Media Engineering and Technology Faculty
German University in Cairo

Modeling sensory-motor experience during object manipulation in Augmented Reality (AR)

Bachelor Thesis

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Supervisors: Dr. Dennis Kuster
Dr.-Ing. Felix Putze
Submission Date: 28 August, 2019

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This is to certify that:

- (i) the thesis comprises only my original work toward the Bachelor Degree
- (ii) due acknowledgment has been made in the text to all other material used

Student Name
28 August, 2019

Acknowledgments

I would like to express my gratitude to both Dr. Dennis and Dr. Felix, my projects supervisors, for their guidance, knowledge, and support. My special thanks are extended to my family and close friends for their support and encouragement throughout this period.

Abstract

What does it feel like when one controls a tool? Would it feel like it is being extended from one's own body? This thesis is a cornerstone for the PALMS study. Plasticity of the minimal self can be defined as the ability to shape or extend Body Image and Body Action. The PALMS project studies the plasticity of the minimal self in healthy aging in tool-use dependent tasks. In our current study, we developed an object manipulation experiment in AR. Whereby having one's hand tracked, one could then move their hand to control a tool(gripper) in AR. The aim of the task is for one to touch the gripper's middle part with the front side of the target cube. Moreover, one should avoid touching the sides of the target cube. One would then put on a tactile glove, which would then generate tactile feedback once the tool comes in contact with a target. The primary question we had for our current experiment was, Would a task with haptic feedback have a better performance than a task without haptic feedback?

For our experiment, we divided the participants into two groups, Group A (without Feedback first) and Group B (With Haptic feedback first). In Group A, in the first two blocks (first half of the trials), one will not get haptic feedback as the tool comes in contact with the target. Then in the second two blocks (second half of the trials), haptic feedback would be present. Such that participants will get haptic feedback as the tool comes in contact with the target. Conversely, in Group B, in the first half of the trials, haptic feedback would be present. Then in the second half of the trials, haptic feedback would be absent.

Results show that Haptic Feedback helped participants to perform the task better. No differences in the average workloads between the two groups or the two conditions were observed. Each participant had their own threshold level, a level of difficulty that a participant fluctuates within. No learning effects in any of the two groups in blocks with the same condition were observed. No sequence effects were observed. The order of the chunk of blocks between the two groups did not appear to show any differences.

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Chapter 1

Introduction

Body Ownership and Body Agency are two of the most important topics in modern psychology. Body Ownership is the notion of body parts being perceived as part of one's own body. While Body Agency can be defined as actions or events that are performed by these body parts. Body Ownership can be termed as Body Schema, and Body Agency can be termed as Body Image.[\[15\]](#) The combination of both Body Ownership and Body Schema is known as the Minimal Self.

Many related studies have been conducted to study our sense of body embodiment in virtual reality environments. Our objectives were to understand minimal self in fully matured human perception and examine how the mature human brain adjusts to change its natural embodiment. This project is a cornerstone to analyze the short and long term effects of the tool usage in AR, PALMS Study. PALMS is a German acronym for Plasticity of the minimal self in healthy ageing. Plasticity of the minimal self can be defined as the ability to shape or extend Body Schema or Body Agency.

For this thesis, We conducted a behavioural pilot study. Which will be later built on to conduct the final PALMS Study. In the current study, we asked one major question, given a virtual task in the augmented reality environment. Would Haptic feedback help in this task or not?

For this task, one would move their hand in the real world. Having one's hand tracked, one would control a tool in the AR environment. By moving their hand in the real world, the tool would then move respectively in AR. The aim of the task is, using a tool (gripper) which is slightly wider than a target cube, One should touch the front side of the target cube with only the middle part of the gripper for two seconds. Avoiding touching the left or right sides of the target cube, as shown in figure 1.1. One also would put on a haptic feedback glove, which would then produce tactile feedback once the gripper comes in contact with the target cube. Touching the target cube with the right part of the gripper would generate haptic feedback on the index finger. Touching the target cube with the left part of the gripper would generate haptic feedback on the thumb. Touching the middle part of the gripper with the front side of the target cube would generate haptic feedback on the palm. Furthermore, We would then require the participants to have their

hand in a fixed gesture, As shown in Figure 1.2. Giving the virtual sense that the tool is extended from between their fingers (index and thumb). Finally one will have twenty seconds to complete this task.

Figure 1.1: The Task ProtoType In 2D

Figure 1.2: The Hand Gesture

The experiment consists of 4 blocks (a chunk of trials), each block will have 60 trials. The experiment will then have two blocks with haptic feedback and two blocks without haptic feedback. Such that in one-half of the trials, participants will get to feel haptic feedback as the gripper comes in contact with the target cube. While in the other half of the trials, Haptic Feedback would not be present. For our experiment, we divided the participants into two groups, Group A (without Feedback first) and Group B (With Haptic feedback first). In Group A, in the first two blocks (first half of the trials), one will not get vibrations (haptic feedback) as the tool comes in contact with the target

cube. Then in the second two blocks (second half of the trials), haptic feedback would be present. Such that participants will get to feel vibrations(haptic feedback) as the tool comes in contact with the target cube. Conversely, in Group B, in the first half of the trials, haptic feedback would be present. Then in the second half of the trials, haptic feedback would be absent.

For our current experiment, we had three primary questions:

- 1- Within each group, Would we see learning effects for any for the two groups? i.e., would the performance for each of the groups separately get better with the time between blocks 1 and 2 of the same feedback condition or blocks 3 and 4 with the same feedback condition?
- 2- Would we observe sequence effects? For example, does the trials with haptic feedback in Group B(with Feedback first) have a different (better or worse) Performance than Group A(without Feedback first). The same would be studied for Without haptic feedback trials.
- 3- Would trials with haptic feedback for the two groups combined have a better performance than the Trials without haptic feedback.

Moreover, we used the NASA TLX Questionnaire which measured the average workload for the two groups and the two conditions in general.

We had constructed five Hypotheses. Our primary hypothesis was that trials with haptic feedback would have a better performance in terms of the difficulty level reached, and the failed trials by the participant. The second hypothesis was that there would be a high learning effect observed in each of the two groups individually. By learning effect, we mean that we expect to see a difference between blocks with the same condition. Block 2 would have better performance than Block 1. Also, Block 4 would have better performance than Block 3. The third hypothesis was that a sequence effect would be found. Such that for example, Haptic feedback Trials in Group A (without Feedback first) would have a better or worse performance than haptic feedback Trials in Group B (with Feedback first). The same would be applied for without haptic feedback trails for the two groups. Furthermore, Our fourth hypothesis was that there would be differences in the average workloads between the two groups, or the two conditions were expected. Finally, Our fifth hypothesis was that each participant is going to have a threshold level, a level of difficulty that a participant fluctuates within, for every one of the four blocks in the experiment.

Chapter 2

Background

2.1 Literature Review

Related work to this thesis can be divided into two categories: The first group is about studies about the minimal self and tool use dependant tasks that discover the association between body-ownership and body-image. While, In the second and final category, We will discuss studies that used haptic Feedback in AR/VR applications.

2.1.1 Plasticity of the Minimal Self

Plasticity of the minimal self can be defined as the ability to shape or extend Body Schema and Body Agency. As discussed by Botvinick and Cohen "Rubber hand illusion is an illusion that may be induced by an experimenter tapping a person's real but hidden hand, while synchronously tapping a rubber hand placed in a visible and plausible position in front of the subject. The real hand is hidden behind a screen. After a short period of such stimulation, the person has the illusion that the rubber arm is their Armand feels the taps from the location of the rubber hand." [7]

By comparing the rubber hand illusion and using tools as a form of embodiment. In a study by De Vignemont [8], it was discussed that if different means of body embodiment, involve only one mechanism or not. This paper concluded many important points. First, they reveal that if the rubber hand is replaced by a different object such as a piece of wood or a tool, it does not give rise to the same illusion. Secondly, that tool-use affect spatial perception, motor imagery, and even time perception. Thirdly, Depending on different tasks, whether being perceptual or motor. Some Perceptual and motor characteristics of the object are not being processed as if they were characteristics related to one's particular body. Not only within the motor embodiment but even among perceptual embodiment, some of the perceptual characteristics of the objects are not being processed as if they were properties of one's body. Finally, For only a short time, Tools can change the characterization of one's body for action. It requires that the action should have the

long-term, flexible representations for bodily parameters such as size, strength, etc.. It should be able to rapidly and temporarily change to fit the current characteristics given by a tool.

Next, We will discuss three studies that conducted experiments to see the link between Body Image and Body Schema.

