thesis. Furthermore, it was meaningful to observe that the fingertip vibrotactile device could still make significant difference while giving a minimum vibrotactile feedback cue by increasing the comfort of wearing. It can be concluded that fingertip vibrotactile feedback provided enough sense of touch for the participants to be responded and engaged in the VE.

5.8.3 Engagement

For the engagement, I was not able to find the significant difference between conditions. During the gameplay with hand tracking, I observed that the participants had difficulty playing the game due to the technological limitations. First, Quest 2 hand tracking used built-in cameras to track the hands movement. However, some parts of the hand or fingers were occluded, and resulted in unintended or inaccurate hand gestures. For example, when they were pinching with a thumb and an index finger, the back of the hand occluded a thumb and so pinching gesture was not correctly implemented during the gameplay. This had the participants repeat the same process of interactions or start over each step of the manipulation again. I could reasonably assumed that the tedious repetition of game steps made the participants less engaged in the VR game and resulted in insignificant results between the conditions. Although the averaged score of GEQ did not show significant differences between conditions in terms of interaction method and vibrotactile feedback, an individual item of GEQ 11 (I play without thinking about how to play) [$F(1, 92) = 6.35$, $p < 0.05$] showed that whole-hand interaction using hand tracking provided higher level of engagement than controller. The participants needed more time and effort to learn how to implement certain hand gestures such as thumb up or pinching with controllers. This outcome is similar to Study 1 of this Thesis and it further supports that effort and time to learn the system could decrease the level of engagement.

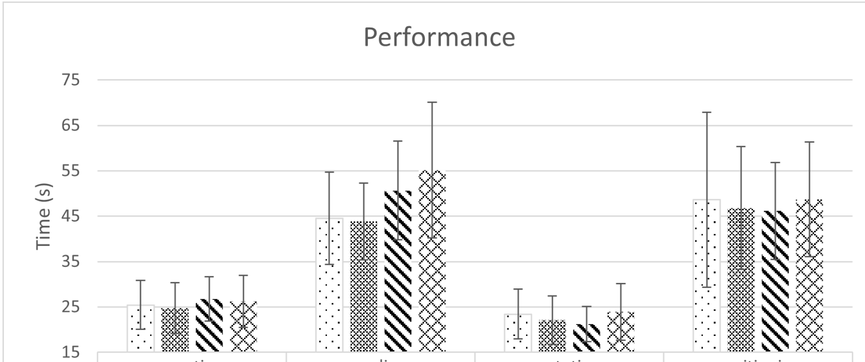
I received and collected the participants' subjective comments and feedback, and one third of the participants preferred playing game without vibrotactile feedback. One of the participants responded that adding vibrotactile made the VE less realistic. Another participant responded that vibrotactile feedback at fingertip made her distracting. However, two third of the participants preferred having vibrotactile feedback. They responded that it made a game more fun and exciting. A couple of participants commented that vibrotactile made them feel like touching a real person. Also, one third of the participants preferred playing with the controller. All the participants who preferred the controller condition made feedback that controller was more accurate and did not have to repeat the same hand gestures due to the occlusion and jittering in Quest 2 hand tracking. However, two third of the participants responded that they preferred whole-hand interaction since it was natural and intuitive to control the hand pose.

5.8.4 Usability

The fingertip vibrotactile device I developed had a SUS score of 78.6 which is considered as good [3]. During the user study, I observed that the instability of the hand tracking system affected the usability. During the gameplay, the participants were required to implement several hand gestures such as pinching and dragging. I could assume that the instability of the hand tracking can impact the SUS score. Nevertheless, I can still infer that the fingertip vibrotactile device that provided the minimum vibrotactile cue at one fingertip is still useful in the VE. This prototype demonstrated the potential of the vibrotactile feedback application in the VR game as well as it can be expanded to social VR context.

5.8.5 Performance

The result represented that controller conditions had higher performance (lower completion time) than hand tracking even though whole-hand interaction provided natural and intuitive interaction. This result was inconsistent with the existing study [51] and Study 1 of this



	creating	scaling	rotating	positioning
CNV	25	44	23	49
CV	25	44	22	47
HNV	27	51	21	46
HV	26	55	24	49

Figure 5.13: Average of completion time across all conditions. Error bars indicate standard error of the mean.

