UNIVERSITY OF TARTU
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Computer Science Curriculum

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The Human Octopus: controlling supernumerary hands with the help of virtual reality

Bachelor's Thesis (9 ECTS)

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Abstract:

This thesis is about investigating the “human octopus” phenomenon which involves controlling various supernumerary hands with the help of virtual reality and hand tracking technology. A set of experiments were developed in order to observe how subjects operate with different number and control strategies of supernumerary hands. The control strategies involved inserting delay into the supernumerary hands and adjusting their movement scale or position. It was found that having more hands to operate with does not necessarily mean that one would be more successful performing a certain task. However, one could make supernumerary hands more effective by adjusting movement scale of the hands if it suits the task better. Furthermore, the natural feeling and ownership of the hands seems to diminish when delay is inserted into the hands or their position is altered. Therefore, body avatar extension is a difficult task and needs to be done carefully in order for it to feel natural. It was also found that using head movement to assist controlling supernumerary hands is something that is worth researching more into. Body avatars with supernumerary hands also have great potential in entertainment industry.

Keywords:

Supernumerary hands, control strategies, virtual reality, experiment

CERCS: P170 Computer science, numerical analysis, systems, control

Inimkaheksajalg: rohkem kui ühe käepaari kontrollimine virtuaalse reaalsuse abil

Lühikokkuvõte:

Selles teadustöös uuritakse “inimkaheksajala” fenomeni, mis kujutab endast rohkem kui ühe käepaari kasutamist virtuaalreaalsuse tehnoloogia abil. Selleks koostati neli eksperimenti, et jälgida kuidas katseisikud tegutsevad erineva arvu käepaaridega, mille juhtimiseks on erinevad strateegiad. Uuritavad juhtimisstrateegiad olid viivituse lisamine, haardeulatuse ning positsiooni muutmine ja pealiigutuste kasutamine. Eksperimentide käigus leiti, et rohkemate käepaaride kasutamine ei taga alati ülesande täitmisel paremat tulemust. Kuid käte haardeulatuse muutmine võib oluliselt parandada efektiivsust, kui see on antud ülesande jaoks sobilikum. Lisaks sellele leiti, et viivituse lisamine ning positsiooni muutmine oluliselt vähendavad käte loomulikkust ning omanikutunnet. Pealiigutuste kaasamine käte juhtimisstrateegiale on aga kindlasti väärt edasist uurimist. Lisaks sellele on transformeeritud kehakujutusega avataridel suur potentsiaal meelelahutusäris.

Võtmesõnad:

Käepaaride lisamine, juhtimisstrateegiad, virtuaalne reaalsus, eksperiment

CERCS: P170 Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine

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1 Introduction

Through the process of evolution, the human species has evolved from its very far ancestor tetrapod, who was first terrestrial animal with four limbs. We have evolved form of their body type but the number of limbs has remained the same. So humans have two lower limbs considered as legs and two upper limbs known as arms. Arms are required to perform the most of the important actions that provide the ability to survive for humans. But what if people had more than 2 arms? Having more upper limbs to operate with, humans would be able to perform more complex actions with less effort. In the present context we will call this phenomenon “the human octopus”.

Already from the ancient civilizations, people are known to believe in mythological creatures and gods that have multiple number of limbs. For example, the numerous gods from Hinduism known as deities such as the governor of the Universe Vishnu, the warrior goddess Durga or the patron of arts and sciences Ganesha. The multiplicity of arms emphasizes the deity's immense power and ability to perform several acts at the same time.

So the idea of having multiple limbs to operate with has lingered somewhere in the mindset of humankind for thousands of years already. Luckily for us, the modern technology is starting to provide us with tools that help to implement the idea of having multiple operable arms to some extent. Although the current improvements in medicine are not advanced enough to extend the number of body parts in surgical way, the modern science has a few other tricks up its sleeves.

Recent improvements in technology of computers and three dimensional displays allow us to create virtual realities that can be perceived by human vision the way we perceive the actual reality. Using three dimensional head mounted display that also monitors our head movement allows us to enter to the virtual reality through the first person point of view. This approach opens up a whole range of new neurological and psychological experiments where everything can be accomplished through programming.

In the present work we use Oculus Rift which is a head mounted display with two high resolution images, one for each eye to provide three dimensional view for the user. It also has sensors to follow user’s head movement and integrated headphones with 3D audio effect to make the virtual reality experience more realistic.

One could enhance the virtual reality experience even further by adding another technological device that will monitor the movement of our arms in relation to the head mounted three dimensional display. This allows one to add two virtual arms into the virtual reality that mimic the actions we do with our real hands. So it feels like your arms are coming to the virtual reality with you. Here, in the current work, we use Leap Motion sensors which allows the user to act with virtual objects like one would do in the real world. Leap Motion can easily be attached to the Oculus Rift and integrated with Unity's game engine.

Technology mentioned above allows us to research various phenomena related to neurological perception of human arms and limbs in general. There are numerous ways to implement this phenomenon. For instance, one could give the subject one arm for each finger. Or one could replicate the existing hand a number of times so that they all follow the movement of our real hand. The main questions that we are looking to answer are the following.

- If the subject had more than two arms to control, would he be able to perform actions more effectively in any way?
- How to solve the problem of controlling multiple arms with just one pair of arms?
- Would the subject perceive the virtual arms as his own or not?

The other interesting aspect to observe is the manipulation of hand movements in the virtual reality prior to the real hand movement. The fact that we are using virtual reality, allows us to insert a delay between the movement of real arms and virtual arms. We can also adjust the movement scale of the virtual arms. It is also possible to change the position of hands according to subject's perspective. Although one's arms might be in different positions, it is possible to bind them to move with one's line of sight. This gives another interesting control strategy that involves head and arm movements combined. One could add those adjustments to the supernumerary hands so they would act separately from the original pair of virtual hands. It is assumed that such manipulation could confuse the brain enough to think that these are not our hands. Hence, we have further questions:

- Would the subject perceive the arm with manipulated movement as his own?
- Is it possible to enhance the effectiveness or precision of arms through time or movement manipulation in any way?
- To what extent we can manipulate the arm movement so that brain would not get too confused about the ownership of the arm?
- How would the subject adapt with the control strategy for supernumerary arms that combines head and arm movement of subject's real body parts?

Purpose of this thesis is to create experiments that implement the idea of supernumerary hands. The plan of the present work is to develop a set of experiments involving different hand setups that are used to complete a specific task over a short period of time. Four core experiments will be put in to practice on small amount of people in order to test the applicability and get initial data to answer the questions of this phenomenon. These four experiments are part of a Unity project which is provided with various tools of customization and prefabs to assist conducting further studies. As can be seen in appendix 1, the thesis comes with packed file which contains the Unity project.

2 Related Studies

Although Oculus Rift and Leap Motion are relatively new technologies, there are still various similar studies and experiments to look up before we start our own investigations. Although most of these previous studies have been conducted with the help of virtual reality the technology used is not as advanced as devices available today.

Several studies have shown that perceptual-motor and visuomotor synchrony (perceptual and visual stimulation that is in synchrony between virtual avatar and real body) is sufficient to create embodiment effects with virtual avatars [1] [2]. This means that participants that have taken part in similar virtual reality experiments tend to report the virtual bodies as the representation of themselves despite the fact they know such experience is faked.

Furthermore, according to a recent study people also show the change in heart rate as a response to the threats to their virtual avatar [3]. Similar psychological effects such as increased sweating have been detected upon the threats in virtual environment [4]. This means that virtual avatars are treated as a convincing representation of the subject's own body in the virtual environment, which makes the virtual reality a viable tool for studying the perception of the human body. On the other hand, the virtual experiences still somewhat differ from real life experiences and it is stated that the presence experience created by virtual reality is also an object of study in its own right [1].

