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The Effects of Whole-Hand Interactions with One Fingertip Vibrotactile Feedback on Cooperative VR Game Experience and Performance

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Abstract

New technologies have recently advanced user experiences in virtual reality, whereas full sensation of diverse modalities has been not achieved yet. If any, haptic feedback has been delivered via bulky gloves. We have developed a novel thimble device that can deliver vibrotactile feedback via one fingertip. With this device, in the present study we investigated the effects of interaction methods and vibrotactile feedback on users' social presence, presence, engagement, workload and performance in a cooperative VR game. Twenty-six participants wearing VR headset played a cooperative VR game with the experimenter under four conditions: (1) controllers with no vibrotactile feedback, (2) controllers with vibrotactile feedback, (3) hand tracking with no vibrotactile feedback, and (4) hand tracking with vibrotactile feedback. Results showed that hand tracking improved participants' presence, engagement, and perceived workload compared to the traditional VR controllers. Also, vibrotactile feedback enhanced presence. However, the VR controllers outperformed the hand tracking interactions in completion time. The usability of hand interactions with vibrotactile feedback shows a promising result. We discussed the trade-offs between user experience and performance of the interaction methods and the potential of vibrotactile feedback in the VR environment.

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1. Introduction

Virtual Reality (VR) is a novel and exciting way to experience diverse realities. The immersive environments created by VR technology stimulate users' senses and provide opportunities to interact with virtual objects and characters. The growth of VR industry is propelled by the increasing adoption of advanced VR hardware and accessories among gamers, the proliferation of innovative software and content, and advancements in 5G technology, cloud-based gaming, and extended reality applications. VR users and gamers demand more realistic sensations and superior user experiences in VR applications and games. As technology progresses, VR hardware with improved display resolution, higher refresh rate, and superior sound quality is becoming increasingly available to users (Almeida et al., 2019). In addition, hand tracking and haptic technologies are crucial for enhancing the user experience in VR, as they complement the fast-evolving visual and auditory sensors (Cummings & Bailenson, 2016).

Social VR is a novel form of online social network that facilitates interactive communication between multiple users in virtual environments (VE) through the use of head-mounted displays (HMDs) (McVeigh-Schultz, Kolesnichenko, & Isbister, 2019). Social VR also enables users to engage in a wide range of shared activities, such as watching movies, playing games, attending concerts, and collaborating at work. Platforms such as VRChat, RecRoom, Microsoft AltSpace, and Meta Horizon Worlds offer users the opportunity to form online social connections, explore virtual environments, experiment with self-representation (Freeman, Zamanifard, Maloney, & Adkins, 2020), and have fun with immersive games (Maloney, Freeman, & Robb, 2020). Social VR platforms provide more immersive experiences and diverse interaction methods than traditional social applications (Wang, 2020). For instance, in a typical online concert setting, audiences are confined to viewing the performance on a flat screen. Conversely, social VR offers users a three-dimensional virtual space, creating an experience akin to being physically at the event. The heightened sense of presence also influences interactions with other audience members. Literature indicates that non-verbal communication, encompassing gestures and touch, constitutes a substantial portion (60-70%) of human communication (Mehrabian, 2017). Utilizing hand tracking along with virtual avatars, as well as tactile sensation may significantly enhance the communication experience within social VR applications.

The current state of social virtual reality (VR) applications has left much to be desired, particularly with regard to the sensation of touch. While haptic feedback significantly enhances the user experience, it introduces challenges related to bulkiness and cost,

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particularly to be delivered during a whole-hand tracking mode. The physical dimensions of vibrotactile devices can create a sense of encumbrance, potentially hindering user comfort and immersion in virtual reality (VR) interactions. Additionally, the effectiveness of a whole-hand interaction method is contingent on the quality of hand tracking technology. While it enables a more natural interaction with bare hands, relying on hand tracking for whole-hand interactions may be less reliable than using traditional controllers with buttons and triggers for controlling hand gestures. These considerations underscore the importance of carefully weighing the benefits of enhanced user experience against potential drawbacks related to task performance. In the present study, we aimed to explore the effects of interaction methods and vibrotactile feedback on user experience and task performance in a cooperative VR game. To this end, the following research questions were investigated:

(1) How do whole-hand interactions using hand tracking influence user experience and performance in a cooperative VR game compared to controller-based interactions?
(2) How does vibrotactile feedback given to a single fingertip influence user experience and performance in a cooperative VR game compared to no vibrotactile feedback?

2. Related Work

2.1. Haptic Feedback in VR

Researchers have studied human sensory modalities to develop technologies that enhance immersiveness in virtual reality environments. In addition to visual and auditory effects, haptic feedback is increasingly being recognized as a method to significantly improve the sense of immersion in VR by providing meaningful tactile sensations. For example, M. Lee, Bruder, and Welch (2017) investigated the impact of haptic feedback on perceived social presence in a virtual environment. Here, the feedback was delivered as a vibration on the floor in relation to another person's walking movement, which enhanced social presence during the experience. Also, Sallnäs (2010) studied the effects of haptic feedback when performing a collaborative task of passing objects. The haptic feedback depicted object material, collision between objects, and the force on the object played by another user. Using a desk-mounted force feedback system, the haptic feedback successfully improved virtual presence, social presence, and performance.

The entertainment industry has a well-established record of creating wearable haptic devices to improve user experience. In the context of VR gaming, researchers have explored various approaches to enhance user experience, such as modifying the design of controllers or inventing new methods for interacting with the virtual world. For instance, Kim, Jeon, and Kim (2017) developed an Arduino-based haptic device for the thumb and index fingertips that delivers haptic and heat feedback based on hand movements within a VR game environment. The haptic system was found to significantly increase the sense of presence in VR compared to no haptic feedback conditions. The findings of the studies demonstrate the potential for utilizing haptic feedback as a means to enhance user experience in a cooperative VR game.

2.2. Hand Tracking in VR

Over the years, researchers have explored various methods to track hand movements in the physical world to be emulated in the virtual one. Early studies and designs of hand tracking methods focused on physical tracking, often integrated with haptic feedback systems. However, early iterations of commercial glove-type devices such as the PHANToM, CyberGrasp, and CyberTouch faced the common drawbacks for their bulkiness and production costs (Burdea, 2000). Almeida et al. (2019) developed a cyber-glove system that tracks hand motions while only covering the back of the hand and leaving the palm open for direct contact with physical objects. This system enabled a greater degree of natural and realistic movement of the wrist and fingers, in contrast to controllers that exhibit a rigid integration between hand and wrist and that offer limited finger shapes. The system also enabled tracking of more complex hand movements such as rotating a door handle. With the cyber-glove system, participants performed the task faster and evaluated the system to be more natural and embodied than using controllers.

