

Evaluation of Touch Gesture Performance on Surfaces in Virtual Reality

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Abstract

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The recent development of Virtual Reality (VR) technologies allows people to do their professional work as well as get some entertainment in VR environments. Users typically interact with VR environments by using VR controllers or in-air gestures. While these input methods allow 6-DOF manipulation of virtual objects, precise manipulation in VR is still challenging. VR controllers do not utilize dexterous manipulations that human fingers are capable of, and in-air gestures do not provide any haptic feedback when fingers touch virtual objects. To enable a more precise and effective VR manipulation, researchers have proposed mid-air haptic feedback techniques that produce the feeling of touching an object at the fingertip and showed promising results for selection tasks. However, it is not studied how well these methods would work for more complex manipulation tasks such as drawing that require precise and continuous control of a finger movement.

This thesis aims to understand the requirement for ensuring precise manipulation in VR by investigating the effect of different levels of haptic feedback on the performance of manipulations tasks in VR. Three levels of haptic feedback were implemented for the study: 1) no haptic feedback, which the user relies only on the visual feedback, 2) virtual haptic feedback, which the user can feel the haptic feedback at the fingertip during contact, and 3) physical haptic feedback, which the user performs touch interactions on a physical surface. In the user study, error, task completion time, and performance quality were measured for selection, tracking, and drawing tasks. Although the main user study could not be conducted due to the COVID-19 situation, a preliminary study showed that having a physical surface is crucial in enabling efficiency, accurate and precise manipulations in VR, and also reducing mental task load of completing manipulation tasks.

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Chapter 1

INTRODUCTION

1.1 Motivation

Recent advances in Virtual Reality (VR) technologies have brought the attention of the public beyond researchers and technology enthusiasts to the potential of VR. VR is often demonstrated as an extremely productive and immersive environment in fictional movies, like Ready Player One, where the users can immediately and conveniently access and interact with virtual objects and environments in a way that is otherwise not feasible in the physical world. With a sensory suit and VR headset, the characters in the movie feel the interactions they make with the virtual environment just like they would in reality. The current VR technologies provide similar immersive experiences to those in the movie in some aspect, by quickly and accurately tracking the user's position and orientation and rendering the virtual world in high-fidelity graphics that are close to reality, in real-time. Researchers have also developed various haptic feedback technologies, by using illusions [37, 20], gyroscopic effects [48, 49], air jets [39], drones [1], Electro-Muscular Stimulation (EMS) [15], and many other methods, to make the virtual environment more realistic with the feeling of force. In addition, many wearable force feedback devices were created, such as haptic gloves [8, 12] that a user can feel the shape and resistance of virtual objects via passive haptic feedback. Along with the development of affordable consumer VR devices, people are already using VR technology for a variety of uses, from professional work to presentation and entertainment [7].

For both VR research and commercial applications, typical interaction methods are utilizing VR controllers and in-air gestures [9]. There are several popular VR controllers on the market that are widely used in research and consumer systems, such as Oculus Rift Touch Controllers, Vive Controllers, and Play Station VR Controllers. While these commercial VR controllers are not perfect because of

underwhelming the haptic feedback of fingers and only supporting big motions by limbs, some projects worked on addressing the problems in order to push these VR controllers into a new generation. For instance, TORC[31] is a rigid VR controller that can be manipulated by users' thumb and two fingers to make users feel virtual object characteristics and behaviors like texture and compliance. Another hope to refine the VR spatial interactions is by in-air gestures which provide 6-DOF finger manipulations. In-air gestures are supported by several modern VR and AR devices, such as Oculus Quest and Microsoft Hololens 2 devices, using cameras installed on the headset. Users can interact with virtual objects using all their fingers by touching or grabbing them. One of the challenges of using in-air gestures is that the user cannot feel the contact between the finger and the virtual object. To address this challenge, many ungrounded haptic feedback methods that use EMS [15], ultrasonic actuators [11, 22, 24, 40] and vibrotactile actuators [38] have been developed. Recent studies have shown that haptic feedback can improve the performance of simple pointing and dragging tasks in VR [29, 40].

Although handheld controllers and in-air gestures can help users interact with the VR environment, and they keep improving their performance, human hands in the physical world are far more advanced. When humans interact with physical objects, they do not just make hand gestures but also sense pressure, traction, and touch from the contact. For example, when a person makes a clay sculpture, they feel the changes in resistance and shape from the fingertip. These physical properties also affect the interaction, the person can interact with the object faster because they feel the contact when the finger touches the clay, and they can move the finger more precise because of the friction that helps to adjust finger movement. Compared with the colorful hand interactions in the physical world, current in-hand gesture systems, even with the in-air haptic feedback, still lack many of the important aspects of physical interactions that help efficiency and dexterousness, which are especially important for complex tasks such as 3D sketching [45], painting [28] or 3D modeling.

Due to the spatial characteristics of 3D design, VR drawing has arisen many interests among specialists in this field. However, while they felt inspired by the 3D view of drawing in VR, the drawing procedures demanded more effort than traditional drawing on a tablet [45]. Even if they spent enough work on it, the result paintings were still not satisfying enough on precision, accuracy, or other qualities that are crucial to professional purposes [6]. The good news is that research already showed that having a physical interaction surface in VR is helpful for designers [5, 6, 14, 25, 31]. Pen interactions in 3D sketching can also benefit from having a physical surface to lean on [14]. Besides, it is already proved that a combination of 2D and 3D sketching is necessary for VR drawing [6, 5, 25], which means introducing a 2D physical drawing surface into 3D VR environment. 2D sketching achieves higher precision and makes users feel more natural, while 3D sketching provides better spatial conception for users[25].

Undoubtedly, people use bare hands more than pens in the real world, and these hand interactions often happen on a surface. I believe that the physics, like the friction, force, postures between the finger and the surface, will also make touch interaction in VR more precise and efficient, similar to prior pen-based interaction studies have demonstrated. Since there is no study that investigates the effect of the physical surface on the performance of bare-finger touch interaction in the VR environment, I designed and implemented a user study.

This thesis project investigates the performance characteristics of touch interaction when there is *no haptic feedback*, *virtual haptic feedback*, and *physical haptic feedback*. No haptic feedback condition represents the setting of most consumer VR applications that use in-air gestures, where the user does not feel anything when touching a virtual object or surface. The virtual haptic feedback condition represents the use of an in-air haptic feedback method, where users can feel pressure and vibration at their fingertips when the finger touches a virtual surface. Physical haptic feedback condition represents real-world interaction, where users hold a physical object and move their finger of the other hand on the object. This setup is not yet common in consumer VR systems because using physical objects do not offer flexibility as virtual objects.

The study could not be completed with actual participants due to the COVID-19 situation. However, I believe that the implementation of the system, the study design, the analysis methods, and the insights that I gained from the preliminary study of myself would prepare the actual study to conduct when in-person studies become available.

1.2 Thesis Overview

This thesis is organized as follows. The following chapter will first present major work related to the touch performance evaluation, including spatial interaction in VR, touch interaction in surface interfaces, haptic feedback, and hand tracking methods in VR.

The experiment setup, interaction techniques, and prototype systems are then described in detail. A VR environment was developed using Unity, where users can manipulate their hands and do several tasks. As for the user's hand tracking, the experiment adopted the OptiTrack motion capture system. Basically, the OptiTrack cameras calculate the 3D position of each marker. After rendering the hand skeleton based on these knuckles' position, users can start executing designed 3D tasks (selection, tracking, drawing) on the display surface by the virtual hand. The selecting task helps figure out how basic selection performances differ in distinctive haptic feedback conditions. In the tracking task, the aim is to evaluate the performance of following a trajectory on the surface. Last but not least, from the drawing experiment,

how different haptic feedback affects the outcome of a complex sketching task was revealed.

This thesis found that physical haptic feedback outperformed no haptic feedback and virtual haptic feedback when the user completed touch selection, tracking, and drawing tasks in VR. Discussion of the results, limitations, and possible future work is concluded as well.

The main contribution of this thesis is the understanding of the effect of different types of haptic feedback on the touch interaction performance in VR. With the insights gained from this study (and from the actual study to be conducted after the COVID-19 situation), researchers will be able to build new hand-based interactions and user interfaces that allow high efficiency and precision in VR.

Chapter 2

RELATED WORK

This chapter reviews some previous related work, discusses the rationale for hand interaction technologies applied in this thesis, and explores possible evaluation methods. At first, this section has a look at research on the evaluation of spatial interaction performances in VR, figure out the pros and cons of VR controllers, and in-air gestures. Consider the limitations of spatial interactions, then a survey on hand interaction performances in touch surface interfaces was investigated, and corresponding evaluation methods. Based on the characteristics of the VR environment, in addition to being physical, touch surfaces can also be virtual. There are several haptic feedback methods that can create a virtual wall in space and each of these is also discussed below. Since the experiment compared bare-hand touch performances under different haptic feedback conditions (*no haptic feedback*, *virtual haptic feedback* and *physical haptic feedback*), this section also explores hand tracking in VR to conduct the experiment with an appropriate system.

The abundant spatial interactions in VR have spurred plenty of research interest because users can create and handle objects at a real-world scale instead of a limited space (e.g., a mobile phone). Touching as one of the most basic functions of human hands, as well as a very common hand interaction in VR, almost exists in all VR tasks. For example, using pointing gesture to execute selection tasks, it is actually a special case of touching. Selecting is quite simple and natural in the real world, but the performance of 3D object selection in VR involves advanced criteria like visual feedback, depth perception, and occlusion management [4]. Undoubtedly, this kind of 3D free spatial interaction maximizes the degrees of freedom by giving up accuracy and easy control. Then came out studies like the ActiTouch [51], which used an electrical method to propose an on-skin touch input technology. The interface used the body as an RF waveguide to which obtained more precise touch segmentation and tracking than free-hand interaction

in VR space. Except for the interactions that evaluate basic VR manipulation tasks, methods exploring more complicated tasks, like better 3D sketching, also draw much attention. Most of them focus on pen interactions [14, 6, 5, 27], for example, CavePainting [28] created a 3D brush based on the analog of 2D brush strokes so that users could interact with the VR environment and work on the 3D painting by a traditional brush. While participants felt excited about this form of artistic creation and the immersed drawing experience, the current 3D drawing problem is also unneglectable. Users encountered great difficulty in control with strokes, which was found to be extremely frustrated [45]. Experiments in this research showed that, when exposed to 3D and 2D drawing interfaces at the same time, after enough interesting attempts in 3D sketching, people usually ended up going back to 2D methods for professional spatial drawing considered the accuracy and precision. Actually, there was a design principle for 3D drawing proposed as “life-size and operability” [45], which gave a guideline for the 3D sketch system. Current free-hand sketching technologies in VR, nevertheless, did not meet with these criteria yet.