Thesis. It could stem from technical limitations in hand tracking previously mentioned. Hand tracking is less stable and inaccurate than controller due to jittering and occlusion from Quest 2 hand tracking system. Among the four different manipulation steps, scaling required the participants to preform the most detailed hand gestures since they needed to pinch and drag along the axis. As shown in (Fig. 5.13), the performance of scaling had significant difference in terms of interaction method $[F(1,\ 188) = 28.26,\ p < 0.05]$. In contrast, the performance of creating, rotating, and positioning did not reflect the technological limitations mentioned above. It was assumed that inconsistent performance outcome was derived from the task complexity. Since creating, rotating, and positioning steps were comparatively simpler and easier than scaling step. In the same context, Study 1 of this Thesis used the same hand tracking system, but the gameplay required the participants to push the buttons along with the music. Unlike Study 2 scaling step, the participants did not need to perform any hand gestures such as pinching.

5.9 Limitations

In this experiment, I observed the ceiling effect in social presence. It was mainly from the unique setting of the cooperative VR game. Compared to other experiments, my experiment had realistically rendered hands of the partner, and players collaborated to create the artifacts in the VE. Moreover, the participants responded that they have never played social VR or a cooperative VR game with whole-hand interaction using hand tracking. In spite of the ceiling effects in the social presence, I found significant differences in other subjective measurements.

Similar to Study 1 of this Thesis, I investigated the individual items of PQ and GEQ and analyzed them. These questionnaires were designed to be used as a whole set, however, it is still meaningful to figure out how the individual items of questionnaires make any differences across the conditions.

This study was fully dependent on the Quest 2 hand tracking and it was hard to find alternative technology that had better level of tracking capability. However, I still observed the technological limitations of hand tracking such as jittering or occlusion that impacted user experience and performance. It was inevitable for my experimental settings, but I expect that the subjective and objective measurements we collected could be different with more stable and accurate hand tracking technology.

Chapter 6

General Discussion

By conducting Study 1 and Study 2 of this Thesis, I could answer the research questions I posed, and observed the limitations that impacted the outcomes of the studies.

1. How do different interaction methods (controllers and hand tracking) in the VR game influence user experience and task performance?

   Both Study 1 and Study 2 of this Thesis showed that hand tracking increased the level of presence. In Study 1, whole-hand interaction using hand tracking also increased engagement in Study 1 since it provided more natural and intuitive interaction than controllers. Hand tracking conditions increased task performance in Study 1 of this Thesis. Hand tracking can implement more precise hand pose than controller and it may help improve the task performance.

2. How does adding vibrotactile feedback in hand tracking influence user experience and task performance in the VR game?

   In Study 1 of this Thesis, vibrotactile feedback may enhance the level of presence, engagement, and task performance.

3. How does adding the vibrotactile feedback in a cooperative VR game influence the user's sense of social presence?

   In Study 2, there was no significant differences in social presence among conditions and there was the ceiling effect. Unlike other studies, the participants experienced intimate cooperation and realistic representation of hands during the gamepaly, and it overrode the effect of the vibrotactile feedback. In addition, task itself was considerably cooperative and so the participants felt high level of social presences regardless of the vibrotactile feedback.

4. How does the fingertip vibrotactile feedback (only at one fingertip) influence user experience and task performance in the VR game?

   In Study 2, fingertip vibrotactile feedback did not show any significant differences in the level of social presence, presence, engagement, and task performance due to technological limitations. As previously discussed, occlusion and jittering of hand tracking impacted the user experience and task performance. However, individual items of presence questionnaire showed that the vibrotactile feedback may enhance the level of presence.

Based on my experiences of development and evaluation of prototype devices, and the limitations I observed from Study 1 and Study 2 of this Thesis, I can provide design guidelines for the future studies.

1. Avoid unstable and inaccurate system and technology that possibly can impact user experience and task performance.

   As I observed in Study 2 of this Thesis, occlusion and jittering impacted user experience and task performance. During the experiment, performing hand gestures were hindered by listed issues. Further, the effect of instability of hand tracking was magnified since hands can perform delicate tasks in the real world. It is best practice to avoid using unstable and inaccurate technology to collect desired subjective and objective data.

2. Social presence should be measured in an appropriate experimental setting.

   As I addressed, social presence can be defined in several aspects. Based on the research questions and experimental setting, it was best to focus on co-presence in Study 2 of this Thesis. However, other studies defined social presence in different ways such as psychological involvement or behavioral engagement. I can suggest to define the social presence associated with the research questions and experimental setting. Along with the definition, it is desired to use the appropriate social presence questionnaire to collect the proper responses.