It is also worth taking notes from the studies conducted in Karolinska Institute, Sweden. There, under the guidance of Professor Henrik Ehrsson, numerous studies have been conducted to learn about the perception of body in the brain through various illusions tapping onto bodily ownership [5]. The most known ones are the third hand and rubber hand illusions, but also invisible hand and out-of-body illusions. Experiments have shown that through the change of perspective it is possible to deceive the brain to accept the fake body parts as its own [6]. These studies reveal that reconstruction of the body in the brain is not as plastic as it was thought to be, but can be somewhat manipulated through creating mismatches in the brain. Those mismatches are created by the controversy between reality and illusions that subjects are put into. However, those illusions seem to work only under very certain rules such as the synchronous stimulation and the usage of arms that look very similar to our own. For example, the third arm illusion where another right arm is positioned next to the subject's real right arm worked only if the fake hand was the same color as the subject's skin color [4]. So there are pretty tight boundaries to what extent we can deceive our brain through visual manipulation and synchronous stimulation. Luckily for us, virtual reality allows to fulfill most of the requirements that are necessary to deceive the brain about ownership of virtual limbs.

Several studies show that extended body avatars can be more useful than normal body avatars when they suit the task better.

Firstly, there is research conducted in Stanford University that investigated how subjects operate with 3-armed-avatar compared to 2-armed-avatar [7]. The third arm was designed to be significantly longer in order to reach further objects more easily. As expected, the subjects were more successful operating with 3-armed-avatar. Their following research that investigated embodiment effects of extended body avatars also claims that people can complete the task more successfully when the virtual avatar is not in one-to-one relationship with one's real body [8]. Another interesting fact discovered was that participants performed more poorly with limbs that were not attached to the virtual body.

In addition to that, there is a study about controlling the supernumerary robotic hand by foot [9]. An experiment was designed to observe how subjects simultaneously catch three falling objects with both three and two hands setup. Once again it was found that three operable arms are preferred due to increased effectiveness. The reason behind it is that the task suits better for three hand setup rather than two hand setup. Furthermore, participants managed to control the third arm by foot without major issues.

There is another study that shows the strong relation between the individual's vision and body perception. It claims that we do not perceive the environment itself but rather the relationships between our body and the environment [10]. Those relations determine the course of the most of our actions for instance grasping the objects or jumping over an obstacle. The article claims that if we would change the size of our hands or length of our feet, the brain would re-evaluate the relations between the object we are about to grasp and our increased size hands [10]. This means that our brain is able to adapt to the changes and perceive the size of our increased arms correctly. In the current study it is presumed that similar adaptions may occur when a delay is inserted into the hands or their movement scale is changed.

So it is known that virtual reality is a convincing method to be used to study the perception of human body. Our brain can also be deceived to accept the fake body part as its own. And modern technology provides us the tools to enter into the virtual reality with a whole new avatar.

3 Methods

3.1 Oculus Rift

Oculus rift is a three dimensional head mounted display used for immersive virtual reality experiences (figure 1). According to their official website their precise and low-latency position tracking for user's head movements makes the virtual reality experience more realistic [11]. It also has two stereoscopic 3D displays, one for each eye, which makes the environment feel more natural. Currently Oculus has released two development kits (DK1 and DK2) and one consumer version of virtual reality devices. According to Wikipedia DK2 which is used in this work has two high resolution (960×1080) displays providing the field of view up to 110 degrees [12].

Oculus is currently one of the most popular and advanced virtual reality devices available for public. Oculus Rift also provides an easy way to attach Leap Motion. Adding the fact that University of Tartu has several headsets available, made it a rather easy choice to use in current experiment.

Figure 1: Oculus Rift Development Kit 2 [13]

3.2 Leap Motion

Leap Motion is a small peripheral USB-device that tracks the users hand movement and allows to recreate them in virtual reality (figure 2). According to the official website it uses two monochromatic cameras and three infrared LEDs to observe the hemispheric area up to 1 meter [14]. As stated on the official website, it's recently released Orion software, specially meant for virtual reality, is a massive step forward for their technology. It provides lower latency, longer distance and overall better and faster hand recognition [15].

Figure 2: Leap Motion Controller [16]

Leap Motion also has core assets package to work with Unity game engine. It receives the images of real hand movements and applies them on the graphical models of virtual hands. In present work we use the latest Orion Windows software to track the hand movement and previous version of Unity Core Assets (2.3.0) to integrate with Unity. Although there is core assets package for Orion (version 4.0.2), an older version (2.3.0) is preferred due to lack of human-like hand models in Orion assets at the time of development.

3.3 Unity

Unity is a game engine that suits perfectly to create small size video games. It is easy to learn and provides quite a lot community made assets to fill the environment. According to the official website Unity has industry-leading multiplatform support including over 20 different platforms [17]. Hence, it is easy to move Unity projects to other systems.

Unity has also virtual reality and Leap Motion integration which makes it a best candidate to create our experiments with. In addition to that Unity supports C# scripting language and has a free personal edition.

4 Development

Development of the core experiments involves integrating Oculus Rift, Leap Motion and Unity in a way that allows to investigate “the human octopus” phenomenon. Therefore, a Unity scene was created to represent the environment of the experiment. Furthermore, various modifications were done to Leap Motion’s Unity core assets package.

4.1 Leap Motion modifications

Leap Motion’s Unity core assets package is mainly meant to display only one pair of hands. So various modifications were done to the existing assets. The most important script in the package is the HandController class (HandController) which serves as the interface between the Unity application and Leap Motion service. It is responsible for receiving the hand images from the recorder and managing the graphics and physics models of virtual hands.

In order to increase the number of hands displayed in the scene, one could simply duplicate the HandController prefab, but that does not give the desired result. This is due to a fact that changing the position of one hand without changing the other’s is not possible within a single HandController. Same goes for identifying which hand is taking part in a collision with another object. Therefore, each HandController was made to represent only one hand by removing the physical and graphical models of the other hand. This enables to change the parametrical values of each hand separately. For logging purposes, a name variable was also added to a HandController class.

For each frame in Unity scene HandController class receives a hand image that represents the current position of the real hands. In order to add the delay into the hands, a hand image buffer was created and added to the HandController instance. Depending on the desired delay certain amount of hand images are buffered into a list in order to use them after the right amount of frames has passed.

Pseudocode for delay implementation:

```
List<Frame> buffer = new List<Frame>();

//Values assigned from Unity’s editor
public int maxLength;
public int frameBack;

public virtual Frame GetFrame() {

        if (frameBack > 0)
        {
            buffer.Insert(0, leap_controller_.Frame());
            if (buffer.Count >= maxLength)
```

```
            {
                buffer.RemoveAt(buffer.Count - 1);
                return buffer[frameBack];
            }
        }
   else {
      return leap_controller_.Frame();
   }
}
```

In order to bind head movement to the hands, one simply has to position the HandController more forward from the camera. When Leap Motion is attached to head mounted display, its software compensates the head movement by simply moving the hands in opposite direction. If HandController is positioned right in front of the camera in the scene, the amount of compensation is correct and one's hands seem to stay in one place when head is moved. But when HandController is positioned more further the compensation becomes too great which makes the hands move with one's line of sight.

HandController class has equivalent editor script to enable changing values from Unity's editor. By default, it has variables for position, size and movement scale. Option to choose amount of frames for a delay was added.

