| | |
|---|---|
| Title | Accelerating Human Reaction in Virtual Reality Using Electrical Muscle Stimulation |
| Author(s) | 葛, 瀚陽 |
| Citation | |
| Issue Date | 2020-03 |
| Type | Thesis or Dissertation |
| Text version | author |
| URL | http://hdl.handle.net/10119/16347 |
| Rights | |
| Description | Supervisor: 宮田 一乘, 先端科学技術研究科, 修士(知識科学) |

Master's Thesis

# Accelerating Human Reaction in Virtual Reality Using Electrical Muscle Stimulation

GE Hanyang

Supervisor MIYATA Kazunori

Graduate School of Advanced Science and Technology
Japan Advanced Institute of Science and Technology
(Knowledge Science)

February 2020

# Abstract

With the development of Virtual Reality (VR) technology, highly immersive VR products are actively sought after by the market and the academic community. VR technology can create and experience the virtual world. The practicality of virtual reality is getting stronger and stronger, and there are various application scenarios and related products, including software and hardware products. For users to experience virtual reality, the developed system needs to present information to users in different ways. These methods rely on human perception. Typical VR applications use video and audio to enhance immersion. The graphics display, the sound display, and the haptic feedback are common ways to display information. Besides visual stimulation and other auditory sensations, there are lots of haptic interactions work.

Electric Muscle Stimulation (EMS) has been actively explored as a solution for muscle recovery in medicine, sports, and physiotherapy. It can provide rich opportunities for human-computer interaction nowadays. It can provide tactile and kinesthetic feedback of haptic interaction. Some researchers have investigated the use of EMS in VR in order to enhance the immersion of VR. This work aims to explore the application using EMS in VR.

This work proposes Pre-Stimuli, a force-feedback approach for accelerating human reaction using EMS and maintaining a sense of agency in VR, which is developed based on previous work of Preemptive Action. According to the human processor model, the user needs a specific reaction time to react to an event in some situations. If the user is stimulated at an appropriate time before the user responds, the user can complete the action through the EMS method, which can improve the users reaction speed while maintaining a sense of agency (control). This approach has positive effects on immersion in VR.

In order to verify the effectiveness of Pre-stimuli on immersion in VR, two main experiments were conducted in this study, the preliminary experiment and the user study. In the preliminary experiment, we measured the participants' average reaction time and explored the Pre-Stimuli for the system engineered for the user study. The proposed

approach can facilitate participants' response time to 210ms which is faster than general human reaction time. The proposed approach obtained an average of 70ms without completely compromising participants sense of control during the experience in VR.

In the user study, we used Pre-Stimuli in combination with three different feedback to investigate the effects of Pre-Stimuli combined with various forms of feedback. Pre-Stimuli was the independent variable in three controlled experiments. The user study asked participants to join three controlled experiments (two trials in each experiment, a total of six trials). The participants are asked to fill out a questionnaire modified from the IGroup Presence Questionnaire (IPQ) after each trial. The IPQ is a scale for measuring the sense of presence experienced in a virtual environment (VE). The results of IPQ show that the experimental group using Pre-Stimuli outperforms the control group without Pre-Stimuli on all subscales.

In conclusion, the contribution of this work has two sides:

(1) We adopted the previous work of Preemptive Action in VR environments.
(2) We applied this approach to different kinds of feedback

It is verified that the proposed Pre-Stimuli systems can enhance immersion in VR.

# Contents

# List of Figures

# List of Tables

# Chapter 1 Introduction

Virtual reality technology is a computer system that can create and experience the virtual world. It is a challenging issue to form a realistic virtual environment containing multiple senses such as sight, hearing, and touch. Furthermore, it is a more advanced technology for realizing digital human-computer interaction in the current period. Users use various interactive devices to interact with entities in the virtual environment to produce an immersive information exchange. With the development of technology, the practicality of virtual reality is getting stronger and stronger, and there are more and more application scenarios and related products, including software and hardware. In this chapter, we will introduce (1) what determines the experience of virtual reality, (2) human senses, (3) general feedback methods in virtual reality. Then we will describe the research purpose and the proposed system. Finally, the composition of this thesis is introduced.

## 1.1. Research background

### 1.1.1. Features of VR

There are the three I's of VR, immersion-interaction-imagination [1], we can improve the VR experience based on these features. In this study, we focus on immersion and interaction in VR. Immersion is the ability to create a sense of presence [2], the feeling that you are there and act there. It means that the virtual environment (VE) simulated by the computer simulation system is very realistic, and the user is fully immersed in the three-dimensional virtual environment. Moreover, immersion is also a crucial characteristic of VR. Interaction means that users can operate and receive feedback on objects in the virtual world. Besides seeing and manipulating graphic objects, users can also touch and feel them [3].

## 1.1.2. Human sense and feedback methods

For users to experience virtual reality, the system needs to present information to users in different ways. These methods use human perceptions. The graphics display system presents images to the human visual system, the sound display system transmits sound to the human auditory system, and the haptic feedback provides sensorial data of virtual objects to the human haptic system.

Haptic feedback is generally divided into two different kinds of classes: tactile feedback and kinesthetic feedback [3]. Tactile feedback: an extension of force feedback but only meaning to feel the materials and textures by touching. Kinesthetic feedback: this feedback can change body posture by leading muscle movements.

Among the various VR software and hardware, in addition to using vision and hearing, there are other attempts to improve the user experience. For example, Haptic Suit Company Hardlight VR invents a fully-loaded suit, Hardlight, including 16 unique haptic feedback zones that are targeted at transmitting each real vibration to each muscle group.


**Figure 1.1 Hardlight suit invented by Hardlight VR**

**(Source:** https://www.kickstarter.com/projects/morgansinko/hardlight-vr-suit-dont-just-play-the-game-feel-it**)**

### 1.1.3. EMS in Human-Computer Interaction

Electric Muscle Stimulation (EMS) is becoming more and more popular among researchers as an approach for muscle recovery in medicine, sports and physiotherapy, and it now offers rich opportunities for human-computer interaction. Haptic feedback has mainly been limited to vibration based tactile feedback, such as the vibration function on mobile phones and different game controllers. EMS as haptic feedback has a great advantage compared to other forms of haptic feedback. The advantage is it can make specific muscles contract to actuate the user's body. This muscle contraction is able to lead to a specific movement of human body ( such as the movement of the fingers). So it can convey information and make a series of body movement [4].

There are some successful examples of EMS applications. For example, the wearable suit from Valkyrie Industries allows users to explore virtual spaces and enable a new touch interaction engine for professional applications. It utilizes EMS to provide the senses of touch and proprioception. The Teslasuit from VR Electronics is also an advanced physical suit providing haptic feedback by EMS.


**Figure 1.2 Valkyrie wearable suit**

(Source: https://www.valkyrieindustries.co.uk/ )

## 1.2. Research Purpose

With the development of VR technology, highly immersive VR applications are increasingly sought after by the market and the academic community. However, it is not easy to use a variety of devices that enhance immersion. The conventional approaches adopt video and audio to enhance immersion. Currently, VR technology can express more realistic video and three-dimensional effect sounds. However, besides visual stimulation and other auditory sensations, only some simple vibrations are used as haptic stimuli. Research is also limited for EMS as haptic feedback. Therefore, this thesis studies the adoption of EMS to improve the immersion of virtual reality.

This study explores the function of EMS on VR immersion before other various feedback.

## 1.3. Research Contribution

Common VR games only use the video displayed with the HMD, the sound from the speakers, and the vibration of the controller to create something immersive. Even the use of the existing EMS feedback method is very simple.

In this study, we adopted the Preemptive Action [5](In this study, we call it Pre-Stimuli in VR environments). The proposed system can stimulate the user at an appropriate timing, to affect the different feedback. Experimental data and user study indicate that Pre-Stimuli has a significant positive effect on feedback in the form of vibration, sound, and EMS. Pre-Stimuli can be applied directly to existing EMS interaction devices without redesigning them. To enhance the immersion of VR applications, designers only need to use Pre-Stimuli at the appropriate time when the user interacts with VR.

In conclusion, the contribution of this work has two sides:

(1) We adopted the Preemptive Action in VR environments.

(2) We applied this method to different kinds of feedback and proved that Pre-Stimuli

can enhance immersion in VR.

## 1.4. Structure of This Thesis

We construct this thesis as follows.
Chapter 2 introduces related research and examples. Chapter 3 describes the preliminary experiments. In the preliminary experiments, we found the timing of Pre-Stimuli that is suitable for the experimental environment of this research and shows its result. Chapter 4 reports the content of the user study and its results. In the user study, we used Pre-Stimuli in combination with three different feedback to investigate the effects of Pre-Stimuli combined with various forms of feedback. Chapter 5 summarizes this research and describes future issues and prospects.

# Chapter 2 Related Work

This study is on the method of how to use EMS. This chapter presents the previous research on EMS, on the Pre-Stimuli which is the use of Preemptive Action in VR, and on how to evaluate the effectiveness of this method.

## 2.1. EMS in HCI

### 2.1.1. EMS Introduction

Electrical muscle stimulation (EMS) is also designated by the name of neuromuscular electrical stimulation (NMES). It uses electric impulses to actuate muscle contraction [14]. EMS was initially invented as a tool for rehabilitation. It has recently attracted the attention of researchers in the field of HCI and emerged as an output paradigm in user interfaces. It can provide abundant haptic feedback or guide user movements.

EMS can be used to stimulate forearm muscles to complete complex actions such as playing the drums [6], enhancing video conferencing [15], and assisting in drawing [16]. In some researches, EMS has moved from actuating forearm muscles to the whole body actuations. People can use EMS to remotely communicate emotional reactions with others by activating different parts of the body [17].

### 2.1.2. EMS in VR

There are many studies on using EMS for haptic feedback in VR using EMS.
Some researchers explored the design of using EMS to provide haptic feedback in VR [18]. A head-mounted display combined with mechanical and EMS actuators was invented to improve the VR by enhancing the fear and pain [19]. To combine the EMS and cutscenes in VR games can also effectively improve the VR experience [20].

### 2.1.3. EMS Devices

Using EMS as an interaction device, the appropriate hardware and software are necessary. We can find some open source EMS toolkits and practical EMS devices that are already available to consumers.

LetYourBodyMove is a portable force feedback toolkit for actuating body movement using EMS. This toolkit consists of three parts, (1) the electrical signal generator, (2) an Arduino nano based control module with Bluetooth wireless communication function, (3) a series of control applications that can be deployed on a variety of mobile devices [21][22].

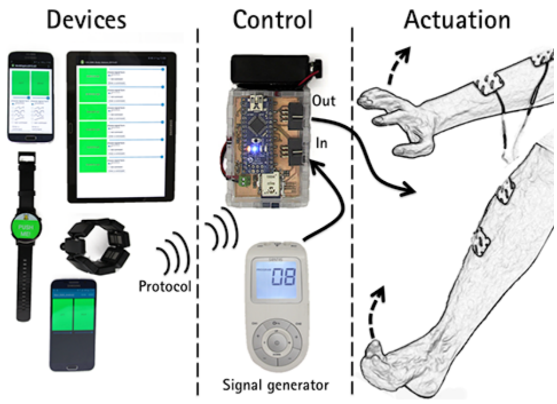


**Figure 2.1 The framework of LetYourBodyMove ToolKit**

(Source: https://bitbucket.org/MaxPfeiffer/letyourbodymove/wiki/Home)

The openEMSstim is an improved model of the LetYourBodyMove ToolKit [23].