Other studies have devised optical-based systems utilizing technological developments that allow for greater freedom of movement with more accurate tracking of hand movements. For instance, Achibet, Marchal, Argelaguet, and Lécuyer (2014) developed a concept of the “virtual mitten” that utilizes a handheld elastic input device with an optical tracking system to enable realistic replication of grasping motions in VR, with passive haptic feedback provided by the device. While this concept has shown promise for certain types of hand gestures, it may not fully support natural movements involved in other types of object manipulation gestures. A whole-hand interaction method entails utilizing the entire hand to manipulate virtual objects. As an intuitive and natural way that is most similar to manipulating objects in real life, this interaction method has the potential to enhance the sense of presence and immersion in the virtual environment. Today, whole-hand interaction using hand tracking technology is

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becoming a commonly used interaction method. For example, Meta Quest 2 provides gesture-based interaction using built-in cameras on its head-mounted display. In a study that compared the interaction methods (Wu, Hsu, Lee, & Smith, 2017), participants showed better performance and gave higher scores for usability when using the whole-hand interaction method than using controllers for performing a typing task on a virtual keyboard. In our study, we investigated how these two interaction methods would affect performance and user experience in a cooperative VR game.

2.3. Cooperative VR Game

Cooperative VR games have gained increasing attention in recent years, as they offer unique opportunities for players to collaborate and communicate in immersive and interactive virtual environments. One important measure to evaluate the enjoyment of a cooperative VR game is the level of perceived social presence (Oh, Bailenson, & Welch, 2018). Social presence in VR refers to the sense of being together or being with another (Biocca, Harms, & Burgoon, 2003; De Greef & IJsselsteijn, 2000). It is also considered a multidimensional construct that encompasses co-presence, psychological involvement, and behavioral engagement (Biocca et al., 2003). While self-presence focuses on the extent to which users perceive themselves as present in the virtual environment, social presence centers on the presence of a co-present entity. Social presence is considered an essential element of social and cooperative VR environments, promoting interpersonal interaction and communication. Its absence could lead to the perception of the mediated entity as merely artificial rather than a social being (K. Lee, Jung, Kim, & Kim, 2006). Also, literature has shown that social relatedness, associated with feeling connected to others, can potentially increase game enjoyment (Ryan, Rigby, & Przybylski, 2006) as well as learner engagement (Furrer & Skinner, 2003). In the current study, we measured users' perceived level of both presence and social presence while performing a cooperative task that requires social interdependence, with a shared notice of common goals and actions between individuals which facilitates cooperation (Deutsch, 1962). Despite previous research in this domain, little research has systematically investigated the effects of interaction methods and vibrotactile feedback in a cooperative VR game. Our study successfully showed the trade-offs between user experience and performance of the interaction methods (i.e., whole-hand interaction and traditional controllers). Specifically, we have contributed to devising a novel thimble-shape one fingertip vibrotactile feedback device and tested it in this context. The result also bodes well for the use of small scale vibrotactile

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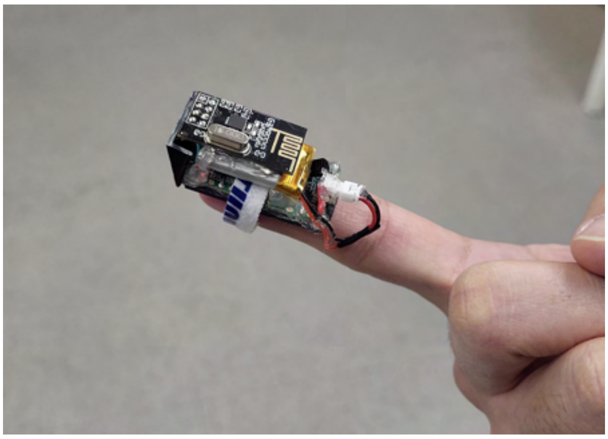

Figure 1.: Fingertip vibrotactile device.

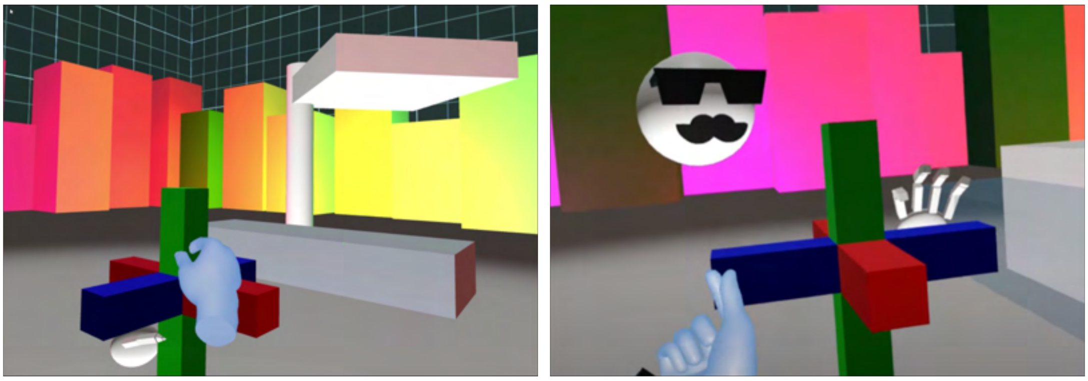

Figure 2.: Virtual environment implemented with Unity game engine.

feedback in a VR game.

3. Method

3.1. Participants

The study recruited a total of 26 participants (16 males, 10 females) with an average age of 23.16 years ($SD = 4.05$). Only right-handedness participants were recruited to collect unbiased data based on the task design. Approval for the study was given by the university's Institutional Review Board (IRB). All participants gave written consent before the beginning of the study.

3.2. Experiment Setup

The experiment utilized two Meta Quest 2 HMDs, one for the participant and one for the researcher. The game required hand gestures which participants either used a Meta Quest 2 Controller or its hand tracking system. To deliver vibrotactile feedback during a hand tracking

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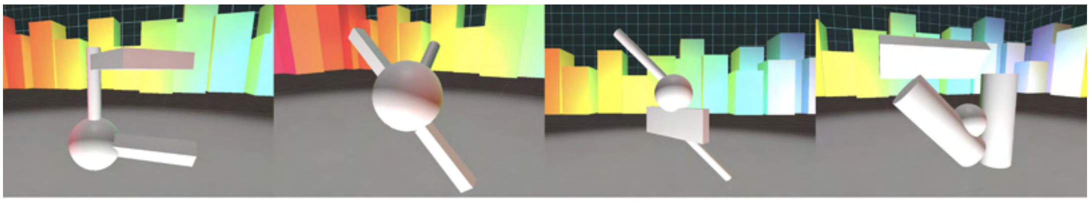
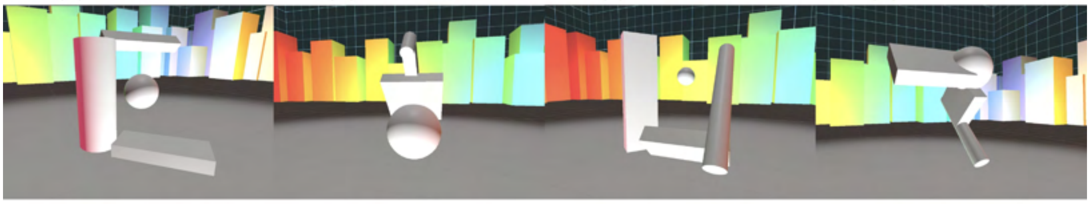


(a) Artifact 1. (b) Artifact 2. (c) Artifact 3. (d) Artifact 4.



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

Figure 3.: Eight different artifacts.

mode, we developed a thimble-shaped vibrotactile device (Figure 1) that can be easily attached to the player's index fingertip. The vibration motors run in 3V DC, 85 mA at 12000 rpm. Motors were controlled by the Teensy 3.2 microcontroller via nRF24L01 modules which allowed wireless communication. One module was installed on the PC as a base station, and the other was mounted on the prototype device.