Link between our sense of limb ownership and self-awareness of actions

In a study by Baier, Bernhard and Karnath, Hans-Otto [3]. They inquired into the clinical relationship and the anatomy of abnormal attitudes and AHP (anosognosia for hemiparesis/-plegia) towards, or perceptions of the affected limb(s), for Hemiparetic stroke patients with disturbed awareness for their motor weakness. The term "anosognosia" is a description of patients who ignored their hemiplegia. And Hemiplegia or Hemiparesis is a condition that affects one side of the body. Seventy-nine acute stroke patients with right brain damage and hemiparesis, different kinds of abnormal attitudes concerning the hemiplegic limb were investigated. 92% of the patients with AHP showed more "disturbed sensation of limb ownership" (DSO) for the paretic/plegic arm or leg. The patients did not feel that their affected limb(s) belonged to their body or even may belong to another person's body. To sum up, The right posterior insular cortex was concluded to be a significant structure that is involved in the genesis of our sense of limb ownership and self-awareness of actions. Thus, a disturbed sensation of limb ownership for hemiparetic/-plegic limbs and AHP are tightly linked both clinically and anatomically.

Furthermore, In a study by Ackroyd, Katie and Riddoch, M Jane and Humphreys, Glyn W and Nightingale, Simon and Townsend, Stella [1], They investigated a patient name HB where he had severe neglect of left and far spatial regions. His ability improved when detecting visual targets in left and far space, only, when he held a tool. Also, He had little tactile knowledge about the location of his hand. By holding a tool, the data suggest that HB's visual space could be extended to have stimuli presented at various distances from his body. This extension of space while holding the tool improved his detection of visual stimuli.

Tool Morphology Constrains the Effects of Tool Use on Body Representations

In a study by Miller, Luke E, and Longo, Matthew R and Saygin, Ayse P [17], They investigated whether the tool's morphology limits one's plasticity or not. They constructed two experiments, experiment one is on hand morphology, and experiment 2 is on arm morphology. They varied whether the tool used in the experiment was structurally similar to one's body part. Using a tactile distance judgment (TDJ), They tested the role of tool morphology in representational plasticity. Experiment 1 is divided into two parts 1A

(hand tool) and 1B (arm tool), by checking the representational plasticity on the hand. Experiment 2 is divided into two parts 2A (hand tool) and 2B (arm tool), by checking the representational plasticity on the arm.

Using the target body surface and forehead (control surface) before and after tool use, Participants judged the tactile distance between pairs of points applied to their tool. Significant representational plasticity in hand shape (increase in width, decrease in length) was discovered when the tool was morphologically similar to a hand (Experiment 1A), but not when the tool was arm-shaped (Experiment 1B). Furthermore, significant representational plasticity was found on the arm when the tool was arm-shaped (Experiment 2B), but not when hand-shaped (Experiment 2A). Their results prove that the morphological similarity between the tool and the hand or arm limits tool-induced representational plasticity.

They concluded that for Tools to have a meaningful effect, they should necessarily need to be shaped like one's body. On the other hand, some tools such as the cutlery are efficient because they have structural characteristics that are very different from our bodies. Nevertheless, the embodiment of an external object can be relying on it having a size or shape similar to one's own body. For instance, the main factor that the rubber hand illusion works is that the object is having the overall shape of a hand.

2.1.2 Minimal self in VR

In this section, We will discuss two studies that were conducted to study the replacement of a person's real body, specifically the arm, by a virtual representation. First, there are two terms used among all three studies:

Proprioceptive drift is the difference between the initially felt place of the hand and the place of the hand after the experiment.

Ownership illusion questionnaire, 7-point scale, which is used by Botvinick and Cohen (1998) in their study. The questions are:

1. Sometimes I had the feeling that I was receiving the hits in the location of the virtual arm.
2. During the experiment, there were moments in which it seemed as if what I was feeling was caused by the yellow ball that I was seeing on the screen.
3. During the experiment there were moments in which I felt as if the virtual arm was my own arm.
4. During the experiments there were moments in which it seemed that my real arm was being displaced towards the left (towards the virtual arm).
5. During the experiment there were moments in which it seemed that the contact that I was feeling originated in some place in between my own arm and the virtual arm.
6. During the experiment there were moments in which I felt as if my real arm was becoming virtual.
7. During the experiment there were moments in which it seemed (visually) that the virtual arm was being displaced towards the right (towards my real arm).

8. During the experiment there were moments in which the virtual arm started to look like my own arm in some aspects.
9. During the experiment there were moments in which I had the sensation of having more than one right arm.

The Rubber Hand Illusion In VR

In this study, They demonstrated if Provided proper multisensory correlations, A a virtual limb, for instance, an arm, can be made to feel as if was belonging to one's body. In a virtual Reality Environment, participants saw a completely virtual arm being horizontally projected out of their right shoulder. Their arms were hidden from their view by a sheet of grey foam fixed to the side of the shelf. The experimenter then taps and strokes the participant's real hand with a 6-degree freedom hand-held 'Wand' device, whose position is being tracked and used to simulate the position of the virtual sphere. This virtual sphere moves relative to the wand.

By having two groups, the first was subjected to synchronous tactile stimulation, where the tap of the real wand matched the virtual sphere. While in the other group had asynchronous tactile stimulation where the tapping was used where the virtual sphere moved to a prerecorded pattern and did not match the tapping. An experiment with 21 male participants, with synchronous tapping, showed positive displacement of ownership towards the virtual hand, as shown by the Ownership illusion questionnaire responses and proprioceptive drift. Conversely, in control experiment with asynchronous tapping was carried out with another set of 20 male participants who did not experience the illusion.

This proves that a completely virtual object can, therefore, be experienced as part of one's self. In the group with synchronous tactile stimulation of the person's real hand and the virtual one, it would result in the same illusion as the rubber hand illusion. This can be shown first by significantly higher responses for questions 1, 2, and 3 compared to questions 4–9. Second, the drift measurement of the perceived hand position should show average drift significantly higher than zero. On the other hand, in the asynchronous control condition, the illusion would not be experienced in this condition. Therefore greater Ownership illusion questionnaire scores and drift in the synchronous condition were shown, when compared to the asynchronous condition.^[19]

A Long Arm Illusion

In this study, they conducted a long arm illusion experiment in VR. With 10 participants per condition, there were 5 conditions in a between-groups experiment. All conditions had visuomotor congruence between the real and virtual arm. In an Incongruent condition, where the virtual arm length was equal to the real length, but there was no visuotactile congruency. In four Congruent conditions, there was visuotactile congruence. In the first category, the virtual arm lengths were either equal to (C1), double (C2), triple (C3) or quadruple (C4) the real ones.

Ownership illusion questionnaire scores showed that the overall level of ownership was high in both categories C1 and I, and they showed a significant difference between each other. Moreover, participants showed body ownership over the virtual arm up to three times the length of the real one, and lesser at four times the length. However, The illusion did decline with the length of the virtual arm being more significant. Throughout the C2-C4 conditions, a measure of proprioceptive drift was positively correlated with virtual arm length. However, there was no correlation between the drift and ownership of the virtual arm, hinting that there exist different underlying mechanisms between ownership and drift. In conclusion, these findings show that multisensory and sensorimotor information can reconstruct our perception of the body shape, size and symmetry even when this is not similar to the normal body sizes.[12]

2.1.3 Haptic Feedback Applications In AR/VR

Haptic feedback

Haptic Feedback is the use of a virtual form of tactile sensation, mostly in the form of vibrations, to communicate with users. These forms of vibrations also known as vibro-tactile, which means the perception of vibration through touch. The Tactile sensation refers to the sense of touch, specifically the information received from varying pressure or vibration against the skin. The somatosensory system constitutes a part of the nervous system, that has a complex organization of sensory neurons and pathways that respond to changes at the surface or inside the body. It also includes many different specialized types of receptors. One type sends information about vibration, one about pressure, one about pain, etc..The vast majority are familiar with haptic Feedback as a form of vibration in a mobile phone or a game controller. The use of haptic Feedback in AR/VR is used mostly to simulate touch events, creating a virtual sense of touch.

Haptic Feedback is a combination of both Tactile and Kinesthetic Feedback. Kinesthetic Feedback: It is the sensation you get in your muscles, joints, tendons. Imagine holding a book in one's hand. Kinesthetic Feedback tells one's brain information about the general characteristics of this book. For instance, its approximate size and its weight. While on the other hand, Tactile Feedback is the sensation one gets in the surface of one's body; for example, one's 'fingers.'. The tissues in one's fingers have numerous sensors on and under one's skin. Tactile Feedback lets one's brain sense information such as vibration, pressure, touch, texture, etc.

Haptic devices are mechanical devices that mediate communication between the user and the computer system. Haptic devices allow users to touch, feel, and manipulate three-dimensional objects in virtual environments. The haptic system consists of the entire sensory, motor and cognitive components of the body-brain system.[9] Haptic devices can be classified into two groups depending on the sense triggered either Tactile or Kinesthetic Feedback devices.