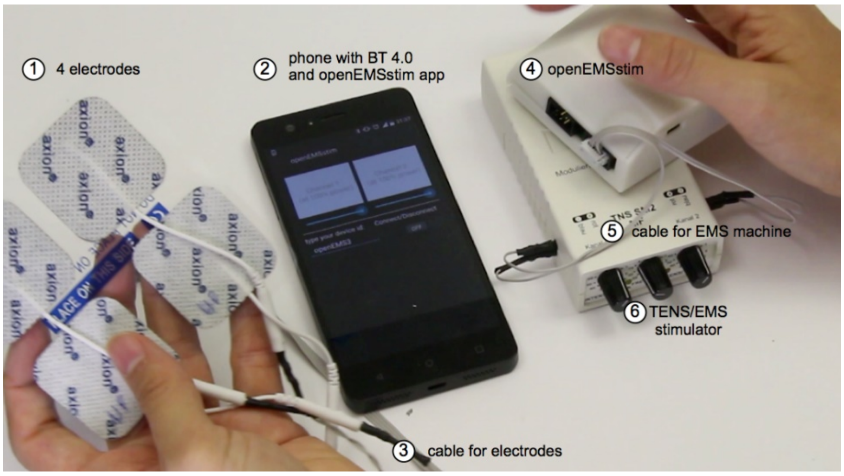


**Figure 2.2 The openEMSstim**

(Source: https://github.com/PedroLopes/openEMSstim)

The UnlimitedHand is a wearable I/O device. It can recognize hand gestures by monitoring muscle movement and generate haptic feedback to users in the form of vibration and EMS [24][25]. The input interface of this device can track the deformations of muscles and tendons with an eight-channel muscle motion sensor so that the device can deduce finger and wrist movements. The output function of UnlimitedHand can generate a weak vibration using the motor and the eight-channel electrodes built into it can produce haptic feedback. As a result, triggering different muscles can cause different movements of the hand. Figure 2.3 shows what the device looks like. In this study, participants should be worn in the middle of the forearm as shown in Figure 2.4.


**Figure 2.3 The outside and inside of the UnlimitedHand**

**Figure 2.4 How to wear the UnlimitedHand.**

EMS output can produce three types of movements: Finger motion, Ulnar/Radial deviations and Wrist motions.

| Electrode Channel delivering EMS | Hand Movements |
|---|---|
| Channel 0 | Contracts Hand |
| Channel 1 | Pulls in Fingers (Index/Middle/Ring) |
| Channel 2 | Pulls in Fingers (Middle/Ring/Pinky) |
| Channel 3 | Pulls in Fingers (Ring/Pinky) |
| Channel 4 | Releases Hand |
| Channel 5 | Open Hand and Wrist Motion(Extension) |
| Channel 6 | Tingle on forearm |
| Channel 7 | Pulls in Fingers (Index/Middle) |

**Table 2.1 Electrode channel delivering EMS and hand movements [25].**

## 2.2. Preemptive Action

The concept of Pre-Stimuli is inspired by S. Kasahara's research, Preemptive Action [5]. In the research of Preemptive Action, they first proposed a preemptive force feedback system that can speed up users' reaction times but does not wholly compromise the sense of control.

In general, these interactive approaches are actuated by EMS of mechanical actuators. They preempt to actuate the user's body to perform tasks or react to events (for example, Stimulated Percussions an EMS based method designed to help instrument learners understand the rhythm by actuating human bodies [6]). However, users do not feel a sense of control in most cases with preemptive haptic feedback.

To solve this problem, they use EMS to actuate the user's body, and the actuation should be conducted within a specific time window. Their research consisted of two experiments. The first experiment helps understand how preemptive haptic feedback timing affects users' sense of control. The second experiment optimizes for both the sense of control and reaction time.

The contributions of their research are:

1. In the case of preemptive timing, when users and the system move congruently, users will feel that they initiated the movement by themselves, but their reaction time is faster than usual.
2. Compared to the general practice of EMS, this method improves the sense of control.

## 2.3. Immersion Evaluation in VR

Presence is a feeling that you think you are experiencing an environment or a place, your body doesn't have to be there [7]. It is the experience of feeling of being in the VR environment. The effectiveness of virtual reality has often been linked to the sense of presence. Researchers believe the sense of experiencing an environment which you are not physically in is a subjective feeling. Therefore, to make users feel they are really in a VR environment and investigate the HCI factors, it is important to measure the sense of presence. In other words, by measuring the presence, we can get the degree of immersion. One of the most popular and reliable way is using questionnaires, but the questionnaires should be already proven.

Many factors in the VR environment can affect user's sense of being there, and there factors are also proved as the items in many credible questionnaires [7][8][9][10]. Barfield and Weghorst is one of the earliest team to invent a questionnaire to measure presence for VR environments [11]. Based on previous work, Witmer and Singer [7] who worked for U.S. army have discovered four factors, control factors (user control in VR), sensory factors (quality of given information, such as the display screen and sound), distraction factors (if the user can be distracted when experience in VR) and realism factors (how realistic the scene design is). The presence questionnaire (PQ) consists of these factors, and it is also the most cited presence questionnaire by other researchers. The immersive tendency questionnaire (ITQ) are from the same work of Witmer and Singer, this questionnaire can measure the tendencies from different users in VR.

Slater, Usoh and Steed developed a new questionnaire SUS. This questionnaire is able to distinguish the real experience and the virtual experiences [32]. So researchers can use this questionnaire to compare the experience in a real environment and a virtual environments.

Schubert, Friedmann and Regenbrecht [10] have proposed three factors to measure the sense of being there, they are spatial presence (the sense of being in the VR environment in physic), involvement (measuring the user's attention when they are in VR and the evaluating the involvement experienced in VR) and experienced realism (measuring the subjective opinion of experience related to realism in the VE). Besides the three factors, they also proposed an attached item to evaluate the general "sense of being there (PRES)" in the IPQ. Based on these factors, the researchers developed and verified a new presence questionnaire, the iGroup presence questionnaire (IPQ) [12]. It is also a frequently-used scale for measuring the sense of presence experienced in a virtual environment (VE) [13].

Schwind et al. [13] compared the three questionnaires, WS, SUS, and IPQ, and finally found that IPQ questionnaire is the best presence measurement. Because IPQ can provide the highest reliability and the timeframe of it is also acceptable. In this study, we also use IPQ as the final measure of presence.

# Chapter 3 Pre-Stimuli in VR

This thesis proposes Pre-Stimuli, a system inspired by Preemptive Action [5] to enhance immersion in VR. Before starting the discussion on the detailed implementation, this chapter explains the basic idea of Preemptive Action, the proposed Pre-Stimuli, and the user study. It can help understand this study easily by explaining the basic concept first.

## 3.1. Preemptive Action

The haptic feedback based systems can speed up the human reaction time physically by means of preemptive actions. These actuated systems can actuate the user faster than common reaction time to perform actions that the users want to do. For example, Stimulated Percussions helps users acquire movement of arms and legs at the timing for learning rhythm in music [6].

However, an interactive system actuating user automatically would eliminate the user's sense of control. As a result, users do not have sufficient sense of "I did this action". The more the system was automated, the less sense of control was felt [31].

To enable the haptic systems to provide users with more control, Kasahara et al. conducted two user studies. In the first user study, they discovered a particular timing which is best to deliver the haptic actuation (using EMS) while maintain the sense of control. In the second user study, they found that the proposed approach increased the sense of control compared with the existing EMS-based devices.

## 3.2. Pre-Stimuli

The approach of Preemptive Action can provide users with sense of control, but how does more sense of control affect the experience especially the experience in VR? Besides many applications of EMS have appeared in the field of VR, the study of Preemptive

Action in the field of VR can lead to a way of improving VR experience.

The human processor model usually consists of three interacting subsystems: (1) the perceptual system, (2) the cognitive system, and (3) the motor system [29]. According to this model, we can decompose a person's reaction time into perception, cognition, and motor action as illustrated in Figure 3.1. Our proposed approach aims to accelerate human reaction while providing user a sense of control in VR.

We conducted two user studies, in our first user study, we used a similar experimental approach (the first user study of Preemptive Action) to explore the optimal preemptive timing. We then applied this preemptive timing to actuate users by means of EMS to conduct our final experiments.

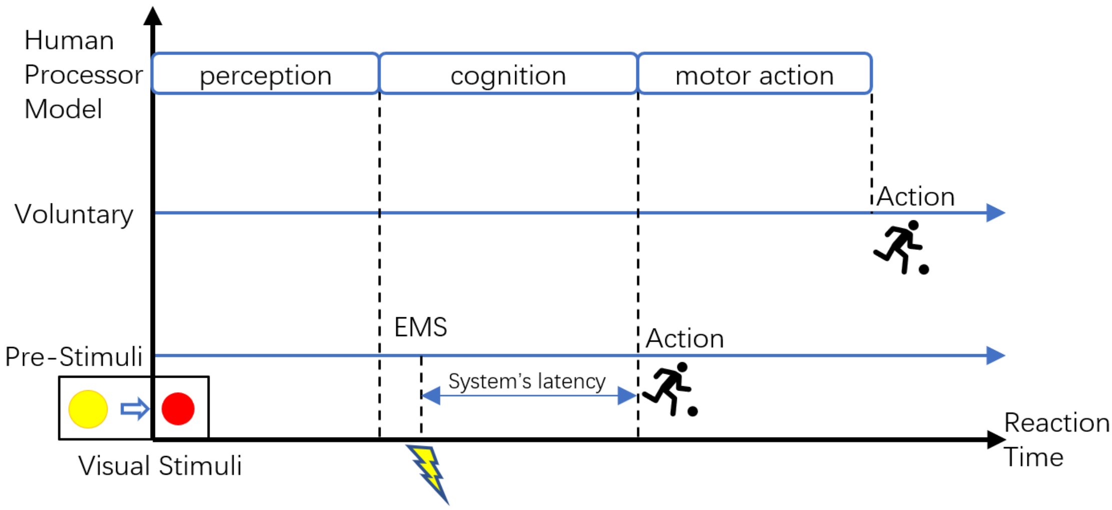


**Figure 3.1 Pre-Stimuli can speed up reaction time.**

## 3.3. Feedback After Pre-Stimuli

In the user study, we used Pre-Stimuli in combination with three different feedback to investigate the effects of Pre-Stimuli combined with various forms of feedback.

For haptic feedback, we implemented EMS feedback and vibration feedback. EMS is a useful tool in the field of HCI. The vibration feedback is a common way to provide haptic feedback. In order to imitate ordinary video games, we also used sound feedback in our experiments. Then we used IPQ to measure the effects of Pre-Stimuli combined with different feedback, and finally found that pre-stimuli can enhance immersion in VR.

# Chapter 4 Preliminary Study

This chapter illustrates our first user study. We explain how to obtain the Pre-Stimuli matching to our experimental environment (described in Section 4.1.1 Experiment Environment) because the experimental environment is different from the previous research of Preemptive Aciton.

## 4.1. Experiment Design

This section discusses the hardware and software environments of Pre-Stimuli system. This work designed a trigger pull simulation based on a canonical psychophysics task to measure reaction time. We implemented the system to deliver the EMS stimuli, which can make the user pull the trigger of the controller from time 0ms to time 350ms in VR. In this system, the stimulation time can be adjusted in 10ms units, so there are 36 timing to be measured.