3.3. Experiment Design

To investigate the effects of the interaction method and vibrotactile feedback, the cooperative VR game was played under four different conditions, which were experienced by every participant.

- Controllers with No Vibrotactile feedback (CNV): the participant used a Meta Quest 2 controller to play the game with no vibrotactile feedback provided.
- Controllers with Vibrotactile feedback (CV): the participant used a Meta Quest 2 controller to play the game with vibrotactile feedback provided through the controller.
- Hand tracking with No Vibrotactile feedback (HNV): the participant used a Meta Quest 2 hand tracking system to play the game with no vibrotactile feedback provided.
- Hand tracking with Vibrotactile feedback (HV): the participant used a Meta Quest 2 hand tracking system to play the game with vibrotactile feedback provided through the developed device (Figure 1).

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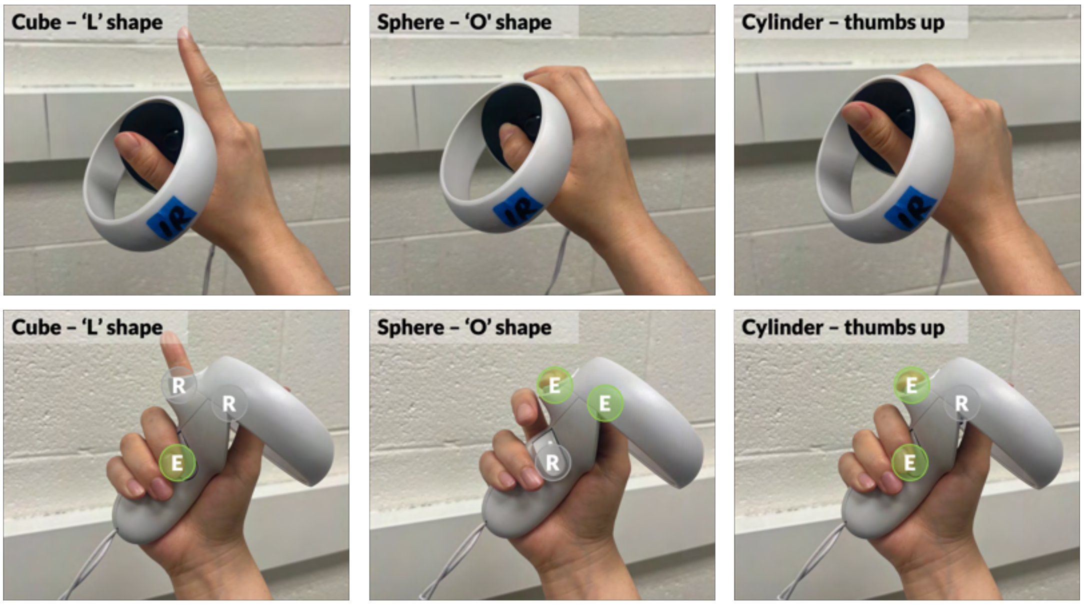

Figure 4.: Controller grip for hand gestures.'E' represents an engaged button and 'R' represents a released button.

3.4. Task

The tasks provided in the VR game required two players to create a sculpture cooperatively: the participant and the researcher. Throughout the game, each player exclusively employed a single hand. The participant used the right hand, represented in a realistic form, while the researcher used the left hand, represented in a mechanized form (Figure 2). This distinction in style facilitated participants in easily identifying their virtual version of the hand. The game was to manipulate and combine simple 3D objects, such as a cube, a sphere, and a cylinder, to create a final artifact (Figure 3). Each artifact consisted of four simple 3D objects, and each simple 3D object had four steps of manipulation in the order of creating, scaling, rotating, and positioning. These object manipulations required participants to make predefined gestures that required two hands, and two players had to cooperate to perform the task. For every step, a transparent guide object was given in the VE, so the players were aware of the object to create, the size to adjust, and the position to locate.

3.4.1. Object manipulation

The first step of object manipulation was creating an object (Figure 5). There were three possible simple 3D objects: a cube, a sphere, and a cylinder. To create a cube, each player made an 'L' hand shape and combined their hands together to make a square (Figure 5(a)). To create a sphere, each player made an 'O' shape together with an index finger and a thumb

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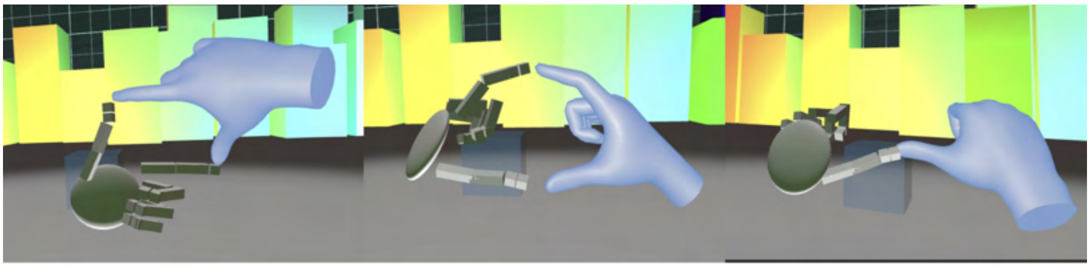
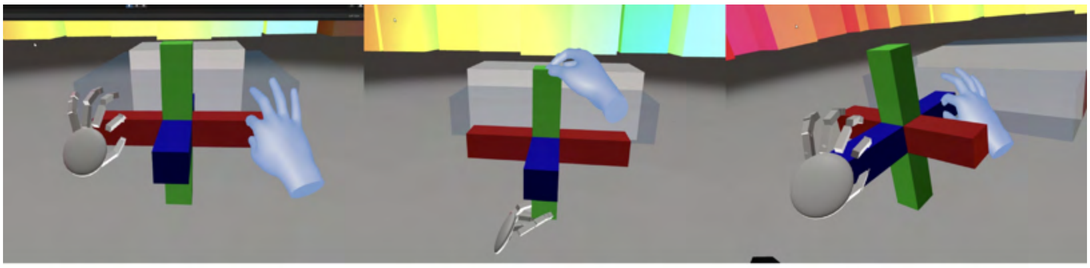


(a) Creating a cube. (b) Creating a sphere. (c) Creating a cylinder.

Figure 5.: Creating objects.



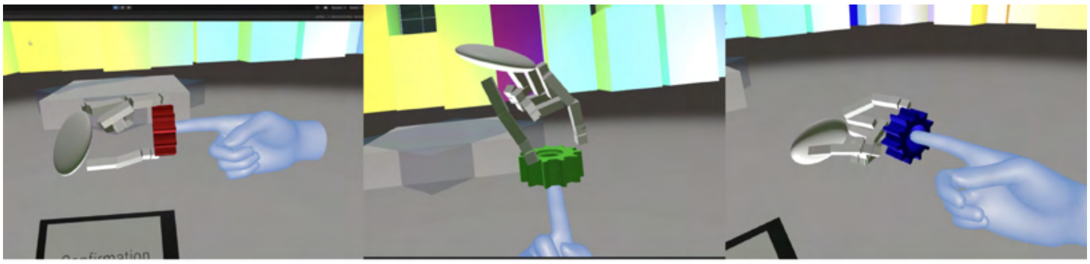
(a) Scaling in X-axis. (b) Scaling in Y-axis. (c) Scaling in Z-axis.