For each hand setup that was planned to use in experiment, corresponding prefab was created and added to the project. These prefabs are the following:

1. One pair of hands;
2. Three pairs of hands with different movement scale;
3. Three pairs of hands with different movement scale and delay;
4. Four pair of hands with different rotations and positions;

4.2 Environment and task

In order to create the experiment itself, a script was written to manage the falling object. The script is called CollideClass.cs and attaching it to an object makes it fall from certain height at random position. For this experiment a small green cube was created. The object is positioned to a rectangular area which can be adjusted to the liking. If the object reaches certain height or collides with any of the hands it respawns at newly randomized position. At each frame a velocity vector is given to the object to make it fall at constant speed.

Each experiment can be divided into phases that have different velocity of falling. There are also pauses between phases because keeping your real hands in Leap Motion's tracking space for more than a minute can be tiring. Experiment starts when the space key is pressed and ends when the time is up.

The script is also responsible for playing sound effects when the object collides with the hand or when the experiment starts or ends. Sound effects are taken from https://www.freesound.org and are licensed to use pretty much in any way that users want as long as the source is referenced [18][19][20].

Since it is necessary to get the results of the experiment, a logging system was created and added to the script. It logs the start and ending of each phase and pause. More importantly it also logs the information about each respawn and collision of the cube. For each experiment a separate text file with subject's name is created which can be analyzed later. Each log file contains the following:

1. Name of the current experiment;
2. Number and speed of each phase;
3. Start and end of each phase and pause;
4. Position and speed of each respawn and collision;
5. Hand that object collided with;
6. Timestamp of each collision and respawn;

An editor script was also added to CollideClass.cs in order to change the parameters through Unity's editor. This means that most of the variables that are present in the scene are not hard coded and can be customized through Unity's editor.

Changing the variables allows to customize the following:

1. Number of phases;
2. Speed of every phase;
3. Duration of phases and pauses;
4. Starting and ending height of the object;
5. Area of drop zone;
6. Name of the log file;

The environment of the scene is a room that has minimalistic furnishing of various classroom prefabs, as can be seen on figure 3. These prefabs are available for free from Unity's assets store [21]. Purpose of such interior is to make the environment feel more natural but not too overwhelming for the subjects. Virtual hands and the camera are positioned front of the table in the middle of the room. Purpose of the table is to keep the subjects from holding their hands too low in order to accomplish better tracking. A wooden box is positioned above the table and it marks the area in which the cube is respawned.

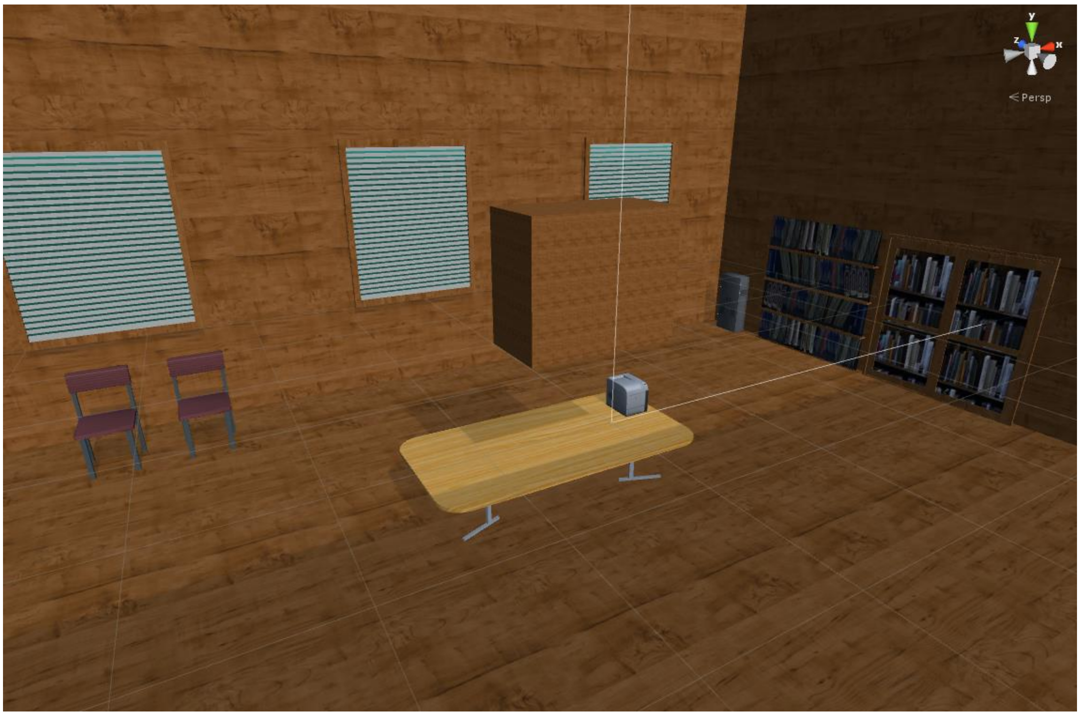

Figure 3: Environment of the scene.

5 Experiments

Four different experiments are developed to investigate how subjects operate with the increased number and delayed movement of hands. The setups differ from each other by the number, position or movement of hands. The task remains the same through all four experiments but the setup of arms varies. This allows us to compare the results of different setups of hands according to one certain task.

5.1 Task

The task is to catch the object which is a little green cube that is dropped from a box above the subject's virtual avatar. The box marks the rectangular area of possible drop positions for the object and can be seen when the subject looks above. The object is returned into the box after the subject has managed to catch it with any of one's hands or when the object hits the ground. Position of the object is randomized each time it is returned to the box and the catch is defined as a collision between a hand and the object. Distance between the spawn height and reset height is 2 units, corresponding to approximately 2 meters in real word measurements. Subject's view of the scene can be seen on figure 4.

Figure 4: Subject's view.

The task is divided into three phases each lasting 1 minute and there is a 30 second pause between the phases. The task has a progressive difficulty that is achieved through different speed of the object in each phase. In the first phase it is 0.5 units per second which makes it rather easy to catch. In the second and third phase the speed is significantly higher, 1.3 and 1.9 units per second respectively. This makes the task much more difficult and requires fast and precise movement of hands.

Subject receives feedback through sound alert that indicates successful catch of the object. Subject is also notified by the sound when each phase begins or ends. There is also countdown sound 4 seconds before end of the pause.

The fact that the task has a progressive difficulty enables to evaluate the results in various ways. The main focus lies on the success rate of each phase and which hands were used the most. It is also worth observing whether the subjects develop different strategies with different setups.

The assessment is supported by questionnaires about different aspects of the hand setups, which are filled after each experiment. There are different statements for each experiment followed by general statements which are to be assessed after all experiments are completed. Each questionnaire consists of grading the statements given below using a Likert-type response scale, from 1 to 5, where 1 stands for strong disagreement, 3 for neither agreement nor disagreement and 5 for strong agreement. In addition to that participants have an option to orally give open feedback and other comments about the experiments.

Statements after all the experiments are completed:

- Having more arms to operate with helps to complete the task more successfully.
- Controlling supernumerary hands felt as if they were all equally my own hands.
- I became better in time when controlling extra pairs of hands.
- I felt physical burden when controlling supernumerary hands.
- I felt mental burden when controlling supernumerary hands.

Experiments are done in the same order as described below in Hand Setups section and each participant completes the whole cycle once.

5.2 Hand setups

Leap Motion's core Unity package includes models for both full length hands and arms only. For this experiment the arms only model is preferred over full length hands. The reason behind that is to prevent subjects randomly hitting objects with their forearm or elbow because in this experiment catching is defined as a collision between any part of the hand and the object. In addition to that catching feels more natural when it is done with arm rather than forearm or elbow. To increase the artlessness even more the hands are given humanlike graphics model which has the similar skin tone of the subject. This is also confirmed by study which found that body ownership illusions work better with hands that has same skin tone as subject itself [4].