2.1 Evaluation of Touch Interaction Performances in Touch Surface Interfaces

Consider the problem of spatial interaction, which is more severe on complicated tasks like 3D drawings, such as hard to control, lack of precision, and heavy mental workload, many researchers have already been working on evaluating and improving the performance of the 3D design. Prior comparative study on 2D and 3D drawing indicated that 3D immersive space can help people be more creative and reflective, while 2D sketching with a surface to rely on was necessary to guarantee the perceived fluency of creation, perceived appropriateness, perceived stimulation by the medium, the movement speed, the sketch sizes, the degree of detail, the functional aspects, and the usage time [25]. Further study was conducted to find key factors that made this kind of difference. Results showed, compared with 2D sketching, drawing precise curves was very challenging in 3D sketching and the imprecision in 3D sketching performances was affected by the scale, lack of physical surface, orientation, and planarity [6]. Thus a physical surface was introduced to some pen interaction design, such as VRSketchIn [14] and SymbiosisSketch [5]. Both of them combined unconstrained 3D sketching for spatial manipulation with constrained 2D surface-based sketching for drawing details. There are other studies working on strategies for more controlled 3D drawing, like the Drawing on air [27], which addressed the free-hand control problem by one-handed drag drawing and two-handed tape drawing. Drawing on air also found their strategy outperformed free-hand drawing and free-hand drawing augmented with a haptic friction effect. In addition to the 3D

drawing, basic tasks like selection, docking, were also investigated for VR performance. Experiments were conducted by the HARP system on low-level 2D manipulation tasks within an immersive virtual environment [32]. The result found that the use of 2D interface widgets and passive haptic feedback can significantly increase users' performance in precise UI manipulation tasks. And users also prefer touch interfaces that provide a physical surface. TabletInVR [44] further investigated the increasing affordances and input capabilities, such as create, select, delete, transform, modify, and navigation, when using a 3D-tracked multi-touch tablet in an immersive VR environment. As for the measurements that are usually adopted to evaluate touch performance on surfaces, this study chooses accuracy, precision, speed, and subjective feelings [2, 18, 35, 26].

2.2 Virtual Haptic Feedback Methods

Several methods can create a virtual surface that is supposed to be felt by the user instead of a vision-based VR screen. These methods can be divided into two categories: by providing kinesthetic or tactile haptic feedback.

One of the most common methods to create kinesthetic haptic feedback is using grounded haptic devices that create movement or force using mechanical linkages installed in the environment. For example, The PHANTOM OMNI haptic device [43] allowed the kinematic interaction with complex virtual environments, so the user's hand could be held at a certain position, or move in a fixed direction just like on a surface. HAIR [46] was composed of a computer vision system, a mechatronic device, and air jets that stimulated users' skin and made users feel the virtual 3D surface. While these methods could provide accurate kinesthetic haptic feedback, they were grounded haptic devices that cannot move freely with the user. Another type of method for creating a virtual surface is to use wearable haptic devices that are attached to a user's body to create kinesthetic haptic feedback. HapticGEAR [20], as an early wearable force display system, could transmit applied forces to the wearer by using a wire-tension mechanism. However, the problems of backpack-type devices like HapticGEAR were limited sensation, heaviness, large size, and hard to implement. Contact sensation needed less equipment, and can be achieved by thin wire [3] based on cutaneous sensation. Electro-Muscular Stimulation (EMS) is also a popular choice to provide virtual haptic feedback about walls and heavy Objects in VR [34]. By actuating the user's shoulder, arm, and wrist muscles through electrical muscle stimulation, EMS can create a counterforce that pulled the user's arm backward and prevented users from passing through the front obstacle. As the user's arm trying to resist this motion, they would perceive force feedback [33]. Some commercial applications even combined EMS with vibrotactile methods to render haptic signals

for the texture of virtual surfaces.

Other virtual haptic methods that offer tactile haptic feedback, like the acoustic radiation pressure which utilizes nonlinear characteristics of ultrasound [22], also help researchers produce many advanced devices [24, 40], for example, the UltraHaptics [11]. Ultrasonic waves allow users to be totally immersed in the VR environment without adornment mounted on hands, which accomplishes a high degree of freedom, but also makes kinesthetic haptic feedback impossible. Hand-worn haptic devices like the wireless V-Glove [17] was able to track the position of the user’s index finger and vibrate the fingertip when it reached an area mapped in the interaction space to simulate a touch feeling. Similar virtual haptic devices [21] like Traxion [38] also used a vibrotactile actuator to create such a virtual feeling of touch. The problem of vibrotactile feedback is the limited force and quick diminution. Consequently, a substitute for kinesthetic feedback by tactile feedback method was proposed, where the Joystick [36] applied vertical stress to the fingertip by an electric motor.

Consider this thesis more focuses on free-hand interaction in the experiment, hand-worn haptic devices draw more attention. Fortunately, the state-of-art touch performance with virtual haptic feedback was achieved by HapThimble [29], which combined kinesthetic feedback and tactile feedback. HapThimble was a finger-worn haptic device that provided various types of haptic feedback, including tactile, pseudo-force, and vibrotactile. It was capable of mimicking physical surfaces for users to do the clicking and dragging tasks in VR with good performance. Specifically, HapThimble obtained an accuracy of 98.75% on the clicking task, and 97.92% for the dragging task, which were much higher than the mid-air tactile feedback like what UltraHaptics created. HapThimble also outperformed fingertip tactile device methods like Joystick on task completion time. In the experiment of HapThimble, the author compared tactile feedback with bare-hand interaction and force-only feedback, tactile feedback won on the speed and accuracy as well.

2.3 Hand Tracking in VR

Evaluation of touch interaction involves VR tracking approaches towards hands. The human hand has a highly complex structure with many characteristics like shape, kinematical structure, dynamics, semantics, and so on, while the hand motion is comparatively constrained [50]. Consequently, the way to model a hand is actually an open question, and the solution is based on the modeling purpose. Basically, there are three types of shape models: geometrical models, physical models, and statistical models [50]. Geometrical models are suitable for rendering hand pose, motion with a small number of parameters. A simpler version of the spline-based geometrical surface model is to alternate the fingers and palms

with homogeneous cylinders or super-quadrics, it can achieve equally good hand surface approximation with less complexity. If the condition of hand surfaces is also out of consideration, like our case, then a cardboard model [50] would be efficient enough for motion-capture computation.

If hand motions happen in a large space, for example, the user moves around the room, then marker-based optical motion capture [47] offers better positional accuracy than other vision-based capture methods, as long as the cameras are correctly placed and calibrated. As a consequence of the small size of fingers with large degrees of freedom, markers that attached to fingers need to be small and close to each one. It is necessary to put 13-20 markers on each hand in order to maintain a high-quality capture. Usually, the distribution of markers includes two or more markers on each finger and at least three on the back of the hand [30]. The number of markers can be reduced by constructing finger motions with inverse kinematics [23], but the implementation and computation workload will certainly increase.

2.4 Summary

The quality of spatial interactions is determined by the level of the user’s spatial sense and space conditions. For instance, if the user has VR expertise, or if the interactive room is large and safe enough for free interactions. However, with a physical plane, the depth variance can be eliminated, and there will be no occlusion as long as the above-the-surface space is free, which helps relieve the current free-hand interaction problems in VR. Having a physical plane also meets the 3D design requirement “life-size and operability” due to its realistic characteristics and capability of compensating for VR. Besides, visual feedback is necessary for bare-hand interaction, even when performing simple VR tasks like selection. In our experiment, visual help was offered when there was no haptic feedback, in order to make the performance under different haptic feedback conditions more comparable. In addition, HapThimble was chosen in our experiment as the device which provided virtual haptic feedback since it showed state-of-art performance on basic VR tasks. As for the hand modeling, because this study only needs to accurately track the status of the pointing finger and the holding hand, a cardboard skeleton model covered all knuckles on hands would be enough in our experiment.

Many research has been working on improving 3D sketching by 2D pen-drawing on tablets, and how a physical surface affects basic task performing in VR. Some studies already compared touch performance of bare hand, bare hand on the physical surface, and bare hand with virtual haptic feedback. However, our research will contribute to the first empirical study of touch gesture performance under different haptic feedback conditions and tasks with different workload levels.

Chapter 3

COMPARATIVE HAPTIC FEEDBACK STUDY

This section describes a comparative study on three different levels of haptic feedback: *no haptic feedback*, *virtual haptic feedback* and *physical haptic feedback*. By investigating their performance on different levels of tasks (selection, tracking, drawing), whether *physical haptic feedback*, or the physical surface would improve the VR bare-hand touch interaction can be figured out.

In the *no haptic feedback* condition, users naturally interact with the VR environment by their bare hands. On the current VR devices market, interactive interfaces for in-air gestures like HoloLens, Leap Motion are common and commercially successful. Undoubtedly, they are less restrained than VR controllers, and the hand interactive experience is pretty similar in our daily life. However, as a consequence of lacking haptic feedback, in-air gestures interactions are weaker at fine-grained interactions, such as doing tasks on a virtual surface. Due to the spatial feature of VR interactions, 3D designers are extremely interested in VR drawing since they can directly view and manipulate their 3D models in real-time. However, a lot of research about free-hand sketching in the VR environment showed that it was hard to control, effort-taking, and professional designers expected higher precision.

A direct solution is to give users a physical surface to rely on as some previous work did for 3D drawing. For instance, SymbiosisSketch [5] and VRSketchIn [14], both of them made use of a physical plane to support detailed pen interactions. Beyond the pen interactions, a tablet in the VR environment was also proved beneficial for bare hand to manipulate basic virtual objects [44]. However, whether a 2D traditional tablet can improve the performance of bare-hand interaction on complex tasks, like drawing, is still unrevealed.

Creating a virtual surface in the VR environment is another feasible solution. Research has been worked on providing human hands with kinesthetic and tactile sense so that users can feel their touch in the air. Some of them are successful in helping performance on simple VR tasks. Such as Muscle-propelled force feedback [33] which involved EMS, UltraHaptics [11] that used vibrotactile stimulation. In addition, HapThimble [29] combined kinesthetic and cutaneous feelings by the servo motor and LRA motor, gave users a realistic perception of compliance. We chose HapThimble to provide the *virtual haptic feedback* in our experiment because it is state of the art on simple 3D touch tasks such as selection and dragging. However, one thing that remains unclear is how well *virtual haptic feedback* works with complex tasks.

Based on the above characteristics of these three kinds of haptic feedback, we can reasonably suppose that they will drive users to have different performance on different levels of tasks. As for tasks, selection, tracking, and drawing are chosen in this study because of prior work already addressed problems and gave some insights when people performed these three. Our purpose is to explore more about how different haptic feedback influences performance on basic as well as advanced VR tasks.