Tactile Feedback Devices

This category can be divided into three approaches cutaneous, active surfaces, and mid-air. The cutaneous method is currently the most commonly used in Tactile feedback devices among the three approaches. An excellent example of the cutaneous approach is vibrations in smartphones or game controllers. The second approach is the active surfaces. An example of this approach could be Project FEELEX [10]. With high resolution and accuracy, Active surfaces have an astounding performance for rendering surfaces. On the other hand, most of these devices are not portable because of their haptic actuators design. Finally, the last approach is Mid-air devices, which serves as a medium for touchless interactions. Being used in haptic Feedback, many studies, Ultrasonic/ultrasound haptic devices are the most common mid-air devices. However, Their size and weight do not make them a good wearable solution for mobile Augmented Reality applications.

Kinesthetic Feedback Devices

This category is divided into three approaches Manipulandum devices, Grasp devices, Exoskeleton devices. Manipulandum is a device that can simulate virtual forces using grounded systems with Different Degrees of freedom. An example could be the phantom device [16]. Grasp devices allow users to interact with their hands and virtual objects. Furthermore, users can push, pull, and move virtual objects similar to the way it is done in the real physical world. An example could be the CyberGrasp by CyberGlove Systems. Finally, Exoskeleton devices are devices which provide forces on natural Degrees of freedom of the body. Depending on the application, the size, weight, and complexity for such exoskeletons could vary. For instance: with grasping interfaces, haptic gloves may be enough; in other scenarios such as walking stimulation it may be necessary to attach a device to the legs.[6]

From their usage in a 3D surface generation, Laboratory prototypes to study the different, Braille systems, Tactile Vision Substitution Systems, Educational Applications, and Games[5]. We will focus on three applications of haptic Feedback in Augmented Reality Applications.

Haptic Feedback in AR Applications

In this study, they created a Tool Kit In AR that provides a realistic physics simulation that mediates interactions between users and objects and also direct interactions between users. They Adapted the Manipulandum Kinesthetic Feedback approach. As mentioned in the paper, an example for this approach could be the following: an instructor can 'grasp' the student's tool to haptically guide it while the student feels the force of the instructor's guiding hand. Similarly, the instructor feels any resistance caused by the student. They can also collaboratively push, stretch, pull the objects (organ and

tools) around the scene, with attached objects stretching and moving accordingly. They converse through a separate voice link.[2]

In this study, They proposed an algorithm to modulate both friction and weight using haptic devices. Simple but effective algorithms for estimating and altering these properties have been developed. The hardware used was PHANToM premium 1.5, which also falls under the Manipulandum Kinesthetic Feedback devices. The first approach allows for stimulating the friction between a tooltip and a surface. The second approach enables a user to perceive an altered weight when holding or lifting an object.[11]

The third and final study is about Tactile augmentation of real and virtual environments. They proposed a technology called REVEL. Which is an AR tactile technology that allows for change to the tactile feeling of real objects by augmenting them with virtual tactile textures using a device worn by the user. When sliding one's fingers on a surface of the object, the user perceives highly distinctive tactile textures augmenting the physical object. [4]

Chapter 3

Methodology

This chapter is a discussion about the tools used in this thesis; their advantages, limitations, and how they were combined to design the experiment.

3.1 Haptic Feedback And Hand Representation

For our purposes, we need to give haptic feedback on the tip on each finger. Particularly, the thumb, index and the palm. As well as have the joint angle data per tendon for each finger. Such that we can use this information to detect whether the participant has their Hand in the correct predefined gesture or not. The only obvious limitation for this glove is that haptic feedback generation is only for the fingertips and the centre of the palm. Thus we cannot give vibrations on different parts of the finger for instance.

CyberTouch 2, a device by CyberGlove Systems, has vibrotactile sensors into the inside of the fingertips as well as the palm, as shown in Figure 3.2. Moreover, it has 22 sensors to represent the Hand in 3D. Three flexion sensors per finger, as shown in Figure 3.3, four abduction sensors, a palm-arch sensor, and sensors to measure wrist flexion and abduction. A flexion sensor is a sensor that measures the amount of deflection or bending. An abduction sensor measures the amount of separation between each finger. A palm-arch sensor is a sensor that measures how far the palm is bent. All these sensory data are in the form of radians.

3.1.1 Using Cyber Touch 2 To Give Haptic Feedback

Using CyberGlove Systems' C++ Framework, we were able to write our own c++ script, which consisted of 6 functions each responsible for controlling for each of the 6 vibrotactile sensors. By passing a value in the range 0-1 for each function, the sensor would then give vibrations relative to this value (a value of zero stands for no vibration and a value of 1 stands for the maximum vibration of the sensor can output). We then exported the script as a DLL(dynamic link library file) which would be then imported in Unity giving access to all 6 functions.

3.1.2 Using Cyber Touch 2 For Making A Virtual Hand Representation

We need a virtual hand representation to make sure if the participant has his/her Hand in the agreed-upon gesture. For our purposes, we only care about the index and thumb representation, As the gesture only consists of the thumb and index being in fixed positions. Using the same method, we used to write the functions to generate haptic feedback. We wrote our functions in c++ to get the amount of deflection for each of the three tendons per the thumb and the index, And the abduction value between the thumb and index. We would then assume that the centre of the Hand is the (0,0) position. We would then measure the vertical distance manually to each of the three tendons per thumb and index respective to the centre. Using these values and the flexion data. For each tendon, we calculated the following to get the vertical distance for each finger respectively:

```
-Vertical Distance For Finger = Sin(Inner Tendon flexion angle) *
Inner Tendon Vertical
-Position from the hand centre + Sin(Outer Tendon flexion angle) *
Middle Tendon Vertical
-Position from Inner Tendon Position + Sin(Outer Tendon flexion angle)
Outer Tendon Vertical Position from the Middle Tendon Position
```

As for the gesture we currently need to recognize, the thumb and index have to be relatively close to each other, in the same vertical position. Knowing the vertical position for each of the fingers, we can determine in real-time if the participant has his/her Hand in the correct gesture. We do so by defining a threshold for example 1 unit and getting the difference between the vertical positions for both fingers, and if this difference is less than or equal 1 unit, then the participant has his/her Hand in the correct gesture.

Figure 3.1: Cyber touch Sensory Data Visualization

Figure 3.2: Cyber touch's 6 vibrotactile sensors

Figure 3.3: Cyber touch's 22 sensors representation

3.2 Hand Tracking

We needed to track the hand motion in real-time. Such that the Tool in the Augmented Reality Environment moves relative to the hand movement in the real world. We first needed to track the hand motion externally then pair both Hand's position and orientation to the virtual tool AR application.

The required tracking system should satisfy the following: 1. Being able to track a big field of detection 2. Being easily mobile and have little to no wiring 3. Has the capability to track both position and orientation in 3D

This Section is a discussion about the different tracking systems that we considered for this experiment.

3.2.1 Color Tracking

The idea was by tracking a coloured marker that is strapped on one's Hand. Then we can track the position of the coloured marker in 2D. As shown in Figure 3.4, Using OpenCV,

We were able to create a program that tracks only one specified coloured. Which would then, in real-time, keep track of the 2d position of this colour.

This is done by mounting the camera above our tracking area. Such that the vertical distance between the tracking area and the camera is always fixed. Then by capturing the image in real-time from the webcam then turns the image into HSV(hue, saturation, lightness) Frame, and by specifying a range (maximum and minimum value) for the colour, we need to track in HSV coordinates. This was done using the predefined function `inRange` in OpenCV. Following, having the new HSV frame, which only has the desired colour, we created a structuring element that is used to dilate and erode image. Dilate and Erode are morphology operators. Erode: This function erodes the source image using the specified structuring element that determines the shape of a pixel neighbourhood over which the minimum is taken. Dilate: This function dilates the source image using the specified structuring element that determines the shape of a pixel neighbourhood over which the maximum is taken. In short, this helps to make the edges of the colour tracked as smooth as possible. Finally, to detect the (x,y) Coordinate, we would then find the contours of the filtered image, then we would find the moment for each contour. A contour is simply the boundary of an object in an image. Whereas An image moment is a certain particular weighted average of the image pixels' intensities. After having the moment for each contour, we would then calculate the area for each, as shown in the following pseudo-code:

```
//The predefined constant value "const_value" in this pseudo code
//determines how big the area of the detected colour should be
//FOR THE X POSITION:
IF ABS(Old X position - moment.m10 / area for contour) > const_value
THEN:
    Current X position = moment.m10 / area for contour
    Old X position = Current X position
//FOR THE Y POSITION:
IF ABS(Old Y position - moment.m01 / area for contour) > const_value
THEN:
    Current Y position = moment.m01 / area for contour
    Old Y position = Current Y position
```

Figure 3.4: The binary Image of the detected color(Left) The original Image with a green dot on the center of tracked Color(Right)

Moreover We exported this C++ program to Unity as a DLL, and then by having the 2D coordinates in real-time in Unity, we would then check how many pixels the colored marker moved each frame and made the Tool in Unity move by a fixed easily calibrated value, For example for each 5 pixels moved in the 2D frame the Tool in Unity will move by 2 units in Unity's world space respectively, as shown in figures 3.5 and 3.6.

