Hong An Pham

THE CHALLENGE OF HAND GESTURE INTERACTION IN THE VIRTUAL REALITY ENVIRONMENT

Evaluation of in-air hand gesture using the Leap Motion Controller

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Hong An Pham
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ABSTRACT

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In recent years, people in the world have perceived how 3D inventions change our life. Along with the rise of the Virtual Reality technology, there are two types of interaction methods for illustrating human 's command in the virtual environment: via controllers and via in-air hand gesture. Using in-air hand gesture is more considered because of natural manipulation and a lower cost for hardware controller. However, comparing with controller device, in-air hand gesture has many limitation of imprecise operation so it is not popular in 3D game and manufacturing industries.

By means of a user study with several levels of users, this research conducts a usability test in order to analyse the factors affect in-air hand gesture interaction. With a virtual environment with an Oculus headset and a Leap Motion controller, users were free to perform gesture actions and acknowledge the world with three sensors: sight, touch and hearing. From the data collection of real time input and user reaction, this research evaluates the human – object relationship in the 3D environment. The score of manipulation error is the valuable key to figure out the usability problems with free hand gesture interaction.

For designers, this research exposes the constraints of object in the 3D world, including the strengths and the weaknesses. The document will not derive any standard guideline or design template; instead of, it refers to the essentials to create a virtual environment in a harmony with the human world.

Keywords: Hand gesture interaction, Usability, Virtual reality, Leap Motion, Cognitive loading

PREFACE

The Bachelor's thesis was submitted as an independent research for my Bachelor's degree in the Degree Programme of Information Technology. It contains my work during 2017 - 2018 under the supervision and guidance of Mr. Lasse Haverinen.

The started idea involves the theory of behavior learning to understand the relationship between human-computer interaction. In my point of view, the theory of behavior learning can change how users took more time for the social network than for family activities. Nevertheless, independent interviews showed an unexpected result: People are pleasant with their choices, they prefer more showing themselves in the social network than outdoor activities. I realized that it requires a longer time to change a standard than create or improve a habit. Above all, a new value might bring helpful techniques for people.

At the end of my story, I want to give my thanks to my flat mate who introduced the hand gesture technology with the Leap motion controller – a major key in my research. He also guided me from the first step in the 3D development in Virtual Reality environment to set up the study testing system. Another thanks go to my friends in Oulu, for all cooperation and joining my experience of human gesture with the Oculus headset.

Oulu, 20.05.2018

Hong An Pham

VOCABULARY

VR: Virtual Reality

AR: Augmented Reality

3D: Three-dimensional space

IoT: Internet of Things

HMDs: Head mounted display, a helmet or facemask provides virtual environment

VR headset: One of HMDs renders virtual reality environment

UX: User Experience Design

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1   INTRODUCTION

1.1   Topic of thesis

Human-computer interaction is one of the most complex steps in a design for VR/AR technology. "Designing for VR should not mean transferring 2D practices to 3D, but finding a new paradigm." (Jonathan 2016, cited 21.05.2018). Different from a flat interface like smartphone or computer screen, the 3D space has no limitation of three dimensions. The boundless interface brings a natural feeling, which attracts the user's attention on the VR interface and allows them to perform freedom actions without restriction. In addition, to accomplish a 3D interface design, the key point is understanding the advantage and the disadvantage of 3D elements to reduce the number of imprecise interaction cases.

At current time, there are two types of methods to interact with objects in the 3D world (apply for both AR and VR technology): via a separate controller and via in-air hand gestures. Using in-air hand gestures is more considered because of natural manipulation and lower cost for hardware device. While the controller device works as a remote which transfers user 's commands from selecting and pressing a button to the VR system, in-air hand gestures allow to perform a command through common hand and finger manipulation to select and point a target. Without a stable input device, in-air hand gesture method has some limitation of imprecise operation so it is not popular in 3D game and manufacturing industries. This research aims to figure out the reason why in-air hand gesture interaction is not applied broadly in real life and technical industries by analysing which factors affect to human-computer interaction. In the final result, by demonstrating the limitation of the in-air hand gesture interaction method, this thesis will expose the relationship between human factors and the 3D object in VR system.

1.2   Interaction in Virtual Reality environment

People in 21st century has seen the race for wearable inventions between giant technology companies. Annual events such as Google I/O, Microsoft Build attract people's attention with announcements of novel improvements for wearable devices. From Sensorama in 1960s, a technical machine gives people the feeling of the 3D immersive world with fully senses e.g. 3D

images, wide vision, sound, vibration, the research of Head mounted displays (HMDs) become a certain base for modern the VR and AR technology nowadays. With the growth of the 3D computer graphic, the VR technology is rising with potential values in various aspects:

- Study: students encounter universe in a closer way by watching stars, having a front seat on board in the spacecraft as an astronaut (Figure 1).
- Medical: approach of learning human anatomy through engaging nervous system graphics, touching a heart and observing how it actually works (Figure 2).
- Industrial machines: combination of a virtual 3D interface with a physical machine allows to approach a compact controller remotely with IoT connections.
- Mobility: traffic simulator is an intuitive technique to learn traffic rules for the first step in driving study.
- Game: players enjoy virtual games in a reality space with the body movement and hand gestures (Figure 3).

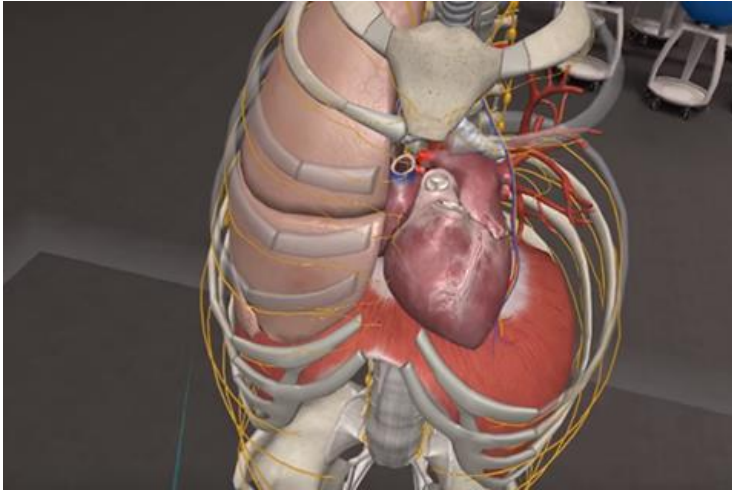*FIGURE 1. Apollo 11 VR interface (Oculus 2016, cited 20.05.2018)*

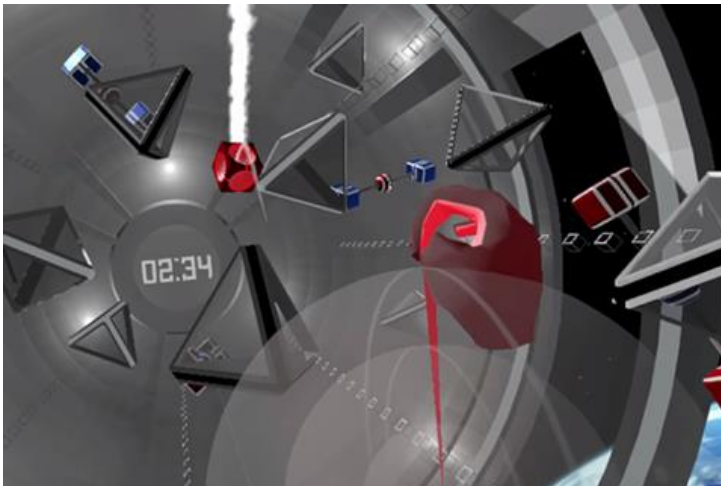*FIGURE 2. 3D Organon VR Anatomy interface (Oculus 2016, cited 20.05.2018)*

FIGURE 3. Weightless game interface (Leapmotion 2014, cited 20.05.2018)

Structure of VR system

The basic structure of VR system includes a rendering system to simulate 3D components in the virtual environment and an input system to collect input information from users such as body's movement, voice recognition, commands.

As a representative for the rendering system, a headset generates dynamic 3D elements that can wake the human up and let them interact with the virtual world through vision, hearing and touch. Using a modern 3D graphic computer, a VR headset generates a reality feeling that people are standing at the Moon and observing how the Earth rotated or fight with monsters as in "Star War" movies. Additionally, the combination of 360-degree perspective and a 5.1 speaker system allows

users to recognize the direction and the sense of an object movement. At current time, there are two types of headsets: the tethered type and mobile-rendered device. Most tethered devices are costly for an individual research purpose, represented by Oculus Rift (Figure 4), sold by $350 (March 2014), with a high quality screen for displaying 3D elements. On the other hand, setting up low-cost mobile-rendered HMDs in range $15 - $50 is a reasonable price for students and individual developers. In that case, 3D components were rendered on a mobile screen, hence, the rendering quality depends on a mobile's chip and a processor, represented by Samsung Gear VR (Figure 5) and Google Cardboards (Figure 6).

FIGURE 4. Oculus rift Development Kit 2 (DK 2)

FIGURE 5. Samsung Gear VR

FIGURE 6. Google Cardboard

In order to track the interaction process in the virtual environment, four cameras were placed at corners of the testing room to record images of human action. From the data of the current position, the system calculates and renders a simulator of the human body or a part of body in the 3D world. Indeed, a combination image of real world with rendered elements answers for the question: how to match the virtual world with reality; and provides data to detect the interaction between the human and 3D objects.