First experiment

In the first experiment subject has one pair of virtual arms that move almost exactly as one's real arms except that arm's movement scale is slightly increased (1.4 times). This allows to increase the area of falling objects in a way that subject is still able to catch them. Otherwise the task would be impossible compared to other hand setups. Hand setup of the first experiment can be seen on figure 5.

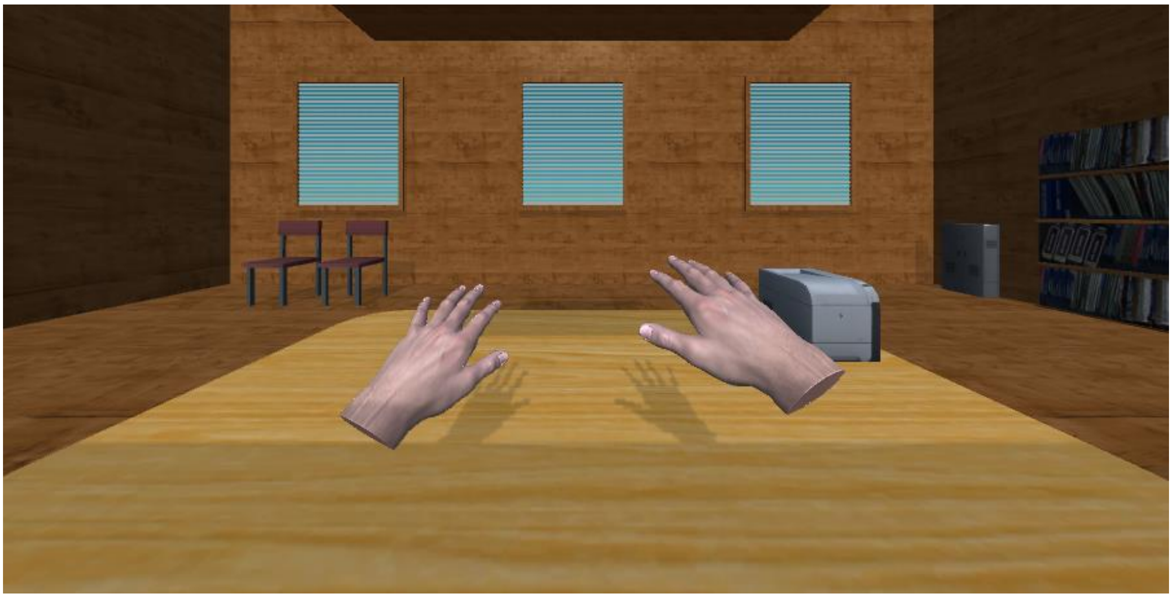

Figure 5: Hand setup of the first experiment.

Statements of first experiment:

- Controlling one pair of hands felt as if they were my own hands.
- I developed a certain strategy to complete the task. If yes, explain it.

Second experiment

The second experiment examines how the subject completes the same task with increased number of hands. Subject is given three pairs of arms (figure 6) which all move simultaneously to one's real arms. All arms are lined up horizontally and each pair has a different value of movement scale depending on the position – inner pair of hands has normal (1.0), middle one has slightly increased (1.5) and outer pair significantly increased (2.0) movement scale. This means that each pair has a different field of grasp depending on its distance from the middle. Subject's task is to catch falling objects with any of one's arms.

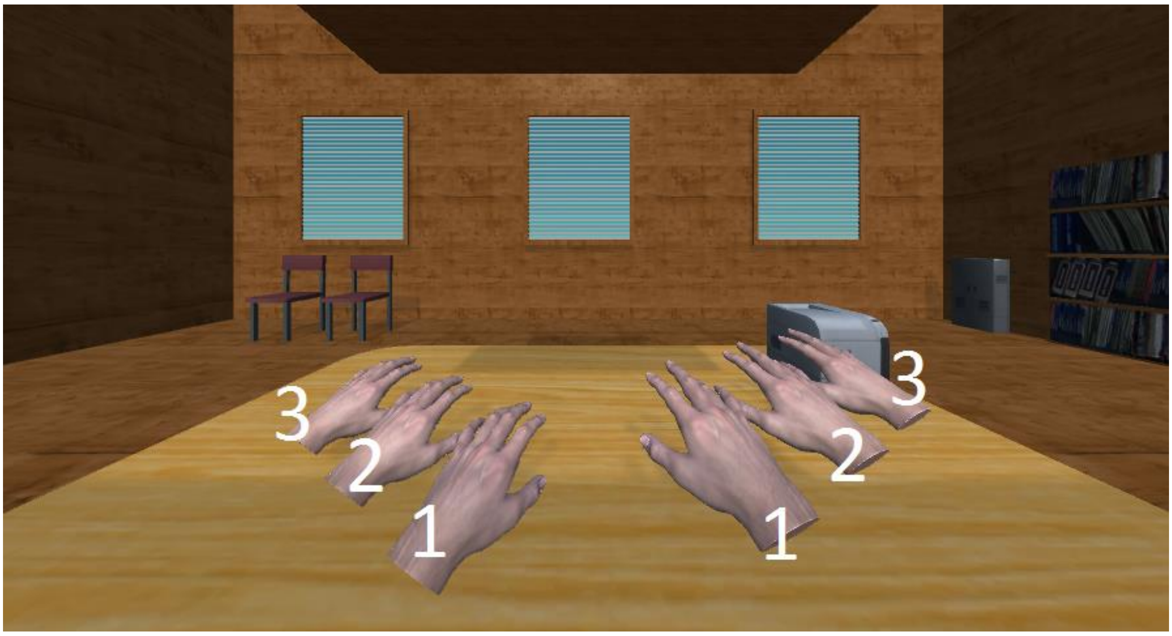

Figure 6: Hand setup of the second experiment. Numbers mark the number of pair.

Statements of second experiment:

- Controlling three pairs of hands felt as if they were all equally my own hands.
- Extra pairs of hands were helpful completing the task.
- I became better in time at controlling extra pairs of hands.
- I developed a certain strategy to complete the task using the supernumerary hands. If yes, explain it.

Third experiment

The third experiment has the same number and movement scales of arms as second experiment, but there is a slight delay in the hand movement depending on the position. The inner pair of arms moves simultaneously to the one's real arms and is considered to be the main pair. Two other pairs have a slight delay depending on the distance from the middle. Second pair has a 15 frames delay and third pair has a 30 frames delay. The task remains the same but now the subject has to adapt to the totally different hand movement. Hand setup of the third experiment can be seen on figure 7.