### 4.1.1. Experiment Environment

**Apparatus**

The experimental setup is depicted in Figure 4.1. The equipment to be used in the preliminary experiments is: UnlimitedHand, HTC Vive, PC and a pair of headphones. The HTC Vive is a virtual reality display device developed by HTC and Valve.The HTC Vive can use a lot of VR software from Valves gaming platform Steam. [26]. The specific configuration of the system is as follows:

CPU: Intel® Core™ i7-8700 CPU @ 3.2GHz

GPU: NVIDIA GeForce GTX2070 8GB

RAM: 16GB

OS: Windows 10 1809

Unity Version: 2018.4.13f1

Headphones: Sony WH-1000XM2

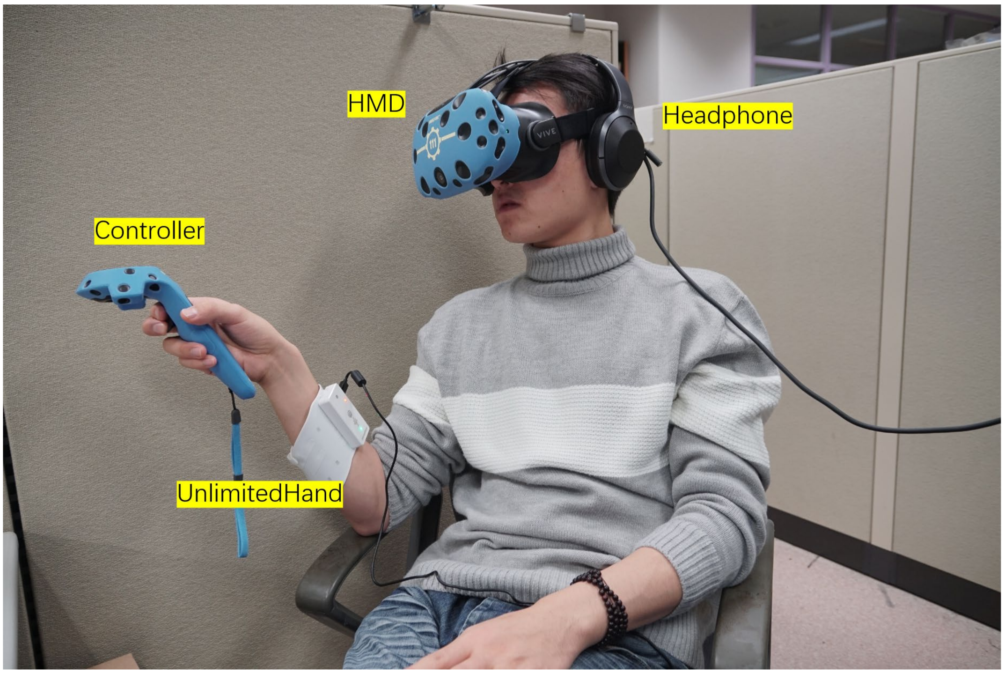


**Figure 4.1 Setup for the experiment.**

**Stimulation apparatus:** Participants wore the UnlimitedHand on their right forearm. The intensity of the stimulus can be adjusted in the Arduino IDE as depicted in Figure 4.2. The intensity of the stimulus is adjusted for each participant to achieve an effect which is to stimulate the index and middle fingers painlessly, yet with enough force to pull the trigger of the controller. The EMS device, the UnlimitedHand, can drive the index finger, the middle finger, and the ring finger. Thus, the participants are required to use his index finger or middle finger to pull the trigger.

**System's latency:** We define the latency of system as the time between the program sending the EMS command and user's motor action done as depicted in Figure 3.1 (Latency = Action time – EMS command time). According to this definition, we got an intrinsic latency of less than 110ms (avg = 108 ms, std.dev. = 7.4) between the generated stimulation command from the system and the participant's finger pulls the trigger of the controller. This latency (108 ms) was subtracted in the whole research through engineering the system properly. Therefore, all reaction time we will describe, refers to the time of participants pull the trigger.

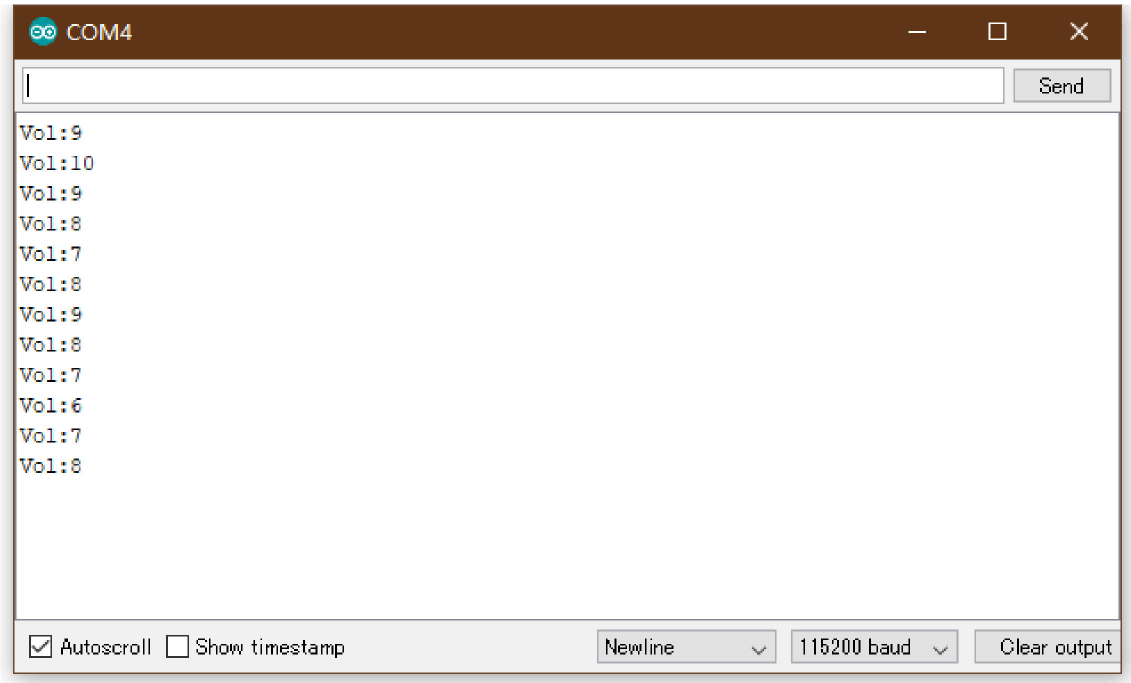


**Figure 4.2 Adjust EMS output intensity for the UnlimitedHand in Arduino IDE.**

## 4.1.2. Experiment Content

**Task**

The task was a simple trigger pull test. The task framework is depicted in Figure 4.3. We asked participants to pull the trigger as fast as possible when they see the floating object changes from yellow to red, depicted in Figure 4.3 and Figure 4.4.

The period before the object changing color is randomized (between 2 and 6 s) to keep participants focusing on the floating object. After each pull the trigger, participants were asked to answer a questionnaire to regard their perceived sense of control for this trigger pull. The questionnaire is a Likert scale question with 0 = "EMS did it" and 6 = "I did it".

The time window of preemptive stimulation ranged from 0ms to 350ms after the coin turned red. In order to sample this time interval as much as possible, we randomly assigned the time of Pre-Stimuli for every trial.

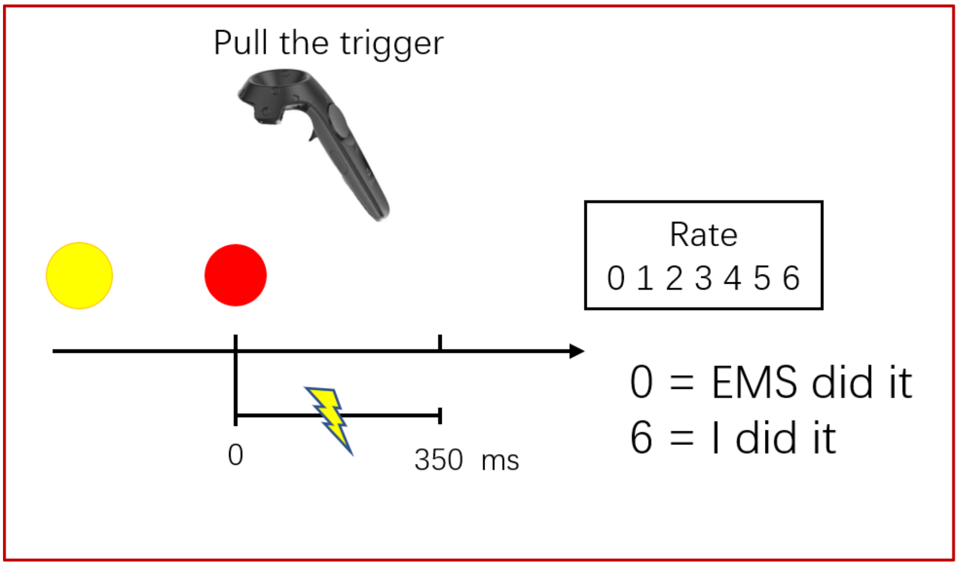


**Figure 4.3 The trigger pull task.**

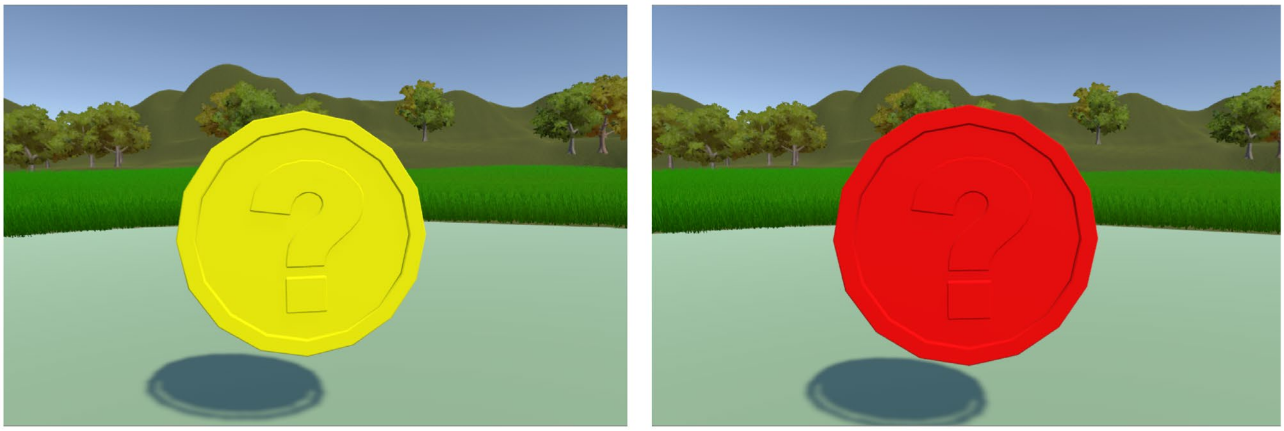

**Figure 4.4 The floating coin turns from yellow to red.**

**Procedure**

Before engaging in the research task, participants should be familiar with HTC Vive. After learning how to use the controller, participants were asked to perform 20 tasks without Pre-Stimuli to record their average reaction time. Then, we asked participants to perform 108 times (We should measure 36 timing. To ensure the accuracy of the data, three trials are conducted at each timing so that each participant should perform 108 trials.) of the trigger pull task. To prevent participants from mental fatigue, they should take a two-minute break every 20 times. After each time, participants were asked to orally answer a Likert scale questionnaire (answer it from 0 = "EMS did it" to 6 = "I did it").

**Participants**

We invited 12 participants (2 female, avg = 26.08 years old; std.dev. = 1.975).

## 4.2. Result

We found that the average reaction time of the participants was 284.6 ms (std.dev. = 46 ms). We collected 1,296 trials from all 12 participants. Each trial has two data points: the score of sense of control and the time participants completing the action (pull the trigger) affected by Pre-Stimuli.

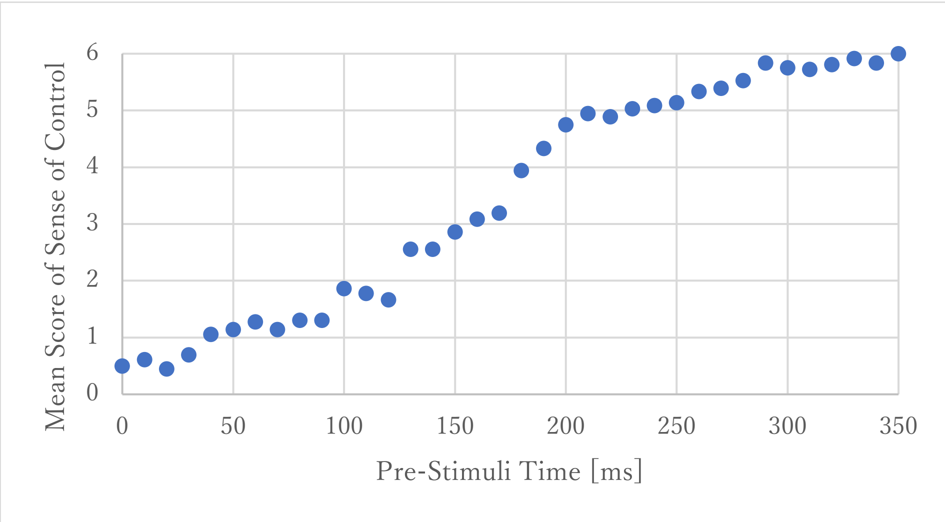


**Figure 4.5 Mean Score of Sense of Control vs. Pre-Stimuli Time.**

If the mean score of sense of control is 0, participants have no sense of control. If the mean score is 6, participants have full control. Thus we can say that when the mean score of sense of control is greater than 4, the system can provide a sense of control while accelerating human reaction. According to the data in Figure 4.5, when the Pre-Stimuli Time is greater than 200ms, the mean score is greater than 4.9 which is significantly high. Therefore, we can use the Pre-Stimuli setup of 210 ms to the formal experiments.