At current time, the VR technique provides two methods to implement two-hand experience: via the controller (Figure 7) and in-air hand gestures (Figure 8). The first method uses separate controllers as two hands to detect accurately current position and type of gesture when pressing a button. The system transfers signal data and recorded images from user input to computer to calculate result. Additionally, most users do not want to pay extra cost for hardware controllers, which is from $30 - $70 per each. However, the sense of touching a metallic object is more static than free hand gestures, as a result, the collision algorithm is more precise. For this reason, interaction with handing controllers applies popularly in the VR game, an environment asks for a high explicit real time data to build a complicated component mapping. In contrast, in-air hand gesture allows user to interact with the virtual environment without hardware. Basically, interaction with hand gestures or finger movement is more complicated without touching a screen to give a direct command, instead of controlling and pressing an input controller. Although the hand vibration causes a wide deviation of imprecise manipulation, free hand gestures typically satisfy the need of observing and controlling virtual objects naturally.

FIGURE 7. Controller interaction

FIGURE 8. In-air hand gesture interaction

Leap Motion Controller – a representative for in-air hand tracking

For set up in-air hand gesture interaction, a hand-tracking device is necessary to follow the finger's movement and map the generated user's hand interaction with 3D elements. While the VR market is growing very fast with different potential hand gestures in VR environment, it seems that there is a lack of development from hardware side. At the time I am writing this thesis in May, 2018, Leap Motion Controller is the only device that can provide a reasonable precise hand tracking which is general availability. As a representative hand tracking device, Leap Motion Controller, was born in 2014, is a potential exclusive solution for all-purpose 3D development with a reasonable cost at $79,99. Basically, Leap Motion Controller includes two core components: a hardware device tracks

real objects and a software "reconstructs a 3D representation of what the device sees" (Alex 2018, cited 03.09.2018). Instead of a complexity setup phase, Leap Motion hardware is a tiny device (Figure 9) that can simply attach with a HMD (Figure 10). The structure of the hardware is quite simple, which consists of two cameras and three infrared LEDs to track infrared light, capture the images of reality objects then store the sensor data in device's local memory. Subsequently, the sensor data is then streamed via a USB controller to the connected computer, so Leap Motion Service – a software can read the process images from raw sensor data. Here, Leap Motion software does an advance algorithm (close source) to track information includes fingers and the environment to simulate images of the real object into 3D data. After the reconstruction step, the software maps 3D data of real object with virtual objects data to calculate the relative interaction happened with them. With a reasonable price, a compact design hardware and an acceptable precision for uncomplicated hand gesture manipulations, Leap Motion Controller is a potential product for students, individual developers and startups.

FIGURE 9. Leap Motion Controller Hardware Device

FIGURE 10. Oculus Rift and Leap Motion Device

1.3   Research question and methods

In VR system, people frequently meet interaction problems when trying to control a virtual object with free hand gestures. Although the shape of hand is implemented precisely on the VR interface, users struggle to pick a cube or place it in the target position. One of the craziest task I have ever done is trying to control a slider from start to end; the knob continued moving after my finger moved far away from the control board. To search for what was wrong during the interaction process, I conducted a user study case about the interaction with the 3D object in the VR environment. By collecting the number of human errors and comparing with time range per action, the picture of hand gesture manipulation reveals the limitation of in-air hand gesture. Furthermore, a supportive recording camera keeps the image of real time finger's movement with statistic data of timing, action and environment. The aim of experiment is searching the answer for two questions:

Question 1. What are the difficulties users frequently meet during the interaction with the 3D object in the VR system by in-air hand gestures?

Question 2. What is the solution to improve in-air hand gesture interaction?

2 THEORY

2.1 User's Cognitive loading in interaction process

Human and environment are always under a sticky relationship and interact to each other. At the biology level, the metabolism between the human body and the external environment occurs hourly to daily, from the scope of cell to the scope of body in several aspects: oxygen, enzyme, energy, reactions. Like a proof, a normal progress verifies a healthy to work effectively. As the same as biology mechanism, a response to environment shapes human action. It is confessed that environment conditions train human action through the two-way interaction. Following Don Norman's paradigm of The seven stages of the Action cycle (Norman 2013, 39), the user's cognitive loading process was separated in two phases (Figure 11). In the first step - Gulf of Evaluation, a user perceives incoming information through five sensors: sight, hearing, touch, smell, taste. To the second phase - Gulf of Execution, the human brain analyzes the input condition to identify what's happened in the real world by comparing perceived data with previous experiences matched from memory. After evaluating the situation, a conclusion comes out by making a decision about which response action to answer the stimulus. This reaction mechanism proclaims that a stimulus can orient and direct human action.

A usable design connects the human world and the environment in a natural way. Thus, an interface needs to be familiar with the human's language since the first time. Executing a correct user research assists understanding the user's history background and gathering collected data for building a minimalist design. Therefore, the user will not meet problematic barriers to accomplish tasks in a simple and natural way. When the user interacts with an interface, he needs ~0.35s to indicate the element, ~0.15s to look up the existed in the working memory, matched it to an experienced then return an action response to the environment. As total, the cost for whole process lasts for 0.5-0.55s (Barrouillet, Bernardin, Portra, Vergauwe & Camos 2007, 572). In the other hand, a new message requires a longer process from the translation phase to analysis the incoming message, forwarding to match data from the working memory and return an appropriate answer in the end of the route. The total cost for the road from Gulf of Evaluation (evaluation process) to Gulf of Execution (action process) lasts for ~0.7s as usual.

There are two essentials when designing for an interaction process: understanding what kinds of received stimuli and what kinds of possible responses there are to answer an incoming stimulus. To enhance the value of the interaction process, a design should have the minimum number of possible errors to reduce the cost for the testing time and the refactor phase. In summary, the **cost saving** principle - a standard guide for an efficiency-to-use interaction process needs to satisfy:

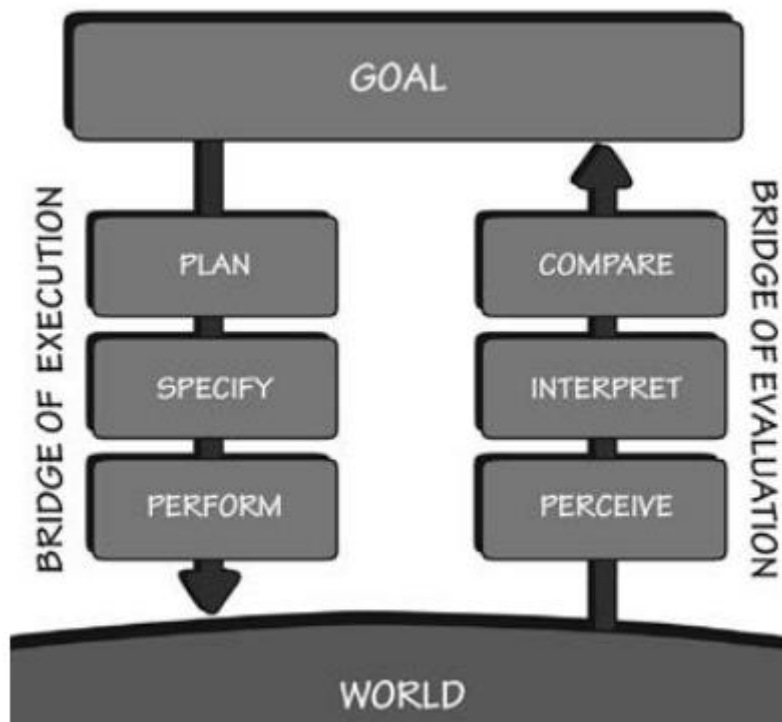- Low cost of Cognitive loading
- Low cost of Response

FIGURE 11. The seven stages of the Action cycle: Gulf of Execution and Gulf of Evaluation. (Norman 2013, 39)

2.2 Usability values

Jakob Nielsen – a Danish web usability consultant - mentions the term **Usability** as a **quality attribute** that assesses how easy user interfaces are to use. The word "usability" also refers to methods for improving ease-of-use during the design process (Jacob Nielsen 2012, cited 20.05.2018).

In the modern Software Design, usability principles were placed at high priority in a design process. To reduce the time for the development and the testing phase, the rule of thumb is minimizing the number of error to low cost of the testing and the refactor process. For example, a minimalist interface attracts the user's attention and promotes the learning process for 'beginner' faster than a complex structure. Thus, an easy-to-learn process will stay in the working memory for a longer period. One more thing designer should learn: the more learnable lesson, the more loyal customer company will have.

Following the theory of Usability, below is a measurement to evaluate a design with five quality components (Jacob Nielsen 1993):

- **Learnability**: the design should be easy to learn so that users can accomplish a basic task at the first time encounter.
- **Efficiency**: once users have learned the design, they can quickly achieve the task.
- **Memorability**: users can remember the design as enough for later return.
- **Errors**: the design must have lower rate of errors to make sure users make few error as possible, and there should be a recovery method from their mistake.
- **Satisfaction**: the design should satisfy user's need in a convinient way to make sure our customer prefers coming back again.