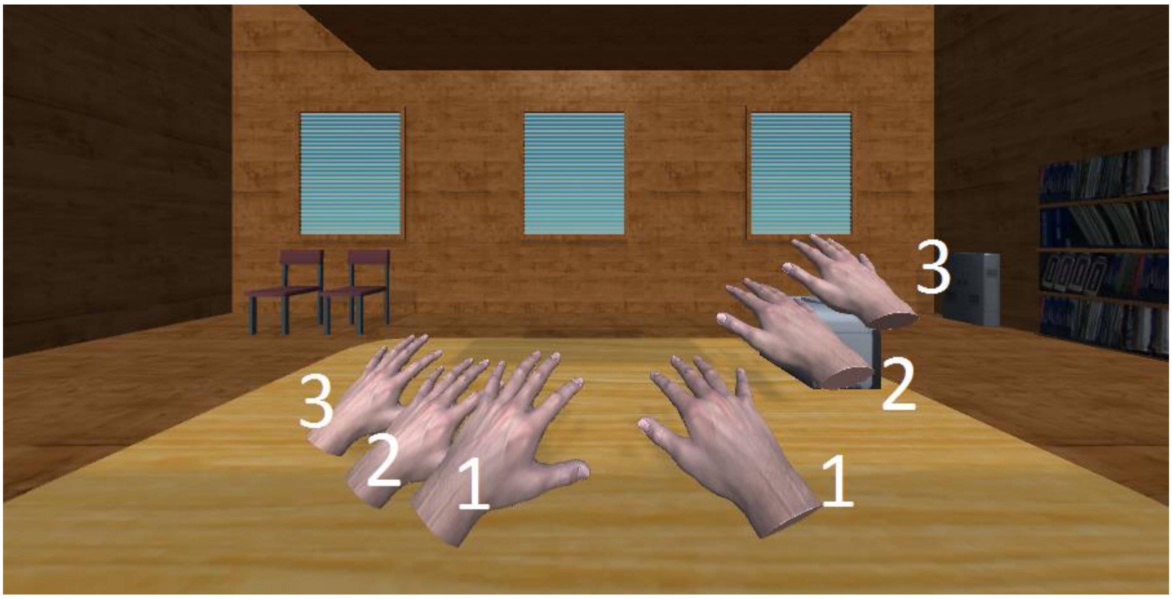

Figure 7: Hand setup of the third experiment. Numbers mark the number of pair.

Statements of third experiment:

- Controlling three pairs of hands with a delay felt as if they were all equally my own hands.
- The feeling of having delayed hands became more natural in time.
- I learned to use delayed hands in a useful way.
- I developed a certain strategy to complete the task using the supernumerary hands. If yes, explain it

Fourth experiment

The last experiment examines how the subject adapts to the control strategy that involves both hand and head movement. Subject has total of four pair of hands that are all in different position and have different rotation as can be seen on figure 8. First pair of arms is located and rotated as one’s real arms and is considered to be the main pair. Second pair of arms is located slightly forward to the left and rotated to face toward the center of area in which the objects are falling. Third pair of arms is similar to the second pair except it is located on the right. The last pair is located horizontally in the center like first pair but is significantly further forward so that it is on the other side of the area in which the objects are falling. Last pair is also rotated to face the center of the area so to a subject it looks mirrored. All pairs of arms except the first are bound to subject’s line of sight. This means that subject can move one’s virtual arms with head movement. If subject turns one’s head left or right the arms move left or right respectively as well. Arms are also bound to move similarly when subject tilts the head left or right or when subject moves head forward or backwards. The further arms are the greater is the movement created by head tracking.

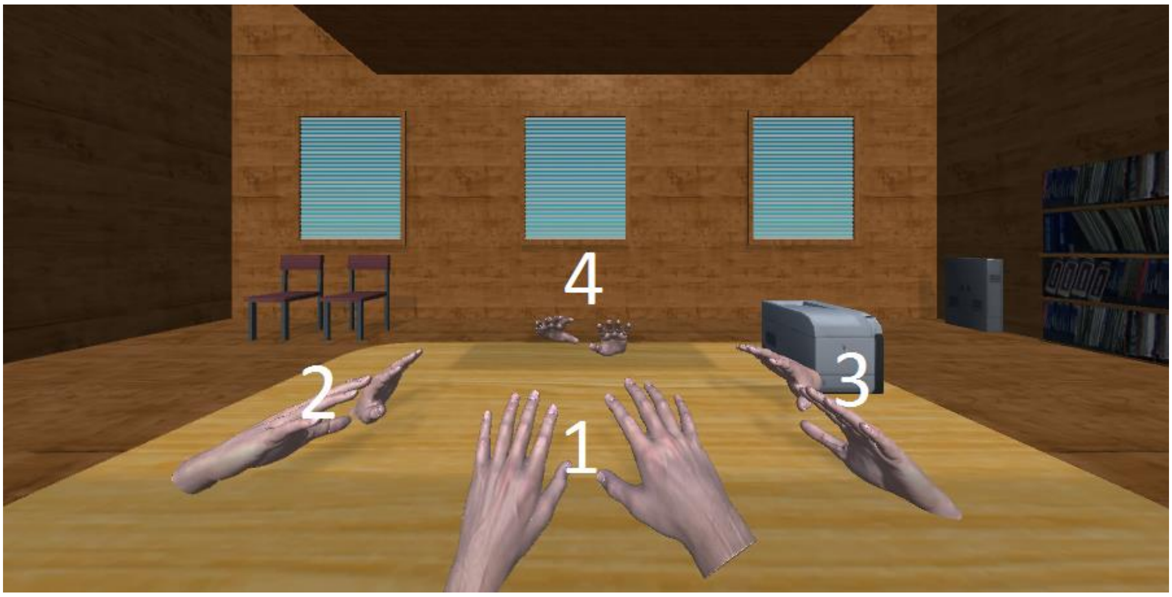

Figure 8: Hand setup of the fourth experiment. Numbers mark the number of pair.

Statements of fourth experiment:

- The hands in other position felt as if they were my own hands.
- It felt natural to control arms with head movement.
- I rather controlled virtual arms with head than real hands.
- I developed a certain strategy to complete the task using the supernumerary hands. If yes, explain it.

5.3 Instructions

Subjects are asked to take part in a virtual reality experiment which involves operating with various supernumerary hands. Each subject is told the short description of the task which can be found below. After reading the short description the subject is asked to sit on a chair. After that it is made sure that subject has enough space to move one's hands freely. Subjects also receive thorough instructions to accomplish best tracking possible with Leap Motion. If subject is ready he is asked to put on the Oculus Rift and headphones. The experiment begins with training phase where subject can exercise with current hand setup. When the subject understands the setup and is ready to proceed, the task is started. After completing the task, the subject is asked to assess a few statements (see below) towards body perception based on a Likert-type response scale. If the subject is ready to proceed, he or she is asked to put on the Oculus Rift again and the next experiment is started. In this manner all the experiments will be done with short breaks between them.

Before the experiments all subjects are provided with the short description that can be found in appendix 2.

6 Results

In total 10 subjects, 8 males and 2 females, volunteered to take part in the experiments. Eight participants were right handed and two participants left handed. Their log files and questionnaires were used to examine each of the four experiments separately. The results are supported by observational findings and participants' comments.

A simple Python script was written to analyze the log files and sum up the data. For each phase it sums up all the misses and catches to calculate it into success rate percentage. It also counts the number of catches for each hand separately.

6.1 First experiment

In the first experiment where subjects had only one pair of hands, subjects were relatively successful at catching falling objects. In the first phase 70% of the subjects managed to catch all the cubes. The mean score for the first phase is 96.04% with standard deviation (SD) of 7.13 which means that subjects were almost equally successful.

In the second phase results between subjects differ the most with mean score of 64.01% and SD of 17.53. As expected the results dropped even more in the third phase where the mean score is 31.3% with standard deviation of 15.61. Success percentage of each subject can be seen on figure 9.

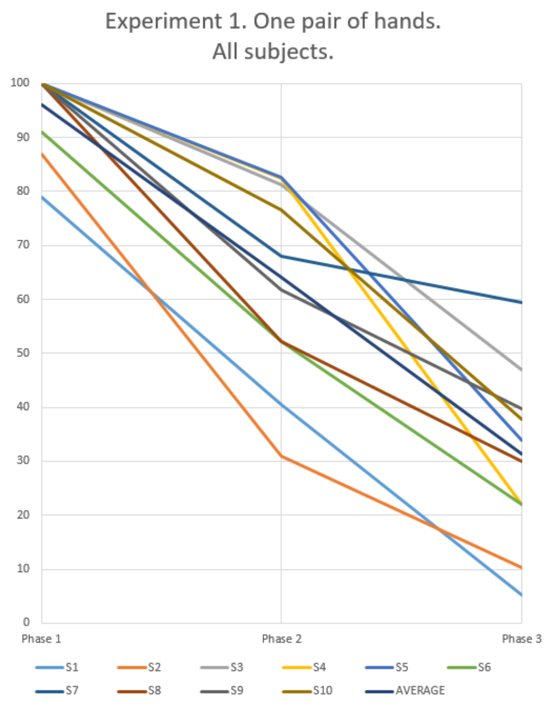

Figure 9: Results of all subjects in experiment 1. Y-axis shows the percentage of caught objects.