Compared to the average reaction time without Pre-Stimuli, we can gain a speed up in the final reaction time of 74.6 ms (Pre-Stimuli gain (74.6 ms) = Average reaction time (284.6 ms) – Pre-Stimuli time(210 ms)), which is aligned with the conclusion of the previous research [5]. And our preliminary study successfully adopted Preemptive Action in VR and the result is more than acceptable.

# Chapter 5 User Study

In the experiments of Chapter 4, we have determined the Pre-Stimuli settings of the equipment suitable for our experiment environment. Using Pre-Stimuli can advance participants response time to 210ms, gaining an average of 70ms and still providing the sense of control for participants.

In the experiments of this chapter, we used Pre-Stimuli in combination with three different forms of feedback to investigate the effects of Pre-Stimuli on various forms of feedback. The three forms of feedback are EMS, vibration and sound.

Therefore, we have to conduct three sets of controlled trials:

1. The experiments with Pre-Stimuli and no Pre-Stimuli under the condition of EMS feedback.
2. The experiments with Pre-Stimuli and no Pre-Stimuli under the condition of vibration feedback.
3. The experiments with Pre-Stimuli and no Pre-Stimuli under the condition of sound feedback.

## 5.1. Experiment Purpose

This experiment is conducted as a controlled trial to explore the effects of Pre-Stimuli on three different types of feedback (two haptic feedback and one sound feedback). Finally, the effects of Pre-Stimuli on immersion in VR are confirmed by evaluating the immersion of each control group.

## 5.2. Experiment Design

This section describes the content of formal experiments, including scene design, experimental conditions, and questionnaires. Specifically, we introduce the scene in which participants will experience, explain how the feedback of three forms are provided in the scene, and how Pre-Stimuli can be leveraged in it to enhance immersion. Finally, the procedure of the experiment are explained.

## 5.2.1. Experiment Environment

**Apparatus**

The experimental setup is the same as in Section 4.1.1. The only thing to note is that both EMS and Vibration feedback in the scene are provided by UnlimitedHand. Sound feedback is provided by the headphones.

## 5.2.2. Experiment Content

**Scene**

The scene is an interactive rapid shooter game. In order to increase the fun of the game and attract the attention of the participants, the yellow target will continually fly left-to right and right-to-left in front of the participant. The participants should aim the target all the time. When the target changes from yellow to red, participants can shoot it with a pistol. They should shoot the target as quickly as they can. The period before the object changing color is randomized (between 2 and 6 s) to keep participants focusing on the target. When the target turns red, Pre-Stimuli will help the participant pull the trigger. When the bullet is fired, one of the three forms of feedback are given to participants. The screen of the scene is depicted in Figure 5.1, Figure 5.2, and Figure 5.3.

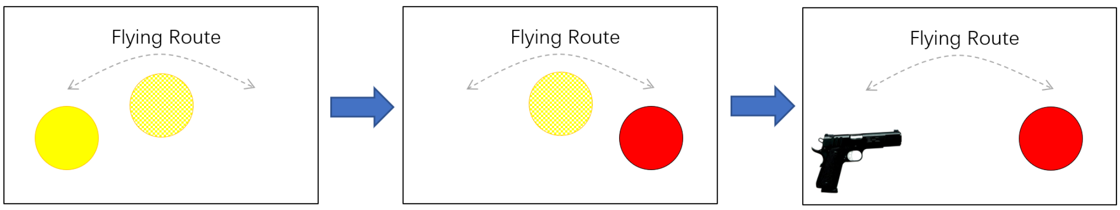


**Figure 5.1 Participant shoot the flying target when it turns red.**

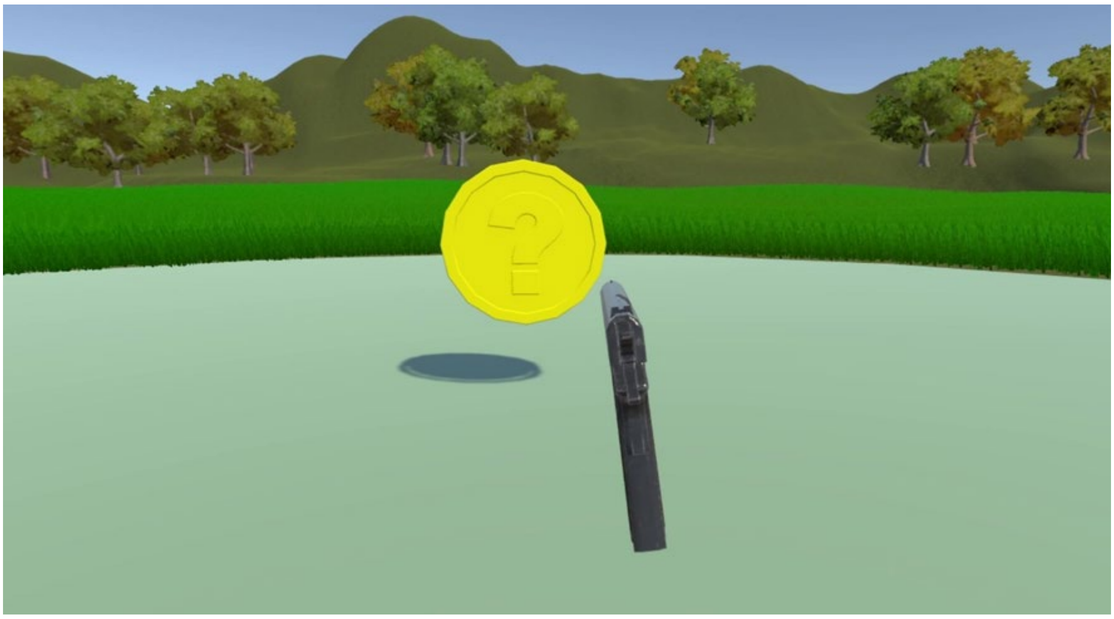

**Figure 5.2 The flying target is originally yellow.**

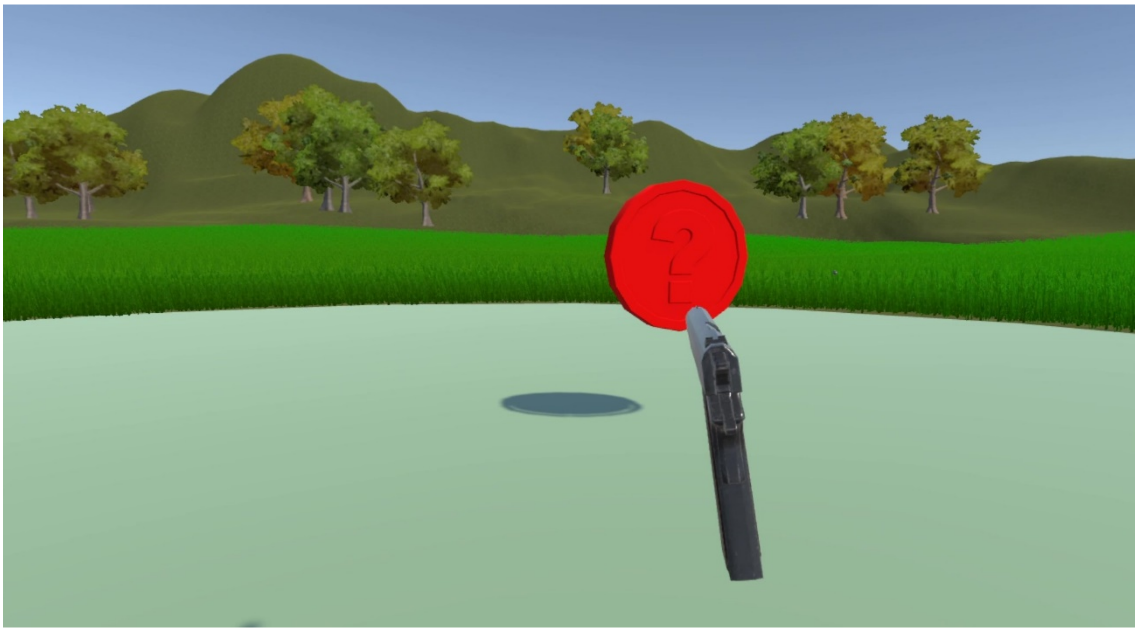

**Figure 5.3 The flying target turns to red.**

**Feedback**

Participants will receive different types of feedback to enhance the gaming experience after shooting in the game.

The three forms of feedback in this experiment are designed as follow:

1. EMS: This feedback is provided by the UnlimitedHand, which can extend the wrist, simulating the recoil of the pistol after firing.
2. Vibration: This feedback is provided by the UnlimitedHand, which can stimulate the arm with vibrations.
3. Sound: This feedback was provided to the participants via headphones, and it is a loud sound of gunshot.

**Procedure**

We introduced EMS and VR to participants, and explained the concept of Pre-Stimuli. We told participants that EMS can stimulate muscles and let them have a try of the EMS functions supported by the UnlimitedHand. If they havent experienced VR, we will let them try HTC Vive for a few minutes and show them how to use the controller.

After wearing the UnlimitedHand which was connected to PC to the participant's right forearm, we calibrated the device to correctly implement the functions of Pre-Stimuli (finger pull the trigger) and EMS feedback. Then participants were equipped with the HTC Vive and headphones, which is running VR scenes on Unity. Once all devices are ready, participants will experience the shooting game with different conditions of feedback.

Since we are conducting three controlled trials, participants will experience a total of six fast shooting games under different conditions as follows:

1. The experiment with Pre-Stimuli under the condition of EMS feedback.
2. The experiment without Pre-Stimuli under the condition of EMS feedback.
3. The experiment with Pre-Stimuli under the condition of vibration feedback.
4. The experiment without Pre-Stimuli under the condition of vibration feedback.
5. The experiment with Pre-Stimuli under the condition of sound feedback.
6. The experiment without Pre-Stimuli under the condition of sound feedback.

In order for the experimental results to be accurate, the orders of each of the six experiments performed by each participant were set to be random, and after each experiment, participants were asked to evaluate their sense of presence by filling a modified IPQ questionnaire.

| Group \ Pre-Stimuli | Pre-Stimuli Available | Pre-Stimuli not Available |
|---|---|---|
| EMS Feedback | IPQ1 | IPQ2 |
| Vibration Feedback | IPQ3 | IPQ4 |
| Sound Feedback | IPQ5 | IPQ6 |

**Table 4.1 6 conditions and answer 6 IPQ**

**Participants**

We invited 18 new participants (3 female, avg = 25.9 years old; std.dev. = 1.955), 12 of them had partaken in the previous study but there are a few days before they take part in this user study.

## 5.2.3. The Questionnaire Design

The questionnaire we used is modified based on the original IGroup presence questionnaire (IPQ) [27] which includes four subscales: (1) spatial presence, (2) involvement, (3)realism, (4) sense of being there.

The questionnaire is a 7-level Likert scale that participants were asked to answer. We used a total of 15 questions. In the formal questionnaire filled out by participants in the experiment, the order of the questions is set to be random [30]. Some questions are very similar to each other but with different anchors (such as Question 4 and Question 6). This is statistically necessary for reducing anchoring as much as possible. The specific questionnaire design is shown as follows.