Figure 3.5: Tool's initial Position

Figure 3.6: Moving the colour marker to the right (Left) The tool moves to the right respectively (Right)

Using the Intel real sense camera which can get the image's depth (i.e. Z coordinate in 3D). We were then able to use the RealSense SDK to get the depth of the coloured marker point (x,y) that we got using the method described above. This would then enable to detect the position of the coloured marker in 3D. First, we had to align both the 2D and 3D frames. Then by we used `getDistance` function to get the distance between x and y coordinates. After which, we used `rs2DeprojectPixelToPoint` function that takes the (x,y) coordinates and the distance between them, To get the uniform, all in the same scale, 3D coordinates for these (x,y) coordinates. Shown in Figure 3.7.

Figure 3.7: Moving the colour marker upwards (Left) The Tool moves upwards respectively (Right)

The next step was to track the orientation in 3D. To do that, We used 3 different coloured markers, shown in figure 3.8, and using the method described above, we used it to get the 3D position of each one separately. We used these three 3D points to calculate the equation of the plane in 3D. To receive these three 3D coordinates as well as the coefficients of the plane in Unity, We used TCP Sockets to send this data over to Unity. The reason for doing it this way rather than using DLLs was that RealSense Framework was required to be imported in Unity for it read this DLL. Because the Realsense Framework was not reliable in Unity, we then used TCP sockets to send the required information instead. After sending the three points to Unity and the coefficients of the plane equation. We first got the central point between the three points, and this was done by getting their average, this point was used to determine the position of the Hand. The final step was to get the orientation of the plane (i.e. the plane formed by the three coloured points). Using the `Quaternion.LookRotation` function in Unity. It takes a vector that can be considered the straight path from 0,0 to the vector's end position. It computes the direction, Quaternion, from the world origin (0,0,0) to specified vector target position. We used this function to get the rotation from the plane's normal, using the coefficients sent from the TCP Socket for the normal vector. We used the following pseudo-code to get the plane's rotations:

```
Quaternion normalRotation =Quaternion.LookRotation(plane.normal)
Vector3 scale = new Vector3(1,1,1)
Vector3 right = Vector3.Scale(normalRotation * Vector3.right, scale)
Vector3 up = Vector3.Scale(normalRotation * Vector3.up, scale)
// line parallel to the 3D plane
Vector3 PlaneParallelLine = (Plane Origin - up) - (Plane Origin +up)
PlaneRotation = Quaternion.LookRotation(PlaneParallelLine)
```

Figure 3.8: Three coloured markers

Now, After having both the position and the orientation of the plane, we evaluate this approach. As for the position tracking, the system was tracking it accurately but under three conditions:

1. The room had to be well lit, as the darker the tracking area was, the more noise existed, and it was harder to track the coloured markers.
2. The choice of the coloured markers had to be taken into account. I.e. Which colours to use. When using colours similar to the skin colour or colours close to other objects in the Real-world scene. It was harder for these colours to be detected.
3. The camera should not be far off from the tracking area, in terms of the vertical distance between the colour to be tracked and the camera. As the further apart the tracking area from the camera, the harder it was able to detect the coloured markers. One solution to make this better was to make the area for detecting each specific colour smaller. This helped to increase the distance between the camera and the tracking area a bit. However, if the camera was at a distance of more than about one and a half meters from the tracking area, Then even when making the area for colour detection so small the tracking failed.

Regarding the orientation tracking, It was not reliably accurate. As the depth for each of the coloured markers fluctuated at about 2-5% of its original value. Thus even when the coloured markers were on the same horizontal plane, having the same Z value in the real world, each of the coloured markers would have a different Z value virtually. Which in turn caused an inaccurate estimation in the orientation.

To conclude, The colour tracking was useful only when estimating the position under-maintained bright light conditions and at a small fixed distance between the tracking area and the camera with coloured markers that could be distinguishable from other objects in the real world scene.

3.2.2 Leap Motion

Leap motion is a hand tracking device, shown in Figures 3.9 and 3.10, that tracks both hands' and fingers' movements and orientations. It has three infrared LEDs, which emits pattern-less IR light. Also, it has two IR cameras.[20] Leap Motion can then accurately determine the hand position and rotation in 3D. It has a maximum field of view of 150 degrees. The effective detection range roughly extends from 0.25 to 60 cm above the device. As it has a Unity package, We were able to test their system quickly. We would then use Leap motion controller in Unity to get the right Hand's position and orientation, which we then paired with the Tool in Unity such that the tool moves and rotates relative to the real Hand, As shown in Figures 3.11 and 3.12. It worked accurately If the Hand lied in the field of view of the device. For tacking to work, the Hand should not be covered or occluded. Which then would make it hard for our purposes as the participants wear the CyberTouch glove in our experiment, which then makes it nearly impossible for the leap motion to track the Hand accurately.

Figure 3.9: Leap Motion

Figure 3.10: Hand positioned above the leap motion

Figure 3.11: Moving the hand to the left (Left) The tool moves to the left respectively (Right)

Figure 3.12: Rotating the hand in the x-axis (Left) The tool rotates respectively in the x-axis (Right)

Leap Motion and Color Tracking

To conclude, Integrating the colour tracking for finding the position and the leap motion for getting the orientation worked accurately with no latency. This helped to take advantage of the more significant field of detection for the position tracking in 3D. However, we still did not find a way to expand the field of detection for the Leap motion. We also were not able to eliminate the disadvantages of using coloured marks tracking.

3.2.3 IMU

An inertial measurement unit(IMU) is an electronic device which is equipped with tri-axis accelerometers, tri-axis gyroscopes, and tri-axis magnetometers, and in some cases barometer. We used mbientlab's MetaMotionR IMU, which is a wireless Bluetooth IMU, which has 9 motion sensing axes (3 for accelerometers, gyroscopes, and magnetometers). We wanted to estimate both orientation and position using the IMU. Check figure 3.13.

In a study by Sebastian Madgwick, he introduced an algorithm that calculates the IMU's orientation. This algorithm uses both 6-axis for accelerometers and gyroscopes to calculate the Quaternion of the IMU's orientation. This orientation filter applies to any IMU consisting of tri-axis gyroscopes and accelerometers. The benefits of such filter rely on the fact that it is computationally inexpensive and effective at low sampling rates. [14] Using the mbientlab C# Framework to get the accelerometer and gyroscope data, we used Madgwick's orientation filter to get the rotation. We then sent this data to Unity over TCP sockets. As shown in Figure 3.14, In Unity, we tested this approach by making the Quaternion of the Tool in Unity equal to the Quaternion of the IMU's. This worked accurately and was able to detect the change in rotation in all three axes.

Figure 3.13: The IMU taped on the centre of the Hand

Figure 3.14: Rotating the Hand in the y-axis (Left) The Tool rotates in the y-axis respectively

To estimate the IMU's position, the idea was first to filter the acceleration data using a low-pass filter (Butterworth) to smooth out the data, Check Figure 3.15 and 3.16. The acceleration data used in both figures was got by moving the IMU to the left slowly, then to the right slowly, and then rapidly moving the IMU in both directions. Followed by slow movements in the right and left directions again. We would then correct for acceleration by multiplying by the gravity. Then we integrated the acceleration twice to get the distance moved by the IMU. This approach works only for sudden short movements, i.e. moving the IMU quickly in one direction then putting it to rest. The reason is the further the IMU moves with getting to rest (velocity is zero) the more error accumulates due to the double integration.

Figure 3.15: Acceleration Data without applying Butterworth filter

Figure 3.16: Acceleration Data with applying Butterworth filter

IMU and Color Tracking

Integrating the colour tracking for tracking the position and the IMU for tracking the orientation worked accurately with no latency. It was the best solution so far. This helped to take advantage of the position tracking in 3D using colour tracking as well as getting accurate wireless orientation detection from the IMU. However, still exists the individual issues for each of the methods, i.e. the field of view for the camera and the light conditions (in colour tracking) and the Bluetooth connection unreliability (in IMU).

3.2.4 HTC VIVE TRACKER

Figure 3.17: HTC Lighthouse

Having the HTC lighthouses with and an HTC Vive Tracker, shown in figures 3.17 and 3.18, was our next option to discover. The lighthouses emit Infrared rays. Vertical and horizontal lasers then sweep across the room, and photosensors capture off these lasers resolving the position and orientation of the trackers. [18] Then using SteamVR SDK in Unity, we were able to test this system. This was the most accurate and reliable tracking we tested. This was achieved by using `Steam-VR-Tracked-Object` script out of the SteamVR SDK. By attaching this script to the tool Unity, this would then link the Tool to the Tracker's transform (position and rotation). This worked perfectly for both position and orientation detection, Figures 3.19 and 3.20. The HTC Vive Tracker is wireless. The lighthouses can then detect the position and the orientation of the Tracker up to an area of 5x5 meters.