When asked if the hands felt as if they were one's own hands, subjects mostly agreed or were neutral. No certain strategies were developed except the usage of hands as one would normally do. Some subjects also realized during the experiment that holding hands higher grants better tracking despite the fact that it was told before the experiment.

There is a slight difference between the hand used in second and third phase as right hand is used more (figure 10). This is probably due to a fact that 80% of the subjects were right handed.

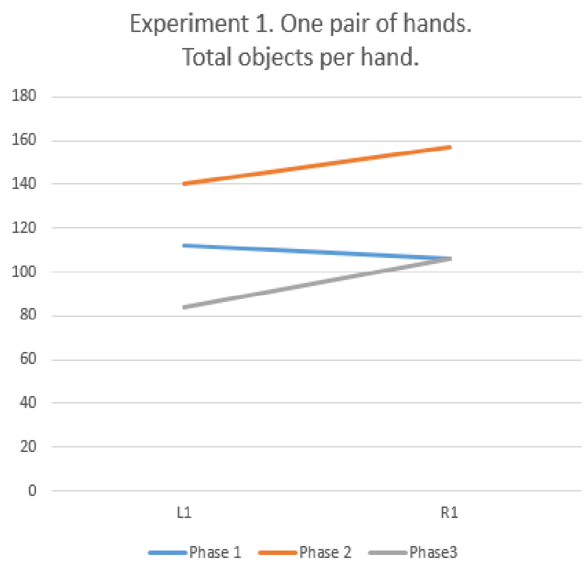

Figure 10: Total objects per hand in experiment 1. Y-axis shows the total number of objects caught.

Difference in performance between genders is also noticeable as females (S1 and S2) performed much poorer than males. Both female subjects claimed that the speed in the last phase was too fast for them to react properly.

6.2 Second experiment

In the second experiment subjects had three pairs of hands with different movement scale and the results are actually very similar to the first experiment with an exception of the last phase. Score in the first and second phase are 96.9±3.02% and 64.64±14.44% respectively. In the last phase subjects managed to catch almost 10% more objects (40.88±15.85%) compared to the first experiment (31.3±15.61). This might be due to a fact that subjects had really hard time catching objects at such high speed and having an increased number of hands simply increased the area that subjects can cover under the drop zone. Results of each subject can be seen on figure 11.

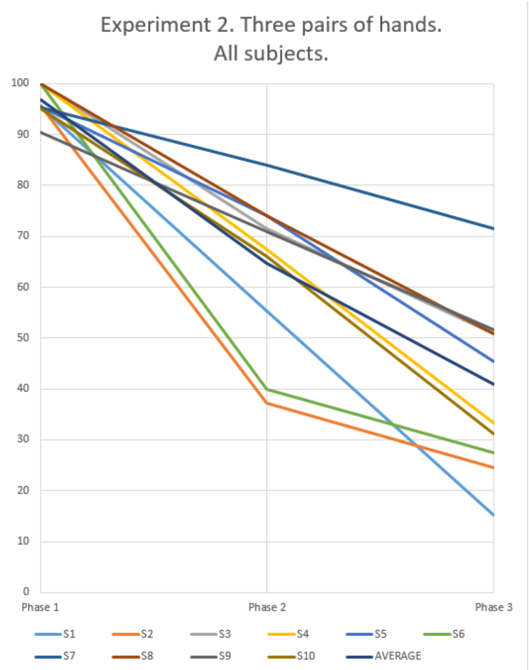

Figure 11: Results of all subjects in experiment 2. Y-axis shows the percentage of caught objects.

Since each pair of hands had different movement scale it is worth observing which hands were used the most (figure 12). It appears that at higher speeds subjects mostly tended to catch objects with the second pair of hands which had a similar movement scale as hands in the first experiment. Surprisingly in the last phase the right hand is preferred much more compared to the first experiment.

Figure 12: Total objects per hand in experiment 2. Y-axis shows the total number of objects caught.

Although the success rate is very similar to the first experiment all subjects agreed that extra hands were helpful completing the task (4.7±0.48%). Observational findings revealed that subjects moved their hands much less since each pair of hands reached a different distance.

Subjects also agreed that all three pairs of hands felt equally as their own hands (4.2±0.63%). Although the whole experiment took about 5 minutes, most of the subjects claimed that they became better in time controlling the extra pairs of hands (3.8±1.48%).

When asked about strategies that subjects developed most of them claimed to have no certain strategy. Nevertheless, a few strategies were still developed such as juggling your hands back and forth really fast or using mainly outer pair of hands due to its higher movement scale.

6.3 Third experiment

In the third experiment subjects had three pairs of hands with different movement scale and delay. Success rate seems to decrease when a delay is inserted into the hands. In the first and second phase the success rates are 89.57±8.35% and 59.09±13.22% respectively which is about 6-7% lower when compared to the first and second experiment. Notably in last phase, subjects still showed better results (38.94±9.63%) than in the first experiment (31.3±15.61%). It is similar to the second experiment's last phase.

When looked at the graph (figure 13), it is seen that for the most of the subjects the difference between first and second phase is greater than between second and third, which is not the case in second experiment. This shows that delayed hands tend to be useful only when objects are falling slowly. It makes sense because at higher speeds the time window of catching the object gets closer to the amount of delay that is inserted in to the hand.

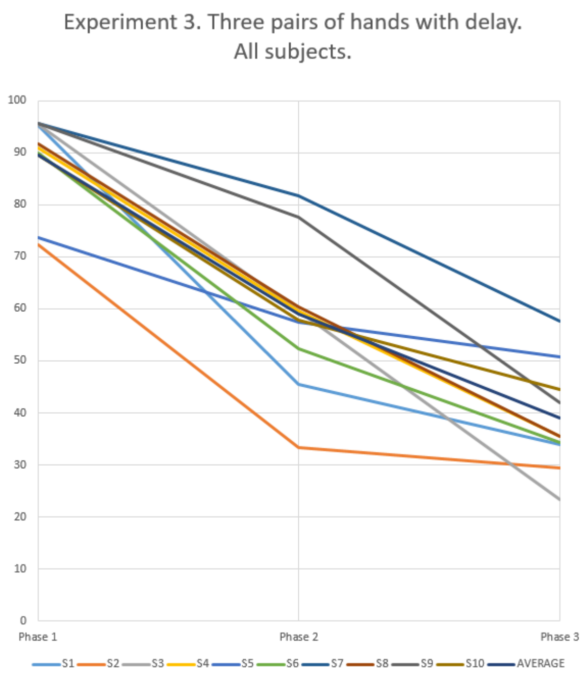

Figure 13: Results of all subjects in experiment 3. Y-axis shows the percentage of caught objects.

Observational findings reveal that subjects mostly tried to use their main pair of hands that did not have a delay. That is supported by subjects' comments that mostly claimed that having a delay in hands is a confusing factor and therefore they mostly preferred using the main pair of hands that did not have a delay. However, when inspecting the figure 14, it is seen that in the last phase subjects actually mostly used the second pair.