2.3 Usability Testing Method

What is Usability Testing?

Usability testing is a method to evaluate an interface with the participant of actual end-users/customers as the testers instead of members in a development team. Directed by the goal of identifying usability problems from the user's point of view, the test was planned to explore how

actual users interact with an interface, their feeling about the flow process and get feedbacks from actual customers. By dividing the test into small tasks, it is obvious to reveal the difficulties that users met during interaction process and detect accurately where the problem came from. The clearer input information, the more statistic data could be collected from testers.

Participants are required to do the same test independently without discussion before the test. During the testing phase, a moderator asks users to accomplish several tasks in the same process or in different phases while an observer (sometimes also the moderator) is supervising out how users encounter a usability problem, how they find a solution and overcome the difficulties with previous experiences. As usual, the test session is recorded in a video with the agreement from the side of the participant. Additionally, the observer also takes note what happened during the test, what users did and their expression. After the test, the moderator analyses the result from collected data and starts making a report about the number of error and successful tasks with real time details. By converting the number of errors and the delay timing statistic data into a chart, the researcher is able to detect what the problem is and where it came from. The explicit detail leads the researcher to the caused usability problem by highlighting the difficulties user met, then, searching for what user needs to overcome the challenge, a recommendation to improve the interface.

By working with actual users, the usability testing method helps to collect actual feedbacks directly from target audiences. Thus, the collected result totally comes from the user's perspective, not from the designer or programmer's point of view. Another important reason is the testing can be conducted from the early phase in the development process, so it helps to save time and cost. Because the usability testing method focuses on user's actions to identify usability problems, there is no requirement for a beautiful design or an accomplished product for the testing purpose. With a low fidelity prototype version, the test exposes usability problems as soon as possible so the design could be fixed and improved before the implementation phase.

How many test users?

Normally, five-users is a reasonable number for a test case. From 83 cases studied by Nielsen Norman Group (Figure 12), the result shows with five users, designer found most of usability problems. With more than five users, the ratio of the number of found errors and the number of users went down, so, the benefit does not deserve to the cost.
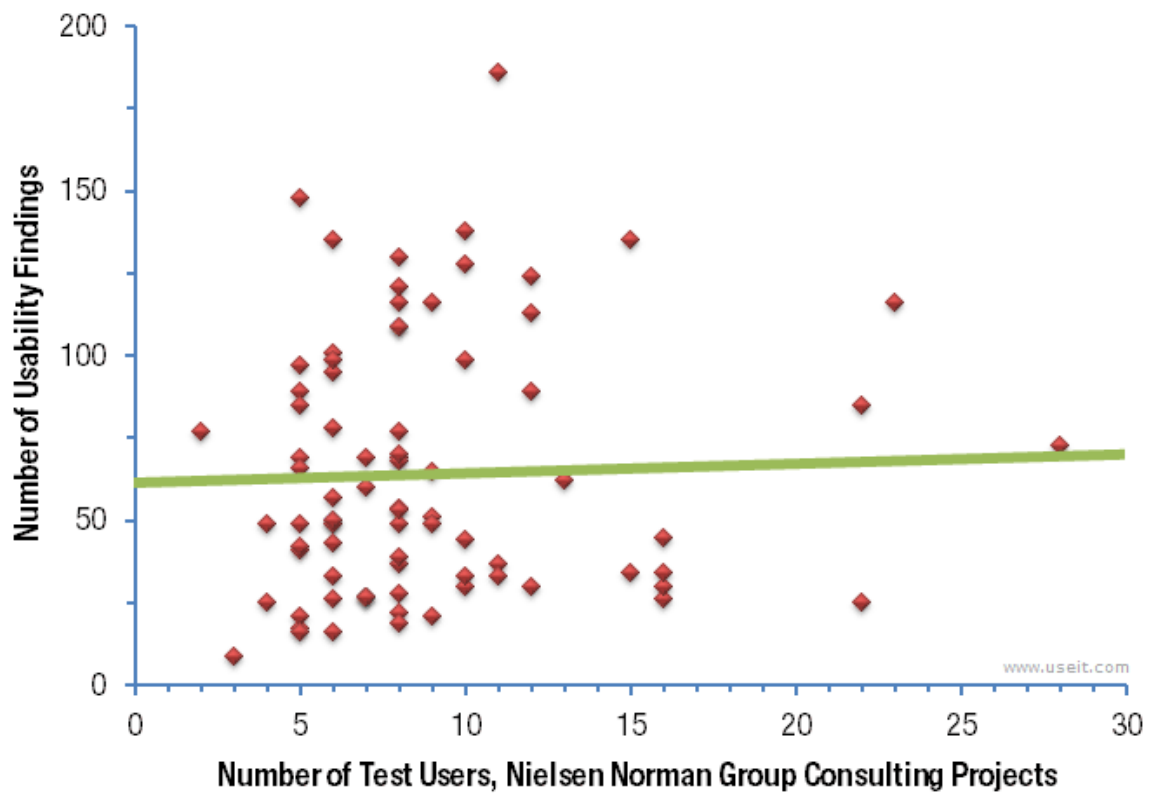
FIGURE 12. 83 cases study result (Jakob 2012, cited 03.09.2013)

3 USER STUDY SETUP

3.1 Subject

This research aims to explore the limitation of in-air hand gestures in the VR system. By dividing participants into two groups: expert users and normal users, our experiment focuses on tracking user gestures in the real time. The result from calculating delay time performance and the numbers of errors reveals what kinds of difficulty users met during the interaction process. Collecting the data of loading time and delayed responding time demonstrates how long users spent to perform each gesture, how many errors they made to accomplish a gesture action. Those numbers will tell which gesture users usually consider wrong and more difficult than the others, how it affects to the interaction process. In the end of case study, collecting data gives the answer for initial questions:

Q1. What are the difficulties users frequently meet during the interaction with the 3D object in the VR system by in-air hand gestures?

Q2. What is the solution to improve in-air hand gesture interaction?
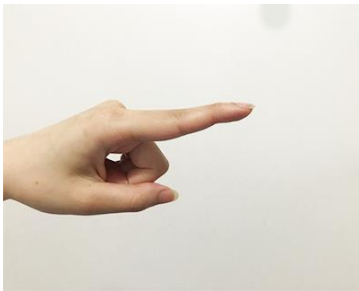
3.2 Hand gesture types

To achieve the goal of analysis in-air hand gesture interaction, four cameras were set up to record images of user 's gesture and finger 's movement. The position of the user is necessary to calculate the collision between user and 3D elements. Actually, the system detects an interaction when an object collides to another. With the image of hand and finger 's movement, the system can define the shape of finger, the border, how and when user's hands touch a virtual object. The real time data is a critical factor to anticipate the potential collision and notice error events. In detail, a fast or slow movement affects to the tracking hand gesture trajectory and handle the interaction process. Two factors which determine the gesture recognition pattern are:

- Shape of fingers and hand: read the image recording by the camera.
- Hand movement: scan trajectory details of the finger movement.

Therefore, in-air hand gestures in VR system were classified into six types based on the meaning of the interaction:

(1) Select (Figure 13a, 13b): capacity of detecting a target with multiple gestures: index finger, one or two hands, static or movement gesture. A select action type includes pointing (one or more fingers) to determine the target and direction, grabbing (one or both hands) to hold the target, tap or double tap (one finger) to activate an object.

(2) Moving (Figure 13c): capability of navigating and changing the position of an object. User can move finger or hand to place the target to destination.

(3) Swipe (Figure 13d): move finger or hand follows one direction for a short time without selector. The action normally means "Go next/previous".

(4) Pinch (Figure 13e): recognize changes of the distance between two fingers, pinch in means two fingers come closer and pinch out means two fingers move away.

(5) Rotation (Figure 13f): move your fingers follow a circle line in clockwise or counter clockwise to rotate the target object.

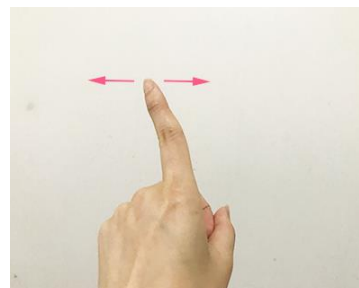(6) Release (Figure 13g): recognize when user releases an object by moving hand away.

(a) Pointing 1 finger
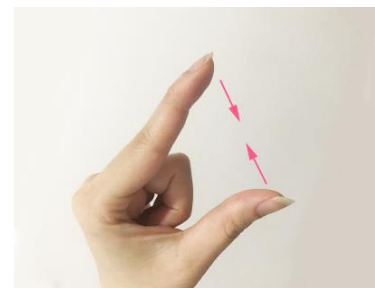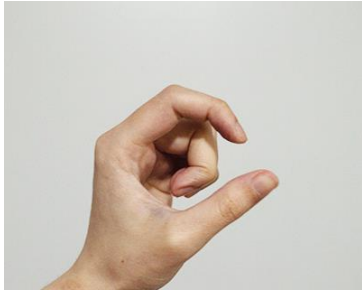
(b) Grab

(c) Pointing and moving

(d) Swipe

(e) Pinch

(f) Rotate 　　　　　　　*(g) Release*

FIGURE 13. Examples of Hand Gesture types in VR system

3.3　Tools

User Interview

In order to explore user's knowledge regarding VR environment, a short interview was conducted at the beginning of the test. Through the discussion, the valuable collected data exposed the background of two groups: professional group and casual group. Before a test, talking helps user feel confident and get familiar in the introduction phase. In addition, for the final interview, users' feedback reveals their actual feelings during interaction process. Beside general questions for reviewing system, by answering questions for separate tasks, users disclose their emotion and actual feeling, which are necessary to understand the interaction process. Combining with tracking data, the number of errors and total time will expose what causes errors.

