# Hand Tracking with Vibrotactile Feedback Enhanced Presence, Engagement, Usability, and Performance in a Virtual Reality Rhythm Game

Hye Sung Moon[a], Grady Orr[b], and Myounghoon Jeon[c]

[a]Virginia Tech, USA [b]Virginia Tech, USA [c]Virginia Tech, USA

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**ABSTRACT**
Recent hand tracking systems and wearable haptic devices have contributed to enhancing user experience in virtual environments (VE). However, controllers are still prevalent in VR games as a main interaction device. Also, haptic devices are rare and not widely accepted by users. In this paper, we examined the effects of interaction methods and vibrotactile feedback on users' sense of presence, engagement, usability, and task performance in a VR game. In our experiment, 36 participants wearing VR goggle played a rhythm game under three conditions: (1) VR controllers, (2) hand tracking without vibrotactile feedback, and (3) hand tracking with vibrotactile feedback at fingertips through the gloves we developed. Results showed that hand tracking improved presence, engagement, usability, and performance, compared to the VR controller. Further, vibrotactile feedback enhanced presence and engagement even more clearly. Results are discussed with the components of VR user experience and practical design guidelines.

**KEYWORDS**
Virtual reality; game; hand tracking; vibrotactile feedback; presence; engagement;

## 1. Introduction

Providing an immersive experience to the virtual reality (VR) user 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 user experience (Cummings & Bailenson, 2016). 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 (Robles-De-La-Torre, 2006). Without haptic feedback in real life, it is impossible to do any ordinary tasks we take for granted. In this sense, numerous studies investigated the effects of haptic feedback on user experiences in the VE (Bennett & Stevens, 2005; Cooper et al., 2018; Fröhlich & Wachsmuth, 2013; Fröhner, Salvietti, Beckerle, & Prattichizzo, 2018; Gonçalves, Melo, Vasconcelos-Raposo, & Bessa, 2019; Jadhav, Kannanda, Kang,

CONTACT Hye Sung Moon. Email: mhss5458@vt.edu
CONTACT Grady Orr. Email: gradyorr@vt.edu
CONTACT Myounghoon Jeon. Email: myounghoonjeon@vt.edu