Figure 6.: Scaling objects.

(Figure 5(b)). To create a cylinder, each player put a thumb up and touched it with the partner's thumb (Figure 5(c)). Controller grips for each gesture were designed to be as similar as possible to barehand control (Figure 4). For example, the 'L' shape was made by releasing the thumb (B Button) and the index finger (trigger button), while gripping the controller with the rest of the fingers bent (grip button).

The second step was scaling an object (Figure 6). To scale an object, each player pinched the end of the axis that they intended to stretch or shrink the object; and then, moved away from the center of the axis while pinching to stretch the object, or moved closer to shrink the object. Players had to move together, either away from or closer to the center of the axis, to successfully scale the object. Players had to repeat the process for all three axes.

The third step was rotating an object (Figure 7). To rotate an object, one player's hand



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

Figure 7.: Rotating objects.

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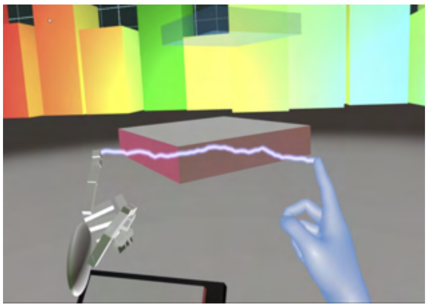

Figure 8.: Positioning objects.

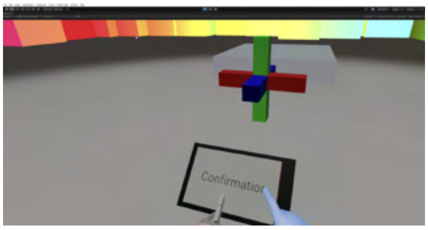

Figure 9.: Confirmation button.

became a knob, and the other player rotated the knob, which rotated the object in the same direction. During the study, participants were asked to position the knob based on the axis they intended to rotate the object. Once the participant positioned the knob, the researcher rotated it until it matched the target orientation. Rotation was only needed in one axis.

The last step was positioning an object (Figure 8). To position an object, players had to put their hands close together to initiate a light string between two index fingers. Once the light string appeared, the hand movement of the right hand player (the participant) determined the direction of the object. The position of the hand when the light string was initiated became the reference point, and the object moved toward the direction where the hand moved. The light string indicated that the positioning feature was enabled. If the players' hands were too far apart, the light string disappeared. Also, when the object approached within a distance of less than 10 cm to the target location, as indicated by the transparent guide, it snapped and aligned itself with the target location.

After each manipulation step, both players (participant and researcher) had to hit the confirmation button to proceed to the next step (Figure 9). If the object was not identical to the transparent guide, players could not proceed to the next step. Players had to create two final sculptures, repeating the above four-step procedure twice for each condition.

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3.4.2. Interaction method

Gesture recognition was categorized based on the touch of a thumb and an index finger. For example, to create a simple 3D object, the gestures were recognized when the fingers of each player touched together. It was the same for pinching in the scaling step, where the pinching gesture was recognized when a thumb and an index finger were contacted. The rules for gesture recognition were the same between the controller conditions and hand tracking conditions. However, for controller conditions, hand gestures were performed by using its buttons and triggers. For example, to make an 'L' shape, participants had 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 the 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 wall-height partition, so they were unable to see each other in the physical world.

3.4.3. Vibrotactile feedback

We provided two different vibration patterns based on the interaction during the gameplay. The first pattern was a monotonous vibration which was presented when one player touched another player's hand with the index finger. For instance, participants could feel the vibration when they were creating or rotating an object. The other pattern was provided when the light string was enabled during the positioning step. 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 identical in both controller and hand tracking conditions.

3.5. Measures

In this study, we measured the participant's perceived social presence, presence, game engagement, and workload after every condition. To measure the level of social presence, we utilized the social presence questionnaire (SPQ) (Harms & Biocca, 2004). We used the subsection of co-presence of the questionnaire set which was appropriate to this experiment setting. To measure the level of presence, we administered a modified Witmer Presence Questionnaire (PQ) (Witmer, Jerome, & Singer, 2005; Witmer & Singer, 1998). To evaluate engagement, we adopted a modified Game Engagement Questionnaire (GEQ) (Brockmyer et al., 2009). To measure workload, we employed the NASA-TLX (Hart & Staveland, 1988).

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Responses were collected using the seven-point Likert scale, and the questionnaire was presented after completing one condition. For the HV condition (hand tracking with vibrotactile feedback) only, we measured the usability of the fingertip vibrotactile device using the System Usability Scale (SUS) (Brooke, 2013; Brooke et al., 1996). To measure performance, we collected completion time for each step of creating an artifact.

3.6. Procedure

This study was conducted amidst the COVID-19 pandemic, and the following safety measures were implemented. Upon arrival outside the lab building, participants underwent temperature checks. Those without signs of fever were allowed into the lab. In the experiment space, participants completed a questionnaire addressing any COVID-19 symptoms, signed the IRB consent form and COVID addendum, and submitted demographic information. Following this, participants watched an instructional video on using Meta Quest 2 with its controllers and hand tracking feature to perform experiment tasks. Participants then completed a motion sickness questionnaire (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001) as a baseline. For the tutorial, participants wore the Quest 2 HMD and performed one of the experiment tasks, once with a controller and once with barehand. Subsequently, participants completed another motion sickness questionnaire. Those who reported no increase in feelings of tiredness, disorientation, or lightheadedness proceeded to the main experiment. In this phase, all participants played the game under four distinct conditions. Each condition had two trials, and each trial consisted of making one artifact. As participants completed the trials, Unity was programmed to collect the completion time for each step for further analysis. After each condition, participants removed the HMD and completed the questionnaire comprised of SPQ, PQ, GEQ, and NASA-TLX. 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, participants were compensated with $10 and the study concluded. The study took around 60 minutes.

4. Results

Tables 1 and 2 show the average and standard deviation of participants' perceived social presence, presence, engagement, workload, and completion time for each interaction method (controller versus whole-hand interaction) and the presence of vibrotactile feedback (no

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Table 1.: Average and standard deviation for each interaction method

	Controller	Whole-hand	F	p
Social Presence	6.57 (0.17)	6.65 (0.14)	0.34	0.561
Presence	5.08 (0.14)	5.76 (0.12)	18.37	<**0.001**
Engagement	4.36 (0.21)	4.74 (0.21)	10.74	**0.030**
Workload				
Mental Demand	45.67 (5.29)	34.52 (4.91)	19.36	<**0.001**
Physical Demand	42.40 (5.75)	36.06 (5.69)	9.98	**0.002**
Temporal Demand	33.94 (4.04)	27.89 (3.80)	5.36	**0.023**
Performance	27.98 (3.85)	21.73 (3.46)	7.48	**0.008**
Effort	46.83 (4.43)	32.50 (4.16)	20.17	<**0.001**
Frustration	26.44 (3.77)	19.52 (3.48)	11.68	**0.001**
Completion Time	138.49 (4.02)	147.36 (3.55)	7.02	**0.010**