7-point scale

To answer how satisfied with the VR system, participants will fill a 7-point scale anchored with "make me more/less productive". Users will rate the 7-point scale anchored individually after testing phase. The rating score reviews on how many points tester gives for the product and what makes user feels usable and utility. As usual, the 7-point scale includes a middle or a neutral point (Krosnick & Fabrigar, 1997), a separate part unlike positive and negative levels. Adding a neutral section reminds user answering with true feelings instead of imagination. 7 points represents for 7-level satisfaction should look like this:
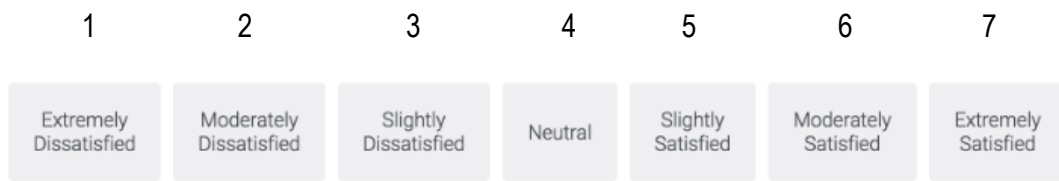
1	2	3	4	5	6	7
Extremely Dissatisfied	Moderately Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Moderately Satisfied	Extremely Satisfied

FIGURE 14. 7-points scale (Vannette 2015, cited 20.05.2018)

Environment

Participants took part in the test in a private room. Beside desktop computers with the Internet support, a VR environment was set up with an Oculus Rift Development Kit 2 device and a Leap Motion controller (Figure 15). In general, the Oculus VR is an affordability headset for studying and testing purpose. Beside the advantage of a compact design and the high quality of display, the Oculus Development Kit 2 has a simple installation for multiple purposes with a free open source SDK for developers. With the low resistance, the low latency displaying with a high-resolution screen, the quality of rendering satisfies the need of playing VR game, controllable ability and watching 3D movie.

To recognize hand gestures, a hand tracking was attached in front of the Oculus device. With a tiny design, the Leap motion is a worthy solution for individual research because it can record and simulate the skeleton of hand through a fast tracking camera (Figure 16). By connecting with the Oculus Rift to display images of hand movement, users are able to observe how their hand interacts with the 3D environment as real as possible. Supported by a large developer community, the Leap motion controller is compatible with various headset devices for multiple platforms such as Orion, Unity, VR headset, Windows. In future, the hand gesture detection technology will become popular for various aspects of life, such as in health care service (restore physical exercise), education, game and mobility service.

FIGURE 15. Setup Oculus Development Kit 2 with Leap Motion Controller device
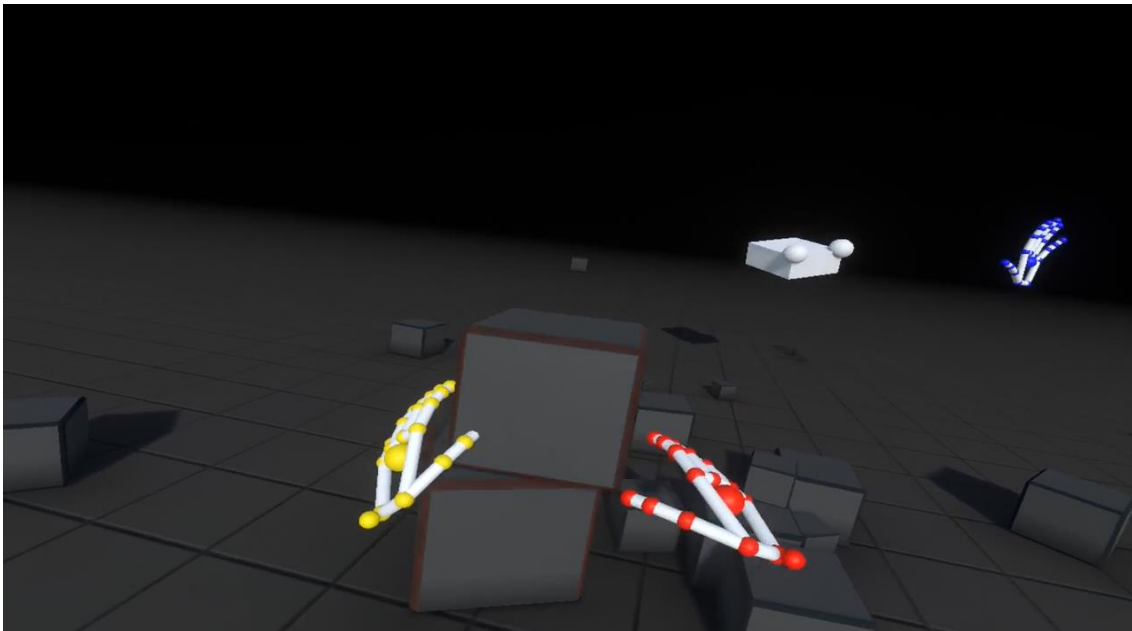
FIGURE 16. VR environment rendered by Oculus Rift with human hand simulator

The experiment works with two demo applications which were built by the official SDK from Leap Motion Inc. Written by the hardware manufacturer themselves, those two applications will work as correct as manufacturer's wish to implement and deliver fully potential features of the hardware device. From this reason, spending time to concentrate on researching hand gesture interaction is placed at high priority than making a new application and a new device.

The first application for user to begin with is named "Blocks" (Figure 17). It comes with a detailed tutorial for practicing hand gesture interaction in Virtual Reality. For user without Virtual Reality

experience beforehand, a clear tutorial helps to slip into a virtual environment. Blocks, as its name would suggest, is an application focuses on the interaction with the block objects. During the interaction process, user performs in-air hand gestures, i.e., grab, move, release, push or flip to control one or some digital objects.

In reality, more than separate objects, user wants to interact with a digital interface. For that reason, the second application named "Button Builder" (Figure 18) is chosen. This application simulates a dashboard controller interface which is similar as in 2D flat design. The familiar design came from 2D User Interface Design elements helps users to start using the interface easily, but also reveals some trouble user could meet when trying to transform 2D elements in 3D design. In this application, user works with familiar 2D elements like button, slider while using hand gestures, i.e. grab, drag, release, hover.

FIGURE 17. Block task: Build a tower
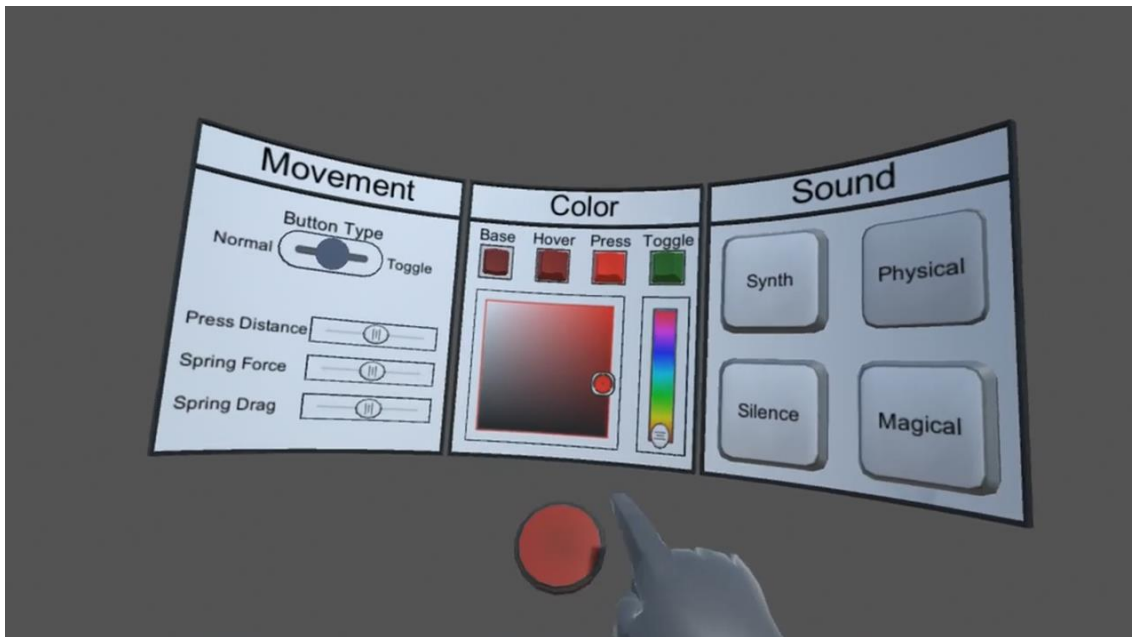
FIGURE 18. Button Builder task: Modify button color

3.4   Study Procedure

During the study, participants will follow steps listed below:

1. Introduction phase:
    -   Greeting and short introduction about the goal of the test
    -   Filing in a pretest questionnaire about the user background
    -   Explaining details about the basic content of test, template, and restriction. Filling a consent form
    -   Starting recording
2. During test: the moderator will instruct a user and observe his/her behavior when a user tries to accomplish two tasks:
    -   Task 1 (Figure 17): to follow the tutorial, a user needs to complete a tower from five different objects.
    -   Task 2 (Figure 18): in the second application, user modifies a board controller and see how different properties apply for the main button.
3. End interview:
    -   The moderator finishes recording and saves it to the computer.