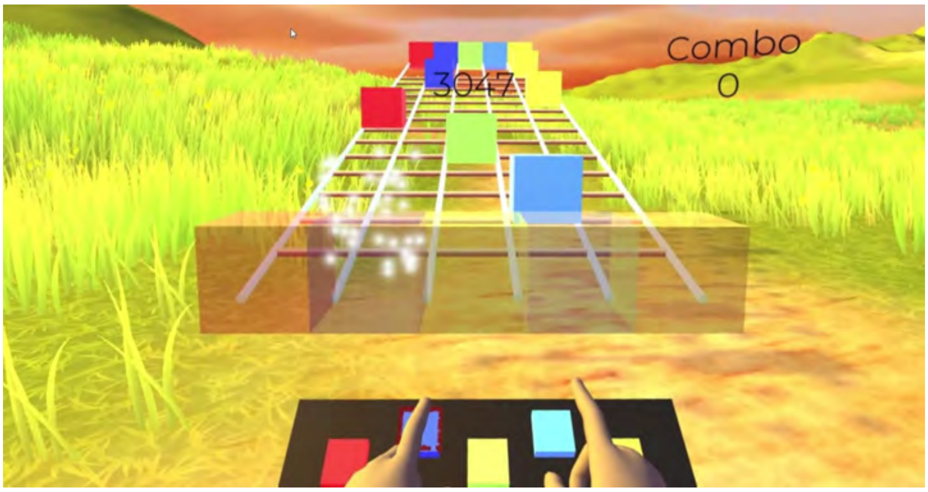



**Figure 1.** Playing a VR rhythm game with virtually rendered hands.

Tolley, & Schulze, 2017; Kim, Jeon, & Kim, 2017; Kreimeier et al., 2019; Kruijff et al., 2016; Maereg, Nagar, Reid, & Secco, 2017; Oskouie & Boulanger, 2019; Ranasinghe et al., 2018; Salazar, Pacchierotti, de Tinguy, Maciel, & Marchal, 2020; Sallnäs, 2010). In spite of numerous research works, it is still rare to find 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. HaptX (HaptX, 2021) is an one of the example device that provides realistic and delicate haptic feedback with pneumatics, but the size of the device causes them to be extremely bulky to wear, and the user needs to carry a backpack all the time. Dexmo gloves (Dexmo, 2022) are another example that provides the force feedback with the servo motors. Their design is comparatively less cumbersome to wear than existing VR haptic devices on the market. However, the users still need to put all 10 fingers into the rings and adjust the straps based on their hand sizes. In addition, to provide force feedback, Dexmo gloves consisted of batteries and motors. As a result, each Dexmo glove has a weight of around 300g. It is almost three times heavier than the Oculus Quest 2 controller which has a weight of 100g. This may cause fatigue for long usage.

In addition to haptic feedback, interaction methods are another aspect that impacts on user experience in the VE (Hrimech, Alem, & Merienne, 2011). Currently, controllers are the primary interaction method in most VR applications, by indirectly manipulating virtually rendered hands in VR with buttons or triggers. For instance, an index finger is bent by interacting with the trigger, and thumb movements 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 VR applications. An example of this is Oculus Quest 2 hand tracking, or the Leap Motion Controller. 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, hand tracking-based interaction provides a natural and intuitive experience, consistency with real world interactions, and freedom from burdensome hardware (Wachs, Kölsch, Stern, & Edan, 2011), resulting in a more immersive user experience. Slater et al. also discussed how interaction mappings influenced a system's fidelity (Slater, Usoh, & Steed, 1995) which can affect users' subjective judgements.

In this paper, we aimed to explore the effects of interaction methods and vibrotactile feedback on the user's experience in a VR game. We 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. We designed the VE for participants to play a rhythm game with three different songs (Fig. 1.). The objective of the game is to obtain the highest score by hitting the buttons as accurately as possible with the music. We also developed a device that delivers vibrotactile feedback at the user's fingertips while hands are tracked by a built-in camera on a VR headset. We made several attempts to improve the user's comfort of wearing to overcome the problems of existing wearable haptic devices we identified previously. First, we implemented vibrotactile feedback only at the fingertips to minimize the size of hardware but to provide enough haptic sensation for our experimental task. In addition, we used thin and soft fabric to provide an ability to move a participant's hands smoothly. Last, we used small and lightweight electronics to make our device comfortable to wear and use.

The main research questions of this paper are:

(1) How do different interaction methods (controllers and hand tracking) in a VR game influence user experience and task performance?
(2) How does adding vibrotactile feedback in hand tracking influence user experience and task performance in a VR game?

## 2. Related Works

### *2.1. Haptics in VR*

Current VR devices are massively 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 a VE. In (Ranasinghe et al., 2018), the authors investigated the effect of multiple sensory stimuli by adding the haptic stimuli (thermal and wind) and olfactory sensation on traditional visual-audio VR hardware. They found that adding the haptic stimuli increased the sense of presence. A study (Gonçalves et al., 2019) 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. Wang et al. (Wang et al., 2020) compared two interfaces, mid-air free drawing and tangible physical drawing in remote collaboration between local worker and expert helper. The results showed tangible physical drawing improved the remote experts' user experience in VR. Another study (Cooper et al., 2018) examined the effect of substitute multisensory feedback on task performance and sense of presence in VR. The study showed that there were significant main effects from use of tactile feedback on task performance and participants' subjective ratings. In (Sallnäs, 2010), the authors presented the experiments where passing objects between two participants in a virtual environment with and without haptic feedback. The result indicated that haptic feedback increased perceived virtual presence, social presence, and perceived performance.