3. To improve user experience in the VR game, use whole-hand interaction.

   The participants felt more presence and engagement with more natural and intuitive interaction in the VR game. If the tasks or games do not require the participants to perform a complex task that cannot be done with hand gestures, it is desired to use whole-hand interaction using hand tracking instead of controllers. Adding vibrotactile feedback can even enhance presence more. But it should be cautiously selected depending on the complexity or type of the tasks as well. In Study 2, controllers showed higher performance due to the task complexity.

4. Consider the trade-offs between bulkiness and usability.

   To implement sophisticated haptic feedback, the size of the haptic device gets larger. Study 1 of this Thesis showed that the haptic gloves clearly showed the effect on performance and subjective measures. In Study 2 of this Thesis, the fingertip vibrotactile device had better comfort of wearing but it provided vibration only at an index finger. It still showed good usability but it did not show significant effect on performance and subjective metrics. This insignificant outcome may not be entirely dependent on the device itself, but it is meaningful to consider the trade-offs between bulkiness and usability.

Chapter 7

Conclusion and Future Works

Based on the Study 1 and Study 2 of this Thesis, I was able to obtain the insight of how the interaction method and vibrotactile feedback influence user experience and performance in the VR games. These experiments supported the existing studies that natural and intuitive interaction increase the level of presence and engagement in the VR. In the VR games where the users need to control the pose of virtual hands to interact with virtual objects, using direct hand tracking can lead to higher levels of presence and engagement compared to interfaces where controllers are used to control the virtual hand pose. Providing vibrotactile feedback may help improve the level of presence and engagement in the VR. Furthermore, the participants only felt the vibration at an index fingertip in Study 2, and it still made some significant differences in terms of presence. I assume that providing haptic feedback in the VR is one possible approach to let users more immersed and engaged in the VE. Stability of hand tracking technology impacted on the user experience and performance in the VR games. Throughout the Study 1 and Study 2 of this Thesis, the participants experienced the jittering and occlusion from hand tracking. Controllers was less natural intuitive than whole-hand interaction but they had higher positioning accuracy, stability than hand tracking.

My findings informed the benefits of hand tracking and vibrotactile feedback in the VR games. I plan to conduct further research to supplement the limitations I found during the experiments. I will investigate social presence in a more appropriate experimental setting. In Study 2 of this Thesis, experimental task provided high level of social presence regardless of conditions. I will design the experiment and task that can reflect the appropriate responses of the participants. I will also diversify the haptic sensation. Vibrotactile feedback in my experiments were monotonously delivered when the participants hit the buttons. I would like to further investigate how the different vibrotactile feedback can affect the task performance. Lastly, I will experiment under different combinations of modality in which we expect to investigate the effects of the combination of auditory, visual, and haptic sensations in the VR games. Throughout two studies, it was insightful to observe that the participants felt more presence and engagement with natural and intuitive interaction in the VE, but at the same time, the instability of system could possibly deteriorate the user's subjective and objective responses.

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Appendices

Appendix A

Study 1 Appendix

A.1 Consent Form

Key Information: The following is a short summary of this study to help you decide whether or not to be a part of this study. More detailed information is listed later on in this form. The objective of this study is to evaluate the effects of VR Haptic Glove on user experiences in VR games. The study will investigate the usability, the level of presence and engagement under two different conditions. If the experiment begins, the participant will play a VR game with VR Haptic Glove and conventional VR controllers. After the experiment, you will fill out the survey.

Detailed Information: The following is more detailed information about this study in addition to the information listed above.

The objective of this study is to evaluate the effects of VR Haptic Glove on user experiences in VR games. The study will investigate the usability, the level of presence and engagement under two different conditions. Before the experiment, you will fill out a demographic questionnaire and have a short (2-3min) familiarization session as a motion sickness test run. Before and after this run, you will fill out a motion sickness questionnaire. If you pass the motion sickness test, you will participate in the actual experiment. The experimenter will also give you enough time between sessions to recover from motion sickness effects if necessary and a participant can ask for breaks at any time during the experiment. In the experiment, you will play a VR game with two different input devices - VR Haptic Glove and conventional VR controllers. You will fill out questionnaires on each session and give your comments after the end of the experiment. For the experiment, you will be compensated 10 dollars, and withdrawing due to motion sickness or dizziness will not affect the amount given. Who can I talk to? If you have any questions or requests for information relating to this research study or your participation in it, or if you want to voice a complaint or concern about this research, or if you have a study related injury, you may contact Dr. Myounghoon Jeon at 906-231-5167.