Note that the study was not conducted with actual participants due to the COVID-19 situation. Nonetheless, this work focuses on the design of the study and analysis methods that will be used for the actual study that will be conducted when in-person user studies become feasible.

3.1 Study Goal

The study goal of this thesis is to investigate:

- If different types of haptic feedback have different effects on enhancing the VR task performance?
- If it is better to have kinesthetic and tactile haptic feedback when doing VR tasks?
- If it is better for users to lean their fingers on something when they do some tasks in VR?

3.2 Hypotheses

Correspondingly, our study was intended to test the following two hypotheses:

- With kinesthetic or tactile haptic feedback, users will complete tasks in VR with higher accuracy and feel less fatigue than when there is no haptic feedback.
- With a physical surface that users can rely on, the users will complete tasks in VR with higher accuracy and feel less fatigue than when there is no physical surface.

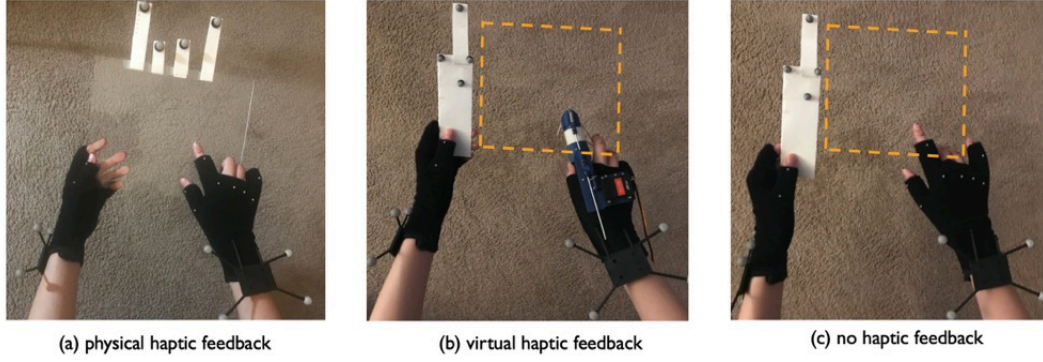


Figure 3.1: Experimental hand configuration in different haptic feedback conditions, including physical haptic feedback(a), virtual haptic feedback(b), no haptic feedback(c). The dotted line represents the virtual display plane.

3.3 Study Design

3.3.1 Independent Variable

- Feedback Type: no haptic feedback, virtual haptic feedback, physical haptic feedback
- Task Type: selection, tracking, drawing

3.3.2 Task

The experiment was designed as a 3x3 within-subject study. In each feedback condition: *no haptic feedback*, *virtual haptic feedback* and *physical haptic feedback*, users performed three tasks: selection, tracking and drawing. The three haptic feedback conditions are illustrated in Figure 3.1. Examples of different task performing were showed in Figure 3.2. Under all of these conditions, users could move freely in the tracked VR space, and they could use any hand gestures that were comfortable to them.

In *no haptic feedback* condition, visual help like trajectory lines was showed to users so that they were aware of the positions of their hands and the display plane in VR. In the *physical haptic feedback* condition, users were provided with a physical flat plane. Additionally, this thesis adopted HapThimble to create the *virtual haptic feedback*.

The experiment was divided into three blocks, one for each of the feedback type conditions. The ordering of the feedback type was counterbalanced using a balanced Latin square method. For each condition of feedback type, the participant was exposed to 3 tasks, ordered randomly. Users needed to complete 10 trials for selection task, 20 trials for tracking task, and three trials for drawing task, then repeated all trials under three levels of haptic feedback conditions.

Overall, each participant executed 99 trials, in a single session lasting 60-75 minutes.

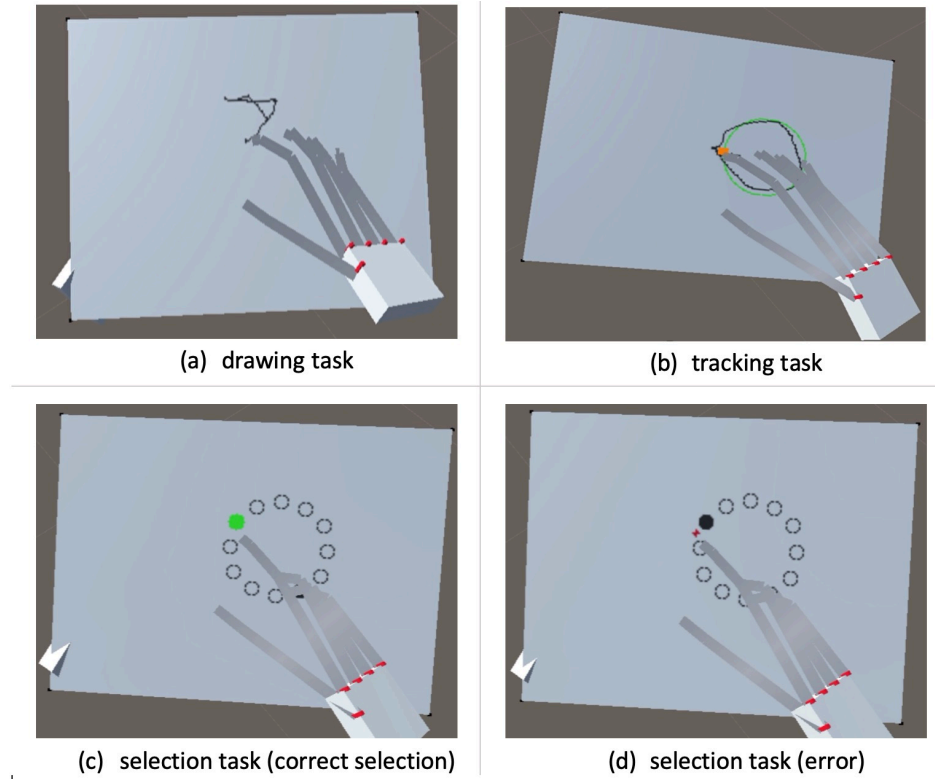


Figure 3.2: Processes of executing different tasks, including drawing(a), tracking(b), correct selection(c) and error selection(d).

3.4 Participants

Due to the COVID-19 situation, we could not conduct the experiment with participants. Instead, the author, who is a 24-years old female student, participated in this study. The participant was right-handed and used her right hand to touch the surface, then do the selection, tracking and drawing tasks. The participant had access to VR devices before and commanded basic interactive skills in VR. But she did not have sketching experience using VR devices, or professional drawing experience.

3.5 Apparatus

3.5.1 No Haptic Feedback

In the *no haptic feedback* condition, the participant wore the Oculus Rift S HMD. Optitrack markers were attached to each knuckle on both hands, one extra marker was placed on the fingertip of the right hand for contact detection. Both palms were attached to an Optitrack rigid body with a different number of markers, six markers for the left palm, and four markers for the right palm. Different rigid bodies

were used for each palm to distinguish them. In total, there were 43 markers on the user's two hands. The participant's left hand held a narrow paper slide with four markers attached in order to create a virtual handheld surface in VR which could not be touched by the right hand. Note that in the *no haptic feedback* condition, no physical drawing surface was used, but there was a virtual one displayed, and a matte gray background was rendered.

3.5.2 Virtual Haptic Feedback

In the *virtual haptic feedback* condition, the participant wore the Oculus Rift S HMD on the head, and wore a replication of HapThimble haptic device [29] on the right-hand index finger.

HapThimble was chosen as the virtual haptic device in this study because it has the state-of-art touch performance with virtual haptic feedback. Other mid-air tactile feedback methods like UltraHapticHap, or fingertip tactile device methods like Joystick, none of them can compare with the accuracy and speed of HapThimble.

The replication device in this experiment adopted the original 3D model structure of HapThimble. Same as HapThimble, this thesis used an LRA motor to create cutaneous feelings, and a servo motor to provide kinesthetic feedback. If the device was detected as being in contact with the plane, the LRA motor would produce a defined contact vibration(Figure 3.3.(a)). When the fingertip went through the plane, the LRA motor would produce a defined grain vibration(Figure 3.3.(b)), and the servo motor would begin pulling the cap in front of the fingertip to give the user a pressure. How many degrees the servo motor rotated was relative to the distance penetrated the surface. When the fingertip reached a maximum distance of 60 (mm), the LRA motor would produce a defined bottom-out vibration(Figure 3.3.(c)), and the servo motor would keep pulling the cap in front of the fingertip to give the user a maximum pressure.

Optitrack markers were attached to each visible knuckle on both hands. As for knuckles that were blocked by the HapThimble, the solution was to attach markers in the corresponding positions on the HapThimble device. One extra marker was placed on the tip of the HapThimble device for contact detection. Both palms were attached to an Optitrack rigid body with a different number of markers, six markers for the left palm, and four markers for the right palm. The participant's left hand held a narrow paper slide with four markers attached in order to create a virtual handheld surface in VR which could not be touched by the right hand. Note that in the *virtual haptic feedback* condition, no physical drawing surface was used, but there was a virtual one displayed, and a matte gray background was rendered.

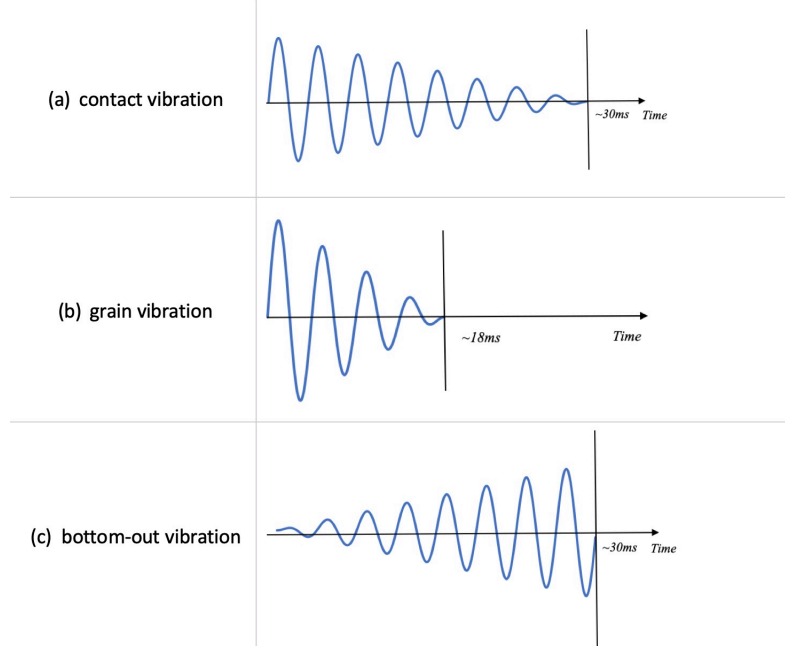


Figure 3.3: Signals to generate different vibration, including contact(a), grain(b), bottom-out(c).