### *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. Haptic glove, Data glove, or VR glove is a form of apparatus that delivers haptic feedback to the user. Many researchers implemented and investigated glove type devices. In (Bouzit, Burdea, Popescu, & Boian, 2002), researchers developed the force feedback glove to provide a better user experience with haptic feedback. A study (Kreimeier et al., 2019) inspected the different types of haptic feedback influencing the task-based presence and performance in VR. Results demonstrated that vibrotactile haptic feedback outperformed force feedback and non-haptic feedback conditions. In (Kuusisto, Ellman, Reunamo, & Kuosa, 2009; Ryu et al., 2008), the researchers designed the pneumatic force feedback glove to provide the haptic sensation. These gloves provide the haptic feedback as well as track the hands movement for gesture interactions in VR. In (Deller, Ebert, Bender, & Hagen, 2006; Jin et al., 2011), researchers developed the data gloves that read the hands and fingers movement in six degrees of freedom which enabled gesture-based interactions in a VE. Also, different types of wearable hardware have been developed to provide the haptic feedback. 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 and high price. However, with advances in computer vision and VR/AR hardware technology, it is becoming more prevalent to use hand tracking in VR games and applications using devices such as Oculus Quest 2.

### *2.3. Hand Tracking*

In this sense, many researchers have investigated the effect of hand tracking-based interaction or the influence of different interaction methods on user experiences under the VE. In (Almeida et al., 2019), the authors developed the cyber-glove that tracks hands and finger movements. They examined how the different interaction methods in the VE affect the sense of presence and performance in door opening tasks. Participants felt more presence and had better performance with the cyber-glove. However, this study was seeking the impact of interaction methods without haptic feedback. A study (Voigt-Antons, Kojic, Ali, & Möller, 2020) investigated the effect of interaction methods on user experiences. 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 our study, but they did not explore the effect of vibrotactile feedback and did not provide objective performance results. In (Oskouie & Boulanger, 2019), the authors 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 where passive haptic was collectively said to be a feeling by holding or touching a physical object linked to the VR system (Sherman & Craig, 2003). However, their focus was passive haptic feedback which is different from our experimental setup that focuses on vibrotactile feedback. Additionally, they did not examine presence, engagement or other subjective evaluations. In (Maereg et al., 2017), researchers 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 experiences during the experiment. In (Kim et al., 2017), the authors 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 ours, but they did not compare controllers and hand tracking-based interaction. Furthermore, they did not measure any objective performance metrics.

### *2.4. Unique Contributions*

Our work differs from existing works in several aspects. First, our study systematically compared both subjective user evaluations and objective task performance under different interaction methods (controllers and hand tracking). Additionally, we investigated the effects of vibrotactile feedback with hand tracking. In our best understanding, there is no existing study comparing subjective and objective evaluations under all three conditions (controllers, hand tracking, hand tracking with vibrotactile feedback). Further, our study was conducted within a VR game environment. Unlike other task-oriented experiments, our experimental task focuses on playing a rhythm game in the VE, which allowed us to gather user experience associated with the game.

## 3. Method

### *3.1. 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 VT Institutional Review Board (IRB)(21-194). All participants gave written consent before the beginning of the study.

### *3.2. Experiment Setup*

For the study, Oculus Quest 2 HMD was used to place participants within a VE. Vibrotactile gloves, we 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 weight of the glove was 40g. The vibration motors run in 3V DC, 85mA at 12000 rpm. Motors were controlled by the Teensy 3.2 microcontroller and Arduino Mega (Fig. 2b.) via three nRF24L01 modules which allow wireless communication (Fig. 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. 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) Glove palm side. (b) Base station. (c) Electronics on the gloves.

**Figure 2.** Vibrotactile feedback gloves and peripheral electronics for wireless communication.

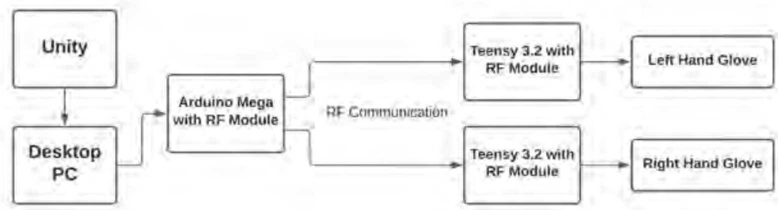



**Figure 3.** Hardware setup diagram.

Experimental environment was developed using Unity version 2021.1 (Fig. 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. Participant had to hit the same colored button when the cubes passed over a set of transparent cubes at the bottom.