If you have any questions about your rights as a research subject or complaints regarding this research study, or you are unable to reach the research staff, you may contact a person independent of the research team at the Biomedical Research Alliance of New York Institutional Review Board at 516-318-6877. Questions, concerns or complaints about research can also be registered with the Biomedical Research Alliance of New York Institutional Review Board at www.branyirb.com/concerns-about-research. How many people will be studied? We plan to include about 100 people at this location out of 100 people in the entire study nationally. What happens if I say yes, I want to be in this research? After consenting to the study, you will participate in VR Haptic Glove experiment. The experiment will take place in the Mind Music Machine Lab in 1158 CRC Knowledge Works II and take no more than an hour for each experiment. The researchers you will interact with can include the primary investigator or any of other study contacts listed above. A participant will useVR Head Mounted Display, VR controllers and VR Haptic Glove we devised. Investigators will be familiar with their use. In the experiment, you will play a VR game with two different input devices - VR Haptic Glove and VR controllers. After the experiment, you will fill out questionnaires on each session and give your comments after the end of the experiment.

For the experiment, you will be compensated 10 dollars, and withdrawing due to motion sickness or dizziness will not affect the amount given. At the end of any of the experiments, you can indicate on the survey whether you wish to be contacted again for participation in other studies at the lab or the other experiment detailed in this study. What happens if I say yes, but I change my mind later? You can leave the research at any time, for any reason, and it will not be held against you. Any data collected from the experiment prior to your withdrawal will not be used in subsequent data analysis. Is there any way being in this study could be bad for me? (Detailed Risks) This study only had minimal risks but a participant might feel motion sickness using the virtual reality headset. You might also experience other virtual reality side effects, which can include but are not limited to, blurry vision, eye strain, headaches, dizziness, fatigue, or nausea. If you feel discomfort or motion sickness from the experiment, you can leave the experiment and no consequence will apply. You will still receive their compensation for the study. What happens to the information collected for the research? We will make every effort to limit the use and disclosure of your personal information, including research study and medical records, only to people who have a need to review this information. We cannot promise complete confidentiality. Organizations that may inspect and copy your information include the IRB, Human Research Protection Program and Virginia Tech. All individually identifiable information collected in this study will be kept in a locked file cabinet in a locked room used by the Mind Music Machine Lab on the Virginia Tech campus for a maximum of 5 years. The results of this research study may be presented in summary form at conferences, in presentations, reports to the sponsor, academic papers, and as part of a thesis/dissertation. Can I be removed from the research without my OK? The person in charge of the research study or the sponsor can remove you from the research study without your approval. Possible reasons for removal include motion sickness, dizziness, or fatigue. What else do I need to know? If you agree to take part in this research study, you will receive 10 dollars for your time and effort. We will not offer to share your individual test results with you.

A.2 IRB Approval Letter

Division of Scholarly Integrity and Research Compliance
Institutional Review Board
North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
http://www.research.vt.edu/sirc/hrpp

MEMORANDUM

DATE:	March 19, 2021
TO:	Myounghoon Jeon, Hye Sung Moon
FROM:	Virginia Tech Institutional Review Board (FWA00000572, expires October 29, 2024)
PROTOCOL TITLE:	VR Haptic Glove
IRB NUMBER:	**21-194**

Effective March 19, 2021, the Virginia Tech Institution Review Board (IRB) approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

https://secure.research.vt.edu/external/irb/responsibilities.htm

(Please review responsibilities before beginning your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 4,7**
Protocol Approval Date:	**March 19, 2021**
Progress Review Date:	**March 19, 2022**

ASSOCIATED FUNDING:

The table on the following page indicates whether grant proposals are related to this protocol, and which of the listed proposals, if any, have been compared to this protocol, if required.

Invent the Future

A.3 Questionnaires

A.3.1 Presence Questionnaire

1. How responsive was the environment to actions that you initiated (or performed)?
2. How natural did your interactions with the environment seem?
3. How much did your experiences in the virtual environment seem consistent with your real world experiences?
4. How involved were you in the virtual environment experience?
5. How quickly did you adjust to the virtual environment experience?
6. How much did the control devices interfere with the performance of assigned tasks or with other activities?
7. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
8. How completely were your senses engaged in this experience?
9. Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
10. How easily did you adjust to the control devices used to interact with the virtual environment?