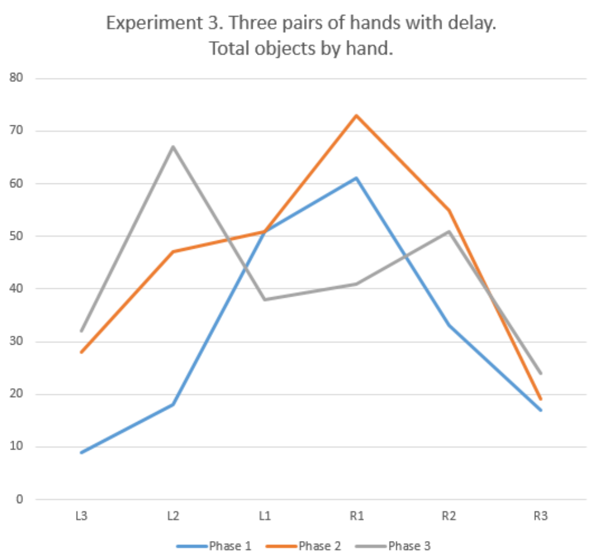

Figure 14: Total objects per hand in experiment 3. Y-axis shows the total number of objects caught.

Although most of the subjects disagreed (2±1.41) about strategy development, a few strategies were still developed with delayed hands. Firstly, two subjects claimed that keeping their hands far forward would keep delayed hands in better position to catch further objects. Therefore, bigger movements were required only to catch closer objects with hands that did not have delay. Second strategy is about using delayed hands like a whip due to a fact that delayed hands would follow main pair of hands shortly after. Such strategy requires predicting the future hand position and indicates that delayed hands might be treated as tools rather than own hands.

It is supported by the fact that subjects mostly disagreed (2±0.81) about feeling that all hands are equally their own and were neutral (3±1.15) about the feeling that delayed hands became more natural in time. One subject claimed that delayed hands rather felt like an extension of main pair of hands and used them as an extra tool.

Once again, when looked at the graph (figure 14), it is seen that right hand is slightly preferred mostly with an exception of last phase, where left hand of second pair tops the chart. It also confirms that third pair of hands, which had the greatest delay, is used least.

6.4 Fourth experiment

In the last experiment subjects had four pairs of hands in different positions and success rate is the worst in all phases having the scores of 78.89±12.38%, 50.99±9.18% and 31.11±11.31% respectively for three phases. However, in the last phase the success rate is almost equal to the first experiment (31.3±15.61%). Results of each subject can be seen on figure 15.

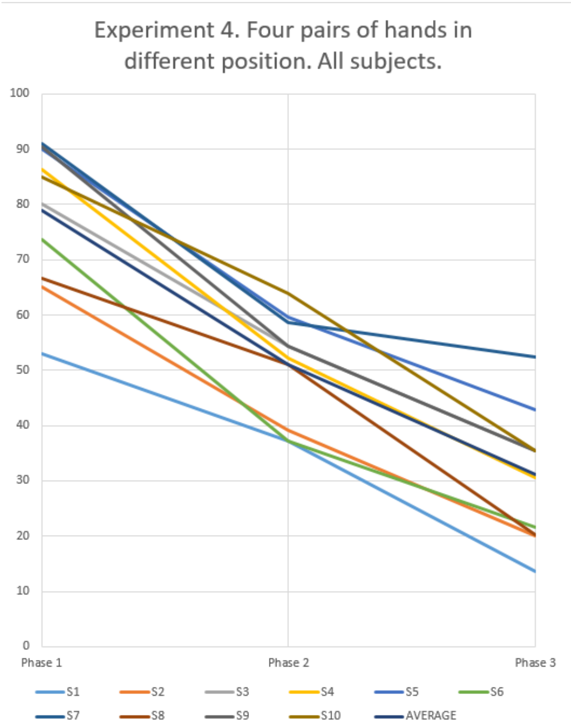

Figure 15: Results of all subjects in experiment 4. Y-axis shows the percentage of caught objects.

Hands on the left and right were designed to catch objects that are falling from the side but most of the subjects found that they were mostly useless. It can be confirmed by looking at figure 16, which shows that second and third pair were used least. This indicates that hands on the side could have been positioned better when designing the experiment.

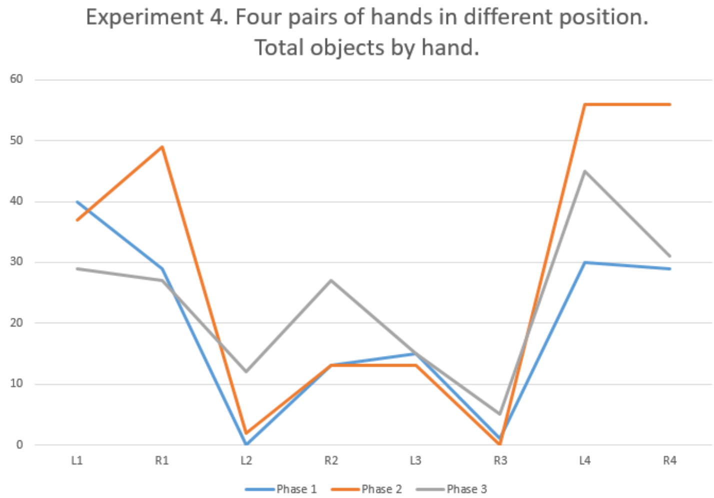

Figure 16: Total objects per hand in experiment 4. Y-axis shows the total number of objects caught.

Fourth pair of hands was mirrored towards subject's view therefore making it more confusing to control. Despite that fourth pair was still used to catch most of the objects with an exception of first phase as can be seen on hands used graph. Reason behind that might be the factor that one could use head movement to assist controlling the fourth pair.

Observational findings reveal that almost all subjects used their head movement to assist controlling the supernumerary hands at one point. When asked if head movement was preferred over hand movement the results were different for most of the subjects, but the average (2.7±1.05) shows that general opinion was almost neutral. Similar result (2.5±1.35) was detected for natural feeling when controlling arms with head movement.

Subjects disagreed (1.9±0.74) about feeling that hands in other position felt as if they were one's own hands. It was also claimed that such hand setup is too confusing and is almost impossible to make fast and precise movements in order to catch objects.

As can be seen on figure 15 and by relatively low standard deviations, subjects are not as much scattered than in the previous experiments. This might also indicate that such hand setup is really confusing, which makes the skill differences of controlling supernumerary hands diminish.

General opinion about developing certain strategies is almost neutral (2.6±1.65). However, a few strategies were still described. The most popular strategy was to cluster all four pairs of hands together and then control only with head movement. However, it was also claimed and observed that such strategy did not work too well. Second strategy was to just use main pair of hands as much as possible.

6.5 All together

When inspecting averages of all the experiments on one graph (figure 17) it can be seen that subjects performed best in the second experiment, where they had three pairs of hands with different movement scale and without a delay.

If we compare the setups with supernumerary hands to just two hand setup we can see that success rate drops less with increased number of hands as the speed increases. This is probably due to the fact that subjects have higher chance to catch an object with increased number of hands than with just one pair.

It was also claimed that in the second experiment supernumerary hands were helpful completing the task. Furthermore, when stated that having more arms to operate with helps to complete the task more successfully over all the experiments with supernumerary hands, the general opinion slightly leans toward agreement (3.3±1.16). Similar result (3.1±0.99) was detected when asked if subjects became better in time when controlling extra pair of hands in general for all experiments with supernumerary hands. Although almost all subjects claimed that it was different for each hand setup.