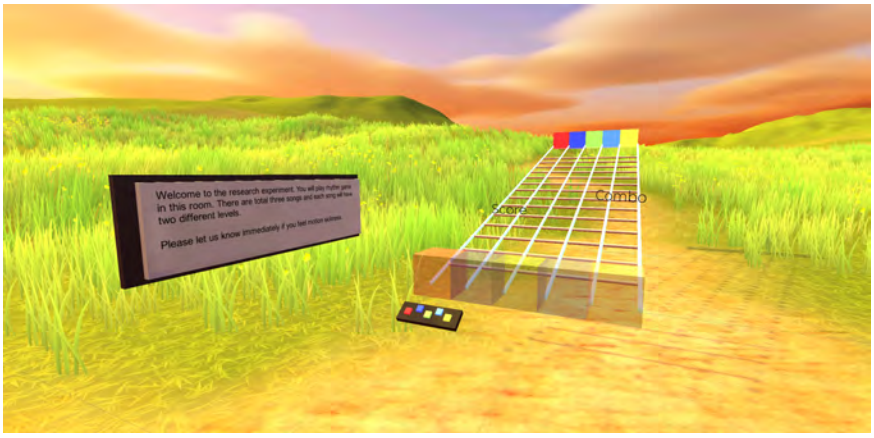



**Figure 4.** Virtual environment implemented with Unity game engine.

### *3.3. Experiment Design*

- `Controllers`: participants used the Oculus Quest 2 controllers to play a VR rhythm game. No vibrotactile feedback was provided in this condition (Fig. 5a.).

(a) Controller condition. (b) Hand condition. (c) Glove condition.

**Figure 5.** Three different conditions for the experimental task.

- `Hand Tracking (Hands)`: participants used the Oculus Quest 2 hand tracking system with no additional hardware to play a VR rhythm game. No vibrotactile feedback was provided in this condition (Fig. 5b.).
- `Hand Tracking with Vibrotactile Feedback (Gloves)`: participants used the Oculus Quest 2 hand tracking system with the vibrotactile feedback gloves to play a VR rhythm game. Vibrotactile feedback was delivered to participants' fingertips (Fig. 5c.).

We 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. We chose songs that have the same Beats Per Minute (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 1.

**Table 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 |

### *3.4. Task*

The task of this experiment was playing a rhythm game in the VE. The gameplay required the participant 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 participant must hit the corresponding buttons. The participant was given a score which was calculated based on the accuracy of hitting buttons. A higher score was attained when the participant successfully hit the buttons in time with the music.

### *3.5. Measure*

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

#### *3.5.1. Presence*

Presence and engagement are the most popular factors to evaluate a game (Martey et al., 2014). Slater et al. defined presence as "a sense of being there" and defined immersion as "something that can be objectively assessed" (Slater, 2003). The authors further discussed that "presence is a human reaction to immersion". In our work, we are focusing on the term "presence" since our work focuses on the user's subjective experience (human reaction) from our experimental setup (immersion).

To measure the levels of presence, we administered a modified Witmer Presence Questionnaire (PQ) (Witmer, Jerome, & Singer, 2005; Witmer & Singer, 1998). Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. 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?

#### *3.5.2. Engagement*

The definition of engagement has been characterized in many aspects including immersion, presence, flow (Csikszentmihalhi, 2020), effort (Dow, Mehta, Harmon, MacIntyre, & Mateas, 2007), and enjoyment (Mayes & Cotton, 2001).

Similarly, to evaluate engagement, we adopted a modified Game Engagement Questionnaire (GEQ) (Brockmyer et al., 2009). Responses were collected using the seven-point Likert scales. Questionnaires were presented after each condition. 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.

#### *3.5.3. Usability*

To measure usability, we used the System Usability Scale (SUS) (Brooke, 1996, 2013). 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.

#### *3.5.4. Performance*

We measured two objective task performance metrics: accuracy and deviation. Accuracy was measured in a binary sense, counted as a hit or a miss. Then, we 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 participant. Therefore, this deviation indicates how well the participant hit the buttons at the right time.