A.3.2 Engagement Questionnaire

1. I lose track of time.
2. Things seem to happen automatically.
3. I feel different.
4. The game feels real.

5. I get wound up (excited).
6. Time seems to kind of stand still or stop.
7. I feel spaced out.
8. I can't tell that I'm getting tired.
9. Playing seems automatic.
10. I lose track of where I am.
11. I play without thinking about how to play.
12. Playing makes me feel calm.
13. I really get into the game.
14. I feel like I just can't stop playing.

A.3.3 System Usability Questionnaire

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Appendix B

Study 2

B.1 Consent Form

Key Information: The following is a short summary of this study to help you decide whether or not to be a part of this study. More detailed information is listed later on in this form. The objective of this study is to evaluate the effects of VR Haptic Gloves and fingertip vibrotactile feedback on user experiences in a cooperative VR game. The study will investigate the user's level of social presence, presence, engagement, and usability under different conditions. If the experiment begins, the participant will play a cooperative VR game with VR Haptic Gloves, fingertip vibrotactile feedback device, and conventional VR controllers. After the experiment, you will fill out the survey. What should I know about being in a research study? Someone will explain this research study to you Whether or not you take part is up to you You can choose not to take part You can agree to take part and later change your mind Your decision will not be held against you You can ask all the questions you want before you decide What should I know about this research study? The purpose of this study is to figure out the effect of effects of VR Haptic Gloves and fingertip vibrotactile feedback on user experiences in a cooperative VR game. We hypothesize that VR haptic glove and fingertip vibrotactile feedback will provide the better sense of social presence, presence, engagement, and the usability than conventional controllers. We expect that your participations in this research study will last approximately 60 90 minutes. You will be asked to wear a virtual reality headset and conduct a cooperative VR game with VR Haptic Gloves, fingertip vibrotactile feedback, bare hands, and VR controllers. Afterwards, you will fill out questionnaires about your experiences. There is a risk that you might become nauseous or dizzy. (More detailed information about the risks of this study can be found under "Is there any way being in this study could be bad for me? (Detailed Risks)".) There is a benefit that you can entertain and be engaged in a VR game. Detailed Information: The following is more detailed information about this study in addition to the information listed above. The objective of this study is to evaluate the effects of VR Haptic Gloves and fingertip vibrotactile feedback on user experiences in VR games. The study will investigate the user's level of social presence, presence, engagement, and usability under four different conditions. Before the experiment, you will fill out a demographic questionnaire and have a short (2-3min) familiarization session as a motion sickness test run. Before and after this run, you will fill out a motion sickness questionnaire. If you pass the motion sickness test, you will participate in the actual experiment. The experimenter will also give you enough time between sessions to recover from motion sickness effects if necessary and a participant can ask for breaks at any time during the experiment. In the experiment, you will play a VR game with two different input devices - VR Haptic Glove and conventional VR controllers. You will fill out questionnaires on each session and give your comments after the end of the experiment. For the experiment, you will be compensated 10 dollars, and withdrawing due to motion sickness or dizziness will not affect the amount given. Who can I talk to? If you have any questions or requests for information relating to this research study or your participation in it, or if you want to voice a complaint or concern about this research, or if you have a study related injury, you may contact Dr. Myounghoon Jeon at 906-231-5167.