Table 2.: Average and standard deviation for with and without vibrotactile feedback

	No haptic	Haptic	F	p
Social Presence	6.56 (0.18)	6.66 (0.13)	0.04	0.124
Presence	5.27 (0.12)	5.56 (0.12)	4.97	**0.035**
Engagement	4.52 (0.20)	4.58 (0.21)	0.68	0.418
Workload				
Mental Demand	41.44 (4.86)	38.75 (5.03)	1.71	0.195
Physical Demand	41.06 (5.84)	37.40 (5.33)	1.05	0.309
Temporal Demand	29.90 (3.53)	31.92 (4.08)	0.28	0.597
Performance	26.83 (3.77)	22.89 (3.45)	1.75	0.190
Effort	40.10 (3.59)	39.23 (3.89)	0.13	0.716
Frustration	24.52 (3.49)	21.44 (3.29)	2.28	0.136
Completion Time	141.95 (3.52)	143.89 (3.84)	0.31	0.582

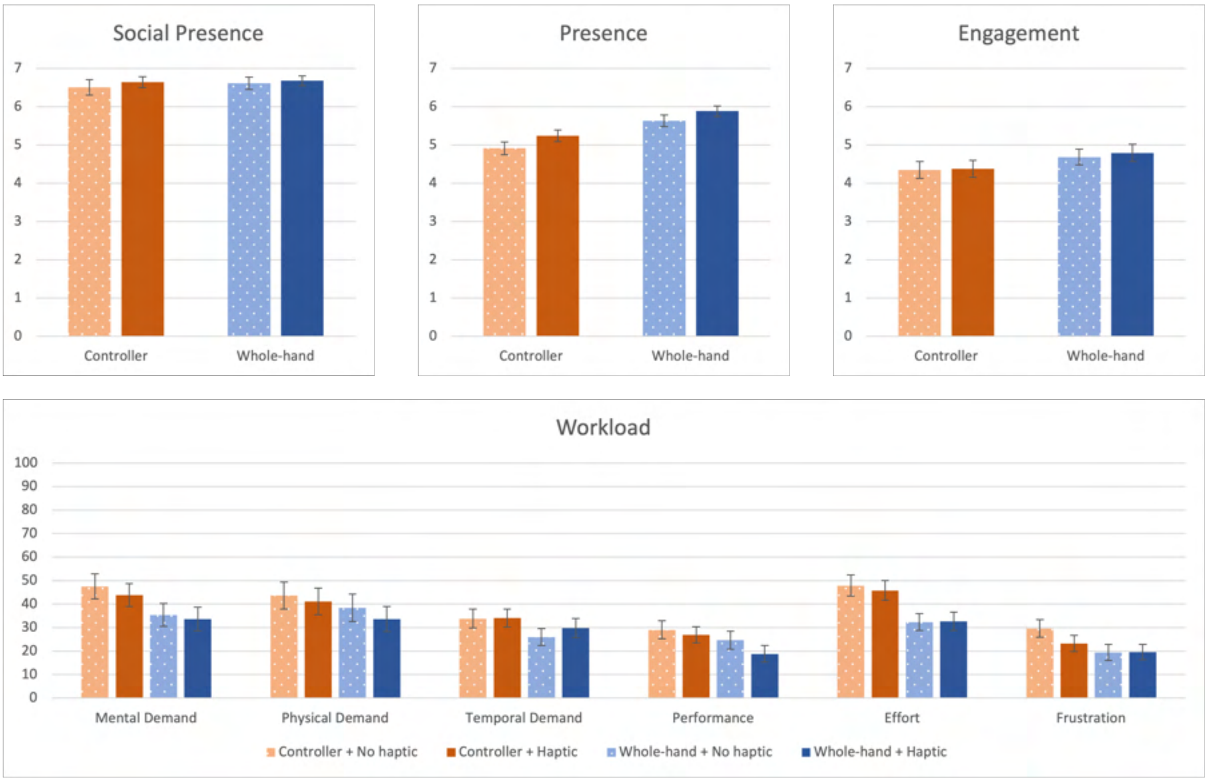

Figure 10.: Mean scores of social presence, presence, and engagement for each experiment condition.

feedback versus feedback). From Shapiro-Wilk tests, we identified normality violations from data on social presence, all six components of workload, and completion time, which we applied the nonparametric aligned rank transform (ART) process (Wobbrock, Findlater, Gergle, & Higgins, 2011). Then, we performed repeated measures ANOVA on all dependent measures. All data analyses were performed using SPSS and R.

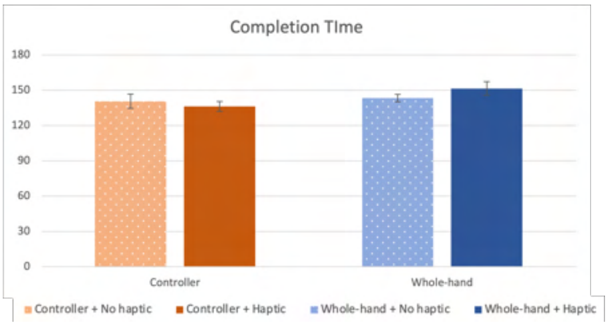

Figure 11.: Mean completion time for each experiment condition.

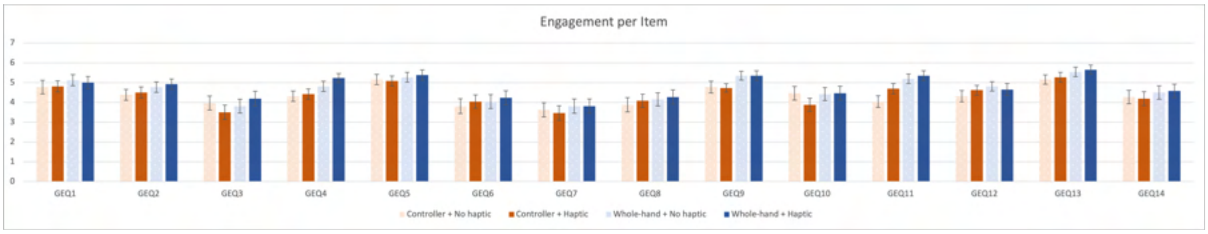

Figure 12.: Mean score of individual items of engagement for each experiment condition.

4.1. Social Presence

Based on participants' responses to SPQ, there was no significant difference observed in terms of interaction methods, $F(1, 75) = 0.34$; $p = 0.561$, and vibrotactile feedback, $F(1, 75) = 0.04$; $p = 0.124$. There was no significant difference in terms of interaction effect, $F(1, 75) = 0.05$; $p = 0.821$.

4.2. Presence

Based on participants' responses to PQ, there was a statistically significant difference in terms of interaction methods, $F(1, 92) = 18.37$; $p < 0.001$, and vibrotactile feedback, $F(1, 92) = 4.97$; $p = 0.035$. Whole-hand interaction using hand tracking conditions had a significantly higher level of presence than controller conditions, and having vibrotactile feedback had a significantly higher level of presence than not having one. There was no significant difference in terms of interaction effect, $F(1, 92) = 0.16$; $p = 0.696$.