- Final interview about the user feedback, following by a Post-test questionnaire and a 7-point scale.

At the beginning, the moderator greets a test user and introduced few words about the goal of the test. Next to a short discussion that helped the user feel comfortable before entering the test, a pretest interview was executed by following the questionnaire documentation (Appendix 2) to collect specific details about the user background and 3D experiences. To prepare for the test, the moderator explained the basic content of test, template, and mission for each task. Test users should know that there is another researcher observe how they evaluate the application, rather that the moderator evaluates them. Participants had to sign an informed consent to acknowledge that the participation is voluntary, the test session was videotaped but their privacy of identification is safeguarded. Before moving to the next part, moderator asked the participant to confirm that he/she was ready for test and started recording program.

Participant must complete two tasks independently without communicating with others. At the start, the moderator explained the mission and some descriptions. Time-on-task measurement started when the moderator finished reading the instruction and ended when user said, "Done". During the test, the moderator asked few questions to evaluate the user's cognitive loading and emotion. By listening to user's answers and observing behaviors, the moderator evaluated the interaction process; detected both physical and virtual constraints in the VR world when a user met an error.

In the first task – Block app (Figure 17), a user had 5 minutes to learn basic interaction rules by following a tutorial. The mission here is that the user needs to complete a tower from five objects. Although participant could create new object or move an existed object, this test recommends using multiple hand gestures to perform picking and dropping action. By observing how user played with 3D objects, the moderator evaluated how a human illustrate a command with a free hand gesture, how many gestures are enough for a VR interaction design.

In the second task – Button Builder, the moderator explained a board controller with various customize options for the main button (Figure 18). By changing properties on board controller, user applied different styles for the main button following the requirements. The aim of this task was observing how a user handles a complex job to figure out which should be avoided when designing a VR input interface.

After the test phase, the moderator and the user came to the final interview and asked the user to answer the forced-choice questions to indicate how satisfied the user are based on 7-point scale. The answer reveals how the user feels effective, efficient and satisfactory after using the product. With different feedbacks from participants, both agreement and disagreement ideas were collected that help to reach the goal of finding what the difficulties for users when perform in-air hand gesture interactions in the VR world are.

3.5   Participants

The test users take responsibility for completing a set of representative tasks as efficient and timely a manner as possible. At the end of the test, the moderator asked the user to provide honest opinions regarding the usability of the application during post session subjective questionnaires and debriefing.

This research recruited test users based on their knowledge regarding 3D experience. To select an appropriate test user, the first thing was considered is whether a new user can handle the task during a short time (about 30 minutes per user). Absolutely, test users were not expected to have experience in the VR environment before. Therefore, users were invited from two groups: the first group includes casual users (user 6-10) who have basic computer knowledge so they can get start with a VR interface and meet no or limited errors in simple tasks such as giving a command, understanding the meaning and how to apply hand gestures. In other hand, the expert group (user 1-5) who have more VR experience in their past were expected to be more efficient. With their previous knowledge about the VR system interface and 3D components, expert users can solve basic tasks in a short time and provide valuable feedback about hand gesture interactions during the test.

Normally, five test users are a reasonable number for a usability test case. Especially, my research focus on calculating the total data of real time that a response is delayed to expose how the usability problems affect the user's hand gesture response. Therefore, the more users, the more real time data could be collected to evaluate how long the user's responding time took.

Overall, test users are youth who are between 19 and 27, almost relate to Computer field study. Two test groups were balance between five expert users who have much experience with the

VR/AR interface and five casual users who have less experience with 3D movie and mobile AR games. Table 1 will summarise background information of test users:

TABLE 1. Description of participants (Heading: C = Computer History, S = Smartphone history; Highlight: Expert group)

#	Participant	C	S	3D experience	VR/AR experience
1	M 19. Ungraduated Student - Business of Information Technology. Listen to Music	15	5	3D movie	VR game with VR headset and separate controllers, test and play smart glass in VR and AR exhibitions
2	M 24. Ungraduated Students - Information Technology. Computer Game	17	5	3D movie, follow VR technology topic, watch HoloLens and VR, AR video. Build 3D game with Unity	No
3	M 27. Software Engineer. Computer game	21	1		Build an AR app of house modeling
4	M 25. Ungraduated Student - Information Technology. Play with new technology	10	4	3D movie. Build game3D with Unity	VR: VR game with VR headset and separate controllers. Played game on Samsung gear and Oculus DK2. AR: Pokemon Go
5	F 24. Software Developer. Reading book, design	8	4	3D movie. Play game 3D	VR: VR game with VR headset and separate controllers with Samsung gear. AR: Design an AR app of house modeling
6	F 20. Exchange Student - International Business. Movie, music, travel	15	3	Google Earth	No

7	F 24. Ungraduated Student - Business of Information Technology. Mobile Game	18	10	Movie 3D	AR: Pokemon Go, Snap Chat VR: Play 4D game in Private room - Game park
8	M 27. Ungraduated Student - Information Technology. Shopping	10	6	3D movie	No
9	F 27. Unemployed. Gym, exercise	12	8	3D movie	AR: Snapchat Sticker
10	M 26. Software Engineer. Computer Game	20	8	3D movie	No

3.6   Result Data

The test kept a recording of number of errors a user made and the total time to finish the task. To compare the different results between users in two tasks, the record data were converted into Microsoft Excel then transformed to tables and charts.

In order to discovery the difficulties a user met in VR system, it is necessary to find out when and how an error happened. To define the caused problem, the error timing and the gesture detail during this period were listed. Although refining explicit data took a lot of time to transfer details into demographic, but the displaying numbers told where the problem is.
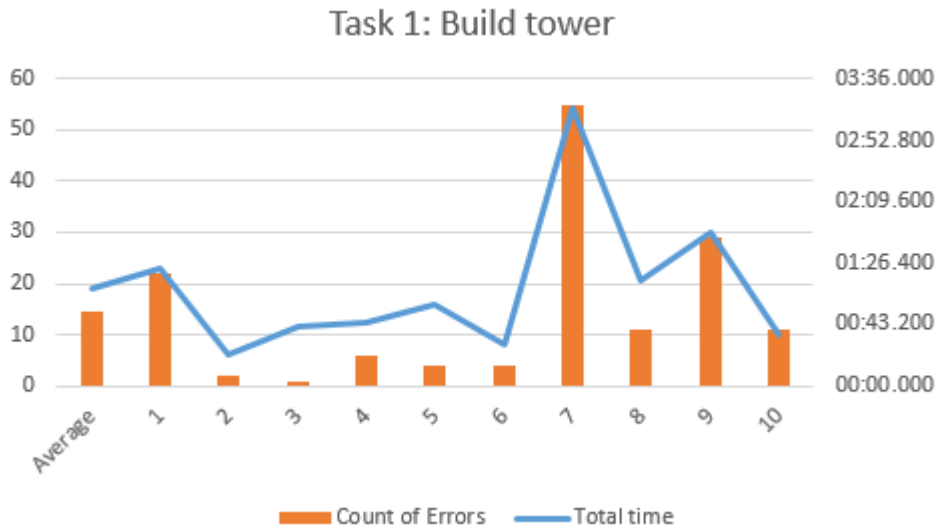
FIGURE 19. The number of errors and total time to accomplished task 1, recorded by per participant (total errors = 145) (Appendix 3)

A remarkable point was found when looking at the graph data is the relationship between the numbers of counted errors and the time to accomplish the mission. It is notable to realize that the bigger number of errors, the more time a user needs to achieve the goal. While Casual group (user 6 - 10) made total 110 errors during 7 min 22 sec, Expert group had a smaller number with only 35 errors in 4 min 8 sec. The comparison says that to reduce the time cost, the interface has to restrict the number of potential errors. Beside error statistic details (Figure 19), users mentioned that the most difficult part is that some gestures did not reflect as expected:

- Grab: in most of the time, a user cannot pick an object (cube) and move it to a proper place. As statistic, the number errors during Grab gesture is 34.5% in task 1 errors.
- Release: object usually stick with a hand or finger so a user cannot drop it to a proper place. As statistic, dropping with a hand took 22.7% errors during task 1.

At the final interview, users confessed that missing the touch sense limited the feelings of how close a user reach to an object. When a hand moved closer or went through a cube, there was no signal to feedback that the hand was quite close to an object and prepared for a short time collision. The lack of the sense of the distance makes users confused and affects to the direction recognition.