The research has been reviewed and approved by the Virginia Tech Institutional Review Board (IRB). You may communicate with them at 540-231-3732 or irb@vt.edu if: You have questions about your rights as a research subject Your questions, concerns, or complaints are not being answered by the research team You cannot reach the research team You want to talk to someone besides the research team to provide feedback about this research How many people will be studied? We plan to include about 100 people at this location out of 100 people in the entire study nationally. What happens if I say yes, I want to be in this research? After consenting to the study, you will participate in VR Haptic Glove experiment. The experiment will take place in the Mind Music Machine Lab in 519A or 565 Whittemore Hall or Durham 188, and take no more than 90 minutes for entire experiment. The researchers you will interact with can include the primary investigator or any of other study contacts listed above. A participant will use VR Head Mounted Display, VR controllers,VR Haptic Gloves, and fingertip vibrotactile feedback device we devised. Investigators will be familiar with their use. In the experiment, you will play a cooperative VR game with four different input devices - VR controllers, bare hands, VR Haptic Gloves, and fingertip vibrotactile feedback device. After the experiment, you will fill out questionnaires on each session and give your comments after the end of the experiment. For the experiment, you will be compensated 10 dollars, and withdrawing due to motion sickness or dizziness will not affect the amount given. At the end of any of the experiments, you can indicate on the survey whether you wish to be contacted again for participation in other studies at the lab or the other experiment detailed in this study. What happens if I say yes, but I change my mind later? You can leave the research at any time, for any reason, and it will not be held against you. Any data collected from the experiment prior to your withdrawal will not be used in subsequent data analysis. Is there any way being in this study could be bad for me? (Detailed Risks) This study only had minimal risks but a participant might feel motion sickness using the virtual reality headset. You might also experience other virtual reality side effects, which can include but are not limited to, blurry vision, eye strain, headaches, dizziness, fatigue, or nausea. If you feel discomfort or motion sickness from the experiment, you can leave the experiment and no consequence will apply. You will still receive their compensation for the study. What happens to the information collected for the research? We will make every effort to limit the use and disclosure of your personal information, including research study and medical records, only to people who have a need to review this information. We cannot promise complete confidentiality. Organizations that may inspect and copy your information include the IRB, Human Research Protection Program and Virginia Tech. If identifiers are removed from your private information or samples that are collected during this research, that information or those samples could be used for future research studies or distributed to another investigator for future research studies without your additional informed consent. All individually identifiable information collected in this study will be kept in a locked file cabinet in a locked room used by the Mind Music Machine Lab on the Virginia Tech campus for a maximum of 5 years. The results of this research study may be presented in summary form at conferences, in presentations, reports to the sponsor, academic papers, and as part of a thesis/dissertation.

Can I be removed from the research without my OK? The person in charge of the research study or the sponsor can remove you from the research study without your approval. Possible reasons for removal include motion sickness, dizziness, or fatigue. What else do I need to know? If you agree to take part in this research study, you will receive 10 dollars in cash for your time and effort. You will be compensated immediately following completion of participation. We will not offer to share your individual test results with you.

Division of Scholarly Integrity and
Research Compliance
Institutional Review Board
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300 Turner Street NW
Blacksburg, Virginia 24061
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MEMORANDUM

DATE: November 16, 2021

TO: Myounghoon Jeon, Kristina Pratt, Hye Sung Moon, Grady Michael Orr

FROM: Virginia Tech Institutional Review Board (FWA00000572)

PROTOCOL TITLE: VR Haptic Glove

IRB NUMBER: **21-194**

Effective November 15, 2021, the Virginia Tech Institution Review Board (IRB) approved the Amendment request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

https://secure.research.vt.edu/external/irb/responsibilities.htm

(Please review responsibilities before beginning your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 4,7**
Protocol Approval Date:	**March 19, 2021**
Progress Review Date:	**March 19, 2022**

ASSOCIATED FUNDING:

The table on the following page indicates whether grant proposals are related to this protocol, and which of the listed proposals, if any, have been compared to this protocol, if required.

Invent the Future

B.2 IRB Approval Letter

B.3 Questionnaires

B.3.1 Social Presence Questionnaire

1. I noticed (my partner).

2. (My partner) noticed me.

3. (My partner's) presence was obvious to me.
4. My presence was obvious to (my partner).
5. (My partner) caught my attention.
6. I caught (my partner's) attention.

B.3.2 Presence Questionnaire

1. How responsive was the environment to actions that you initiated (or performed)?
2. How natural did your interactions with the environment seem?
3. How much did your experiences in the virtual environment seem consistent with your real world experiences?
4. How well could you actively survey or search the virtual environment using touch?
5. How involved were you in the virtual environment experience?
6. How quickly did you adjust to the virtual environment experience?
7. How much did the control devices interfere with the performance of assigned tasks or with other activities?
8. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
9. How completely were your senses engaged in this experience?
10. Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
11. How easily did you adjust to the control devices used to interact with the virtual environment?

B.3.3 Engagement Questionnaire

1. I lose track of time.
2. Things seem to happen automatically.
3. I feel different.
4. The game feels real.
5. I get wound up (excited).
6. Time seems to kind of stand still or stop.
7. I feel spaced out.
8. I can't tell that I'm getting tired.
9. Playing seems automatic.
10. I lose track of where I am.
11. I play without thinking about how to play.
12. Playing makes me feel calm.
13. I really get into the game.
14. I feel like I just can't stop playing.

B.3.4 System Usability Questionnaire

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.

5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.