4.3. Engagement

Based on participants' responses to GEQ, there was a statistically significant difference in terms of interaction methods, $F(1, 92) = 10.74$; $p = 0.003$. Whole-hand interaction using hand tracking conditions had a significantly higher level of engagement than controller conditions. There was no significant difference in terms of vibrotactile feedback, $F(1, 92) = 0.68$; $p = 0.418$, and interaction effect, $F(1, 92) = 0.24$; $p = 0.630$. The interaction effect was observed in one of the 14 questionnaire items: GEQ 3 "I feel different", $F(1, 92) = 6.53$; $p = 0.017$. While vibrotactile feedback increased such feeling in whole-hand interaction, the feedback decreased the feeling in controllers.

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4.4. Workload

Based on participants' responses to NASA-TLX, there was a statistically significant difference in terms of interaction methods on all six components: Mental Demand, $F(1, 75) = 19.36$; $p < 0.001$, Physical Demand, $F(1, 75) = 9.98$; $p = 0.002$, Temporal Demand, $F(1, 75) = 5.36$; p 0.023, Performance, $F(1, 75) = 7.48$; $p = 0.008$, Effort, $F(1, 75) = 20.17$; $p < 0.001$, and Frustration, $F(1, 75) = 11.68$; $p = 0.001$. For all, controller conditions had a higher level of workload than whole-hand interaction using hand tracking conditions. There was no significant difference in terms of vibrotactile feedback nor interaction effect in any of the components.

4.5. Completion Time

For completion time, there was a statistically significant difference in terms of interaction methods, $F(1, 75) = 7.02$; $p = 0.010$. Whole-hand interaction using hand tracking conditions had a significantly longer completion time than controller conditions. There was no significant difference in terms of vibrotactile feedback, $F(1, 75) = 0.31$; $p = 0.582$, and interaction effect, $F(1, 75) = 0.34$; $p = 0.564$.

4.6. Usability

Usability was measured only after the HV condition, where participants experienced the developed vibrotactile device on their index finger. Participants rated the device on average of 80 ($SD = 13.91$) which indicates the device was considered "good" to use (above 71; (Bangor, Kortum, & Miller, 2009)).

5. Discussion

This study investigated the effects of interaction methods and vibrotactile feedback on user experience in a cooperative VR game. Focusing on the levels of social presence, presence, engagement, workload, and performance, we compared whole-hand interaction using hand tracking with the traditional controllers, as well as with and without vibrotactile feedback. We observed whole-hand interaction to provide higher perceived presence and engagement with a lower workload; however, controllers were better in task performance. Providing vibrotactile feedback also led to an increased level of presence. There was no significant difference in the effect of vibrotactile feedback between the two interaction methods.

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5.1. Social Presence

We expected the use of whole-hand interaction using hand tracking and the provision of vibrotactile to increase the level of social presence. However, there was no significant difference in social presence observed among the four conditions. In fact, all four conditions scored close to the full score of 7 with a minimum average of 6.64, showing a ceiling effect of social presence. Based on the observation and feedback from participants, it can be inferred that the task itself required collaborative interactions between the participant and the experimenter to manipulate the object together, leading to high dependence on one another. Also, the participants could see the other user's virtual representation inside VE including head and hand positions. This intimate cooperation and ability to see each other in the VE may have overridden the effect of the interaction methods and vibrotactile feedback, ultimately resulting in participants responding to feel a high level of social presence regardless of the conditions. The results did not align with the existing experiments which showed haptic feedback to increase social presence in the VE, potentially due to the differences in experimental settings. For example, previous literature that provided vibrotactile feedback as a metaphor for footsteps significantly increased the level of perceived social presence M. Lee et al. (2017). In this setting, there was no cooperative task that encouraged interaction or communication between the users, verbal or non-verbal. The haptic feedback was used as a main cue to portray the partner's movement with respect to the user. However, the current study used haptic feedback in relation to the status of an ongoing task that two users were cooperatively performing. Giannopoulos et al. (2008) also investigated the effect of haptic feedback while performing a cooperative task within a shared VE. However, they utilized a desktop-based setting where users could only rely on the virtual representation of the partner's thumb which was utilized to nudge each other for taking turns. Here, the haptic feedback played a significant role in communicating between partners, therefore having an impact on the sense of togetherness.

Another potential reason for the ceiling effect could be due to the fact that most participants had no experience with social VR applications, not to mention a cooperative game that uses whole-hand gestures to cooperatively manipulate and create artifacts. The unfamiliar experience of cooperation in VE with a realistic virtual representation of hands might have resulted in a high perception of social presence for all conditions, regardless of interaction modality and vibrotactile feedback.

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5.2. Presence

In line with our hypotheses, whole-hand interaction using hand tracking induced a higher feeling of presence inside VE than controllers. While controller conditions required users to recall hand positions on buttons and triggers to make certain hand gestures in VE, whole-hand interaction using hand tracking allowed users to manipulate objects naturally and intuitively. Whole-hand interaction also enabled a more realistic representation of hand gestures inside VE. Controllers, on the other hand, allowed limited hand gestures inside VE which required users to follow the mappings on which button and trigger to press on the controller. The result of a more realistic interaction mechanism resulting in a higher level of presence agrees with previous studies that explored how naturalism affects the level of presence in VE (Bowman, McMahan, & Ragan, 2012; Cummings & Bailenson, 2016). Providing haptic feedback also positively affected the level of presence while playing the cooperative VR game. The increase in scores was most significant in three question items of the PQ questionnaire: PQ1 (How responsive was the environment to actions that you initiated or performed?), PQ5 (How involved were you in the virtual environment experience?), and PQ9 (How completely were your senses engaged in this experience). Providing vibration in accordance with the ongoing task enhanced the feeling of being connected or in tune with the virtual environment. Notably, the device that delivered vibrotactile feedback was a thimble-sized object attached to a single index finger. Previous studies have shown the benefits of utilizing haptic devices to enhance user experience in VR; however, they are not commonly accepted due to limitations such as their bulkiness and high price (Moon, Orr, & Jeon, 2022). In the present study, the thimble-shaped haptic device showed the potential to successfully enhance immersiveness inside VR using a less intrusive method than wearing or adding bulkier haptic devices.

5.3. Engagement

Along with the results above, whole-hand interaction using hand tracking was evaluated to provide a better user experience than controllers in terms of engagement in the game. The differences were most significant in responses to GEQ4 (The game feels real) and GEQ11 (I play without thinking about how to play). Similar to its effect on presence, the benefits of whole-hand interaction to manipulate objects naturally as in the real world made users feel the game to be more real. Also, it was evident that using controllers required users to constantly consider how to use the interaction method throughout their experience with the game.

Providing vibrotactile feedback did not play a significant role in the overall level of engagement or any of the individual question items. Also, no significant difference was observed in the effect of vibrotactile feedback between interaction methods. However, when investigating deeper into individual question items, a significant difference was observed in responses to GEQ3 (I feel different). According to the original study of the questionnaire, the state of “feeling different” falls into the category of psychological absorption inducing “an altered state of consciousness” where emotional responses tend to occur outside of one’s conscious awareness (Brockmyer et al., 2009). In our study, participants responded to have felt more different with the vibrotactile feedback in whole-hand interaction conditions where the feedback positively affected users to be more absorbed in the game; on the contrary, the feedback made participants feel less different and absorbed in the game during controller conditions.