1. (PRES1) In the computer generated world I had a sense of "being there".
   not at all 0 1 2 3 4 5 6 very much
2. (SP1) Somehow I felt that the virtual world surrounded me.
   fully disagree 0 1 2 3 4 5 6 fully agree
3. (SP2) I felt like I was just perceiving pictures.

fully agree 0 1 2 3 4 5 6 fully disagree

4. (SP3) I did not feel present in the virtual space.

   did not feel 0 1 2 3 4 5 6 felt present

5. (SP4) I had a sense of acting in the virtual space, rather than operating something from outside.

   fully disagree 0 1 2 3 4 5 6 fully agree

6. (SP5) I felt present in the virtual space.

   fully disagree 0 1 2 3 4 5 6 fully agree

7. (INV1) How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

   extremely aware 0 1 2 3 4 5 6 not aware at all

8. (INV2) I was not aware of my real environment.

   fully disagree 0 1 2 3 4 5 6 fully agree

9. (INV3) I still paid attention to the real environment.

   fully disagree 0 1 2 3 4 5 6 fully agree

10. (INV4) I was completely captivated by the virtual world.

    fully disagree 0 1 2 3 4 5 6 fully agree

11. (REAL1) How real did the virtual world seem to you?

    completely real 0 1 2 3 4 5 6 not real at all

12. (REAL2) How much did your experience in the virtual environment seem consistent with your real world experience ?

    not consistent 0 1 2 3 4 5 6 very consistent

13. (REAL3) How real did the virtual world seem to you?

    0 1 2 3 4 5 6

    about as real as an imagined world istinguishable from the real world

14. (REAL4) The virtual world seemed more realistic than the real world.

    fully disagree 0 1 2 3 4 5 6 fully agree

15. (PRES2) I felt like the shooting event was a real one.

    fully disagree 0 1 2 3 4 5 6 fully agree

Participants answers are shown in the appendix. In this questionnaire, PRES = General Presence, SP = Spatial Presence, INV = Involvement, REAL = Experienced Realism.

## 5.3. Result

This section describes the statistical analysis of the questionnaire results obtained in Section 5.2 using SPSS 25 [28]. The results show that in each group of control experiments, the experimental group using Pre-Stimuli outperforms the control group without Pre-Stimuli on all subscales.

### 5.3.1. Quantitative result

Figure 5.4, Figure 5.5, and Figure 5.6 depicts the results from the questionnaire of IPQ. The results show four subscales of the questionnaire: (1) spatial presence (SP), (2) involvement (INV), (2) realism (REAL), (4) sense of being there (PRES).

**EMS feedback group**

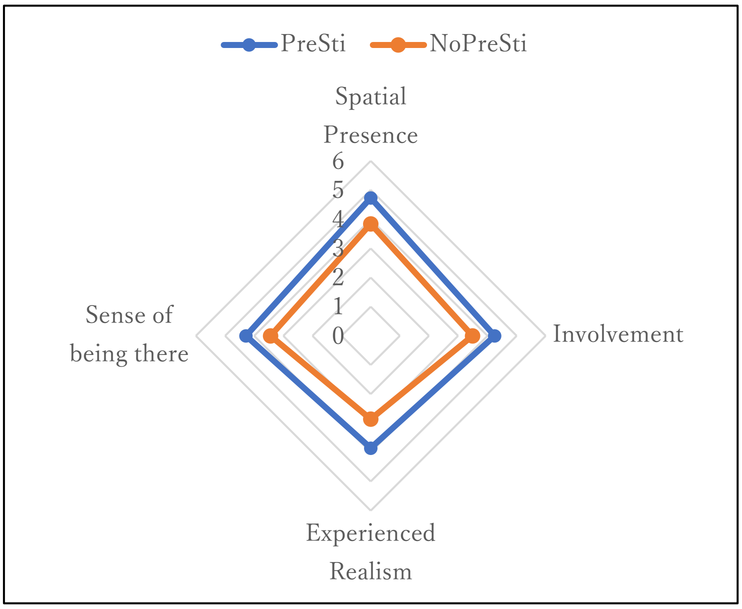


**Figure 5.4 IQP Score per condition of EMS feedback group.**

In the EMS feedback group, Pre-Stimuli elicited a higher spatial presence (avg = 4.73; std.dev. = 1.33) compared to No Pre-Stimuli (avg = 3.84; std.dev. = 0.91). Pre-Stimuli was also associated with a stronger involvement (avg = 4.25; std.dev. = 0.93) compared to No Pre-Stimuli (avg = 3.49; std.dev. = 1.01). Experienced realism was reported to be higher with Pre-Stimuli (avg = 3.85; std.dev. = 1.01) compared to No Pre-Stimuli (avg = 2.86; std.dev. = 0.98). Finally, the sense of being there was higher with Pre-Stimuli (avg = 4.28; std.dev. = 1.67), followed by No Pre-Stimuli (avg = 3.44; std.dev. = 1.50).

To check for statistical significance, we conducted one-way ANOVA tests. We found that $p < 0.01$ is on all subscales. This means that Pre-Stimuli outperforms No Pre-Stimuli according to the IPQ questionnaire under EMS feedback condition.

**Vibration feedback group**

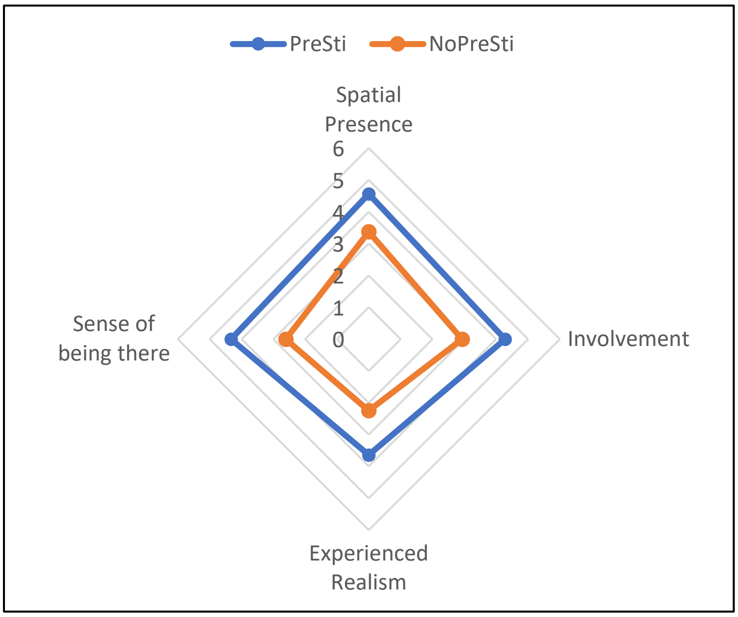


**Figure 5.5 IQP Score per condition of Vibration feedback group.**

In the Vibration feedback group, Pre-Stimuli elicited a higher spatial presence (avg = 4.55; std.dev. = 1.01) compared to No Pre-Stimuli (avg = 3.37; std.dev. = 0.82). Pre-Stimuli was also associated with a stronger involvement (avg = 4.28; std.dev. = 0.74) compared to No Pre-Stimuli (avg = 2.93; std.dev. = 0.98). Experienced realism was reported to be higher with Pre-Stimuli (avg = 3.64; std.dev. = 0.97) compared to No

Pre-Stimuli (avg = 2.25; std.dev. = 0.96). Finally, the sense of being there was higher with Pre-Stimuli (avg = 4.33; std.dev. = 1.35), followed by No Pre-Stimuli (avg = 2.61; std.dev. = 1.25).

To check for statistical significance, we conducted one-way ANOVA tests. We found that $p < 0.01$ is on all subscales. This means that Pre-Stimuli outperforms No Pre-Stimuli according to the IPQ questionnaire under Vibration feedback condition.

**Sound feedback**

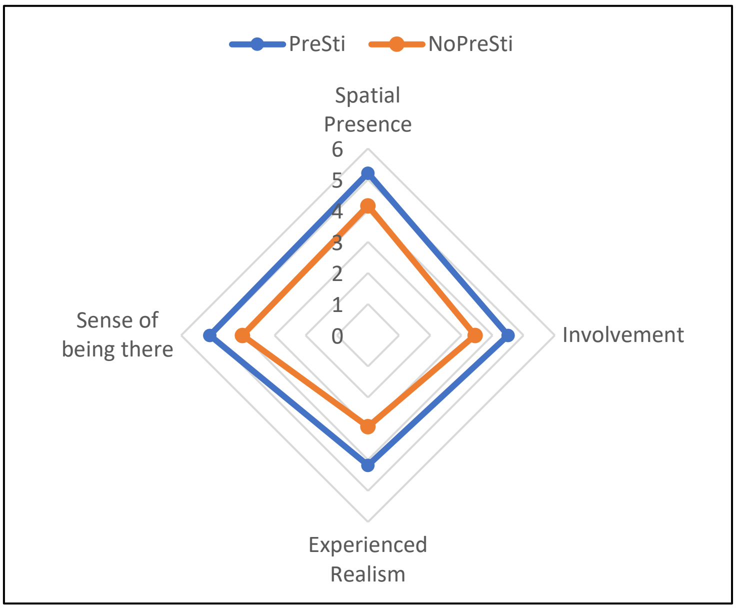


**Figure 5.6 IQP Score per condition of Sound feedback group.**

In the Sound feedback group, Pre-Stimuli also elicited a higher spatial presence (avg = 5.21; std.dev. = 0.91) compared to No Pre-Stimuli (avg = 4.16; std.dev. = 1.09). Pre-Stimuli was also associated with a stronger involvement (avg = 4.50; std.dev. = 0.82) compared to No Pre-Stimuli (avg = 3.44; std.dev. = 1.01). Experienced realism was reported to be higher with Pre-Stimuli (avg = 4.18; std.dev. = 0.82) compared to No Pre-Stimuli (avg = 2.94; std.dev. = 0.91). Finally, the sense of being there was higher with Pre-Stimuli (avg = 5.08; std.dev. = 1.24), followed by No Pre-Stimuli (avg = 4.03; std.dev. = 1.52).

To check for statistical significance, we ran one-way ANOVA tests. We found that $p < 0.01$ is on all subscales. This means that Pre-Stimuli outperforms No Pre-Stimuli according to the IPQ questionnaire under Sound feedback condition.

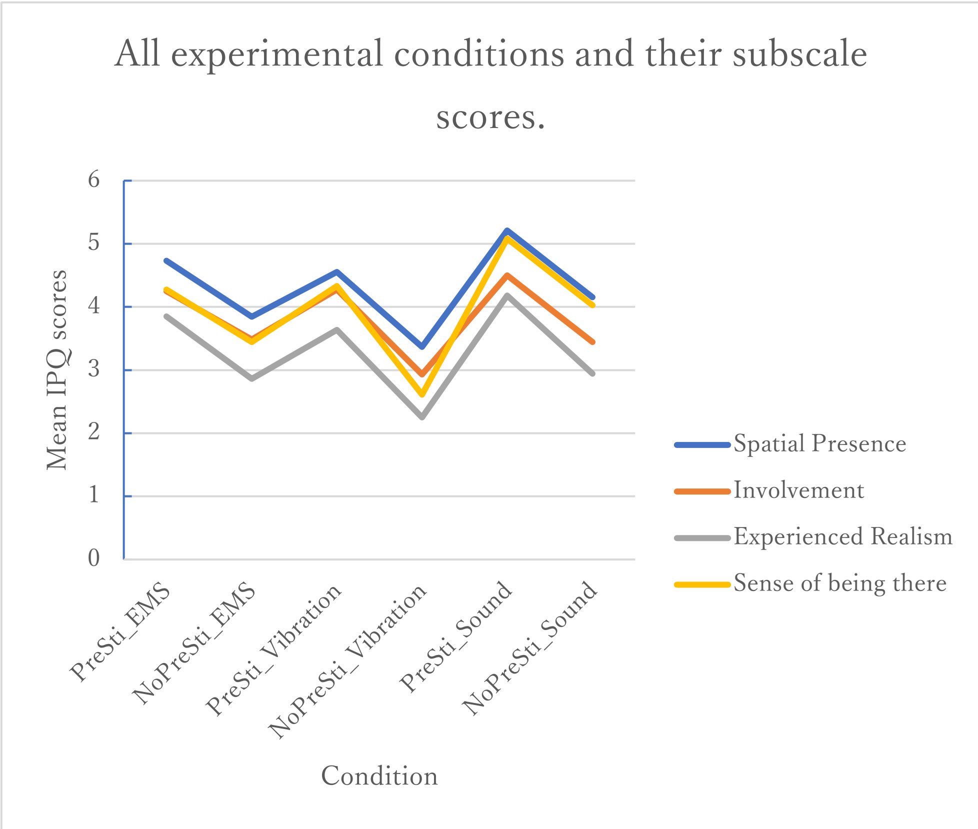


**Figure 5.7 All experimental conditions and their subscale scores.**

From the data in Figure 5.7, we observed that, whether or not Pre-Stimuli is used, the score of the sound feedback group is the highest, and the score of the vibration feedback group is the worst. This is because of the limitation of the device, the vibration function of UnlimitedHand is relatively weak.