### *3.6. Procedure*

When 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 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 participant completed the pre-motion sickness questionnaire to create a baseline for subjective measures. We adapted and modified MSAQ as described by Brooks et al. (Brooks et al., 2010). Responses were collected on a 0 to 10 scale. After completing the pre-motion sickness questionnaire, The participants were wearing HMD and placed in the VE to get familiar with the environment. The participants were instructed how to interact in VE with Oculus Quest 2 controllers and hand tracking. After completing the instruction, the participants were given the post-motion sickness questionnaire. If any of the items had differences more than 6, we considered them not eligible for this experiment. The pre and post motion sickness questionnaire items are listed as follows:

(1) I feel sick to my stomach.
(2) I feel faint-like.
(3) I feel annoyed/irritated.
(4) I feel sweaty.
(5) I feel queasy.
(6) I feel lightheaded.
(7) I feel drowsy.
(8) I feel clammy/ cold sweat.
(9) I feel disoriented.
(10) I feel tired/fatigued.
(11) I feel nauseated.
(12) I feel hot/warm.
(13) I feel like I am spinning.
(14) I feel as if I might vomit
(15) I feel uneasy.
(16) I feel floating.

The participant 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 participant was instructed to remove the HMD and complete the SUS questionnaire. SUS questionnaire was given only at the tutorial to avoid the bias from different order of the songs. Once completed, the participant was 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 participant completed all songs, Unity was programmed to collect accuracy and deviation data for further analysis. After the six trials, the participant removed the HMD and completed the PQ and GEQ for the associated condition. After completing the survey, the participant put on the equipment for the next condition, for which the order was predetermined to be counterbalanced, and the participant restarted the procedure by playing the tutorial song again. The order of the songs and conditions were counterbalanced in all possible combinations so that every participant played in different order to avoid the learning effect. After all the conditions were completed, the participant filled out a subjective feedback questionnaire which allowed us to collect comments regarding the participant's experience with the songs or equipment within the study. The participant was compensated with $10 and the study concluded. The study took around 60 minutes.

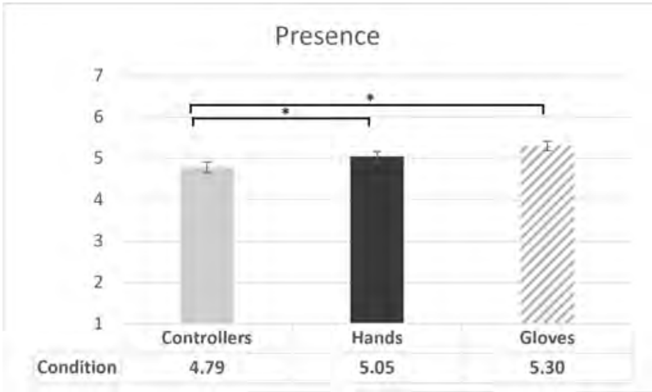



**Figure 6.** Average of all PQ questionnaires across the conditions. Error bars indicate standard error of the mean. *$p$ < .0167.

## 4. Results

### 4.1. Presence

For presence, we averaged all questionnaire items and performed a one-way repeated measures analysis of variance (ANOVA), using three conditions as our independent variables and the mean score of the presence questionnaire as our 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?), we 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, we 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 we 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, $p < 0.0167$].

### 4.2. Engagement

For engagement, we 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, $p < 0.0167$].