5.4. Workload

Responses to all six components of NASA-TLX showed a lower workload of whole-hand interaction using hand tracking in comparison to controllers. All of its six components, including mental demand, physical demand, temporal demand, performance, effort, and frustration showed statistical significance. Based on responses on GEQ11 (I play without thinking about how to play), it can be inferred that the need to remember and recall to make hand gestures in VE during controller conditions could have resulted in a higher workload, especially in mental demand where the biggest difference between interaction methods was observed. It is notable that whole-hand interaction successfully enhanced user experience for a cooperative VR game while imposing lower workloads than controllers.

5.5. Completion Time

While whole-hand interaction using hand tracking enhanced the user experience for presence, engagement, and workload, it resulted in lower performance than controllers in terms of the time required to complete a cooperative task. The tradeoff between perceived user experience and objective performance implies that the choice of interaction methods should consider the relative importance of entertainment and performance. For example, if the task values how users enjoy the experience, using whole-hand interaction method would be more adequate. However, if accurate and efficient performance is important in task, using controllers would be more appropriate. During the study, we observed several technical limitations of the current

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hand tracking system of Meta Quest 2 for its embedded hand tracking system. For example, when participants were making a pinching gesture with a thumb and an index finger, a thumb was often obscured behind the back of the hand and was not visible to the headset. Such occlusion resulted in the system not detecting the pinching gesture, and the inaccurate detection made participants repeat the process until the system correctly identified the gesture. This issue, however, was not the case in the controller condition.

5.6. Usability

The fingertip vibrotactile device developed in this study obtained an average SUS score of 80 which is considered ”good” to use (Bangor et al., 2009). During the user study, there were a few incidents of instability in the hand tracking system. This could have negatively affected how participants evaluated the usability of the device. This was especially evident when participants had to make a pinching gesture that required the index finger to touch the thumb. The hand tracking system used in this study sometimes failed to successfully recognize the index finger to which the device was attached. However, such failures were relatively negligible as can be observed by the lower level of frustration in conditions where haptic feedback was provided than when not. Also, the vibrotactile device used in this study provided a minimum vibrotactile cue at one fingertip only which obtained a positive response from participants for its usability. The prototype demonstrated the potential of a vibrotactile feedback application in VR games as well as in the social VR context.

5.7. Implications

Cooperative VR games represent an immersive and socially engaging dimension of interactive experiences. Unlike traditional gaming formats, these games transcend the boundaries of conventional screens, allowing players to collaboratively navigate and interact within shared virtual spaces. This genre emphasizes teamwork, fostering a sense of camaraderie as participants collectively tackle challenges and objectives. The three-dimensional nature of VR amplifies the depth of engagement, enabling players to communicate not only verbally but also through virtual gestures and movements, enriching the cooperative dynamic. The heightened realism and shared virtual environments in VR cooperative games create an immersive sense of presence, where participants feel connected and synchronized with their virtual counterparts. In this study, we noted that a cooperative task characterized by high social interdependence led to an elevated level of social presence, recognizing the presence of another player and the

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interpersonal connection, irrespective of the chosen interaction method or the inclusion of vibrotactile feedback. However, the selection of the interaction method significantly influenced the overall user experience. Notably, employing the whole-hand interaction method with hand tracking features resulted in a superior virtual environment presence, increased engagement, and reduced workload compared to traditional VR controllers. Despite the controllers demonstrating better objective performance metrics, such as shorter completion times, participants subjectively felt that they performed better in the whole-hand condition. This sentiment was accompanied by perceptions of exerting less effort and experiencing reduced demands and frustration. These findings underscore the nuanced impact of interaction methods on user perception and satisfaction, suggesting that, in cooperative VR content, users tend to favor holistic hand tracking experiences for a more immersive and enjoyable cooperative virtual experience. With continuous improvement in hand tracking technology, the fusion of social interaction and cutting-edge technology in cooperative VR gaming can introduce a new frontier of collaborative play, where shared experiences extend beyond the confines of the physical world.

While the current study was centered around the context of gaming, its findings hold broader applicability to various domains, such as cooperative work and learning. Tasks that necessitate mutual dependence to solve a shared objective align with the definition of cooperative work. Features of cooperative games, such as joint commitment, attitudes toward cooperation, and anticipated positive emotions, can foster cooperation in practical applications (Morschheuser, Riar, Hamari, & Maedche, 2017). Cooperation is also an important aspect in the realm of education, where cooperative learning emerges as an approach emphasizing mutual dependency and collaboration among students to achieve common learning objectives (Jong, Lai, Hsia, Lin, & Lu, 2012; Slavin, 1980). In comparison to individual learning, cooperative learning not only promotes active engagement and interpersonal skills but also shows more effective in enhancing both learning achievement and motivation (Slavin, 2012; Wang, 2012). The study relates to the emerging trend of gamification as a valuable approach for bolstering learning motivation (Vos, Van Der Meijden, & Denessen, 2011).

The study's implications suggest practical considerations for choosing interaction methods in VR applications. For tasks prioritizing a natural emulation of experience or heightened immersion, the whole-hand method, complemented by a vibrotactile device, is recommended. Conversely, tasks emphasizing precise control and performance benefit from the use of controllers. The addition of a fingertip device providing vibrotactile feedback in this scenario can enhance the level of presence without compromising the overall user experience. These insights contribute to a more informed and strategic approach in selecting interaction methods based on specific task requirements and objectives.

6. Limitations

Despite our efforts to optimize the controller grip to closely emulate barehand postures, the hand gestures involving finger movements were more natural and in favor of barehand condition. Handling the controller required additional effort, potentially leading to a decrease in their perceived levels of presence and engagement. Additionally, the study involved a relatively small number of participants and there was an imbalance in gender distribution. We did not obtain any additional information from participants, such as prior experience or familiarity with VR, which might have affected user performance and experience in this study." In this study, we could not observe any significant effect of interaction methods and vibrotactile feedback on the level of perceived social presence. Because our game was focused on cooperation between players, we were interested in how the studied variables would affect players' feelings of social connection inside the virtual space. However, our game required players to cooperatively manipulate objects and their actions were highly dependent on another player's actions throughout the experience. Such characteristics of the game resulted in the observed ceiling effect with nearly full scores on every question item included in the questionnaire. This left no room for improvement in the measured social presence based on the differences in conditions. A future study can investigate the impact of interaction methods and vibrotactile feedback in a cooperative game with less dependency between players. Also, using a more appropriate questionnaire that provides a larger spectrum about social presence would further investigate how players perceive the presence of a partner.

7. Conclusion

To understand the impact of interaction methods and vibrotactile feedback on user experience in a cooperative VR game, this study compared the use of controller and whole-hand interaction, with and without haptic feedback. Our study involved manipulation of objects with high dependence on actions of two players. Given the cooperative characteristics, our VR game was evaluated to provide high social presence in all studied conditions. However, using a natrual and intutive whole-hand interaction method to manipulate virtual objects enhanced user experience with a higher score in perceived presence, a higher score in perceived engagement, and a lower score in perceived workload, in comparison to commonly used VR controllers. Meanwhile, the current hand tracking system has a room for technological improvement to accurately track and replicate hand gestures in the virtual world. The use of vibrotactile feedback also showed improvement in perceived presence while playing the cooperative VR game. It is also noteworthy that the thimble-sized haptic device developed in this study successfully induced significant effect in increasing immersiveness in the experience with its small size and low cost.