3.5.3 Physical Haptic Feedback

In the *physical haptic feedback* condition, the participant wore the Oculus Rift S HMD. The hand tracking by Optitrack and display via HMD was the same as in the *no haptic feedback* condition. Except that the participant's left hand held a 255×205 (mm) physical see-through acrylic plane with a four-marker rigid body attached in order to create a virtual surface in VR. On the contrary to the other two conditions, *physical haptic feedback* allowed users' right hand to feel the touch. Note that in the *physical haptic feedback* condition, a physical drawing surface was used, there was a virtual one displayed, and a matte gray background was rendered.

3.5.4 Implementation

In all the three conditions, the hand position, orientation, and skeleton were tracked at 100 Hz using OptiTrack motion capture cameras like Figure 3.4. Basically, the OptiTrack cameras calculate the 3D position of each marker, and rigid bodies were tracked automatically. After the rigid bodies for palms were located, knuckles were integrated to different fingers based on the distance calculation to palms. A simplified 3D cardboard model of tracked hands and the 255×205 (mm) virtual display surface were rendered via the HMD. Single marker was easy to lose tracking than the rigid body. So if some markers are missing in a certain frame, then the hand will be rendered based on the current palm position with the same gesture as the last frame. It is a feasible solution because users tend to keep the hand gesture

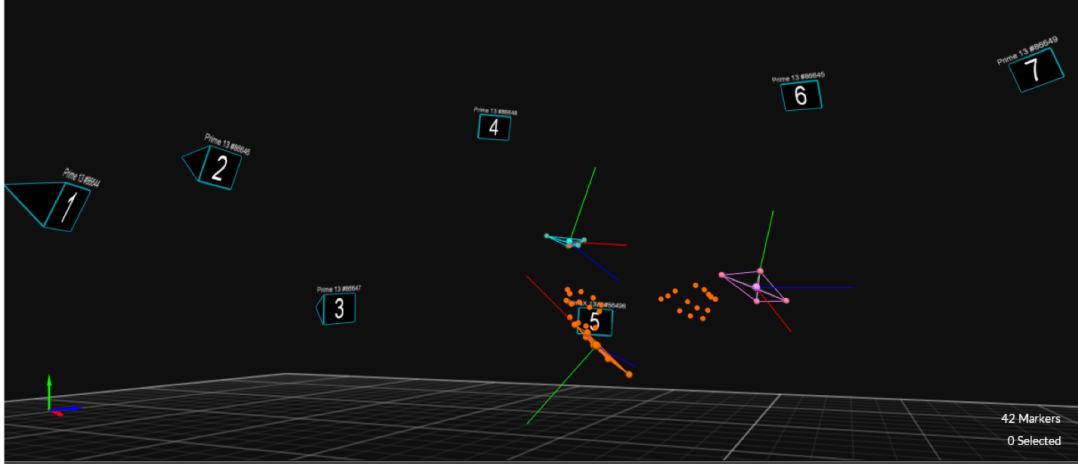


Figure 3.4: OptiTrack perspective view for hand tracking.



Figure 3.5: The distributions of markers attached to the free hands(a) and HMD(b).

stable when they perform the VR touching interactions in this experiment. The HMD was also tracked by the tracker with 6 markers attached. The distributions of markers attached to the free hands and the HMD are shown in Figure 3.5. The contact was decided based on the distance between the right-hand index fingertip and the plane. 3 (mm) OptiTrack facial markers were used on fingers, other markers attached to the rigid body was 9 (mm) OptiTrack markers. The Oculus Rift S display had a refresh rate of 80Hz. The software for the experiment was implemented in C# using Unity for rendering and interaction, and OptiTrack's Motive software for motion capture.

3.6 Procedure

The participant was introduced to stand inside of the experiment room that was tracked by the OptiTrack system, with any hand gestures as long as the user was capable of holding or wearing the devices that were needed in different haptic feedback conditions. In addition, hands could be at any position in front of the user, and the virtual surface would be rendered at the same place via HMD.

To test the user's continuous touch tracking capability under different haptic feedback conditions in VR, the participant was required to follow the showed trajectory (circle, triangle) on the display surface, and draw the path along with it by the right index finger. Specifically, the circle target stroke had a radius of 30 (mm), another one was a 60×50 (mm) triangle, and both of them were approximately at the center of the virtual surface in VR. For each target line, the user needed to repeat tracking ten times, as fast and accurately as people would on a conventional touchscreen. Every trial started with a target stroke rendered in green, along with a green starting button and a red stopping button. The user needed to point at the green button which was exactly at the starting point to start the trial, follow the green path, eventually, back to the start point, and click the stopping button which terminated the tracking trajectory. During the tracking part, the user was allowed to leave the canvas and move hands freely. However, the user should notice that only when the finger touched the surface, the tracking was regarded successful and the tracking stroke would be displayed.

Besides, the study investigated the user's continuous touch drawing capability under different haptic feedback conditions in VR. The same participant was required to draw three different pictures (bullet-shaped building, apple, writing) on the 3D surface with the right index finger, as fast and accurately as people would on a conventional touchscreen. Two sketches (a bullet-shaped building, an apple [5]) were given as references, and users were only required to write a simple word like "human". The size was unrestricted because it was a free drawing part, but the user should take efforts to replicate the given sketches as many details as possible, such as the shape, texture, and elements. For each sketch and the writing part, the user only needed to execute the task once. Every trial started with a blank plane rendered in white, along with a green starting button and a red stopping button at the corner. The user needed to point at the green button to start the trial, do the drawing task, eventually, click the stopping button which finished the drawing. During the drawing part, the user was allowed to leave the canvas and move hands freely. However, the user should notice that only when the finger touched the surface, the drawing was regarded successful and the drawing stroke would be displayed.

As for the selection task, the aim is to test the user's pointing capability under different haptic feedback conditions in VR. The user is supposed to point on targets with different sizes and go through

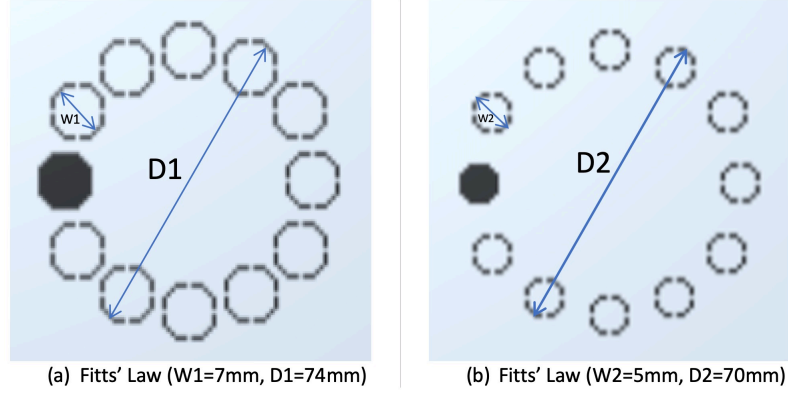


Figure 3.6: Fitts' Law test with different target size W and distance to target D .

different distances, this kind of pointing task is well known as Fitts' law [16]. Same as the other two tasks, users are supposed to execute the selection task by the right index finger, and as fast and accurately as people would on a conventional touchscreen. This experiment has two reciprocal pointing tasks in a 3D context. Both of them are two-dimensional (2D) tasks using serial target selections. The 2D task is one of the main performance testing procedures in ISO 9241-9 employing the Fitts' paradigm. Actually, it is a pragmatic extension to Fitts' law to support touch interactions commonly found in the wearable device [10], smartphone [42], tabletop [41] and so on. This study adopted the same settings of the Fitts' law 2D task, as Figure 3.6 showed, one had 7 (mm)-radius circle targets along with a maximum distance of 74 (mm). Another one had 5 (mm)-radius circle targets along with a maximum distance of 70 (mm). They were approximately at the center of the virtual surface in VR. Overall, each of them would be repeated 5 times, and involved 12 times of selecting in a random order every round. Every trial started with a target circle rendered in black, along with the other 11 circles rendered in a green line. The user needed to point at the black target circle, if it was successful, then the target would turn into green, otherwise, an error happened and the user should try again. After the participant finished one selection, the next target would turn into black immediately, and the user was supposed to point at that one. One thing that needed to be mentioned here was that if the user kept the fingertip on the surface, but the contact position was not inside of the target circle, then this kind of action was regarded as an error. In another word, the participant should pull up the finger from the surface after selecting, and go back to the surface again to do the next clicking. When all 12 selections were finished, one trial ended automatically. During the selection part, the user was allowed to leave the canvas and move hands freely. Besides, when the finger touched the surface, there would be a red dot at the contact position to make the participant be aware of the selection performance.

3.7 Data Preparation

During all experiments, a log-file was automatically written for each trial in order to measure the participants' behavior, e.g. overall task completion time, touch positions on the surface, hand positions, action errors, drawing/tracking result. In detail, the right-hand index fingertip movements were stored as sequences of 3D points sampled at 60 Hz, and each 3D point was represented by a 3D vector. If the finger touched the surface, the contact position would be recorded as the point on stroke produced by the user. The contact point was represented by a 2D vector which was calculated based on the relative location to the surface. Noise points were produced when the user approached the start and stop button during the drawing task. Consequently, data near the start and stop button were discarded to make strokes more consistent with the user's drawing.

3.8 Measures

Since there was only one user, this study conducted two way ANOVA with replication to analyze various measures. $p = 0.05$ was chosen as the level of significance.

The free drawing task recorded the task completion time, number of sample data, and computed the drawing speed (DS) which is defined in Formula 3.1.

$$DS = P/T \quad (3.1)$$

where DS is the drawing speed, P is total number of sample points on strokes, T is the task completion time.

In the tracking task, the first measure is the task completion time. The second one is Mean Projected Deviation (MPD) which calculates the average distance of the drawn stroke from the target stroke [6]. For triangles, MPD is defined in Formula 3.2 which means the average deviation from the local X-axis of each line. For circles, MPD is the average deviation from the target circle, and it is determined by Formula 3.3.

$$MPD_{(triangle)} = \frac{1}{n} \sum_{i=1}^n \sqrt{(p_i \cdot y)^2} \quad (3.2)$$

$$MPD_{(circle)} = \frac{1}{n} \sum_{i=1}^n \sqrt{(\sqrt{(p_i \cdot x)^2 + (p_i \cdot y)^2} - l/2)^2} \quad (3.3)$$

In selection task, the selection error, movement time (MT), and Fitts's index of difficulty (ID) [16]

were measured. Then examined the relationship between MT and ID by linear regression showed in 3.4.

$$MT = a + b \cdot ID = a + b \cdot \log_2 \left(\frac{2D}{W} \right) \quad (3.4)$$

3.9 Questionnaires

After finishing all task in each condition, participants were required to fill out a questionnaire and the NASA Task Load Index (NASA-TLX) [13].