31
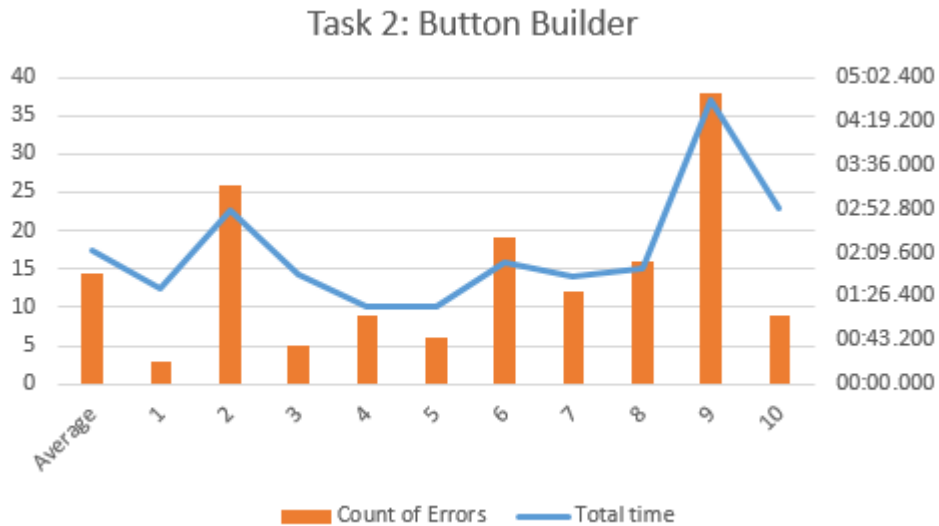
FIGURE 20. The number of errors and total time to accomplished task 2, recorded by per participant (total errors = 143) (Appendix 4)

In the task 2, there was a similar trend following the rule of scaling total time by the number of errors. Users saw that the task 2 component is more complex than building tower in task 1. Although participants took more time on task 2, it is seen that less errors happened. From user feedbacks and error analysis chart (Figure 20), the most popular error happened when a user tries to remove fingers from changing the color slider bar, which took 53.1%. Users complained about the non-stop knob when they move fingers away from the slider, which occurred by the wrong detection gesture and the hand vibration during the interaction.

Number of errors

FIGURE 21. The number of total errors per hand gesture type (total errors = 288, slip errors – blue = 10, mistake errors – red = 278) (Appendix 5)

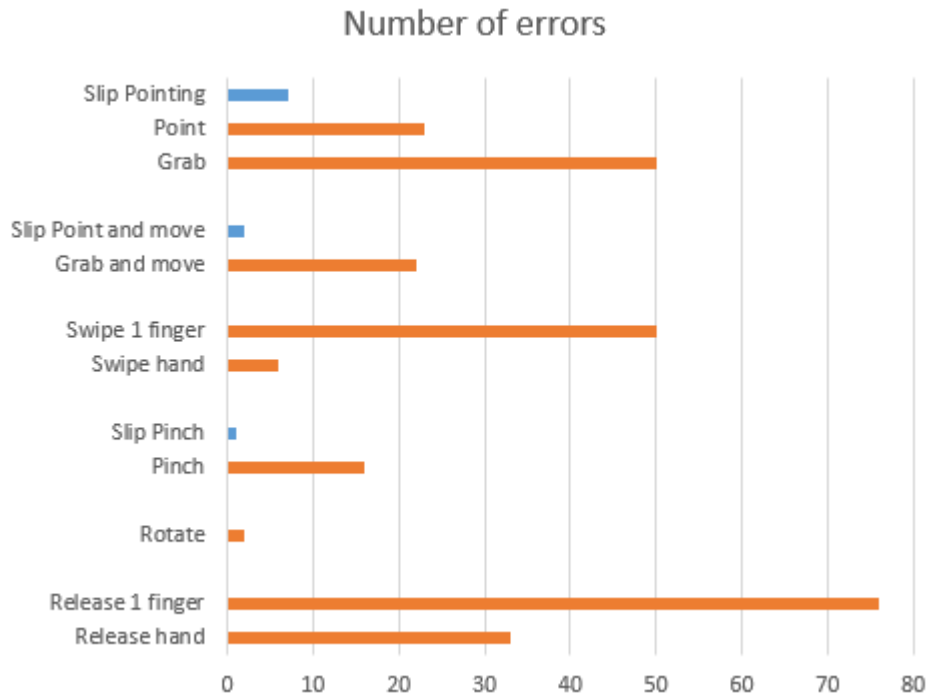There are two types of errors: slip and mistake. If a slip occurs under unconscious thought and users make an action as an accident unintentionally, a mistake happens when the users know what they are doing but the result does not come as expected. From the total errors chart (Figure 21), users usually did mistake errors (96.5%) more than slip errors (3.5%). Users made feedback that without a real metallic object to grab, their hands vibrated a lot. Thus, the caused reasons for slip errors may come from missing touch sense while performing hand gestures without a real object and the hand vibration. About the mistake, the most of errors happened in Select and Release gestures (27.8% and 37.8%). Both of two gesture types had a common problem at detecting the endpoint, when user tried to move fingers away from an object to finish an action but the object was still moving. For Swipe and Rotate gestures, when user tried to move an object by moving a finger follow a line, but the object did not follow the correct direction and stopped before or after the endpoint of the finger.
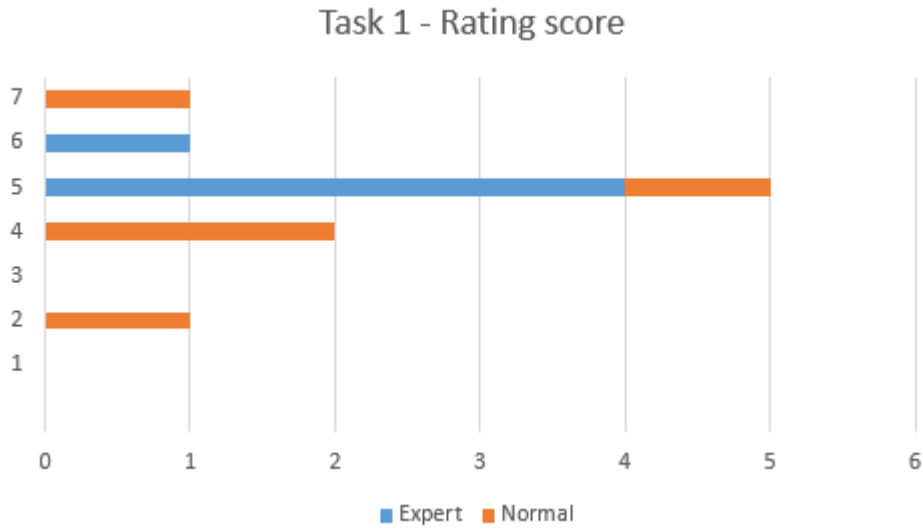
FIGURE 22. Rating score for task 1 per usage, rating on 7-point scale (see Figure 14)
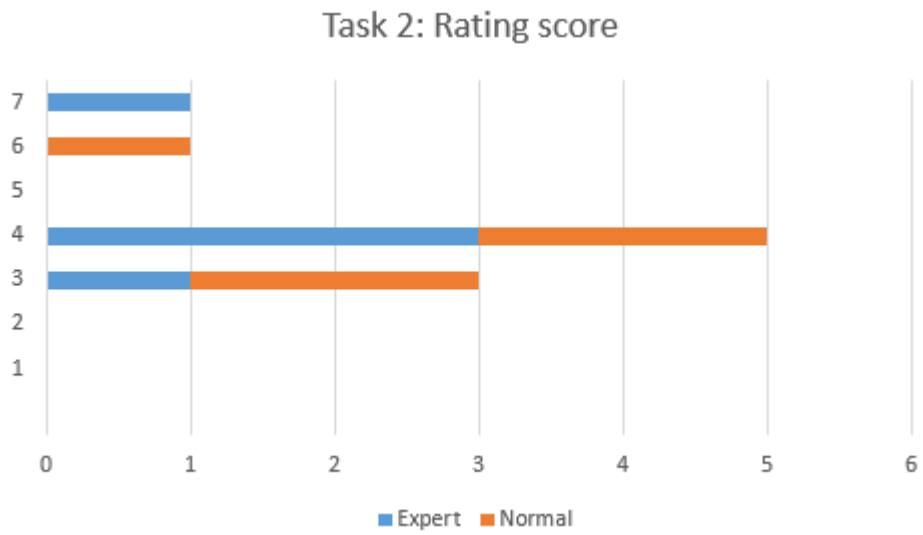
FIGURE 23. Rating score for task 2 per usage, rating on 7-point scale (see Figure 14)