Figure 3.18: HTC Vive Tracker strapped on Hand

Figure 3.19: Moving the Hand to the Right (Left) The tool moves to the Right (Right)

Figure 3.20: Rotating the Hand in the x-axis (Left) The Tool rotates in the x-axis respectively (Right)

3.2.5 Tracking Approaches Summary

Approach	Detection	Field of detection	Wireless
Color Tracking	position	1.5*1.5 m	No
Leap Motion	orientation	60*60cm	No
IMU	orientation	5 meters away from bluetooth Receiver	Yes
HTC Vive Tracker	position and orientation	5*5m	Yes

To Sum up, For the Color tracking given good light conditions and coloured markers that could be distinguishable from other objects for the real-world scene, It worked reliably for position tracking. For the Leap Motion, It worked accurately for both rotation and position tracking. There were main two issues, though, the tracking detection field of tracking was small, and the Hand would not be detected when wearing a glove. For the IMU, it worked accurately only for the rotation tracking, with a relatively large field of detection. Finally, The HTC Vive tracker has a reliable, accurate wireless rotation and position tracking that can work under any light conditions. Moreover, the Tracker can be tracked in an area up to 5 square meters, and the Tracker can be recognized from the ground level up to a height of 2 meters. Finally, as the Tracker is strapped on one's Hand, wearing the glove will not be of an obstacle to track the Hand. Therefore, HTC Vive tracker ended to be our choice for tracking the Hand's position and orientation in 3D.

3.3 Augmented Reality Environment

For our choice for an Augmented Reality glasses, We choose Meta2 Augmented Reality Headset, Figure 3.20. Compared to the HoloLens, for instance, Meta2 has a considerably bigger field of view. Moreover, programs running on the Meta2 Glasses does not need to be a standalone application. Which means the AR program is running on both the computer and the headset at the same time. This allows us to run multiple programs that communicate with the AR program at once.

The only problem we faced was when having the HTC Vive tracker and the headset working at the same time. The problem was the tracking for the Tool seems to jitters sometimes, and at other times the tracking stops at all. After trying many possible room setups, we finally came up with a solution for it. The problem was that the Infrared sensor, used for the depth perception, in the meta glasses interferes with the signals coming out of the lighthouse. To solve this, we strapped two cardboards on the side of the headsets with slits at the edges. Then we inserted another cardboard with white paper on it, inside this slit. This prevents the IR signals to interfere with the signal for the lighthouse.

Figure 3.21: Meta 2 Headset

Figure 3.22: Meta 2 Headset with cardboard in front of its IR sensor

Chapter 4

Experiment Design And Data Collection

4.1 Experiment Design

This chapter is a discussion about how everything was put together to conduct the Experiment.

4.1.1 Experiment Loop

In Figure 4.2, One can observe the scene during which the Experiment takes place. It consists of a blue cube, a grey tool (with a phantom hand above it), figure 4.1, and a white plane. The whole scene is attached to the head's movement, such that if the participant moved their head left or right, they would still see the scene. The aim of the task is that one would control the grey tool (the gripper) to try to touch the middle part of the tool with the blue cube. At each trial, the blue cube will move to a new different position. After which the tool should then move to touch the cube with only the middle part. If the right or the left parts of the tool touched the blue cube for more than 2 seconds, The trial would be considered as a failure. If the tool went inside the cube for more than 2 seconds, The trial would be considered as a failure. If the participant took more than 20 seconds to do the task, The trial will be over and considered as a failure. After the trial is over (success or failure), the blue cube will disappear. Moreover, at the end of each trial, The participant should move the tool over the red mark (the starting position of every trial) so that they start over the next trial, check figure 4.3 .

Figure 4.1: The tool

Figure 4.2: The Scene view

Figure 4.3: Red mark appears once the trial is over

Half of the trials of the Experiment will be without haptic feedback, and the other half is with haptic feedback. In trials where there is no haptic feedback, Participants will not feel anything once they get in contact with the cube. Where trials were there is haptic feedback, Participants will get to feel vibrations on their fingertips through the glove as they move the tool to get it in contact with the blue cube as follows: 1. Touching with the middle part of the tool generates vibrations on the center of the palm 2. Touching with the left part of the tool generates vibrations on the thumb 3. Touching with the right part of the tool generates vibrations on the index finger. The vibrations will be strong for the first second, and then they become mild afterwards.

The Experiment consists of two phases:

Training phase: It consists of 20 trials with the same conditions as the actual experiment phase. The first ten trials are without feedback followed by another ten trials with haptic feedback. Once the participant is ready, then we can start the Experiment.

Experiment phase: The Experiment consists of 4 blocks (a chunk of trials), each block will have 60 trials. Before each block begins, One will be alerted using voice alert if the trials of this block have haptic feedback or not. After finishing 20 consecutive trials, One will have 10 seconds rest. After finishing the first block, One will have 1-minute rest, and after finishing the first and second block (i.e., the middle of the Experiment), one will have 2 minutes rest. After the third block, one will have 1-minute rest, after the fourth and final block the Experiment will be over. One will be asked to fill out questionnaires after each block. This questionnaire is the NASA TLX questionnaire, and we changed its five 7-point scales to a scale from 1(low) to 5(high). After the Experiment is done, the participant will get to fill one more questionnaire (Figure 4.4).

Voice alerts will inform one of the following events in the Experiment: 1. When the training phase starts 2. When the training phase is over 3. When the Experiment starts 4. Whether the block of trials has haptic feedback or not 5. When there is a (10 seconds, 1 minute, 2 minutes) rest 6. When to resume after the rest 7. Each particular failure occurs: 7.a- Trial timeout 7.b- Touched inside the cube for more than 2 seconds 7.c- Touched the cube with the tool's left or right sides for than 2 seconds 8. When the Experiment is over.

During the Experiment, there was a tolerance when checking for the Touched inside the cube and Touched the cube with the tool's left or right sides failures. For the Touched the cube's sides failure, one can touch up to 20% of the cube's sides, and it will not be considered as a failure. For the Touched inside the cube failure, one can touch up to 40% of the cube, and it will not be considered as a failure.

An adaptive experiment is an experiment where the stimuli and responses determine the physical characteristics of the stimuli on each trial occurred in the previous trial or sequence of trials. Staircase Procedures are used in many laboratories because of their simplicity and ease of understanding. One type of Staircase Procedures is the Simple updown staircases. In this paper, they defined step size is the difficulty level, stimuli, of the task. Given a task of a 3down/1up Staircase procedure, the user is required to do the

task successfully three times in a row, for step size to decrease. However, when making a single mistake, the step size will increase. The value by which the step size increase or decrease is constant. This Step size will constantly change, but the probability of correct Trials will always stay constant. Using such an approach, it is easy to know the threshold step size for each participant in a given experiment.[13] Each block of trials was adapting the adaptive difficulty model, Simple up-down staircases. Which means that after three consecutive successes, the gripper width decreased by a fixed unit, and for only one failure, the gripper width increased by the same fixed unit. In the Experiment phase, the gripper width equals to the blue cube's width + 20% of the blue cube's width. For every three consecutive successes, the gripper width decreased by 1% of the cube's width and increased by 1% for a single failure. The aim was to know if there is a certain difficulty threshold reached by each participant.

Finally, we divided the participants into two groups. The first group, Group A (without first), had the first two blocks without haptic feedback, then the next two blocks with haptic feedback. The second group, Group B (with first), had the first two blocks with haptic feedback then the next two blocks without haptic feedback. The aim was to check if the performance of each of the 2 blocks with the same condition is relative to whether they have feedback or not, not for their order.

An important note should be mentioned, when designing this current Experiment, we abandoned the idea to have the participant hold their hand in one fixed hand gesture, as discussed earlier in both introduction and methodology. The reason was that it was uncomfortable to have this gesture for more than 5 minutes. Instead, as will be discussed in section 4.1.3, We had the participants holding on an object in their hand. Moreover, we only used the position tracking. As it was tough to achieve the task while the tool was rotating relative to one's hand.

Experiment Questionnaire

Thank you very much for participating in our experiment. We would like to ask you a few questions. Your privacy is protected because your name will not appear on this questionnaire or on your decision tables.

1. What is your age ? _____

2. What is your gender?

Male____ Female____

General Questions: Please circle the number that represents your best answer.

1. Was the task intuitive?

1 2 3 4 5

Not intuitive

Very intuitive

2. Was the task comfortable?

1 2 3 4 5

Not Comfortable

Comfortable

What aspects of the task affected your comfort negatively?

- AR Glasses were too tight or heavy
- Glove was uncomfortable (not the vibrations given by the glove)
- The tracker was too heavy on my hand
- My arms got tired after a while

Others,
please specify: _____

3. Were the vibrations given by the glove strong?

1 2 3 4 5

Weak

Strong

Very Strong

4. Do you agree? The haptic feedback helped me perform the task better.

1 2 3 4 5

Strongly disagree Strongly agree

5. Do you agree? I understand the reason why I failed a certain trial.

1 2 3 4 5

Strongly disagree Strongly agree

6. Do you agree? I was able to distinguish between different vibrations happening at the same on each finger. (i.e. having vibrations on both palm and thumb or palm and index)

1 2 3 4 5

Strongly disagree Strongly agree

If not, Which of these vibrations you couldn't distinguish?