The self-made questionnaire covered the task (selection, tracking, drawing) performing experience like fatigue, efficiency, confidence in contact, and qualities of the interaction techniques. Questions including “Which type of haptic feedback do you prefer?”, “How you feel about different haptic feedback conditions?”, “How confident you are in different haptic feedback conditions?”, “How much fatigue you feel in different haptic feedback conditions?”, “What is the best experience in the test?”, “What is the worst experience in the test?”, “How you feel about the system?” etc. Consequently, this study was able to measure user satisfaction, task difficulty, perceived properties of the task (selection, tracking, drawing) process under different haptic feedback situations (*no haptic feedback*, *virtual haptic feedback*, *physical haptic feedback*).

The NASA Task Load Index (NASA-TLX) is widely used in assessing a task about its workload, effectiveness, perceived performance, etc. The user was supposed to rate for each task on six subjective subscales: mental demand, physical demand, temporal demand, performance effort, and frustration. Then the six measurements were also compared pairwise by the user to decide their perceived importance related to workload.

Chapter 4

PRELIMINARY RESULTS

The results presented in this section are preliminary results from a single user. Testing data was correctly collected, valuation methods were chosen by rationality and corresponding analysis was conducted. For the following performance measurements, ANOVA test was showed as an example for future analysis, pairwise T test would also be adopted after in-person study was allowed. Although the results and analysis here are not statistically meaningful, they provided guidelines for the actual study in coming.

4.1 Selection Performance

4.1.1 Error

If the user touched the surface but the pointing position was not inside the target object, an error was produced. This task recorded the number error selections in each trial(one round of 2D Fitts' Law test), then summed them up to calculate the error rate. The user made the least mistakes in the *physical haptic feedback* condition, followed by *virtual haptic feedback* and *no haptic feedback*. And selecting smaller objects led to more errors. Nevertheless, there were no significant differences in the error rate or the number of errors for the two Fitts' Law tasks performed under the three conditions ($F_{(2,59)} = 18.90, p = .0502$). While these two Fitts' Law tests with different target size W and distance to target D affected the error notably ($F_{(1,59)} = 34.71, p < .05$). As a state-of-art device that can generate virtual haptic feedback, HapThimble was efficient with a low error rate on basic VR tasks like clicking and dragging. But the producers of the original HapThimble mentioned that they manipulated 55×55 (mm) virtual objects in the experiment for clicking or dragging tests, while the distance between targets was fixed as 20 cm[29], both of the parameters were much larger than ours. In addition, although

Table 4.1: Error rates and the numbers of errors for Fitts' Law tests in different haptic feedback conditions.

Haptic Feedback	Error Rate / Number of Errors	
	Fitts' Law (W=14, D=74)	Fitts' Law (W=10, D=70)
physical haptic feedback	20.00% / 12	38.33% / 23
virtual haptic feedback	30.00% / 18	46.67% / 28
no haptic feedback	43.33% / 26	53.33% / 32

HapThimble was claimed to be small, portable, it was still hard to wear a cylinder body with 25 (mm) diameter, meanwhile, touch an exact tiny place (5mm, 7mm in our case) on the tablet compared to the bare hands. Consequently, the unexpected high error rate might be caused by our relatively small size of the portable surface, which brought about the small target size and small movement distance. All these factors, undoubtedly, increased the uncertainty and difficulty of selection tasks.

4.1.2 Fitts' Law MT/ID Relationship

Except for the selection error, this study also looked into some essential elements of Fitts' Law test by building linear regression for MT and ID, then examine the correlation for the fit. From 4.1 and 4.2, a conclusion could be drawn that the selecting performance in the *physical haptic feedback* condition best fitted Fitts' Law. Samples in *no haptic feedback* were more randomly distributed, one that far deviated from the fitted line was produced when the user missed the correct position. Then the participant would be easy to mess up with the spatial location without any haptic feedback, therefore, spent extra time finding a route to go back to the track. As for some off-the-track samples in *virtual haptic feedback*, the cause could also be the Hapthimble sacrificing some degree of freedom of the hand, extra time was needed to recognize the virtual feedback which was quite demanded especially when the target size and movement distance was small. In general, the fit results in the Fitts' Law (W=14, D=74) test was better than the Fitts' Law (W=10, D=70) test. This was understandable because the former one presented bigger target objects while the user's movement distances had little difference in these two tests.

Besides, if attention was paid to the slope (b value) of the linear regression result for each haptic feedback condition and in both Fitts' Law tests, the *physical haptic feedback* condition had the smallest b value, the second on was *virtual haptic feedback*, then was the *no haptic feedback*. Since smaller b value would contribute to shorter movement time (MT) and larger throughput (TP) which were definitely preferred, the user achieved best selection performance when a physical surface was offered to rely fingers on.

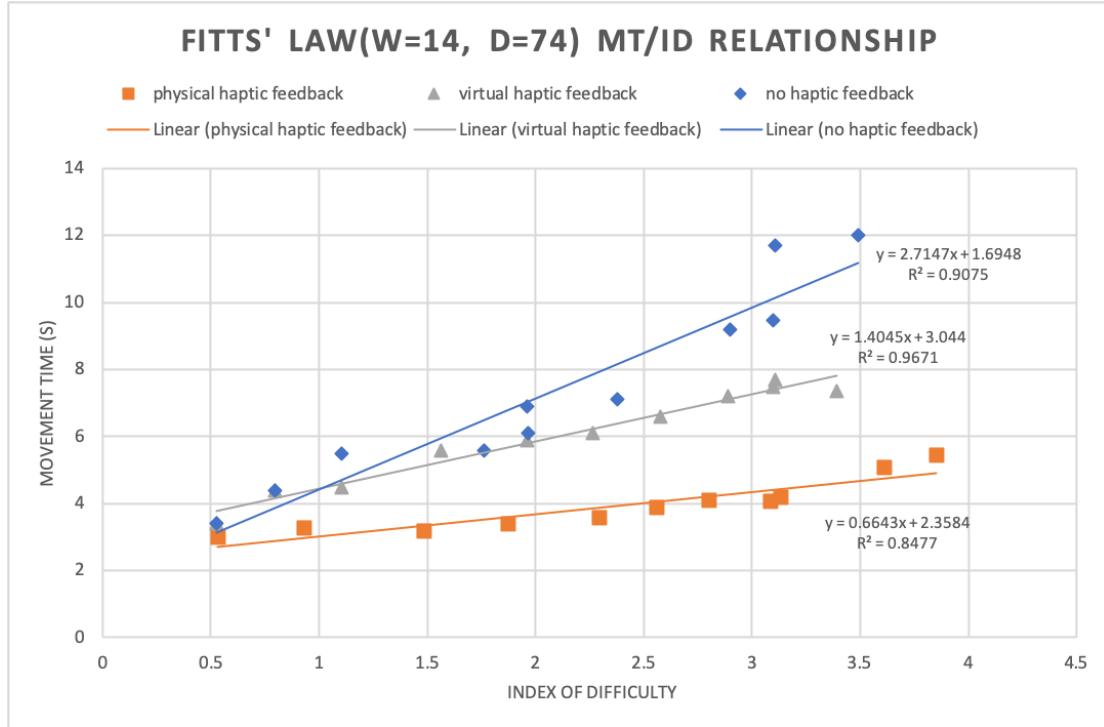


Figure 4.1: Fitts' Law Movement Time (MT) / Index of Difficulty (ID) Relationship.

4.2 Tracking Performance

4.2.1 Strokes Trends

Figure 4.3 was the visualization of circle-and-triangle trackings (b). Circles and triangles were drawn in different conditions (a). Each of the result illustrations integrated tracking results for 10 tracking trials. In the *physical haptic feedback* condition, the circle and triangle tracking strokes drawn by the user were much more centered on the given path than the other two, and their shapes were matched with the given one. Both circles and triangles under the *virtual haptic feedback* condition were split a little than the results in *no haptic feedback* condition. However, the shapes under the former situation were smoother. It seemed to be harder for the user to hold the finger in the wanted right position under the latter one. Since virtual haptic feedback would make the user keep feeling the virtual plane, the user could focus on the task. On the opposite, when the user felt nothing in the *no haptic feedback* condition, the hand situation could be distracting. For example, the user might move a lot while being unsure about the exact places of hands or the surface.

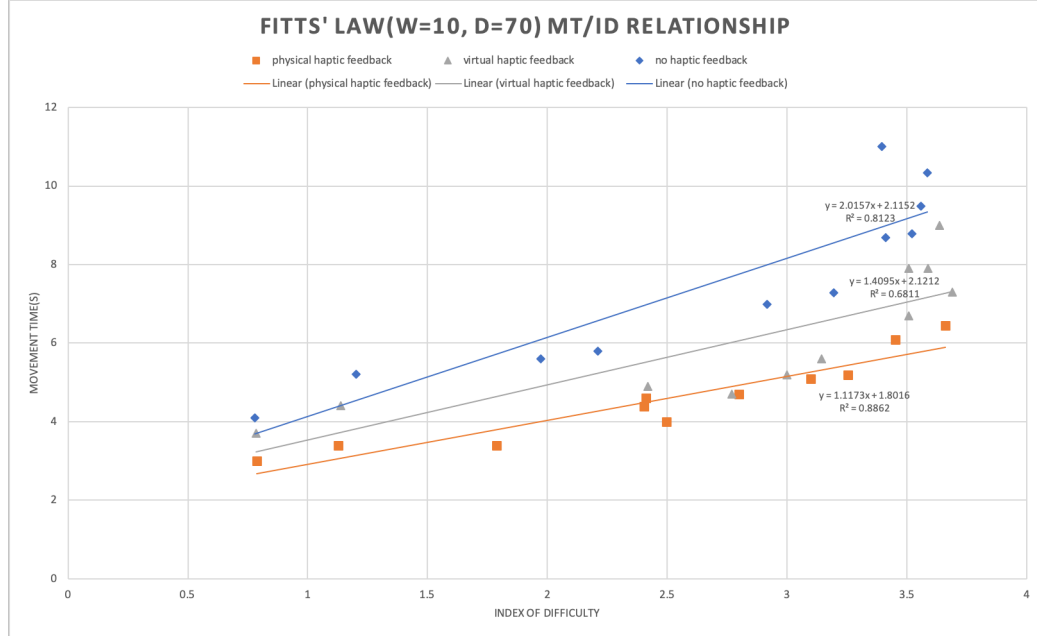


Figure 4.2: Fitts' Law Movement Time (MT) / Index of Difficulty (ID) Relationship in different haptic feedback conditions.