General Rating Score
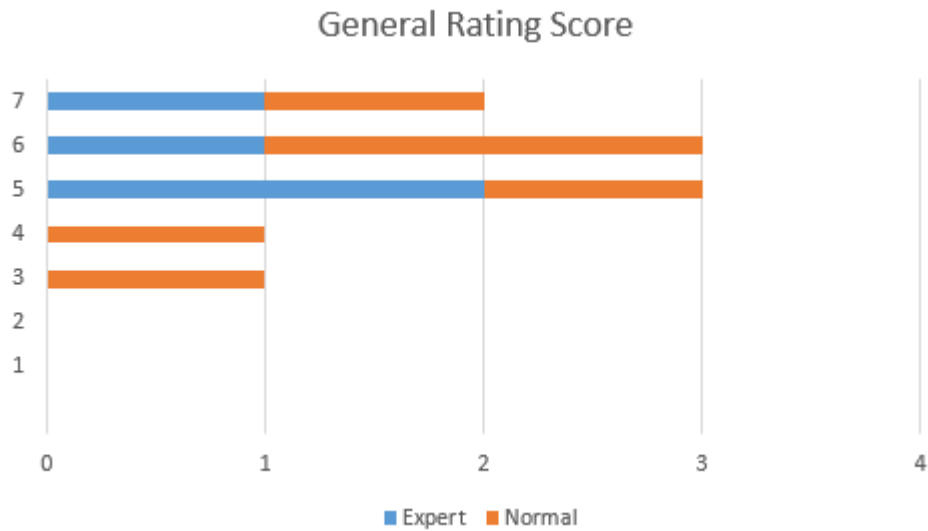
FIGURE 24. Rating score for overall test per usage, rating on 7-point scale (see Figure 14)

About the rating score, the average values are neutral point (4.2, 4.8) and positive level (5.4). Although the number of errors is remarkable (average 14 errors/user/task), participants did not seem frustrated with the system because of two main reasons. In the side of Casual group, users appreciate the free hand gesture interaction in VR system as a new experience: a novel adventure is excited with a "new" technology they have never met before. The confident impression attracts user's attention more than error trouble with a dream of virtual world in the future. In other hands, Expert users, who usually follow the VR/AR technology, understand the limitation of the incomplete VR system and in-air hand gestures. At current time, sensor hardware cannot detect the gesture perfectly because of physical constraints in material, hand vibration, imprecise manipulation. There should be a few more years for developing hardware device and improving headset technology.

4 DICUSSION

So far from the collected data result, this chapter aims to answer two research questions in beginning of test plan. Before coming to a recommendation, this part reveals the problems users met during the test, then, next to a discussion about finding supportive solutions to overcome the difficulties. Comparing to the theory of the two core values for an efficiency-to-use interaction process: Low cost of Cognitive Loading and Low Cost of Response, the evaluation follows two problems which correspond to two steps in a loading process. First, Capability of Indicate, occurs in Evaluation phase (Figure 11), includes ability of identification and controllability. And the second, Capability of Response, happens in Execution phase (Figure 11), relates to user's action to answer incoming stimuli includes giving hand gestures and expressing emotion.

4.1 Challenge of In-air Hand Interaction in VR environment

Gathering user's feedback and from the demographic of errors, this section analyzes the limitation of in-air hand gestures. The discussion reveals the reason which caused the confusing user experience process by highlighting a number of challenges when designing free hand gestures for a VR interface.

Hard control problem. Looking at the collected data of errors which were categorized by gesture types (Figure 21), it is seen that users met some problems when controlling their hand fingers and a virtual 3D object. The first difficulty is about the different implementation between a real hand and a simulated virtual hand. During the "Block" test, objects are usually sticky with the user's hand so it is hard to drop it into the proper place with Grab and Release gestures. In the user's point of view, they dropped a cube in a position by moving the hand to the target location, but from the rendered screen, the cube was dropped in a different position. Consequently, the user had to repeat the picking process again and again, from grab to select and release to drop a cube in proper position. The iteration made the process last longer and broke the law of Low cost of Cognitive Loading.

Secondly, user's hand fingers always vibrate and could not be stable during the interaction process. Consequently, the user feels difficult to control the virtual object with hand fingers. As result data, the hand vibration problem causes slip and mistake errors in reading imprecise final position at the

end of action. In the task 2 "Button Builder", the most annoying error happened when the user tried to move a finger away from a slider bar, which took 53.1% of total errors. If user pointed to a position in slider, the knob moved to the target location, but it still slid more after the user moved the finger away. The hand vibration took more time to recover from slip errors, which increased the cost of Response.

An object was obscured by another. The 3D space in both the real world and the VR world has no limitation of three dimensions. So, there are various ways of filling objects into the space that might cause a problem of visibility so that an object may be obscured by another. In the "Block" game, sometimes, a smaller cube was obscured behind a bigger sphere, so, it is hard to find the cube, come closer and grab it. The obscuring problem makes the user need more time to find and reach an object, so the process lasts longer than usual, which increases the cost of Cognitive Loading.

Missing touch sense. In a virtual environment, a virtual object does not reply with a tactile response as the same as a real metallic object. With nothing in hand, user acknowledges an interaction only via display screen. Missing the touch sense limits the feelings of how close the user reached to an object. From this reason, the user often feels confused to identify what happened, whether the user reached the target or not. During the test, when a hand moved closer or went through a cube, there was no signal to feedback that the hand came close to object and prepared for a collision. As a result, 2/10 participants (number 7 and number 9 – See Appendix 3 and 4) was frustrated and felt nervous because they could not do grabbing and pointing gestures properly to select a target. In the final interview, they showed an angry expression and complaint how missing touch sense problem limited their controllability and they had no idea how to recover from missed grabbing. Because of confusing, number 7 and number 9 took more time than usual to complete a task (3min15sec / avg.1min9sec and 4min40sec / avg.2min12sec), which increased both the cost of Cognitive Loading and Response time.

Limited Hand gesture types. At current time, a number of available gestures is less than a number of necessary actions. As mentioned in Chapter 3.2 Hand gesture types, in-air hand gestures were classified into six types based on the meaning of the interaction: Select, Grab, Point and move, Swipe, Pinch, Rotate and Release (Figure 13). In reality, an enormous number of required actions are more than six types of interaction, which lead to a problem of missing gestures to implement a new action.

4.2 Recommendations

With the in-air hand gesture limitation of mind, the author suggests a recommendation list for improving the hand gesture interaction. This section aims to help user overcome the difficulties by avoiding potential errors before they happen, as well as a solution to recover after errors. Corresponding to the two values of cost saving, the outcome helps to improve the in-air hand gesture behavior by lowing cost of Cognitive Loading and Response process.

Improving hard control problem. For a design, **Feedback system** is always placed at a high priority to make certain a user follows a work properly. Without a feedback signal, it is difficult to control the current situation because of lacking information about where the user is standing. When a collision happens, a target point needs to be highlighted to attract the user's attention and keep the user's eye focus on the change event. Additionally, for a case of slip error or incomplete gesture, the user wants to know the position of the collision by highlighting the target object and the shadow of the hand. As a result, the user receives a clear feedback to know if his/her gesture action is precise or imprecise.

To control the hand gesture effortlessly, designers should **simplify the task flow** by reducing the number of tasks in a flow and how complicated a task is. Also, the trend of the minimalist design with a fresh interface and natural manipulations could help to avoid a complex process. To design a natural process, the designer may consider selecting familiar hand gestures instead of a complicated serial one. By decreasing the number of hand gestures and simplifying how complicated a gesture is, human brain saves time for retrieving hand gesture information from the memory, so that the interaction process becomes faster. For example, in "Button Builder" application, to move a knob in a slider: instead of selecting or grabbing the knob with hand fingers, moving the finger follow the bar, there should be an option that allows users to select an endpoint and the knob could automatically transform to the new position. By reducing the number of steps from two (point to select and move) to one (point) and switching to a simpler gesture (use pointing instead of grabbing with two fingers), the process becomes faster and more accurate.

In case of moving an object to a wrong position, it requires a **Recovery Ability** to cancel the current process and playback to the previous situation. In "Block" application, what if a cuboid was moved to an incorrect position, then a user wish to back to the last step. The 3D space is too large to remember and detect the last position. Even if human brain can retrieve the last position of the

cuboid from memory, the distance may be too far to bring the object back. Therefore, to reduce the cost for memory loading and the cost for response time, designers should provide a playback option to recover the last status with limited human-thinking loading. As a suggestion, a design should support for the Undo/Redo method.

Improving obscuring problem. To be interactive, 3D elements must understand the human thought, and a user could acknowledge a 3D object in the virtual environment. To low the cognitive loading cost, a VR interface should follow the standard of the human language. Firstly, a 3D object in virtual world must be a **storyteller** who is capable of telling about itself, giving a user information details and instructing the process. There should be an essential instruction to tell what is inside, what kind of ability it has and what a user can do with the material. To declare the ability of identification, a 3D object must show a signal of "available" gestures in the human language. With a notification about itself, a 3D object becomes visible and active even if it was obscured. Additional solution is **a global map** to show the position of available objects in the same place (or same area), which helps the user detect a target quickly.

Improving missing touch sense problem. To recover from the confusing feeling when interacting with an object, a precise feedback system is very important to help a user detect when and how their action went wrong. Beside highlighting object in the middle of impact event, it is a natural way to notify a user when the user's hand comes near to an object and there will be a collision – an interaction event in a short time. Furthermore, there should be a notification to tell that user's hand passed through an object. It helps users to track their gesture more accurately and find a recovery solution when meeting a slip error because of their hand vibration. A proper notification also brings users a certain feeling instead of being frustrated with the system when their hand cannot reach object after few minutes repeating a gesture.