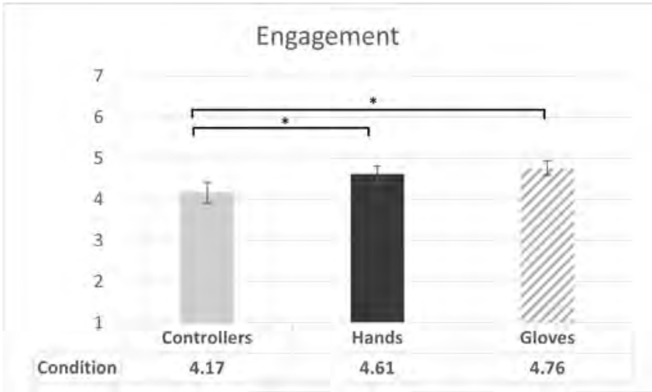



**Figure 7.** Average of all GEQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

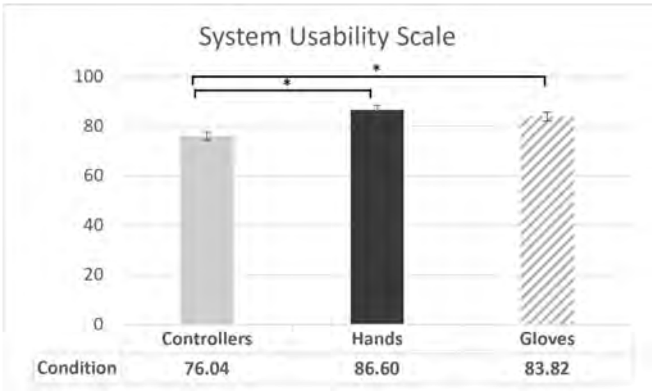


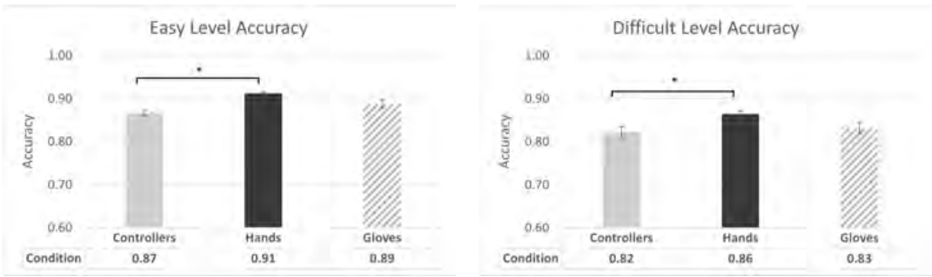

**Figure 8.** Average of all SUS questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

### *4.3. Usability*

We evaluated usability using the SUS questionnaire (Brooke, 1996). To analyze the data, we used a one-way repeated measures ANOVA, using three conditions as our independent variables and SUS score as a dependent variable. We 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].

### *4.4. Performance*

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



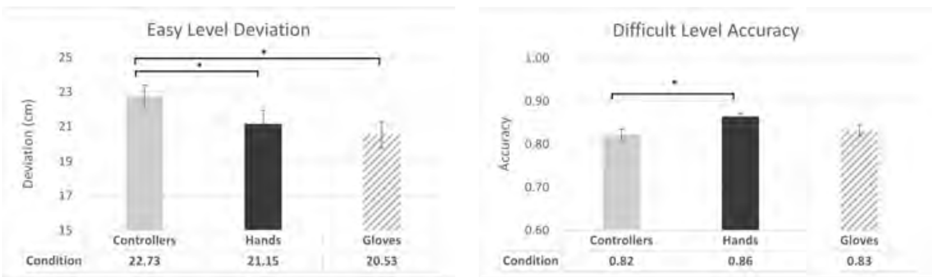

(a) Easy level accuracy. (b) Difficult level accuracy.

**Figure 9.** Average of all cubes' accuracy across the conditions. Error bars indicate standard error of the mean. *$p < .0167$.

### 4.4.1. Accuracy

We 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 [$t(35) = -2.72$, $p < 0.0167$]. We did not observe any significant interaction effect [$F(2, 210) = 0.06$, $p = 0.94$].

### 4.4.2. Deviation




(a) Easy level deviation. (b) Difficult level deviation.

**Figure 10.** Average of all cubes' deviation across the conditions. Error bars indicate standard error of the mean. *$p < .0167$.

Similarly, we 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 ($M = 20.16$, $SD = 4.00$) 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 [$F(2, 210) = 0.223$, $p = 0.89$].

## 5. Discussion

To investigate the effects of interaction methods and vibrotactile feedback on user experiences in a VR game, we compared results including subjective metrics, task performance and feedback from the participants. We observed that hand tracking and vibrotactile feedback enhanced the subjective judgements as well as task performance.