4.2.2 Mean Projected Deviation

Both of different haptic feedback ($F_{(2,59)} = 23.25, p < .05$) and different required tracking path ($F_{(1,59)} = 52.61, p < .05$) contributed to the mean projected deviation of the strokes drawn by the user for tracking actions. The *no haptic feedback* condition had the highest deviation, then was the *virtual haptic feedback*, the deviation for *physical haptic feedback* was optimal. The values for circle-tracking were in order as $M = 1.94mm, SD = 1.79mm$; $M = 4.81mm, SD = 4.67mm$; and $M = 5.93mm, SD = 5.42mm$. And values for triangle-tracking were in order as $M = 4.85mm, SD = 4.36mm$, $M = 9.54mm, SD = 8.62$, and $M = 10.22mm, SD = 9.78mm$. the Lower mean projected deviation means that the tracking result obtained more conformity with the target one, while lower standard deviation means the performance was more stable. Consequently, the user still had the statistically best tracking performance in the *physical haptic feedback* condition, which was consistent with the tracking trajectory trends as well.

The difference between the two patterns (circle, triangle) suggested that drawing a straight line in VR might be more difficult, compared to curve lines. Especially when there was no haptic feedback for the user to rely on, and spatial sense was quite demanded in such a case. This hint echoed the straight-line texture drawing about the “bullet” that was mentioned in the drawing results section.

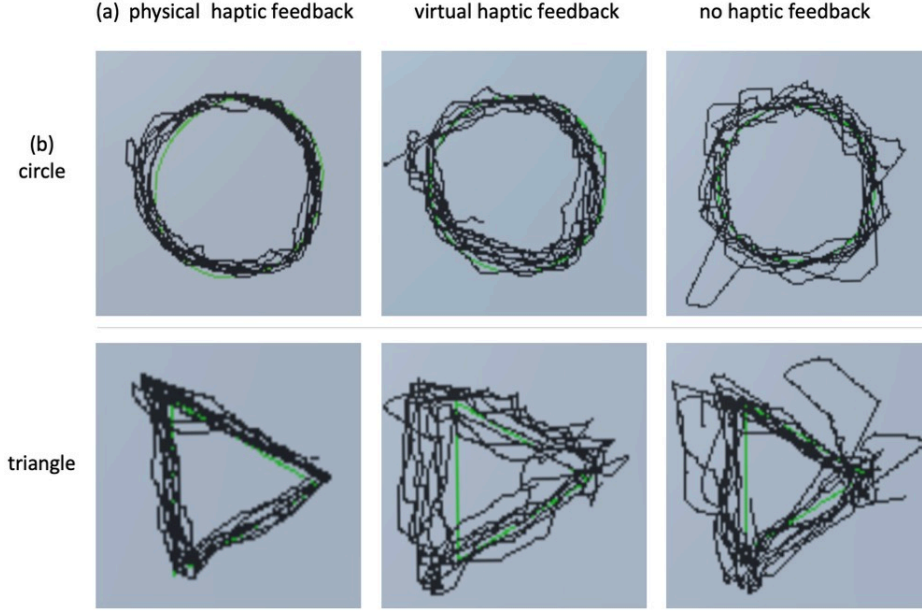


Figure 4.3: The user's tracking strokes of all trials in different conditions(a) and tasks(b).

4.2.3 Task Completion Time

There were significant differences in the tracking task completion time for the two tasks performed under the three conditions ($F_{(2,59)} = 11.79, p < .05$). When tracking a circle, the time needed to finish the task for the *physical haptic feedback* condition ($M = 11.81s, SD = 1.19s$) was much less than that for the virtual ($M = 18.37s, SD = 4.79$) and no ($M = 16.80s, SD = 2.56s$) haptic feedback condition conditions. Triangle tracking tasks have the similar result, the *physical haptic feedback* condition resulted in the shortest time ($M = 8.50s, SD = 0.84s$) followed by *no haptic feedback* condition ($M = 14.88s, SD = 6.88s$), and *virtual haptic feedback* condition ($M = 15.27s, SD = 3.50s$). Recall the tracking quality in different haptic feedback conditions, the participant spent less time when a physical planed was offered because both speed and performance were achievable. But in the *virtual haptic feedback* condition, the user might be distracted by the HapThimble device due to the mental tactile sense requirement. It might be surprising that when the user was in the *no haptic feedback* condition, tracking also finished quickly than in the *virtual haptic feedback* condition. But unlike the *virtual haptic feedback* condition where the user could still make efforts and take time to guarantee the tracking quality, the *no haptic feedback* certainly caused some frustration to users. Lack of patience, the user would end the task as soon as possible, regardless of the performance.

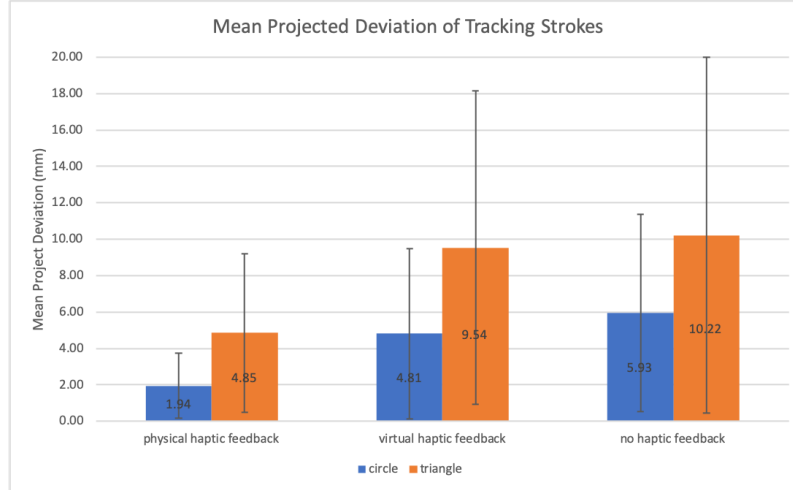


Figure 4.4: Mean Projected Deviation in tracking sessions. Error bars are standard deviation.

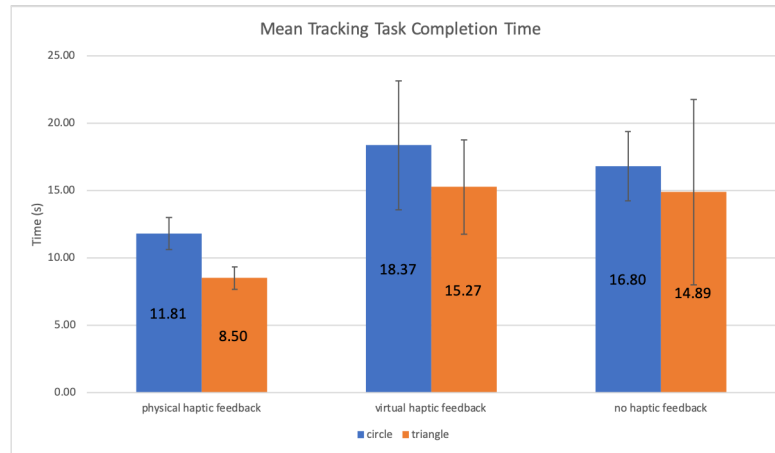


Figure 4.5: Mean task completion time in tracking sessions. Error bars are standard deviation.

4.3 Drawing Performance

4.3.1 Sketches

The drawing result showed interesting clues about drawing performance under different haptic feedback conditions. This section presented all drawn sketches in Figure 4.6. Results in the *physical haptic feedback* condition looked better in aesthetics than the same task in other conditions. The shapes of apple and bullet were more clear, smooth, and in line with the given example. The user was able to come out with more details, especially the shadow lines on the apple and the straight lines on the bullet texture. The writing in the *physical haptic feedback* condition was also more readable, all letters were approximately at the same horizontal level, and their tilt degrees were consistent as well. The apple and bullet which were drawn in the *virtual haptic feedback* condition go wildly but they could still keep

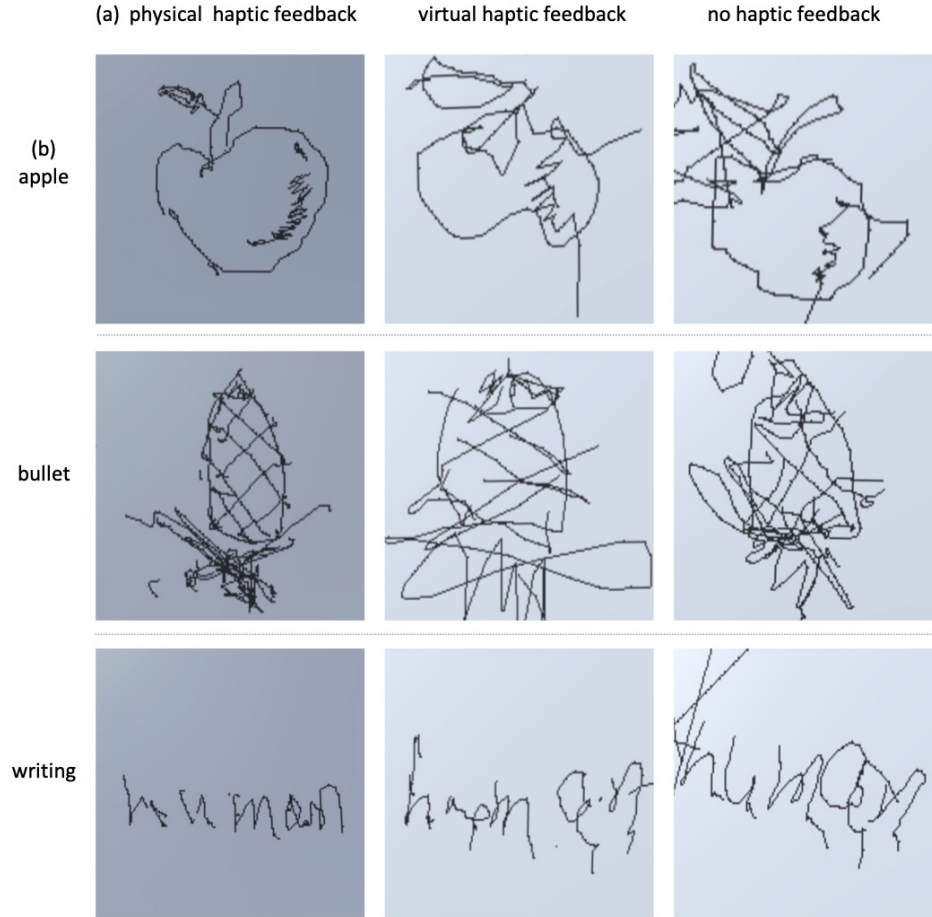


Figure 4.6: The user’s drawing results. Sketches drawn in different conditions(a) and tasks(b).

the shape in general. The writing result in the *virtual haptic feedback* condition ruined certain letters like the “u” in “human”, although the configuration of letters was reasonable. Undoubtedly, the user performed worst if there was *no haptic feedback*. Drawing and writing results were hard to recognize because of the noisy lines created by the participant.