Improving limitation of hand gesture types. For the missing gesture case, there are usually two options: the first option is applying the same gesture for different actions, which normally causes misunderstanding which action the gesture actually matches with. The second option is combining two or more gestures to create a new gesture with a new meaning. However, a user needs more time to remember the new gesture and learns how to perform a combination with several steps. To accomplish a complex interaction, there will be two options, either **combining gestures** to have a new action or simplifying the task flow and switching to a simple basic hand gesture. Absolutely, minimizing a complicated task flow depends on how complex it is and how it is possible to reduce

the steps or the design elements. Designers may consider the loading time cost and how possible to minimize a design with keeping the quality and quantity of functionalities.

4.3   Answer to Research Questions

Based on the statistic data collected from the user study case, this section summarizes the discussion result to answer initial research questions:

Q1. What are the difficulties users frequently meet during the interaction with the 3D object in the VR system by in-air hand gestures?
Answer: The highlight difficulties came from both the user's side and the 3D element's side, and they are:
- Hard control problem: happened with hand finger and object controllability
- An object was obscured by another
- Missing touch sense
- Limited Hand gesture types

Q2. What is the solution to improve in-air hand gesture interaction?
 Answer: In regard to lowing the cost for the human loading time and the response time, the improving solution aims to avoid potential errors before they happened, as well as to recover after errors, includes:
- Feedback system: the most important and popular solution to reduce the number of errors
- Simplify the task flow
- Recovery ability
- Object must be a storyteller
- A global map
- Combining gestures

5   CONCLUSION

In this document, I conducted a user study case on the concept of using usability testing method to expose the limitation of in-air hand gesture interaction in the VR environment by setting up a virtual environment with an Oculus headset and a Leap Motion controller. From the data collection of the real time input and the user's feedback, this research reveals the weakness of in-air hand gesture which came from the nature of the human hand gesture and from the limitation of the system interface. After that, I categorized and presented the difficulties in the interaction process and a recommendation list to improve the hand gesture interaction.

To summary, in-air hand gesture recognition is not a new technology but it is still not applied broadly in modern industries. The reason is that hand gesture manipulation method still has some physical constraints and digital constraints such as unclear hand movement, vibration hand, lacking of touch sense, a sequence of complex hand gesture. In the near future, I hope that this research will be a supportive source for User Experience designers who are interested in designing for the VR/AR environment to develop a public design standard for virtual elements and that the interface becomes productive and utility.

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APPENDICES

Appendix 1 CONSENT FORM

Appendix 2 INTERVIEW QUESTIONS

Appendix 3 DETAILED STATISTICS – TASK 1

Appendix 4 DETAILED STATISTICS – TASK 2

Appendix 5 DETAILED STATISTICS – GESTURE ERROR DIARY

I am volutarily taking part in a research test conducted by Ms. Hong An Pham for the purposes of her thesis research. I understand that my participation will be recorded (audio and video).

I understand that data and information I share today will be handed confidentally and anonymously.

I understand that the recordings will not be used for any other purposes than for thesis research to complete Bachelor of Information Technology in Oulu University of Applied Sciences. I understand that the recordings will be destroyed after the conclusion of the study.

I will not be indentified by name of by showing my face. My personal information will be protected.

Signature:

Name:

Date:

INTERVIEW QUESTIONS

Pre-test

How old are you?

What is your occupation? (Details about school, job)

What are your hobbies?

How long have you been using computer (desktop, laptop)?

How long have you been using smartphone?

Have you experienced 3D environment?

Have you experienced virtual environment? (VR/AR)

During test

Are you ready for the test?

Do you understand the task?

What are you going to do?

How do you reach your goal?

Did you reach your goal? How do you know that you reach your goal?

Do you need any favour?

Post-test

How was the test?

Were you comfortable in the testing environmwnt (Place, devices, sound, moderator...)?

Review task:

- Rate for how easy to ascomplish the task (1 - Difficult, 4 – I had some problem, 7 – I feel confident)
- What is the most difficult thing? Why?
- What is the easiest thing? Why?

How did you feel when interact with object by hand in virtual environment?

Were you nervous about the test?

Did you meet some pain, tired, or terrible feeling?

Rate for how you feel confortable with the test (1 – Terrible system, 4 – I had some problem, 7 – Very comfortable and convinient)

What should be improved?

Would you recommend the free-hand gesture process to someone else?

Participant #	Total time	Count of Errors	Customer rating (7-point)
Average	01:09.132	15	
1	01:23.232	22	5
2	00:22.009	2	5
3	00:41.902	1	5
4	00:45.102	6	5
5	00:56.564	4	6
6	00:29.659	4	7
7	03:15.446	55	2
8	01:13.442	11	5
9	01:48.036	29	4
10	00:35.924	11	4

DETAILED STATISTICS – TASK 2   APPENDIX 4

Participant #	Total time	Count of Errors	Customer rating
Average	02:12.083	14	
1	01:33.947	3	7
2	02:52.076	26	3
3	01:47.957	5	4
4	01:16.364	9	4
5	01:16.465	6	4
6	01:58.980	19	4
7	01:46.712	12	6
8	01:54.205	16	4
9	04:40.315	38	3
10	02:53.807	9	3

Total Errors		288
Drop a cube	Right hand - 5 fingers	1
Grab a cube	Right hand - 5 fingers	1
Grab a cube	Right hand	14
Drop a cube	Right hand	3
Swipe	Right hand -4 fingers	1
Grab a cuboid	Right hand	17
Lift a cuboid	Two hands	5
Drop a cuboid	Two hands	5
Point and moving	Right hand	2
Point to select the end point	Right hand	1
Swipe to left	Right index finger	2
Press button	Right index finger	7
Move finger away from end point	Right index finger	3
Move finger away	Right index finger	44
Slip Press button	Right hand	1
Slip press	Right index finger	1
Slip select and move	Right index finger	2
Point to select the end point	Right index finger	1
Move finger away	Left index finger	4
Point to select the end point	Left index finger	1
Select and move knob	Left index finger	1
Slip rec selector	Left index finger	1
Point and move rec selector	Left index finger	2
Point and move rec selector	Right index finger	2
Press a button	Both index finger and middle finger select two button at the same time, system detect wrong 2 fingers and detect wrong selected button	1
Press a button	Right finger	1
Pinch	Two hands	5

Grab a cube	Left hands	1
Point to select the end point	Right hand index	1
Move finger away	fold right index finger	2
Swipe down	Index right finger	3
Swipe left	Index right finger	1
Slip press sound button control board	Index right finger	2
Swipe to right	Right index finger	4
Grab a cube	Left hand	5
Pinch to create cube	Two hands	5
Generate new cube unconsciously	Two hands	1
Grab a cuboid and lift up	Left hand	1
Grab the fell cube	Right hand	1
Grab and hold a cuboid up	Left hand	4
Grab to hold another cuboid up	Right hand	1
Grab to hold cuboid up	Right hand	2
Grab and place cuboid on the top of cube	Right hand	1
Drop a cuboid	Left hand	2
Grab cuboid and press down	Left hand	1
Create a icosahedron	Two hands	2
Grab the fell icosahedron	Two hands	1
Grab a generated icosahedron	Two hands	1
Drop and place a cuboid	Right hand	1
Drop the cuboid	Right hand	4
Drop a cuboid	Right hand	10
Grab and move a cuboid	Right hand	1
Grab a icosahedron	Right hand	1
Grab the icosahedron	Right hand	1
Drop the icosahedron	Right hand	1
Pinch to create new cube	Two hands	3
Swipe down to move knob down	Right index finger	1

Point and select the end point	Right index finger	1
Swipe left rec point	Right index finger	1
Swipe the knob up	Right index finger	2
Swipe right	Left index finger	1
Point and move rec button	Right index finger	1
Pinch to create and place new cube	Two hands	1
Drop cube by move hand away	Two hands	1
Hold to place a new cube on top of tower	Two hands	1
Swipe to right	Left hand -> Two hands	1
Hold to place cube on the top of tower	Two hands	1
Drop cube, move hand away	Two hands	1
Point to end point	Right index finger	1
Press	Right index finger	1
Swipe to left rec selector	Right index finger	1
Push vertical knob to end point	Right index finger	1
Press to end point	Right index finger	1
Press	Right index finger	1
Fold finger to move knob down	Right middle finger	1
Grab a cuboid	Two hands	1
Move cube and drop	Left hand	1
Drop cuboid on top of cube	Right hand	1
Grab a cuboid	Left hand	7
Select a button	Right hand	1
Two hands lift cuboid up		1
Grab the cuboid when it fell	Right hand	1
Grab the cuboid with Left hand	Two hands	2
Move finger away	Right index finger + middle finger	1
Press	Right index + middle finger	1
Point and move up	Right index finger	3

Slip Press sound button	Right middle finger	1
Swipe up	Right index finger	8
Slip Press sound button	Right hand	1
Press knob	Right index finger	1
Move finger away Knob continue moving	Right index finger	1
Swipe rec selector	Left index finger	1
Swipe left	Right index finger	1
Swipe left	Left index finger	2
Point	Right index finger	1
Swipe top	Right index finger	2
Point and move	Right index finger	2
Swipe up	Right middle finger	1
Slip press sound button	Right ring finger	1
Move finger away	Right index + middle finger	1
Lift a cuboid up	Left hand	1
Drop a cube + Right hand push a cuboid	Left hand	1
Push a cuboid inside	Right hand	1
Point to select end point	Right index finger	1
Swipe push knob	Right index + middle	2
Swipe push knob	Right index finger	1