- palm and index
- palm and thumb

7. Do you agree? Vibrations on each finger was strong enough to be distinguishable.

1 2 3 4 5

Strongly disagree Strongly agree

Figure 4.4: End of the experiment questionnaire

4.1.2 Room Setup

For the room setup, it was straight forward. We attached a tripod to a small table, to which one lighthouse was attached to a tripod. We put a black mark on the table to which participant will indicate as the starting position of the plane. During the Experiment, lights were turned off to make the AR view crisper. No Bluetooth or infrared devices should be present in the room during the Experiment as they interfere with the lighthouse's IR transmissions.

4.1.3 Experiment Instructions

In the Experiment, participants will put on a Meta2 Augmented reality headset over their head. In the virtual field, one will see a white plane, a grey tool, and a blue cube. As shown in Figure 4.5, One will be asked to control this tool by holding an object in one's hand, and by having the HTC Vive tracker attached to one's hand. As well as, One will also put on a glove, Cyber touch 2, Which gives haptic feedback on one's fingers (thumb, index, and palm) as soon as the tool comes in contact with the cube, In trials where there is haptic feedback. There are two reasons we decided to let the participant hold an object in their hand: 1. It gives a pragmatic sense of holding the end of the tool 2. For comfort, as it limits their wrist movement thus avoiding their hand to be in awkward angles.

Participants will initially put their hand over the black mark on the table. By enabling the (tool can move) check-box In the experiment loop game object in unity. The tool then moves relative to that initial point. By moving one's hand over the table, one will be able to control a tool in the augmented reality view. Participants can move their hand forward, backward, left, and right. After each trial, one will also be instructed to return one's hand at the original starting position, by moving the tool over the red mark.

Participants will be handed over a manual explaining the experiment loop in details. Also, after the participant puts on the AR Glasses and the glove, they can move their hand around to get how it feels, And they can interact with the cube to feel vibrations on each finger. After which, If the participant does not have any questions. We start the training phase, followed by the experiment phase. Finally, Participants will be given comfort advice. They are advised to look straight ahead, not to twist their hand, put their left hand on their lap and Keep their back straight. Phones will be handed over to the experimenter as well. Figure 4.6 shows the steps required, and the approximate time for each step, to conduct the Experiment from start to end.

Figure 4.5: Hand: Wearing Glove (Left) With Tracker (Middle) holding Object (Left)

Experiment Flow

Number	Step	Duration
1	Adjust the seat position such that the participant is not too close or too far from the table	1 minute
2	Give both consent form and experiment manual to the participant	5 minutes
3	Give an additional overview of the experiment	
4	Plug in all devices (HTC Vive Tracker, Cyber Touch, Meta 2 Headset, Base Station) to power	1 minute
5	Let Participants wear the cybertouch glove	2-3 minutes
6	Put on the headset, forehead first then the back of the head Use the strap and adjustable wheel to make the headset fit	
7	Put on the Tracker on one's palm and let the participant hold the black object	
8	Ask the participants to place their hand over the black mark on the table	N/A
9	Run The experiment in unity	N/A
10	Instruct the participant to keep their hand still Then enable the tool movement in unity	N/A
11	Instruct the participant to move their hand around and get to feel the haptic feedback once they are in contact with the still cube	1-2 minutes
12	Open LSL and start recording the two streams (tool position and Trial events)	1 minute
13	Choose to either start the experiment with or without feedback And type in one's name in the logger game object in unity	N/A
14	Ask the participant if they have any questions	N/A
15	Start the experiment	30-45 minutes
16	After each block ask the NASA TLX questionnaire	During the one minute rest
17	When Experiment is over stop the unity program	N/A
18	Take off the headset and remove the glove and tracker from one's hand	1 minute
19	Ask the participant to fill the end of experiment Questionnaire	2 minutes

Figure 4.6: Experiment flow with estimated duration for each step

4.2 Data Collection

For this experiment, we had 18 participants with an average age of 25 with a standard deviation of 3. 11 of these were males (61.1%) and 7 were females(38.9%). Fifteen participants were recruited, by getting paid, for the Experiment by advertisement around the University campus. All of the 18 participants were college students which all of which had given consent by signing in the consent form.

Using the lab streaming layer (LSL), We were able to record data at the end of each trial. This was achieved by sending out a stream of 11 messages. The data we recorded was the following: 1. Time Stamp 2. The current phase(Experiment or training phase)

3. Trial State, Was the trial successful or not 2. The reason for a failed trial, if any 4. The tool's current size 5. Amount of time to finish the trial successfully 6. Blue cube's X position 7. Blue cube's Z position 8. The number of times to the blue cube with the middle part of the tool 9. The number of times to the blue cube with the left or right parts of the tool 10. Current block number 11. Participant's name. The data was in CSV form.

Next, We analyzed the CSV files recorded for each participant. This was done using Pandas (Python data manipulation and analysis library). The CSV files were divided into two groups; the first was where the first two blocks did not have haptic feedback then the next two blocks had feedback, the second group was where the first two blocks had haptic feedback then the subsequent two blocks did not have haptic feedback.

Chapter 5

Results

In this section, we discuss the results discovered, after analyzing the data collected throughout the experiment as well as the questionnaires filled out by the participants. We checked 1- if there were differences between blocks with the same conditions within the same Group, 2- if there were differences between blocks with the same conditions for the two groups (sequence effects), 3- if there was a difference between with/without haptic feedback conditions in general. When comparing the results for the first and third criteria, we use Repeated ANOVA measures. While When comparing the results for the second criteria, we use ANOVA test. Throughout the analysis, we use the following conventions. Group A is the Group that started without haptic feedback. Blocks 1 and 2 did not have feedback, while blocks 3 and 4 had haptic feedback. Conversely, Group B is the group that started with feedback. Blocks 1 and 2 had feedback, while blocks 3 and 4 did not have haptic feedback.

5.1 Within Each Group Comparison

This section is a discussion about the results found when comparing the within-group performance for each Group. We checked for each Group, whether there is a difference in the performance between different blocks. We compared the performance between Block 1 and Block2 then Block2 and Block3, then Block3 and Block 4. The aim was to check if learning effects were observed or not, for each Group separately.

5.1.1 Average Failures

Here we checked if there was a statistical significance in the average number of failures for all participants per block in the two groups. For both Group A(Without haptic feedback first) and Group B(With haptic feedback first), we found that there is only statistical significance in the mean of failures for all participants between block 2 and 3 for each Group, Figures 5.1 and 5.2. No other statistical significance for the means between blocks

with the same condition, Block 1 and Block 2 Or Block 3 and Block 4 for the respective groups were found. We notice that in Group A (Without haptic feedback first), there is a decrease in the average failures between blocks 2 (without haptic feedback) and 3 (with haptic feedback). On the other hand, there was an increase in the average failures between blocks 2 (with haptic feedback) and 3 (without haptic feedback) for Group B (With haptic feedback first). This shows that there was a significant increase or decrease in the average number of failures once the haptic feedback condition was changed. In the following table, we show the average failures for blocks 2 and 3 and the P-value for each, for the two blocks.

	Group A (Without haptic feedback first)	Group B (With haptic feedback first)
Block 2 Average Failures	6.9	3.9
Block 3 Average Failures	4.8	7
P-value	0.002	0.010

Group A (Without First) Block 2-3 Average Failures for each Participant

Figure 5.1: Group A Average Failures per participant for blocks 2 and 3

Figure 5.2: Group B Average Failures per participant for blocks 2 and 3

5.1.2 Average Finish Time

Recall that for a participant to have a successful trial, he/she should complete the task under 20 seconds. Here we checked if there was a statistical significance in the average finish time for all participants per block for the two groups. No statistical significance between the means for the finish time, Within each Group(between different blocks in the same Group) were found.

5.1.3 Average Minimum size

Recall that after three consecutive successful trials, the tool size decreases by 1% and increase by 1% for one failure. Here we checked if there was a statistical significance in the average minimum size reached for all participants per block in the two groups. For both Group A(Without haptic feedback first) and Group B(With haptic feedback first), we found that there is only statistical significance in the mean of the minimum size reached for participants between block 2 and 3 for each Group, Figures 5.3 and 5.4. No other statistical significance for the means between blocks with the same condition, Block 1 and Block 2 Or Block 3 and Block 4 for the respective groups were found. We notice that in Group A(Without haptic feedback first), there is a decrease in the average minimum size reached between blocks 2 (without haptic feedback) and 3 (with haptic feedback). On the other hand, there was an increase in the average minimum size reached between blocks 2 (with haptic feedback) and 3 (without haptic feedback) for Group B(With haptic feedback first). This shows that there was a significant increase or decrease in the average minimum size reached once the haptic feedback condition was changed. In the following

table, we show the average minimum size reached for blocks 2 and 3 and the P-value for each, for the two blocks.