4.3.2 Task Completion Time

The time that the user spent on finishing a picture was various on tasks. As it showed in the Figure 4.7, the user took more time on drawing apple and bullet in the *physical haptic feedback* condition, which was expected, because the user could lean the finger on the plane and sketch in details. As for the same-word writing, the user finished more quickly in the *physical haptic feedback* condition than the other two. Consider the sketch result in the last section, the participant accomplished easier writing in the *physical haptic feedback* condition. However, due to the inconsistency among tasks, the statistic

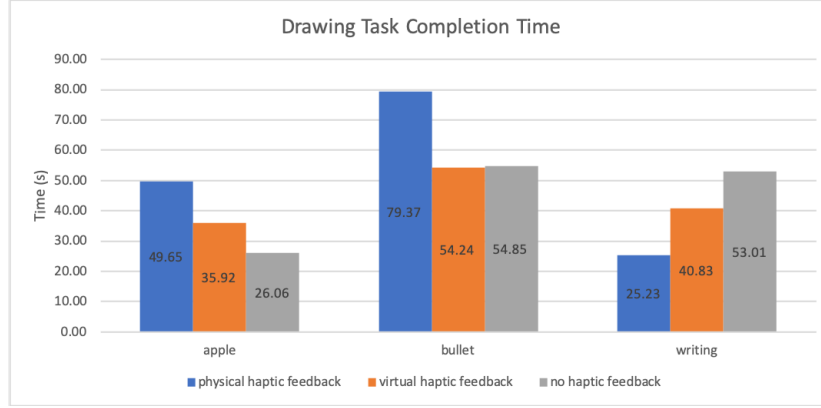


Figure 4.7: The user’s drawing completion time in different conditions and tasks.

conclusion on the task completion time could not be made. There were no significant differences in the total time for the three drawing tasks performed under the three conditions ($F_{(2,8)} = 0.22, p = .81$).

4.3.3 Pointing Finger Trajectory

This section also visualized the 3D positions of the user’s pointing fingertip (Figure 4.8) in order to find some interesting insights about the drawing performance. The user’s pointing finger can focus on a relatively small space when a physical plane was held. From the sketching result in the previous section, the user was working on a detailed drawing or stable writing in this situation. Finger movements in other conditions were more wildly which indicates looser control. Although sometimes the participant input many spatial data, such as the “bullet” sketching under the *virtual haptic feedback* condition and the writing process in the *no haptic feedback* condition, the strokes on the display surface did not have high-quality as what in the *physical haptic feedback* condition. This happened when the user’s finger moved a lot but did not contact with the drawing surface, which was a waste of efforts. One more important thing that could be learned from the finger trajectories is that the user’s finger moved on the y-axis with minimal variation under the *physical haptic feedback* condition. The movement was caused by the plane with the left hand as well as the right-hand gesture change. The second smallest y-axis movement distance happened in the *virtual haptic feedback* condition, and the user got the maximum y-axis movement distance in the *no haptic feedback* condition. Since the y-axis was exactly the direction of the surface, some ideas could be proposed about the benefits of haptic feedback on stability. In this drawing experiment, having a physical plane to rely fingers on worked best in keeping drawing fingertip stable, and the *virtual haptic feedback* was better than nothing.

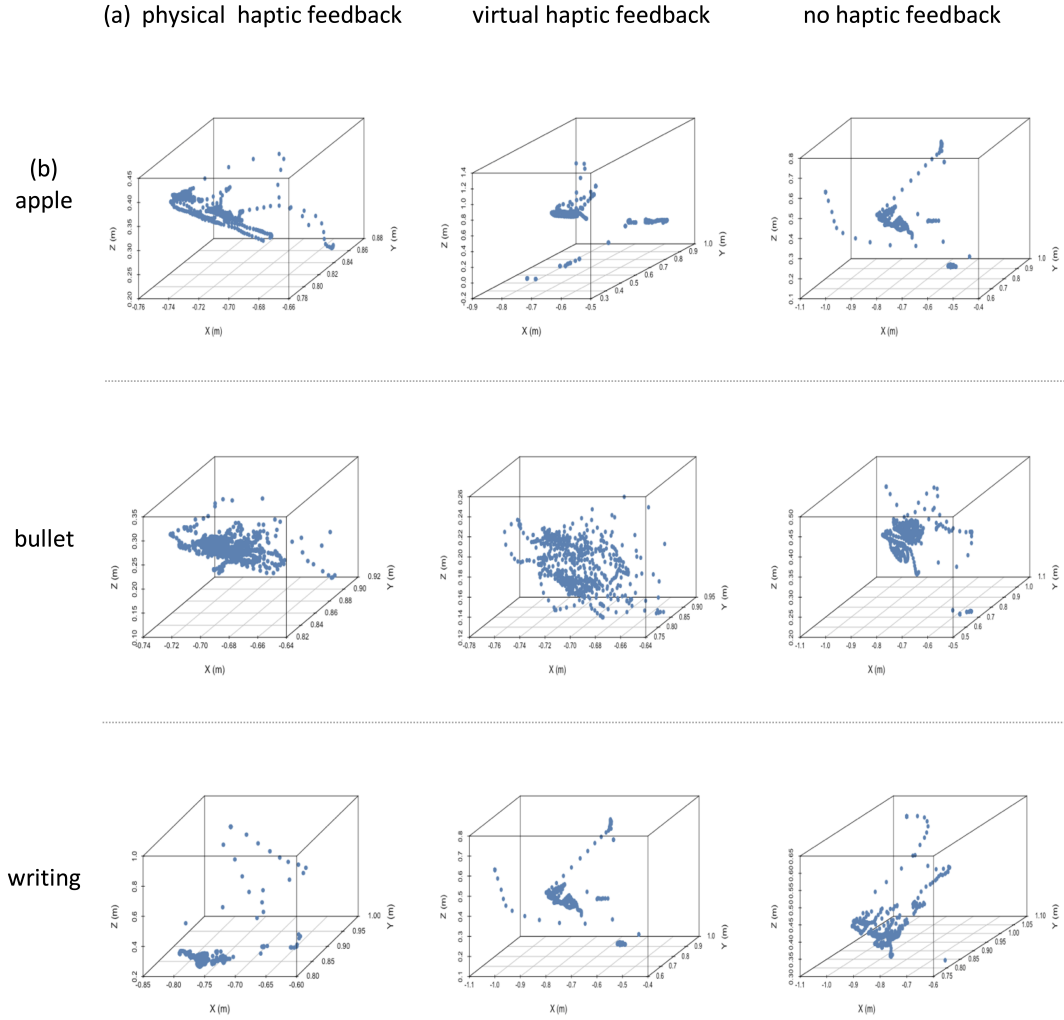


Figure 4.8: The user's pointing finger trajectory in different conditions(a) and tasks(b).

4.3.4 Supplemental Study: Drawing Behavior on Drawing Speed

This study went further and looked into the drawing speed which is not only corresponding to the completion time, but also related to the sample number on strokes. The drawing speed comparison was presented in Figure 4.9. In general, users left more strokes on the surface when *physical haptic feedback* was available. The drawing process may be more efficient under the *physical haptic feedback* condition, as long as users did not stop the finger on the surface deliberately for a long time. This is reasonable since the user would be more hesitant when approaching the virtual display surface without a physical one. Hovering over the plane did not contribute to the drawing result, as the pointing data was not regarded as a successful drawing.

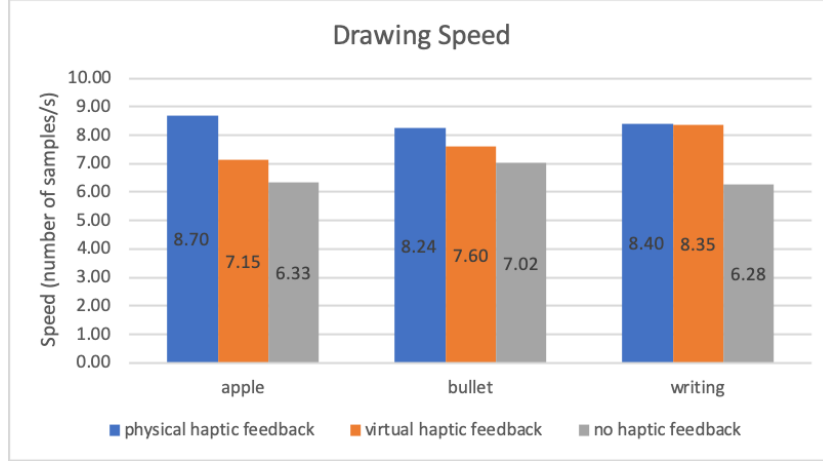


Figure 4.9: The user's drawing speed in different conditions and tasks.

4.4 Questionnaires

The user preferred *physical haptic feedback* in all tasks. She mentioned the problem of doing tasks without a physical surface was that her finger kept moving in all directions. For example, when the fingertip moved up and down, some strokes were missing because it was not on the surface. In this case, the user would go back to the missing part and tried to fix it which was even more demanding, usually ended up picking the wrong restart position and leaving unwanted noisy lines. Even if the user managed to hold her finger on the surface, another situation was moving too fast and wildly as a result of lacking continuous force feedback like frictions. Consequently, unexpected deformation of results was likely to occur. When only low-level haptic feedback was provided, due to these issues, the user tended to be more hesitant when executing simple tasks, but losing patience on complex tasks. Another important point was about the system, the user could feel In addition, one shortcoming about the system's usability was the direction of the surface and the hand position would affect the tracking quality by cameras. Since the experiment used an acrylic plane, it would create reflective lights in a certain direction, thus interrupting the marker tracker. And the hand gesture sometimes would be rigid due to the tracking loss.