## 5.3.2. Qualitative results

At each end of the entire experiment, we asked participants to describe their feelings. All of participants agreed that Pre-Stimuli could make the subsequent feedback stronger, whether the feedback was vibration, sound or EMS. The enhanced feedback improves the overall VR experience.

Participants No. 6 (P6) preferred EMS feedback and thought it is more vivid than vibration feedback. P10 was a bit nervous when we first started experimenting with Pre-Stimuli, but P10 got used to it after a few experiments, and can obviously feel that Pre-Stimuli enhanced the effect of subsequent feedback. P11 preferred EMS feedback, and thinks the experience of the sound feedback group is more like an ordinary shooting game. P13 said that Pre-Stimuli can not only speed up user's reaction time, but also reduce the cognitive burden to pull the trigger. P14 preferred the experience of the sound feedback group, but in the sound feedback group, he said it is not easy to tell if we use Pre-Stimuli or not. P15 was a little surprised at the first trial with Pre-Stimuli, P15 said he had never experience EMS as an HCI approach but he felt well in the next trial.

In addition, two other participants were unacceptable to EMS. Even if we adjusted the EMS stimulation to the minimum necessary for the experiment (at least actuating the finger to pull the trigger), they still felt uncomfortable. Despite no other participants said it hurt, each of them said the stimulus hurt while the intensity of the stimulus was set in the lowest level (cannot actuate the finger).

## 5.4. Discussions

The result of the user study is exciting, indicates that Pre-Stimuli can significantly improve the experienced realism, spatial presence, involvement and the sense of being there in the scene in which users need to quickly interact with the happened event. Thus, Pre-Stimuli can enhance VR experience.

When we applied Pre-Stimuli, the results show that Sound feedback outperforms the two other conditions, however, there is little difference between the effect of vibration feedback and electrical feedback. When we didn't apply Pre-Stimuli, Sound feedback still perform the best. And the EMS feedback have a better performance than vibration feedback. But these conclusions could have been influenced by the device functions, making the comparison between different feedback meaningless.

During the experiment, participants' responses will sometimes be slower than the average reaction time so that participants could feel for themselves whether we used Pre-Stimuli. In this situation, the Pre-Stimuli stimulation will become more apparent, because they find that they have not yet judged whether the trigger needs to be pulled, however, their action has already been completed. When they are in a good state of mental concentration, even if the experimental conditions contain pre-stimuli, they believe that the triggering action is done by themselves. Participants felt that Pre-Stimuli made the three feedbacks after the shooting even stronger. Most participants said they thought Pre-Stimuli made all the feedbacks feel better.

# Chapter 6 Conclusion

This chapter summarizes this study. The overall summary is explained first, and then the future topics and developments related to this research are explained.

## 6.1. Summary

We propose the use of EMS for haptic feedback in VR. We introduced our approach, Pre-Stimuli, which adopted the Preemptive Action and can improve VR experience by enhancing the effects of other feedback.

In this study, to explore the effects of Pre-Stimuli on VR immersion, a preliminary study and a user study were conducted. In the preliminary study, we found the best settings of Pre-Stimuli suitable for the system by analyzing the data from the experiments. And these settings were applied to formal experiments.

In formal trials, three controlled experiments were performed with Pre-Stimuli as a variable. The experimental results show that Pre-Stimuli can enhance VR immersion by acting on various types of feedback. And it has been proved that the effect of EMS can be improved at the software level by programming without modifying the existing EMS equipment.

The contributions of our approach, which have been validated in our user study, are (1) accelerating human reaction while providing the sense of control in VR, (2) this approach can be applied with different feedback and improve the experience in VR, (3) this approach can be applied directly on existing EMS interaction devices without redesigning new EMS devices.

## 6.2. Discussion

The scene design in the formal experiment is a bit monotonous and cannot be called a complete game; at most, it is a small part of a shooting game. In complex interaction scenarios, the role of Pre-Stimuli has yet to be proven.

This study only explored Pre-Stimuli with vibration feedback, EMS feedback and sound feedback. The influence of Pre-Stimuli to visual feedback is not discussed in this study. Our approach is also subject to the limitations of EMS. If the user cannot accept EMS, then this method becomes useless. EMS can make user's muscle fatigue so that user would feel uncomfortable.

## 6.3. Future topics

One direction for future work is to combine Pre-Stimuli with complex VR contents to extend the use of Pre-Stimuli. Future versions of Pre-Stimuli can benefit from the development of EMS and VR contents. For example, if we can apply Pre-Stimuli on better advanced EMS devices, the user experience could even be better such as providing EMS to sensitive people.

# Bibliography


[1] G. Burdea and P. Coiffet, *Virtual reality technology*, 2nd ed. John Wiley & Sons, 2003, pp. 25-28.

[2] J. Jerald, *The VR Book: Human-Centered Design for Virtual Reality*. [s.l.]: ACM Books, 2016.

[3] G. Burdea, *Force and touch feedback for virtual reality*. New York, N.Y.: J. Wiley and Sons, 1996.

[4] J. Knibbe, A. Alsmith and K. Hornbæk, "Experiencing Electrical Muscle Stimulation", *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 2, no. 3, pp. 1-14, 2018. Available: https://dl.acm.org/doi/10.1145/3264928. [Accessed 27 January 2020].

[5] S. Kasahara, J. Nishida and P. Lopes, "Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency", *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI 19*, 2019. Available: https://dl.acm.org/doi/abs/10.1145/3290605.3300873. [Accessed 27 January 2020].

[6] A. Ebisu, S. Hashizume, K. Suzuki, A. Ishii, M. Sakashita and Y. Ochiai, "Stimulated percussions", *Proceedings of the 8th Augmented Human International Conference on - AH 17*, 2017. Available: https://dl.acm.org/doi/abs/10.1145/3041164.3041202. [Accessed 27 January 2020].

[7] B. Witmer and M. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire", *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225-240, 1998. Available: https://www.mitpressjournals.org/doi/abs/10.1162/105474698565686.

[8] M. Schuemie, P. van der Straaten, M. Krijn and C. van der Mast, "Research on Presence in Virtual Reality: A Survey", *CyberPsychology & Behavior*, vol. 4, no. 2, pp. 183-201, 2001. Available: https://www.liebertpub.com/doi/10.1089/109493101300117884. [Accessed 27 January 2020].

[9] T. Schubert, F. Friedmann and H. Regenbrecht, "Embodied Presence in Virtual Environments", *Visual Representations and Interpretations*, pp. 269-278, 1999. Available: 10.1007/978-1-4471-0563-3_30 [Accessed 27 January 2020].

[10] T. Schubert, F. Friedmann and H. Regenbrecht, "The Experience of Presence: Factor Analytic Insights", *Presence: Teleoperators and Virtual Environments*, vol. 10, no. 3, pp. 266-281, 2001. Available: 10.1162/105474601300343603 [Accessed 27 January 2020].

[11] W. Barfield and S. Weghorst, "The Sense of Presence within Virtual Environments: {A} Conceptual Framework", *Human-Computer Interaction: Software and Hardware Interfaces*, vol. 2, no. 8-13, pp. 699-704, 1993.

[12] "igroup presence questionnaire (IPQ) overview | igroup.org – project consortium", *Igroup.org*, 2020. [Online]. Available: http://www.igroup.org/pq/ipq/index.php. [Accessed: 27- Jan- 2020].

[13] V. Schwind, P. Knierim, N. Haas and N. Henze, "Using Presence Questionnaires in Virtual Reality", *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI 19*, 2019. Available: https://dl.acm.org/doi/10.1145/3290605.3300590. [Accessed 27 January 2020].

[14] "Electrical muscle stimulation", *En.wikipedia.org*, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Electrical_muscle_stimulation. [Accessed: 27- Jan-

2020].
[15] S. Hanagata and Y. Kakehi, "Paralogue: A Remote Conversation System Using a Hand Avatar which Postures are Controlled with Electrical Muscle Stimulation", *Proceedings of the 9th Augmented Human International Conference on - AH 18*, 2018. Available: https://dl.acm.org/doi/10.1145/3174910.3174951. [Accessed 27 January 2020].
[16] P. Lopes, D. Yüksel, F. Guimbretière and P. Baudisch, "Muscle-plotter: An Interactive System based on Electrical Muscle Stimulation that Produces Spatial Output", *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST 16*, 2016. Available: https://dl.acm.org/doi/10.1145/3019606. [Accessed 27 January 2020].
[17] M. Hassib, M. Pfeiffer, S. Schneegass, M. Rohs and F. Alt, "Emotion Actuator: Embodied Emotional Feedback through Electroencephalography and Electrical Muscle Stimulation", *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI 17*, 2017. Available: https://dl.acm.org/doi/abs/10.1145/3025453.3025953. [Accessed 27 January 2020].
[18] P. Lopes, S. You, L. Cheng, S. Marwecki and P. Baudisch, "Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation", *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI 17*, 2017. Available: https://dl.acm.org/doi/abs/10.1145/3025453.3025600. [Accessed 27 January 2020].
[19] M. Kono, T. Miyaki and J. Rekimoto, "In-pulse: inducing fear and pain in virtual experiences", *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology - VRST 18*, 2018. Available: https://dl.acm.org/doi/abs/10.1145/3281505.3281506. [Accessed 27 January 2020].
[20] M. Khamis, N. Schuster, C. George and M. Pfeiffer, "ElectroCutscenes: Realistic Haptic Feedback in Cutscenes of Virtual Reality Games Using Electric Muscle Stimulation", *25th ACM Symposium on Virtual Reality Software and Technology on - VRST 19*, 2019. Available: https://dl.acm.org/doi/abs/10.1145/3359996.3364250. [Accessed 27 January 2020].
[21] M. Pfeiffer, T. Duente and M. Rohs, "Let your body move", *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI 16*, 2016. Available: https://dl.acm.org/doi/abs/10.1145/2935334.2935348. [Accessed 27 January 2020].
[22] "LetYourBodyMove", *Bitbucket.org*, 2020. [Online]. Available: https://bitbucket.org/MaxPfeiffer/letyourbodymove/src/master/. [Accessed: 27- Jan- 2020].
[23] "PedroLopes/openEMSstim", *GitHub*, 2020. [Online]. Available: https://github.com/PedroLopes/openEMSstim. [Accessed: 27- Jan- 2020].
[24] E. Tamaki, T. Chan and K. Iwasaki, "UnlimitedHand: Input and Output Hand Gestures with Less Calibration Time", *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST 16 Adjunct*, 2016. Available: https://dl.acm.org/doi/abs/10.1145/2984751.2985743. [Accessed 27 January 2020].
[25] "UnlimitedHand – Touch and feel the game world.", *Unlimitedhand.com*, 2020. [Online]. Available: http://unlimitedhand.com/. [Accessed: 27- Jan- 2020].
[26] "HTC Vive", *En.wikipedia.org*, 2020. [Online]. Available: https://en.wikipedia.org/wiki/HTC_Vive. [Accessed: 27- Jan- 2020].
[27] "igroup presence questionnaire (IPQ) Item Download | igroup.org – project consortium", *Igroup.org*, 2020. [Online]. Available: http://www.igroup.org/pq/ipq/download.php. [Accessed: 27- Jan- 2020].
[28] "SPSS Software", *Ibm.com*, 2020. [Online]. Available: https://www.ibm.com/analytics/spss-statistics-software. [Accessed: 27- Jan- 2020].