	Group A(Without haptic feedback first)	Group B(With haptic feedback first)
Block 2 Average Minimum size	9.4	5.7
Block 3 Average Minimum size	6.9	9.5
P-value	<0.001	002

Figure 5.3: Group A Average Minimum size reached per participant for blocks 2 and 3

Figure 5.4: Group B Average Minimum size reached per participant for blocks 2 and 3

5.2 Between Groups Comparison (Sequence effects)

This section is a discussion about the results found when comparing between the two groups. The aim was to check if the ordering for the blocks matters. The question was, will the performance for the blocks with the same conditions differ between the two groups or not. This was done by comparing Block 1 (without haptic feedback block) for Group A and Block 3 (without haptic feedback block) in Group B. The same was done for Block 2-Group A and Block 4-Group B, Block 1-Group B and Block 3-Group A, and Block 2-Group B and Block 4-Group A.

5.2.1 Average Failures

Here we checked if there was a statistical significance in the average number of failures between Blocks with the same haptic feedback condition between the two groups. No statistical significance between average failures for the corresponding blocks for the two groups was found. Figure 5.5 shows the Average failures for participants per block for the two groups.

Figure 5.5: Comparing Average failures for participants per block For the two Groups A and B

5.2.2 Average Finish Time

Here we checked if there was a statistical significance in the average finish time between Blocks with the same haptic feedback condition between the two groups. No statistical significance in Average Finish Time between Block 1-Group A and Block 3- Group B was found. No statistical significance in Average Finish Time between Block 2-Group A and Block 4- Group B was found. However, there is a statistical significance in the average Finish Time between Block 3-Group A(mean Finish time is 5.03 seconds) and Block 1-Group B(mean Finish time is 5.45 seconds) with p-value 0.019. Also, there is a statistical significance between Average Finish Time of Block 4-Group A (mean Finish time is 4.9 seconds) and Block 3-Group B(mean Finish time is 5.2 seconds) with p-value 0.044. Which then suggests that for Group A (without haptic feedback first) in blocks with haptic feedback conditions (blocks 3 and 4), finished the task faster than Group B (with haptic feedback first) in blocks with the same condition (blocks 1 and 2). Figure 5.6 shows the Average Finish time for participants per block for the two groups. Finally, we also observed, in the table below, that the overall average finish time for Group A(Without haptic feedback first) is lower than Group B(With haptic feedback first) in total and it is statistically significant with p-value equals to 0.038.

	Group A(Without haptic feedback first)	Group B(With haptic feedback first)
Overall Finish Time Mean (Seconds)	5.12	5.61

Figure 5.6: Comparing Average Finish time for participants per block For the two Groups A and B

5.2.3 Average Minimum size

Recall that after three consecutive successful trials, the tool size decreases by 1% and increase by 1% for one failure. Here we checked if there was a statistical significance in the average minimum size reached between Blocks with the same haptic feedback condition between the two groups. No statistical significance between average minimum size reached for the corresponding blocks for the two groups was found. Figure 5.7 shows the Average minimum size reached for participants per block for the two groups.

Figure 5.7: Comparing Average minimum size reached for participants per block For the two Groups A and B

5.3 Between Haptic Feedback Conditions Comparison

This section is a discussion about the results found when comparing between the with and without haptic feedback trials for the two groups combined. The purpose is to see if there is a difference between the trials with haptic feedback for the two groups (Block 1- Group B, Block 2- Group B, Block 3- Group A, and Block 4- Group A) and the trials without haptic feedback for the two groups (Block 1- Group A, Block 2- Group A, Block 3- Group B, and Block 4- Group B)

5.3.1 Average Failures

Here we checked if there was a statistical significance in the mean failures between haptic feedback trials in both groups and without haptic feedback trials in both groups. We found that there is a statistical significance between the mean failures in trials with haptic feedback and the mean failures in trials without haptic feedback. With haptic feedback Trials having average failures of 4.416 while the without haptic feedback Trials have average failures of 6.694. P-value is <0.001 . Which then shows that participants had a lower failure rate in the with haptic feedback trails. Figures 5.8 and 5.9 show the average failures for each participant for both with and without haptic feedback conditions for the two groups.

Group A (Without First) Average Failure For each condition per participant

Figure 5.8: Average Failures for participants in the with haptic feedback and without haptic feedback trials for Group A

Group B (With First) Average Failure For each condition per participant

Figure 5.9: Average Failures for participants in the with haptic feedback and without haptic feedback trials for Group B

5.3.2 Average Finish Time

Here we checked if there was a statistical significance in the average finish time between haptic feedback trials in both groups and without haptic feedback trials in both groups.

We found that there is no statistical significance between the two conditions with and without haptic feedback in the Finish Time mean was found.

5.3.3 Average Minimum size

Recall that after three consecutive successful trials, the tool size decreases by 1% and increase by 1% for one failure. Here we checked if there was a statistical significance in the average Minimum size reached between haptic feedback trials in both groups and without haptic feedback trials in both groups. We found that there is a statistical significance between the mean minimum size reached in trials with haptic feedback and the mean minimum size in trials without haptic feedback. With haptic feedback, Trials have an average minimum size of 6.3 while the without haptic feedback Trials have an average minimum size of 9.4. P-value is <0.001 . Which then shows that when participants had haptic feedback present in the trial, they were able to achieve a better threshold than without haptic feedback trials. Figures 5.10 and 5.11 shows the average minimum size reached for each participant for both with and without haptic feedback conditions for the two groups.

Figure 5.10: Average Minimum size reached for participants in the with haptic feedback and without haptic feedback trials for Group A

Figure 5.11: Average Minimum size reached for participants in the with haptic feedback and without haptic feedback trials for Group B

5.4 Questionnaires Analysis

In this section, we discuss the results found we analyzing the data collected from both the two questionnaires used in the experiment. We recall that we used the NASA TLX questionnaire between each block to check the workload for this block, respectively. Besides, we used another questionnaire, check section 4.1.1, this questionnaire evaluated the ease, understandability, and comfort of the overall experiment. Each question in both questionnaires had a minimum score of 1 and a maximum score of 5.

5.4.1 In between blocks Questionnaires (NASA TLX)

Here we checked the average workload for each block for the two groups, As shown in Figure 5.12. This average workload is the mean of all the six questions together. We found that there is no statistical significance between the mean of the average workload:

1. In between-group comparison (between different blocks in the same Group)
2. Between the two groups (sequence conditions)
3. Between feedback conditions.

Figure 5.12: Comparing the overall average workload For the two Groups A and B

4th question

Next, we observed that there was a statistical significance when comparing the overall average load for the 4th question (How successful were you in accomplishing what you were asked to do?) between the two groups. Group A (Without haptic feedback first) had an average score of 3.86 while Group B (With haptic feedback first) had a score of 3.25, the p-value when comparing the two groups is 0.001. Which suggests that Group A(Without haptic feedback first) found that they did worse than Group B(With haptic feedback first). Figure 5.12 shows a comparison between the average workload for the 4th question For the two Groups. Figure 5.14 shows the average workload for question 4 for each of the blocks for the two Groups. Which then shows that when comparing the blocks together for Group A (Without haptic feedback first). We see that Block 1 had a lower mean than Block 2. Block 2 had a Higher mean than Block 3. Finally, Block 3 had higher mean than Block 4.a, And there was a statistical significance in the means between all three comparisons.

No other statically significant results were found for the five other questions when checking for 1. Between the two groups (sequence conditions) 2. Between feedback conditions.

Figure 5.13: Comparing the average workload for the 4th question For the two Groups A and B

	Group A (Without First)	Group B (With First)
Block 1 4th Question Mean	3.333333333	3.266666667
Block 2 4th Question Mean	4.166666667	4.233333333
P value	0.022	0.282
Block 2 4th Question Mean	4.166666667	4.233333333
Block 3 4th Question Mean	3.833333333	4.166666667
P value	0.009	0.760
Block 3 4th Question Mean	3.833333333	4.166666667
Block 4 4th Question Mean	2.666666667	2.733333333
P value	0.081	0.347

Figure 5.14: Average workload for question 4 for each of the blocks for the two Groups A and B

In between-group comparison observations

For Group A(Without haptic feedback first), in the (How hurried or rushed was the pace of the task?) Question, participants had a mean of 1.78 in block 2 and 2.44 in block

3, and the result was statically significant p-value of 0.004. For Group B(With haptic feedback first), in the (How insecure, discouraged, irritated, stressed, and annoyed were you?) Question. Participants had a mean of 2.9 in block 2 and 1.9 in block 3, and the result was statically significant p-value of 0.04. Furthermore, Block 3 had a mean of 1.9, and Block 4 had a mean of 2.5 with a resulting P-Value of 0.51.