### 5.1. Presence

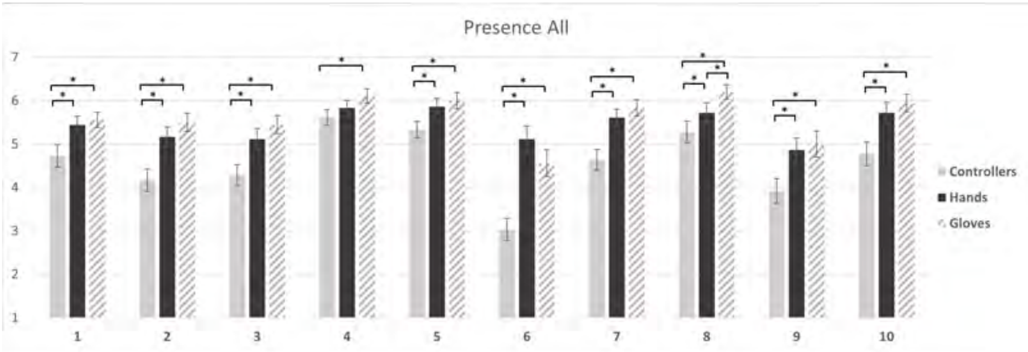



**Figure 11.** Average of individual PQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$.

A lesson we took from our experiment is that participants felt more presence when they were using hand tracking in a VR game than using controllers. 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 participants felt more natural, intuitive experiences as well as felt consistent with the real world on hand manipulation. Furthermore, controllers cannot implement accurate hand movements. With the controllers, fingers are bending only in one-dimensional axes corresponding to the triggers, and each joint's movements are limited by system default values. This concurs with the hypothesis that realistically rendered hands lead to high levels of presence (Bowman, McMahan, & Ragan, 2012; Schwind, Knierim, Chuang, & Henze, 2017). Additionally, given the fact that task's focus was on the hand interaction method, our observation supports the previous finding that the sense of presence was influenced by interaction mechanisms (Cummings & Bailenson, 2016).

Another observation we made was, 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. We also observed from 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 our interest, we 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 participants felt significantly more involved in gloves condition than controllers condition while there was no significant difference between hands and controllers conditions. It may be inferred that vibrotactile feedback increased the user's sense of presence. We 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.

### *5.2. Engagement*

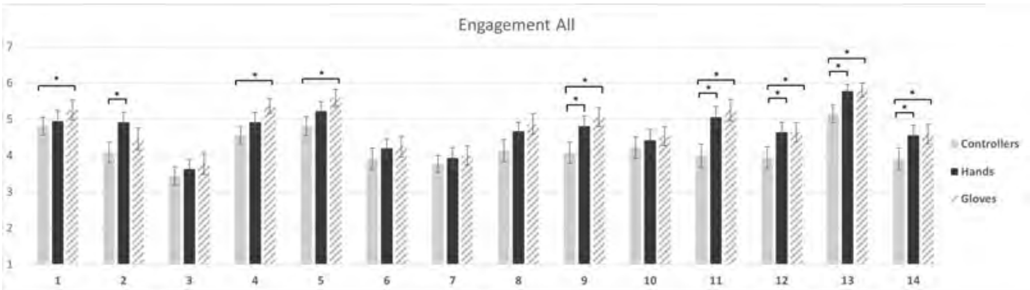



**Figure 12.** Average of individual GEQ questionnaires across the conditions. Error bars indicate standard error of the mean. $*p < .0167$

We discovered that hand tracking significantly engaged 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 participants were more engaged in a VR game with hand tracking. When we scrutinized the individual items in modified GEQ 9 (Playing seems automatic) and GEQ 11 (I play without thinking about how to play), participants responded that hand tracking is more realistic, automated, and easy to use. According to (McMahan, Lai, & Pal, 2016), higher interaction fidelity is derived from the exact capture and measure of the user's action as well as consistency of body movements and interactions between real and virtual worlds. In our case, hand tracking had higher interaction fidelity than controllers. Our finding can further support the existing study that high interaction fidelity increases the engagement in the VE (Rogers, Funke, Frommel, Stamm, & Weber, 2019). Further, our result is consistent with previous studies (McMahan, Bowman, Zielinski, & Brady, 2012) that higher interaction fidelity and natural interaction (Bowman et al., 2012; Martey et al., 2014) increased the sense of engagement and presence in the VE.