[29] S. Card, T. Moran and A. Newell, *The Psychology of Human-Computer Interaction*. London: Lawrence Erlbaum, 1983, pp. 23-44.
[30] "Questionnaire on Experiences in Virtual Worlds", *Igroup.org*, 2020. [Online]. Available: http://www.igroup.org/pq/ipq/ipq_english.htm. [Accessed: 01- Feb- 2020].
[31] B. Berberian, J. Sarrazin, P. Le Blaye and P. Haggard, "Automation Technology and Sense of Control: A Window on Human Agency", *PLoS ONE*, vol. 7, no. 3, p. e34075, 2012. Available: https://doi.org/10.1371/journal.pone.0034075. [Accessed 3 February 2020].
[32] M. Usoh, E. Catena, S. Arman and M. Slater, "Using Presence Questionnaires in Reality", *Presence: Teleoperators and Virtual Environments*, vol. 9, no. 5, pp. 497-503, 2000. Available: https://doi.org/10.1162/105474600566989. [Accessed 4 February 2020].

# Acknowledgements

Upon the completion of this thesis, I am grateful to those who have offered encouragement and support during the course of my study at JAIST.

Special acknowledgment is given to my respectable supervisor Prof. Miyata Kazunori, whose patient instruction and constructive suggestions are beneficial to me a lot.

I would also like to acknowledge our Assistant Prof. XIE Haoran who always gives me kinds of academic instruction and sprit spur.

I would also like to thank my fellow students in Miyata Lab for their cooperation and of course friendship. In addition, I would like to express my gratitude to all the professors and students who have helped me in JAIST.

Finally, I must express my very profound gratitude to my parents and to my girlfriend for providing me with unfailing support and continuous encouragement throughout my years of study.

# Appendix

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 1 | 0 | 1 | 0 | 1 | 0 |
| SP1 | 3 | 3 | 5 | 3 | 4 | 3 |
| SP2 | 4 | 4 | 4 | 4 | 5 | 4 |
| SP3 | 3 | 3 | 6 | 3 | 6 | 4 |
| SP4 | 6 | 0 | 1 | 0 | 1 | 0 |
| SP5 | 6 | 3 | 6 | 3 | 4 | 3 |
| INV1 | 3 | 0 | 2 | 0 | 1 | 0 |
| INV2 | 6 | 3 | 4 | 3 | 4 | 3 |
| INV3 | 4 | 2 | 4 | 1 | 3 | 2 |
| INV4 | 1 | 0 | 1 | 0 | 1 | 0 |
| REAL1 | 3 | 6 | 1 | 6 | 6 | 6 |
| REAL2 | 4 | 3 | 5 | 3 | 4 | 0 |
| REAL3 | 2 | 6 | 6 | 6 | 6 | 0 |
| REAL4 | 1 | 0 | 1 | 0 | 1 | 0 |
| PRES2 | 3 | 2 | 2 | 1 | 4 | 1 |

**Appendix 1 All IPQ scores of P1**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 4 | 4 | 6 | 4 | 5 | 5 |
| SP1 | 4 | 4 | 6 | 4 | 6 | 5 |
| SP2 | 4 | 3 | 4 | 3 | 4 | 3 |
| SP3 | 5 | 3 | 5 | 5 | 4 | 3 |
| SP4 | 4 | 4 | 4 | 6 | 4 | 4 |
| SP5 | 4 | 4 | 5 | 3 | 6 | 5 |
| INV1 | 4 | 5 | 5 | 5 | 6 | 4 |
| INV2 | 5 | 6 | 6 | 4 | 6 | 6 |
| INV3 | 5 | 1 | 6 | 2 | 5 | 5 |
| INV4 | 5 | 4 | 6 | 3 | 5 | 4 |
| REAL1 | 4 | 3 | 4 | 3 | 5 | 4 |
| REAL2 | 4 | 4 | 5 | 3 | 5 | 4 |
| REAL3 | 4 | 4 | 5 | 3 | 5 | 3 |
| REAL4 | 4 | 3 | 5 | 1 | 3 | 3 |
| PRES2 | 5 | 5 | 6 | 4 | 6 | 4 |

**Appendix 2 All IPQ scores of P2**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 6 | 4 | 6 | 5 |
| SP1 | 6 | 4 | 6 | 5 | 6 | 5 |
| SP2 | 6 | 6 | 6 | 5 | 6 | 6 |
| SP3 | 6 | 5 | 2 | 4 | 6 | 1 |
| SP4 | 6 | 4 | 1 | 2 | 3 | 1 |
| SP5 | 6 | 4 | 5 | 4 | 6 | 5 |
| INV1 | 6 | 6 | 6 | 6 | 6 | 6 |
| INV2 | 6 | 5 | 6 | 5 | 6 | 6 |
| INV3 | 1 | 1 | 2 | 1 | 1 | 0 |
| INV4 | 2 | 4 | 3 | 5 | 4 | 1 |
| REAL1 | 3 | 2 | 6 | 4 | 4 | 3 |
| REAL2 | 1 | 2 | 1 | 1 | 1 | 0 |
| REAL3 | 1 | 2 | 1 | 1 | 1 | 1 |
| REAL4 | 1 | 0 | 1 | 0 | 1 | 0 |
| PRES2 | 4 | 5 | 1 | 0 | 2 | 0 |

**Appendix 3 All IPQ scores of P3**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 6 | 3 | 6 | 6 |
| SP1 | 6 | 0 | 6 | 0 | 6 | 6 |
| SP2 | 6 | 5 | 6 | 6 | 6 | 5 |
| SP3 | 6 | 4 | 6 | 5 | 6 | 6 |
| SP4 | 6 | 6 | 5 | 6 | 6 | 5 |
| SP5 | 5 | 6 | 6 | 0 | 2 | 6 |
| INV1 | 5 | 6 | 6 | 3 | 5 | 5 |
| INV2 | 6 | 3 | 2 | 0 | 5 | 0 |
| INV3 | 6 | 6 | 6 | 5 | 6 | 1 |
| INV4 | 5 | 0 | 1 | 0 | 6 | 6 |
| REAL1 | 2 | 5 | 2 | 1 | 6 | 2 |
| REAL2 | 6 | 0 | 1 | 0 | 4 | 4 |
| REAL3 | 5 | 0 | 1 | 0 | 1 | 2 |
| REAL4 | 1 | 1 | 2 | 0 | 6 | 0 |
| PRES2 | 1 | 0 | 6 | 4 | 6 | 6 |

**Appendix 4 All IPQ scores of P4**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 5 | 4 | 6 | 5 | 6 | 5 |
| SP1 | 4 | 3 | 4 | 3 | 5 | 4 |
| SP2 | 5 | 5 | 6 | 5 | 5 | 4 |
| SP3 | 6 | 4 | 6 | 5 | 5 | 4 |
| SP4 | 5 | 4 | 5 | 4 | 5 | 4 |
| SP5 | 5 | 3 | 4 | 3 | 5 | 4 |
| INV1 | 6 | 5 | 6 | 5 | 6 | 5 |
| INV2 | 5 | 4 | 5 | 4 | 6 | 4 |
| INV3 | 5 | 4 | 3 | 2 | 5 | 5 |
| INV4 | 5 | 4 | 5 | 4 | 5 | 4 |
| REAL1 | 4 | 2 | 3 | 2 | 3 | 3 |
| REAL2 | 5 | 3 | 6 | 5 | 5 | 4 |
| REAL3 | 4 | 3 | 5 | 4 | 5 | 4 |
| REAL4 | 4 | 2 | 6 | 5 | 4 | 2 |
| PRES2 | 4 | 3 | 4 | 3 | 5 | 5 |

**Appendix 5 All IPQ scores of P5**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 5 | 4 | 5 | 3 | 6 | 5 |
| SP1 | 3 | 4 | 5 | 3 | 5 | 2 |
| SP2 | 5 | 5 | 6 | 6 | 6 | 5 |
| SP3 | 3 | 4 | 5 | 4 | 6 | 5 |
| SP4 | 3 | 4 | 3 | 1 | 6 | 3 |
| SP5 | 3 | 4 | 5 | 1 | 6 | 3 |
| INV1 | 6 | 6 | 6 | 5 | 6 | 5 |
| INV2 | 5 | 4 | 5 | 0 | 6 | 5 |
| INV3 | 4 | 4 | 5 | 1 | 2 | 1 |
| INV4 | 5 | 4 | 4 | 1 | 6 | 4 |
| REAL1 | 5 | 4 | 5 | 6 | 2 | 3 |
| REAL2 | 5 | 5 | 5 | 4 | 6 | 5 |
| REAL3 | 5 | 5 | 5 | 1 | 6 | 4 |
| REAL4 | 5 | 4 | 4 | 0 | 2 | 2 |
| PRES2 | 6 | 4 | 4 | 1 | 6 | 5 |

**Appendix 6 All IPQ scores of P6**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 6 | 3 | 6 | 6 |
| SP1 | 6 | 5 | 6 | 4 | 6 | 6 |
| SP2 | 6 | 4 | 6 | 4 | 6 | 6 |
| SP3 | 6 | 5 | 6 | 4 | 6 | 6 |
| SP4 | 6 | 5 | 4 | 3 | 6 | 6 |
| SP5 | 6 | 4 | 6 | 4 | 6 | 6 |
| INV1 | 6 | 5 | 6 | 5 | 6 | 6 |
| INV2 | 6 | 5 | 6 | 4 | 6 | 6 |
| INV3 | 2 | 5 | 2 | 2 | 1 | 1 |
| INV4 | 6 | 5 | 6 | 5 | 6 | 6 |
| REAL1 | 2 | 1 | 2 | 1 | 2 | 0 |
| REAL2 | 6 | 5 | 6 | 4 | 6 | 6 |
| REAL3 | 6 | 5 | 3 | 3 | 6 | 6 |
| REAL4 | 6 | 4 | 6 | 4 | 5 | 5 |
| PRES2 | 6 | 4 | 6 | 5 | 6 | 6 |

**Appendix 7 All IPQ scores of P7**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 5 | 4 | 6 | 4 |
| SP1 | 6 | 5 | 5 | 4 | 6 | 4 |
| SP2 | 5 | 4 | 5 | 3 | 6 | 4 |
| SP3 | 6 | 4 | 5 | 5 | 6 | 4 |
| SP4 | 3 | 4 | 4 | 3 | 6 | 4 |
| SP5 | 5 | 4 | 4 | 5 | 6 | 4 |
| INV1 | 6 | 5 | 5 | 3 | 6 | 4 |
| INV2 | 3 | 5 | 5 | 3 | 6 | 3 |
| INV3 | 3 | 3 | 4 | 4 | 2 | 3 |
| INV4 | 5 | 3 | 3 | 1 | 6 | 2 |
| REAL1 | 4 | 2 | 5 | 4 | 2 | 5 |
| REAL2 | 6 | 4 | 5 | 3 | 6 | 4 |
| REAL3 | 6 | 4 | 5 | 4 | 6 | 4 |
| REAL4 | 4 | 2 | 3 | 0 | 6 | 2 |
| PRES2 | 6 | 4 | 5 | 3 | 6 | 3 |