8. Acknowledgments

References

Achibet, M., Marchal, M., Argelaguet, F., & Lécuyer, A. (2014). The virtual mitten: A novel interaction paradigm for visuo-haptic manipulation of objects using grip force. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 59–66).

Almeida, L., Lopes, E., Yalçinkaya, B., Martins, R., Lopes, A., Menezes, P., & Pires, G. (2019). Towards natural interaction in immersive reality with a cyber-glove. In *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)* (pp. 2653–2658).

Bangor, A., Kortum, P., & Miller, J. (2009). Determining what individual sus scores mean: Adding an adjective rating scale. *Journal of Usability Studies*, *4*(3), 114–123.

Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a more robust theory and measure of social presence: Review and suggested criteria. *Presence: Teleoperators & Virtual Environments*, *12*(5), 456–480.

Bowman, D. A., McMahan, R. P., & Ragan, E. D. (2012). Questioning naturalism in 3d user interfaces. *Communications of the ACM*, *55*(9), 78–88.

Brockmyer, J. H., Fox, C. M., Curtiss, K. A., McBroom, E., Burkhart, K. M., & Pidruzny, J. N. (2009). The development of the game engagement questionnaire: A measure of engagement in video game-playing. *Journal of Experimental Social Psychology*, *45*(4), 624–634.

Brooke, J. (2013). Sus: a retrospective. *Journal of Usability Studies*, *8*(2), 29–40.

Brooke, J., et al. (1996). Sus-a quick and dirty usability scale. *Usability Evaluation in Industry*, *189*(194), 4–7.

Burdea, G. C. (2000). Haptics issues in virtual environments. In *Proceedings of Computer Graphics International 2000* (pp. 295–302).

Cummings, J. J., & Bailenson, J. N. (2016). How immersive is enough? a meta-analysis of the effect of immersive technology on user presence. *Media Psychology*, *19*(2), 272–309.

Presence, Just Accepted MS.
https://doi.org/10.1162/PRES_a_00403

De Greef, P., & IJsselsteijn, W. (2000). Social presence in the photoshare tele-application. In *Proceedings of the 3rd International Workshop on Presence.*

Deutsch, M. (1962). Cooperation and trust: Some theoretical notes. *Nebraska Symposium on Motivation.*

Freeman, G., Zamanifard, S., Maloney, D., & Adkins, A. (2020). My body, my avatar: How people perceive their avatars in social virtual reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–8).

Furrer, C., & Skinner, E. (2003). Sense of relatedness as a factor in children's academic engagement and performance. *Journal of Educational Psychology*, *95*(1), 148.

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine*, *72*(2), 115.

Giannopoulos, E., Eslava, V., Oyarzabal, M., Hierro, T., González, L., Ferre, M., & Slater, M. (2008). The effect of haptic feedback on basic social interaction within shared virtual environments. In *Haptics: Perception, Devices and Scenarios: 6th International Conference, EuroHaptics 2008* (pp. 301–307).

Harms, C., & Biocca, F. (2004). Internal consistency and reliability of the networked minds measure of social presence. In *Proceedings of the 7th International Workshop on Presence* (Vol. 2004).

Hart, S. G., & Staveland, L. E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in Psychology* (Vol. 52, pp. 139–183). Elsevier.

Jong, B.-S., Lai, C.-H., Hsia, Y.-T., Lin, T.-W., & Lu, C.-Y. (2012). Using game-based cooperative learning to improve learning motivation: A study of online game use in an operating systems course. *IEEE Transactions on Education*, *56*(2), 183–190.

Kim, M., Jeon, C., & Kim, J. (2017). A study on immersion and presence of a portable hand haptic system for immersive virtual reality. *Sensors*, *17*(5), 1141.

Lee, K., Jung, Y., Kim, J., & Kim, S. R. (2006). Are physically embodied social agents better than disembodied social agents?: The effects of physical embodiment, tactile interaction, and people's loneliness in human–robot interaction. *International Journal of Human–Computer Studies*, *64*(10), 962–973.

Lee, M., Bruder, G., & Welch, G. (2017). Effect of vibrotactile feedback through the floor on social presence in an immersive virtual environment. *Journal of Vision*, *17*(10), 357–357.

Maloney, D., Freeman, G., & Robb, A. (2020). A virtual space for all: Exploring children's experience in social virtual reality. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (pp. 472–483).

McVeigh-Schultz, J., Kolesnichenko, A., & Isbister, K. (2019). Shaping pro-social interaction in vr: an emerging design framework. In *Proceedings of the 2019 CHI Conference on Human Factors in*

Presence, Just Accepted MS.
https://doi.org/10.1162/PRES_a_00403

Computing Systems (pp. 1–12).

Mehrabian, A. (2017). *Nonverbal communication.* Routledge.

Moon, H. S., Orr, G., & Jeon, M. (2022). Hand tracking with vibrotactile feedback enhanced presence, engagement, usability, and performance in a virtual reality rhythm game. *International Journal of Human–Computer Interaction*, 1–12.

Morschheuser, B., Riar, M., Hamari, J., & Maedche, A. (2017). How games induce cooperation? a study on the relationship between game features and we-intentions in an augmented reality game. *Computers in Human Behavior*, *77*, 169–183.

Oh, C. S., Bailenson, J. N., & Welch, G. F. (2018). A systematic review of social presence: Definition, antecedents, and implications. *Frontiers in Robotics and AI*, *5*, 114.

Ryan, R. M., Rigby, C. S., & Przybylski, A. (2006). The motivational pull of video games: A self-determination theory approach. *Motivation and Emotion*, *30*, 344–360.

Sallnäs, E.-L. (2010). Haptic feedback increases perceived social presence. In *Haptics: Generating and Perceiving Tangible Sensations: International Conference, EuroHaptics 2010* (pp. 178–185).

Slavin, R. E. (1980). Cooperative learning. *Review of Educational Research*, *50*(2), 315–342.

Slavin, R. E. (2012). Cooperative learning and achievement: Theory and research. *Handbook of Psychology, Second Edition*, *7*.

Vos, N., Van Der Meijden, H., & Denessen, E. (2011). Effects of constructing versus playing an educational game on student motivation and deep learning strategy use. *Computers & Education*, *56*(1), 127–137.

Wang, M. (2012). Effects of cooperative learning on achievement motivation of female university students. *Asian Social Science*, *8*(15), 108.

Wang, M. (2020). Social vr: A new form of social communication in the future or a beautiful illusion? In *Journal of Physics: Conference Series* (Vol. 1518, p. 012032).

Witmer, B. G., Jerome, C. J., & Singer, M. J. (2005). The factor structure of the presence questionnaire. *Presence: Teleoperators & Virtual Environments*, *14*(3), 298–312.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators & Virtual Environments*, *7*(3), 225–240.

Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 143–146).

Wu, C.-M., Hsu, C.-W., Lee, T.-K., & Smith, S. (2017). A virtual reality keyboard with realistic haptic feedback in a fully immersive virtual environment. *Virtual Reality*, *21*, 19–29.