In addition, our 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 (Brockmyer et al., 2009) demonstrated our 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 (Moneta & Csikszentmihalyi, 1996, 1999). Csikszentmihalyi's research (Csikszentmihalyi & Csikzentmihaly, 1990) identified eight major components of flow including direct and immediate feedback, sense of control, and effortless concentration on the task. In our study, hand tracking has higher levels in listed components than controllers due to hand tracking's natural, intuitive, and effortless interactions. The combination of following elements results in higher levels of flow experience and enjoyment (Chen, 2007; Sweetser & Wyeth, 2005).

Individual GEQ questionnaires showed that the vibrotactile feedback increased the levels of engagement more clearly. 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. 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), we 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.

### *5.3. 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 (Bangor, Kortum, & Miller, 2009). Although all three conditions are above the average, hands and glove conditions are significantly more usable than controllers in our experiment. However, there was no significant difference between hands and gloves conditions.

### *5.4. Performance*

We found that hand tracking showed higher accuracy than controllers among both difficulty levels. Our result is consistent with the case studies (McMahan et al., 2016) that task performance increases as interaction fidelity increases from moderate (controllers) to high (hand tracking) levels. We 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. We may assume that hand tracking significantly improved the accuracy and assisted to hit the buttons at the right time in a VR game. Lastly, we saw that there was no significant statistical difference between hands and gloves conditions which tells us that both conditions have similar performance.

## 6. Limitations

In spite of our attempts to minimize the size of gloves and increase the comfort of wearing, we 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 hand movements uncomfortable. Furthermore, due to safety regarding the COVID pandemic, we instructed participants to wear additional plastic gloves underneath the vibrotactile gloves. We assumed that uncomfortable experience could possibly neutralize the significance between hands and gloves conditions in terms of task performance. Nevertheless, we found that delivering the vibrotactile feedback enhanced individual ratings in questionnaires.

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 our approach was legitimate.

## 7. Conclusion and Future Work

In this paper, we explored the effects of interaction methods and vibrotactile feedback on the user's sense of presence, engagement, usability, and performance in a VR game. We developed usable vibrotactile gloves to deliver the vibrotactile feedback to the participants. Based on the results, we outlined four inferences from our 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.

Our findings provided the benefits of hand tracking and vibrotactile feedback in a VR game. We plan to conduct further research to supplement the limitations we found during the experiment. We will implement more comfortable and convenient hardware to collect reliable and unbiased results by developing a lighter version of the haptic device. This will be a ring shape or a lighter version of the gloves. Moreover, we will clearly identify the impact of interaction method, haptic feedback, and multi-modality in a VR game. In our experiment, tasks were intended for participants to hit multiple buttons in a stationary position. In the future studies, we will construct a creative and interactive game where participants can more dynamically interact in the VE. We will also diversify the haptic sensation. Vibrotactile feedback in our experiment was monotonously delivered when participants hit the buttons. In the future work, we will implement varied vibration feedback for different situations (e.g., right or wrong responses). Lastly, we 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 a VR game.

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## Authors

**Hye Sung Moon** is a Master student in the Department of Computer Science at Virginia Tech. He completed his undergraduate studies in Electrical Engineering at Iowa State University in 2019. His research interests include VR/AR, Human-Computer Interaction, and Haptics.

**Grady Orr** is an undergraduate student in the Department of Computer Science at Virginia Tech. His interests include Haptics, Social Interaction in Virtual Spaces, and Telepresence.

**Myounghoon Jeon** is an Associate Professor in Industrial and Systems Engineering at Virginia Tech. He received his PhD from Georgia Tech in 2012. His Mind Music Machine Lab conducts research on HCI with a focus on emotion and sound in the application areas of automotive user interfaces, assistive robotics, and arts in XR environments