**Appendix 8 All IPQ scores of P8**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 2 | 2 | 3 | 0 | 4 | 3 |
| SP1 | 3 | 3 | 4 | 0 | 4 | 2 |
| SP2 | 6 | 4 | 4 | 5 | 5 | 4 |
| SP3 | 3 | 3 | 3 | 1 | 4 | 3 |
| SP4 | 4 | 3 | 2 | 1 | 4 | 3 |
| SP5 | 2 | 5 | 3 | 0 | 6 | 3 |
| INV1 | 6 | 6 | 6 | 6 | 6 | 6 |
| INV2 | 6 | 5 | 5 | 3 | 6 | 5 |
| INV3 | 2 | 1 | 4 | 2 | 2 | 1 |
| INV4 | 4 | 3 | 3 | 1 | 4 | 2 |
| REAL1 | 6 | 4 | 6 | 5 | 4 | 3 |
| REAL2 | 4 | 2 | 2 | 1 | 4 | 3 |
| REAL3 | 3 | 2 | 2 | 1 | 4 | 3 |
| REAL4 | 2 | 1 | 3 | 0 | 3 | 2 |
| PRES2 | 3 | 2 | 3 | 1 | 4 | 3 |

**Appendix 9 All IPQ scores of P9**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 5 | 4 | 6 | 6 |
| SP1 | 6 | 5 | 6 | 4 | 6 | 6 |
| SP2 | 6 | 6 | 6 | 6 | 6 | 6 |
| SP3 | 6 | 5 | 5 | 2 | 6 | 6 |
| SP4 | 6 | 4 | 4 | 3 | 6 | 6 |
| SP5 | 6 | 5 | 6 | 5 | 6 | 6 |
| INV1 | 6 | 5 | 6 | 6 | 6 | 6 |
| INV2 | 6 | 5 | 3 | 3 | 6 | 6 |
| INV3 | 1 | 1 | 2 | 1 | 1 | 0 |
| INV4 | 6 | 6 | 6 | 6 | 6 | 6 |
| REAL1 | 2 | 1 | 4 | 1 | 2 | 1 |
| REAL2 | 6 | 5 | 5 | 5 | 6 | 6 |
| REAL3 | 6 | 4 | 5 | 2 | 6 | 6 |
| REAL4 | 6 | 3 | 3 | 2 | 6 | 5 |
| PRES2 | 6 | 5 | 6 | 3 | 6 | 5 |

**Appendix 10 All IPQ scores of P10**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 5 | 5 | 3 | 6 | 6 |
| SP1 | 6 | 5 | 5 | 4 | 6 | 6 |
| SP2 | 6 | 6 | 6 | 4 | 6 | 6 |
| SP3 | 6 | 3 | 3 | 3 | 6 | 5 |
| SP4 | 6 | 5 | 5 | 4 | 6 | 5 |
| SP5 | 6 | 1 | 4 | 3 | 6 | 5 |
| INV1 | 2 | 5 | 5 | 2 | 6 | 6 |
| INV2 | 6 | 5 | 3 | 4 | 6 | 6 |
| INV3 | 2 | 1 | 2 | 2 | 1 | 0 |
| INV4 | 6 | 5 | 6 | 3 | 6 | 5 |
| REAL1 | 2 | 1 | 3 | 3 | 6 | 1 |
| REAL2 | 6 | 5 | 5 | 4 | 6 | 5 |
| REAL3 | 3 | 5 | 5 | 4 | 2 | 1 |
| REAL4 | 6 | 5 | 6 | 2 | 6 | 5 |
| PRES2 | 6 | 5 | 6 | 4 | 6 | 5 |

**Appendix 11 All IPQ scores of P11**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 4 | 5 | 4 | 5 | 6 | 5 |
| SP1 | 6 | 5 | 6 | 5 | 6 | 5 |
| SP2 | 6 | 5 | 6 | 6 | 6 | 6 |
| SP3 | 6 | 5 | 6 | 4 | 6 | 5 |
| SP4 | 6 | 6 | 6 | 6 | 6 | 5 |
| SP5 | 6 | 5 | 6 | 2 | 6 | 3 |
| INV1 | 6 | 4 | 6 | 5 | 6 | 5 |
| INV2 | 6 | 3 | 3 | 3 | 4 | 3 |
| INV3 | 2 | 2 | 2 | 5 | 2 | 1 |
| INV4 | 5 | 5 | 5 | 4 | 6 | 4 |
| REAL1 | 2 | 3 | 2 | 2 | 1 | 1 |
| REAL2 | 6 | 3 | 5 | 4 | 6 | 5 |
| REAL3 | 6 | 5 | 5 | 4 | 6 | 5 |
| REAL4 | 4 | 3 | 4 | 1 | 6 | 5 |
| PRES2 | 6 | 6 | 6 | 4 | 6 | 5 |

**Appendix 12 All IPQ scores of P12**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 5 | 3 | 5 | 3 | 5 | 4 |
| SP1 | 4 | 5 | 5 | 1 | 5 | 4 |
| SP2 | 6 | 5 | 6 | 6 | 6 | 5 |
| SP3 | 6 | 4 | 6 | 1 | 6 | 5 |
| SP4 | 4 | 2 | 4 | 6 | 5 | 5 |
| SP5 | 4 | 4 | 5 | 1 | 6 | 3 |
| INV1 | 3 | 2 | 4 | 1 | 6 | 3 |
| INV2 | 2 | 3 | 5 | 5 | 3 | 2 |
| INV3 | 5 | 5 | 5 | 4 | 4 | 4 |
| INV4 | 2 | 3 | 2 | 0 | 5 | 3 |
| REAL1 | 4 | 2 | 4 | 5 | 3 | 2 |
| REAL2 | 3 | 2 | 3 | 1 | 5 | 4 |
| REAL3 | 3 | 2 | 3 | 1 | 4 | 3 |
| REAL4 | 2 | 1 | 3 | 0 | 3 | 1 |
| PRES2 | 3 | 2 | 3 | 0 | 5 | 3 |

**Appendix 13 All IPQ scores of P13**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 4 | 4 | 4 | 3 | 5 | 5 |
| SP1 | 3 | 3 | 2 | 2 | 3 | 3 |
| SP2 | 5 | 3 | 4 | 6 | 5 | 4 |
| SP3 | 5 | 4 | 4 | 3 | 5 | 5 |
| SP4 | 1 | 0 | 3 | 0 | 1 | 0 |
| SP5 | 3 | 2 | 1 | 0 | 4 | 5 |
| INV1 | 6 | 5 | 6 | 3 | 6 | 5 |
| INV2 | 5 | 2 | 3 | 0 | 5 | 4 |
| INV3 | 5 | 4 | 6 | 6 | 3 | 4 |
| INV4 | 5 | 4 | 3 | 0 | 6 | 5 |
| REAL1 | 5 | 4 | 5 | 4 | 4 | 3 |
| REAL2 | 4 | 1 | 4 | 0 | 5 | 3 |
| REAL3 | 4 | 2 | 2 | 1 | 3 | 2 |
| REAL4 | 2 | 0 | 1 | 0 | 3 | 2 |
| PRES2 | 2 | 1 | 3 | 0 | 5 | 2 |

**Appendix 14 All IPQ scores of P14**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 6 | 4 | 6 | 3 | 6 | 4 |
| SP1 | 6 | 5 | 5 | 2 | 6 | 4 |
| SP2 | 6 | 6 | 4 | 5 | 6 | 4 |
| SP3 | 5 | 5 | 3 | 3 | 6 | 4 |
| SP4 | 6 | 4 | 6 | 3 | 6 | 4 |
| SP5 | 6 | 4 | 5 | 2 | 6 | 4 |
| INV1 | 4 | 3 | 6 | 2 | 4 | 3 |
| INV2 | 3 | 1 | 5 | 3 | 6 | 4 |
| INV3 | 1 | 1 | 3 | 1 | 1 | 2 |
| INV4 | 6 | 3 | 5 | 1 | 6 | 4 |
| REAL1 | 3 | 3 | 3 | 2 | 2 | 2 |
| REAL2 | 5 | 4 | 3 | 3 | 6 | 4 |
| REAL3 | 6 | 4 | 5 | 2 | 6 | 4 |
| REAL4 | 4 | 3 | 3 | 0 | 5 | 0 |
| PRES2 | 6 | 5 | 3 | 1 | 6 | 4 |

**Appendix 15 All IPQ scores of P15**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 2 | 1 | 4 | 3 | 3 | 2 |
| SP1 | 2 | 1 | 4 | 2 | 4 | 3 |
| SP2 | 4 | 4 | 5 | 5 | 6 | 5 |
| SP3 | 3 | 3 | 3 | 1 | 4 | 2 |
| SP4 | 4 | 2 | 3 | 3 | 4 | 2 |
| SP5 | 2 | 1 | 3 | 2 | 5 | 2 |
| INV1 | 2 | 1 | 2 | 3 | 5 | 2 |
| INV2 | 3 | 2 | 3 | 1 | 3 | 2 |
| INV3 | 3 | 3 | 4 | 3 | 2 | 2 |
| INV4 | 2 | 1 | 4 | 3 | 4 | 2 |
| REAL1 | 4 | 3 | 4 | 5 | 4 | 3 |
| REAL2 | 2 | 1 | 3 | 2 | 4 | 3 |
| REAL3 | 2 | 1 | 3 | 1 | 4 | 2 |
| REAL4 | 1 | 0 | 3 | 1 | 4 | 2 |
| PRES2 | 1 | 0 | 2 | 1 | 4 | 2 |

**Appendix 16 All IPQ scores of P16**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 5 | 4 | 5 | 4 | 6 | 5 |
| SP1 | 5 | 4 | 6 | 3 | 6 | 4 |
| SP2 | 6 | 6 | 6 | 6 | 6 | 6 |
| SP3 | 5 | 4 | 5 | 3 | 6 | 4 |
| SP4 | 5 | 2 | 5 | 3 | 6 | 5 |
| SP5 | 6 | 3 | 4 | 5 | 6 | 5 |
| INV1 | 6 | 4 | 4 | 4 | 6 | 5 |
| INV2 | 4 | 3 | 5 | 2 | 2 | 2 |
| INV3 | 3 | 3 | 5 | 2 | 2 | 2 |
| INV4 | 6 | 4 | 6 | 3 | 6 | 5 |
| REAL1 | 4 | 4 | 3 | 4 | 2 | 2 |
| REAL2 | 5 | 4 | 3 | 1 | 6 | 5 |
| REAL3 | 4 | 3 | 2 | 1 | 6 | 4 |
| REAL4 | 2 | 2 | 2 | 0 | 5 | 1 |
| PRES2 | 5 | 2 | 4 | 2 | 6 | 5 |

**Appendix 17 All IPQ scores of P17**

| Items | IPQ1 | IPQ2 | IPQ3 | IPQ4 | IPQ5 | IPQ6 |
|---|---|---|---|---|---|---|
| PRES1 | 1 | 3 | 2 | 3 | 2 | 2 |
| SP1 | 1 | 2 | 2 | 6 | 3 | 2 |
| SP2 | 2 | 5 | 5 | 5 | 5 | 6 |
| SP3 | 1 | 1 | 1 | 0 | 1 | 1 |
| SP4 | 1 | 1 | 1 | 1 | 4 | 2 |
| SP5 | 2 | 3 | 3 | 4 | 3 | 2 |
| INV1 | 1 | 3 | 1 | 5 | 4 | 1 |
| INV2 | 5 | 2 | 5 | 5 | 3 | 2 |
| INV3 | 2 | 2 | 5 | 5 | 4 | 3 |
| INV4 | 2 | 2 | 2 | 1 | 3 | 2 |
| REAL1 | 5 | 6 | 6 | 3 | 2 | 4 |
| REAL2 | 2 | 1 | 5 | 0 | 3 | 2 |
| REAL3 | 2 | 2 | 1 | 1 | 4 | 3 |
| REAL4 | 6 | 3 | 2 | 1 | 3 | 3 |
| PRES2 | 1 | 1 | 2 | 0 | 3 | 3 |

**Appendix 18 All IPQ scores of P18**