4.5 NASA-TLX

The results of task load with the NASA TLX procedure were shown in Figure 4.10, which indicated that on average, there is no significant difference in three haptic feedback conditions ($F_{(2,17)} = 2.48, p = 0.13$) or each subscale among three haptic feedback conditions ($F_{(5,17)} = 0.86, p = 0.53$). Since different haptic

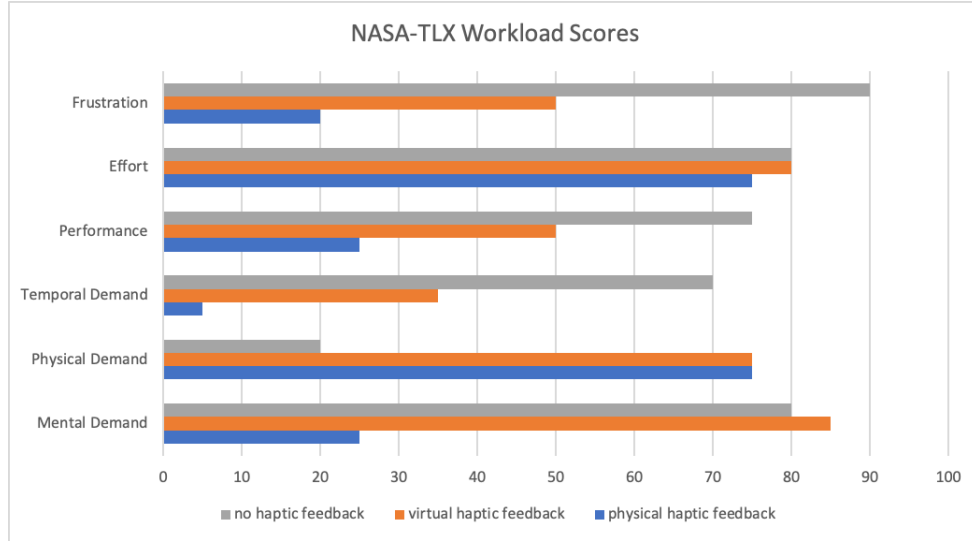


Figure 4.10: NASA TLX task load scores of executing different tasks in the three haptic feedback conditions.

feedback required effort for different work. But it could still be figured out that the workload of *physical haptic feedback* was rated as smallest except for the “physical demand” because the user needed to hold the acrylic surface for about 20 minutes during doing in the *physical haptic feedback* condition. On the opposite, the “physical” workload was quite low in the *no haptic feedback* condition, while all other factors were very demanding under this situation where the user interacted with free hands. For *virtual haptic feedback*, efforts were required both physically and mentally. Cause the user wore the HapThimble device for around 20 minutes and should keep the mind on the virtual haptic feelings. The following pairwise tests were consistent with the scaling result. Physical demand affected the performance in the *physical haptic feedback* condition most. For *virtual haptic feedback*, the most important demanded perceived factor was mental capability. Frustration and mental demand got the same top weight in the workload of *no haptic feedback*. Besides, all haptic feedback conditions demanded average efforts which indicated VR tasks were kind of strenuous in general.

To summarize our findings from the user study, *physical haptic feedback* was significantly better than the *virtual haptic feedback* and *no haptic feedback* in terms of drawing speed and tracking performance. From the experiment, having a physical plane helped with aesthetic value when drawing. Selections performance also best fitted Fitts’ Law under the *physical haptic feedback* condition. The participant preferred *physical haptic feedback*, followed by *virtual haptic feedback*. In general, the user suffered most when there was no haptic feedback at all. However, due to the users’ number and limited trials, statistically significant differences in workload and selection error were not observed in any of the metrics used for analysis.

Chapter 5

DISCUSSION and FUTURE WORK

Previous research [5, 6, 14, 25, 31] demonstrated that a physical surface could enable more efficient pen interactions for virtual object manipulation tasks like 3D drawing in VR. A physical surface can provide tactile haptic feedback as well as kinesthetic haptic feedback for users when they perform tasks on the surface in VR. With the development of virtual haptic feedback technologies, realistic haptic feedback can also be stimulated by arousing human illusions about the touch surface, which is known as virtual haptic feedback. As professional 3D designers already dive into the VR spatial work field, they increasingly developed an urgent demand for more efficient, effective, and high-quality interactions, as a reason for a professional or commercially valuable 3D design requires more drawing functions and precision than entertainment. An approaching future can be foreseen that more people tend to make use of VR interactivity. In that situation, due to the sole single-point interaction and need to be carried by the user all the time, pen interactions will not be enough for people from various fields, and for all kinds of purpose. However, hands are the most dexterous parts of our human body, and people use hands almost everywhere. Consequently, hand interactions in VR are destined to be the routine just like how people interact with the real world by bare hands.

5.1 Haptic Feedback and Tasks

Consequently, this study investigated hand interactions on surfaces in VR by touch gestures. The result was observed that the level of haptic feedback and the difficulty of tasks significantly influenced touch

performance in VR. The physical surface improved the aesthetics quality of sketches even the user did not have 3D drawing experience nor was she an expert in drawing or design. Since only one user participated in the experiment, who needed to complete all trials in the within-subject study which was quite time-consuming, only simple sketches were required in the drawing part. If more users can be recruited, including people from the 3D design area in the future, and they are allowed to create complex sketches or free sketches, the result is supposed to be more promising and convincing. The user was more willing to spend time on drawing physical surface, 43% more than *virtual haptic feedback* and 59% more than free-hand drawing without haptic feedback in specific. The user was also more confident in the *physical haptic feedback* condition, since she inputted more useful touch data per time unit. The drawing speed was 15% faster than *virtual haptic feedback* and 27% faster than *no haptic feedback*. What varied more obvious was the writing performance, it was 38% quicker in the *physical haptic feedback* condition than *virtual haptic feedback* and only took the half task completion time of *no haptic feedback*, while *physical haptic feedback* still ranked top concerned the quality.

The tracking results under three levels of haptic feedback were quite consistent with the drawing part, since tracking can be regarded as simple drawing with some visual help. This study used the mean projected deviation from the user's tracking path to the target one. This measurement basically indicates the goodness of the strokes fit and the accuracy of the tracking process. Averagely, *physical haptic feedback* had 53% less errors than *virtual haptic feedback*, and 58% better than *no haptic feedback*. So *physical haptic feedback* combined with the visual help could lead to a good performance, but if it was also beneficial for the other two types of haptic feedback, our study did not show useful insights. The performance of HapThimble in the tracking task was expected to be better because it stimulated both of the tactile and kinesthetic haptic feedback. However, it had a similar deviation with *no haptic feedback* and more time-consuming. Based on the illustration of tracking pathes (Figure 4.3), it can be noticed that they were smoother than tracking results of *no haptic feedback*, the line was more straight, but deviated from the target line in a whole. Consequently, in addition to the distraction from the task by mental demand this thesis mentioned in the results section, the size of the HapThimble may still be an explanation. In the other two conditions, the marker tracked as the pointing tip was directly attached to the user's index finger. The user could see and feel it when touching, so it could be easily located at a wanted point. But HapThimble increased the diameter of the fingertip by 2-3 times, which could cause a problem for users to figure out the touching tip.

The correlation of the Fitts' Law MT/ID relationship did not fit well in the *virtual haptic feedback* and *no haptic feedback* conditions. Thus may also made the error rate show no significant clues on different haptic feedback. Another possible reason might be the contact tracking method. Currently,

the way to decide whether a fingertip is in contact with the surface in this study was calculating their euclidean distance. This measurement would be affected by the tracker, such as the fingertip was not tracked by the camera, then will absolutely influence the accurate selection. Another possible influence might be the delay caused by the HapThimble, which also means the delay of the *virtual haptic feedback*. The user might contact the surface and made a mistake without knowing the fingertip's position.

In general, our experiment gave insights that when users perform tasks in VR, if there is kinesthetic or tactile haptic feedback, it will be better for accuracy and fatigue than the no-feedback condition or even visual feedback. Additionally, when users perform tasks in VR, if there is a physical surface for users to rely on, it will be better for accuracy, fatigue.

5.2 Limitation and Future Work

There existed some factors, other than the three haptic feedback conditions, may also affect the study result. Although this thesis aimed to evaluate ungrounded haptic feedback, HapThimble is a body-grounded interface, it has a grounding physical barrier. Virtual haptic devices do not have physical results, experiences with no haptic feedback even do not have any touch feeling, physical interfaces certainly work distinctly, these might also contribute to the different touch performance on VR surfaces.

The performance of HapThimble in our experiment was not always as expected because the servo motor that provides kinesthetic haptic feedback to the fingertip has a 60 ms delay. Consequently, there exists a situation where the user already went through the surface, but the cap did not give out a force in time. One possible solution is to use a prediction algorithm and proactively start the servo motor to avoid the latency. However, if users keep moving fingers up and down near the surface, it will be difficult to estimate the appropriate timing or distance threshold for the prediction algorithm. A more sophisticated algorithm that predicts the user's action in advance by measuring the hovering behavior [19] may solve this problem. As for the contact detection algorithm, a contact sensor can be adopted instead of calculating distance. Besides, the size of HapThimble was not suitable for manipulating small targets. However, the authors of HapThimble commented that it is very difficult to reduce the size while preserving the feedback quality [29]. Future work can turn into other virtual haptic feedback methods that involve smaller devices on producing vibrotactile feedback [31]. Another point is to evaluate precise selections on different targets so that the level of precision can be clarified.

The third problem was the low hand tracking performance of the system. Due to the COVID-19 situation, the experiment had to be conducted in a small room. So the camera settings may not be optimal, and the whole environment was easy to be interrupted by illuminatory or light-reflective

objects. In addition, an intuitive algorithm was used to render the cardboard hand skeleton, which required all markers to be tracked by the cameras. For more stable and robust tracking, I may use the Sleight of Hand [23] method that can track the full movement of fingers using a reduced marker sets. This method can be utilized to reduce the hand tracking workload and the difficulty of hand skeleton rendering.

The biggest limitation of our study was the limited number of users. All results presented in this thesis were from a single user and therefore were not statistically meaningful. However, the intent of this thesis is to develop measures and analysis methods and get some insights before running an actual experiment with participants. Since the current devices were only made for right-handed users, after it is possible to recruit a diversity of people, left-handed users should also be under consideration.

The future work will, therefore, focus on polishing the study setup, including improving the tracking performance and hardware performances, and conducting experiments with actual participants. If the future study proved the preliminary results, then the big blue picture is to create a new touch interface that users can have a surface to lean their fingers. This thesis wants to go further than just making a study or helping people figure out which type of haptic feedback works best. There are all kinds of hand interactions, not only entertainment, but also for professional usage. Current existing interactive systems are not enough to meet the needs of consumers from all walks of life. Consequently, more efficient interactions are in urge demand, and building touch interaction interfaces that provide physical haptic feedback is promising for VR hand interaction technologies.

Chapter 6

CONCLUSION

Witnessing the need for precise and efficient interaction for 3D design and the potential of utilizing physical surface with pens, I am positive that the hand interactions on physical surfaces would be appreciated by the designers and professionals. Virtual haptic feedback methods create a virtual surface and provide users with sensitive touch feelings. However, it was unrevealed if having such haptic feedback would be sufficient for efficiently and effectively completing challenging tasks such as drawing. This thesis investigated the impact of different-level haptic feedback on various VR tasks, including selecting, tracking, and drawing. Three conditions were implemented in high-fidelity, including the replication of the state-of-art virtual haptic feedback method, HapThimble [29]. A preliminary experiment showed that having a physical surface to rely on can be beneficial for interactive hand-based VR tasks by improving speed, accuracy, and precision. I hope this finding would help with the further exploration of different haptic feedback, and shed some light on new VR interactive technology design. However, more research is needed to expand the study to large groups and obtain statistically important results in the end.

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