5.4.2 End of Experiment Questionnaire

This was an analysis for the end of the experiment questionnaire. Each question had a minimum score of 1 and a maximum score of 5. Recall the following questions:

Q1- Was the task intuitive?

Q2- Was the task comfortable?

Q3- Were the vibrations given by the glove strong?

Q4- Do you agree? The haptic feedback helped me perform the task better.

Q5- Do you agree? I understand the reason why I failed a certain trial.

Q6- Do you agree? I was able to distinguish between different vibrations happening at the same on each finger.

Q7- Do you agree? Vibrations on each finger were strong enough to be distinguishable.

The table below shows the means and standard deviations for all of the seven questions. Moreover, we found that 82.4% found the headset to be too heavy in the (What aspects of the task affected your comfort negatively?) sub-question.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Mean	4.11	3.06	3.17	4	4.2	4.17	4.11
Standard Devi- ation	1.02	1.06	0.79	0.77	1.06	1.1	1.08

5.5 General Findings

In this section, we talk about general findings discovered when analyzing the data.

Failure Cause

Recall that there are three ways for failing a trial 1- touching the side more than 2 seconds (T/S). 2- going inside the cube for more than 2 seconds (T/I) 3- not being able to finish the trial under 20 seconds (T/O). We found touching the side of the cube failure was always the main cause for failing a trial with a rate of more than 90% of the causes of the overall failures. This pattern was observed for all four blocks in the two groups. In Figure 5.15, we see that 94% of the failure cause for Block 1- Group A was touching the side of the cube for more than 2 seconds. In Figure 5.16, We observe for Block 1

-Group A that failures such as touching inside the cube or a trial timeout are dependent on only 3 participants and not something shared between all participants, we observe similar patterns for all other blocks in the two groups.

Figure 5.15: Failure causes for Group A (Without First) Block 1 (without haptic feedback)

Figure 5.16: Failure causes for each of the participants in the Group A (Without First) Block 1

Accumulated failures per trial For all participants

Here we checked the number of failed trials for all participants in a chunk of ten trials. I.e., we summed the number of failures each participant did throughout trials 1-10 then summed these failures with all participants the did failures thought trials 1-10. In figures 5.17 and 5.18, we observed that blocks with haptic feedback had the most failures in the last two couples of 10 trials, which then suggests that participants failed the most when the trials got harder. While in the without haptic feedback condition, we see that failures fluctuate regardless. We observe this pattern between the with and without haptic feedback conditions for the two groups.

Figure 5.17: Accumulated failures For every ten trials for all participants. Group A Blocks 1 and 3

Figure 5.18: Accumulated failures For every ten trials for all participants. Group B Blocks 1 and 3

Side Touch Counter

An interesting fact was observed when checking for the following. We checked to see the number of trials that the participant touched the side and manage to succeed. We found

that in Group A (without haptic feedback), participants had more number of trials where they touched the side and still succeed. Check figure 5.19. Group A had a mean 36.2 trials per block where participants touched the side and succeeded, while Group B (With haptic feedback first) had a mean 27.3 trials per block where participants touched the side and succeeded. Which then suggests when starting with two different conditions, it affects the strategy approached to do the task by the two groups.

Figure 5.19: Comparing the side touches in successful trials For the two Groups A and B

Failures over Total attempts ratio of Gripper Size Per Participant

Recall that a participant starts with a fixed gripper size at the beginning of each block. For every three consecutive successes the gripper size decrease (more difficult trial) and a single failure the gripper size increases (easier trial). Here we checked for the number of trails that a participant failed at a specific gripper size, over the total attempts (successes and failures) of this gripper size. We see that for Group A (Without haptic feedback first) block 1 (without haptic feedback), Figure 5.20, 1- a specific participant fluctuates within a close range of gripper size usually 11 to 13, 2- a participant may have a gripper size that he/she couldn't succeed in, 3- The largest gripper sizes (easier trials) usually had a low ratio. This then proves that for a participant, there is a certain threshold of difficulty that he/she reaches. A similar pattern can be observed in Block 3 (with haptic) Group A (Without haptic feedback first), Figure 5.21, which then proves the same thing in the with haptic feedback block. The same pattern can be observed for all the other blocks in Group A (Without haptic feedback first) and B (With haptic feedback first).

Group A (Without First) Block 1 (without haptic feedback)

Figure 5.20: Failures over The total attempts for each participant's gripper size that they failed at.
In Group A Block 1

Figure 5.21: Failures over The total attempts for each participant's gripper size that they failed at. In Group A Block 3

5.6 Summary

Recall we had constructed five Hypotheses:

- 1- Trials with haptic feedback would have better performance
- 2- There will be a high learning effect observed in Group A (without Feedback first) and in Group B (with Feedback first)
- 3- A sequence effect would be observed: such that Haptic feedback Trials (blocks 3 and 4) in Group A (without Feedback first) would have a better performance than haptic feedback Trials (blocks 1 and 2) in Group B (with Feedback first).
- 4- No differences in the average workloads between the two groups or the two conditions were expected.
- 5- Each participant is going to have a threshold level for every one of the four blocks in the experiment

After discussing all the results shown. We see that when having haptic feedback present, participants had a better success rate, and a harder level was reached, which Proves our first hypothesis. Also, opposing our second hypothesis no learning effect was observed trials with the same condition in the two groups, participants did not get effectively better between the first and second blocks or the third and fourth block.

Moreover, contradicting our third hypothesis, no sequence effects were discovered for the minimum size reached or the mean failures. Thus, the order of the two chunks of blocks did not matter. I.e., Having the with haptic feedback blocks first and vis vera. Furthermore, proving our fourth Hypothesis. We showed that there is no difference in the overall average workload between the two groups. Finally, proving our fifth hypothesis, we showed that for each participant, there is a threshold difficulty level that he/she reaches for every block in the two groups.

Chapter 6

Conclusion and Future Work

In this work, we discussed what the minimal self is. Then we reviewed studies that were developed to research the body ownership and body image in VR. Next, we explained what haptic feedback is, and discussed the different types of haptic feedback devices. As well as we showed studies that use haptic feedback in AR. Which in turn offers an immersive environment.

To design our current experiment, we needed to track the hand's motion in AR. Such as both rotation and position could be presented in AR. We discussed four different tracking approaches: 1- Color Tracking (position) 2- IMU (rotation) 3- Leap motion (position and rotation) 4- HTC Vive Tracker (position and rotation). HTC Vive tracker was our choice for the final tracking system. For its reliable accuracy, and significant field of detection for both rotation and position tracking. Moreover, It did not have any of the disadvantages of the other tracking methods. Such as not depending on certain light conditions as the Color Tracking requires. Or not being occluded if the hand is covered as the Leap Motion. Moreover, we used the Cyber Touch 2 glove. To generate tactile feedback as the tool comes in contact with the target. Touching the target cube with the middle part of the gripper would generate haptic feedback on the palm. Touching the target cube with the left part of the gripper would generate haptic feedback on the thumb. Touching the target cube with the right part of the gripper would generate haptic feedback on the index.

The task in our experiment was that one would control a tool in AR. By moving their hand relatively in the real world. The aim was then to use this tool to touch only the front face of the target cube with the middle part of the tool. If a participant touches the sides of the cube for more than two seconds, it will count as a failure. If a participant touches the inside of the cube for more than two seconds, it will count as a failure. Moreover, finally, there was a 20 seconds time limit for the task to be achieved. If a participant took a longer time, it would count a failure.

We discussed that we divided the participants into two groups, Group A (without Feedback first) and Group B (With Haptic feedback first). In Group A, in the first two blocks did not have haptic feedback while the two blocks after that had haptic feedback.

Conversely, in Group B, the first two blocks had haptic feedback while the two blocks after that lacked haptic feedback. We were looking for within-group learning effects, sequence effects between the two groups, and finally, if the presence of haptic feedback helped to perform the task better or not.

We then analyzed the data collected. Displaying results which proved our first, fourth, and fifth hypotheses. Showing that: 1- Haptic Feedback helped participants to perform the task better 2- No differences in the average workloads between the two groups or the two conditions 3- Each participant had their threshold level. While opposing our second and third hypotheses. Showing that: 1- no learning effects in any of the two groups in blocks with the same condition 2- No sequence effects were observed, The order of the chunk of blocks between the two groups did not appear to show any differences

This project is a cornerstone for the PALMS study. One development is that the same experiment will run while recording brain activity using EEG. Also, a Piezoelectric wafer would be used in between blocks to measure one's Tactile perception. Moreover, We would then measure direct short term effects of running the task. Weeks later, we would then run the experiment on the same participants to check the long term effects. Another development is currently being built. Which, will mix the hand tracking in the AR environment with the Real-world. Such that one would use the virtual tool to touch a real cube in the Real-world. With a cube-shaped tracked robot in the Real-world, One would use the virtual tool to touch the Real-world Cube. One would get to feel the haptic feedback once the virtual tool comes in contact with the Real World Cube.

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