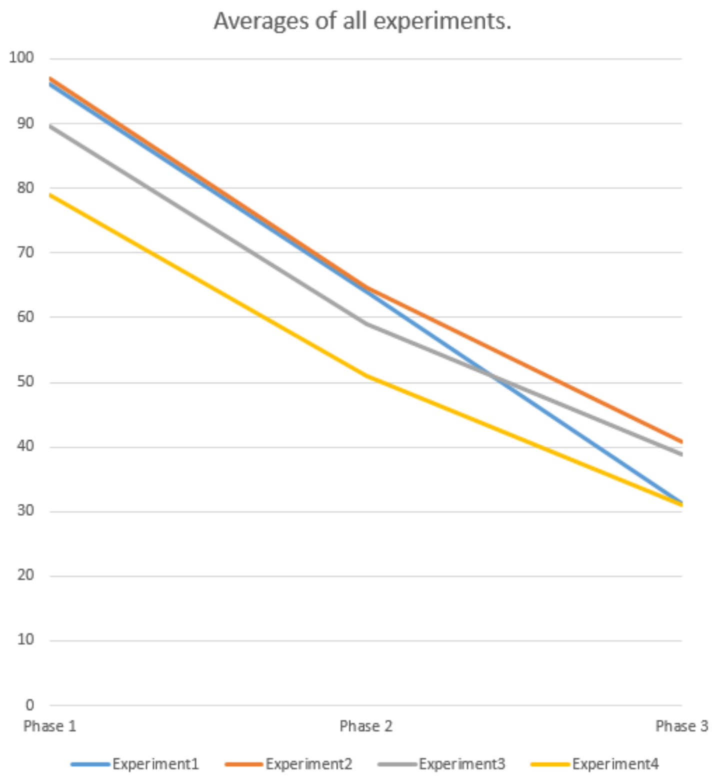

Figure 17: Averages of all experiments. Y-axis shows the average percentage of caught objects.

In the last experiment the performance is much poorer than in other experiments despite having the highest amount of arms. Controlling four pairs of hands that are all in different position requires a lot of coordination. Although supernumerary arms had head movement to assist controlling them, most participants still preferred to move them naturally with real hands. Some claimed that having such hand setup is too confusing specially when it requires fast reactions at higher speeds.

7 Discussion

The idea of having increased number of limbs to operate with has lingered somewhere in the mindset of humankind for thousands of years. In ancient civilazations this resulted in believing in mythological creatures and gods that have multiple number of limbs allowing them to perform several acts at the same time. What if humans actually had more than two arms? Would they be able to perform different tasks more effectively or successfully? Using the help of virtual reality, it was possible to investigate this interesting phenomenon. By increasing the number of hands and adding different control strategies to them, it was observed how subjects perform a certain task. It was also asked how natural those different hand setups feel. It was presumed that at some point the altered body schema would make the ownership feeling of the virtual hands diminish.

7.1 Results

It was found that having more arms to operate with does not necessarily mean that one would perform the task more successfully. However, the subjects had relatively small amount of time to practice. It was noticed during the development of the experiments that if one operates with certain hand setup for longer period of time, one gets significantly better at controlling increased number of hands.

Although adjusting the movement scale of hands could make them more effective resulting in less hand movement, it is highly dependent on the task. It is worth observing how subjects would perform on more than just one task. Altering the behaviour of hands could really improve performance at some specific tasks.

The natural feeling and ownership of the hands seems to diminish when a delay is inserted into them or their position is altered. It was stated that such manipulation gives the feeling that supernumerary hands are rather an extensive tool than part of one's body schema. Although such manipulation made controlling supernumerary hands rather clumsy, they were still somewhat helpful towards completing the task.

There seem to be performance difference between genders as females generally performed poorer. It was also observed that female subjects had slightly shorter hands which leads to smaller field of grasp. However only two females (S1 and S2) took part in our experiment therefore this conclusion is not very reliable.

Another interesting aspect was detected as the subject (S7) who claimed to play a lot of video games that require fast reactions, has the best result in almost every phase throughout all four experiments even though it was his first virtual reality experience. Reason behind that might be that people who play competitive video games tend to have better reaction time and easier time adapting to new virtual environments.

It is also worth mentioning, that even though the supernumerary hands were not most effective, almost all of the subjects found the experience to be 'really trippy', interesting, cool and entertaining overall.

When it comes to involving head movement to control strategy, it is definitely worth researching more into it. Although in current experiment, subjects were almost neutral about preferring head movement over hand movement, almost all the subjects used head movement to assist controlling supernumerary hands at one point. However, the question about effectiveness of head movement based control strategy remains unanswered.

7.2 Limitations of the present experiments

Observational findings and opinions of participants were also used to evaluate applicability of the experiments. Several shortages were discovered when carrying out the experiments.

Firstly, it is really difficult to find a speed that suits perfectly for all subjects. In the current experiments three different velocities were used. In the first phase the speed was slow enough for subjects to catch about 90% of the objects. In second phase, which seemed to suit the subjects most, the success rate was around 60%. However, in the last phase least successful subjects had really rough time catching the objects, reaching the success rate around 10%. Therefore, for further research it is suggested to increase the number of phases and velocities to suit the intraindividual variability of the subjects better. Another approach would be that speed of the object increases during the experiment when subject manages to catch it. In this manner every subject could develop the speed that suits him or her best.

Secondly, there were some problems with Leap Motion's hand tracking. All subjects encountered the disappearance of hands at some point leading to increased number of missed objects. It was also observed that even though each subject received the best instructions possible about tracking, at higher speeds subjects tended to move their body too eagerly or keep their hands beneath the hemisphere of Leap Motion therefore causing the loss of tracking. During the process of development, it was found that it takes serious amount of experience to truly understand the tracking capabilities of Leap Motion.

Furthermore, in current experiments the area in which the objects dropped was rectangular. This caused a few occasions where subjects caught only glimpse of the object or did not see it at all because they were looking on the other side or leaned too much forward. Therefore, another shape of area is recommended to use, such as circular or sectorial shape. Ideally the size of the area should also be in relation to subjects' hand length.

It was also stated by subjects and confirmed by observational findings that the task in current experiments requires fast reactions. This might draw focus of this experiment away from observing how subjects operate with supernumerary hands to observing how fast the subjects react.

It is strongly recommended to address these problems before applying them on larger scale or conducting further researches. In conclusion, it is difficult to design the task in a way that suits all the subjects.

7.3 Applications

Are there any specific applications to this kind of study? What can the society gain from it? There are numerous fields of expertise that could potentially benefit from further studies. However, psychological experiments, such as this thesis, are only a small part towards developing beneficial applications for the society.

Recent improvements in robotics and bionics could really benefit from these kind of studies. The latest developments in bionics are almost from science fiction category. Scientists and engineers have managed to develop modular prosthetic limbs that can perform almost every action that human body limbs can with almost the same level of precision. The main problem is the stimulation of these highly advanced arms by humans itself. Therefore, developing new control strategies, for instance involving the head or leg movement, could really improve the stimulation of prosthetic limbs. Technology is not far away from giving the amputees a new set of high tech limbs to operate with.

Similar difficulties occur when controlling the systems that need high level of stimulation. If such systems cannot be fully automated and need the human specialist to control them, then having an extra pair of hands or totally new advanced control strategy could be really useful. For example, some complex level industry vehicles such as cranes or harvesters might be better controlled with an extra pair of hands. Or some sort of military technology such as drones or tanks. Increasing the effectiveness of multitasking with increased number of arms or advanced control strategies could be really helpful in these fields.

Understanding how the brain perceives the human body would also help to find new solutions in medicine to cure disorders with ‘body image’. Such as medical situations where brain refuses to accept its own body parts, known as ‘body neglect problems’. And of course its opposite known as ‘phantom limbs’, where the patient has lost his limb, but can still feel it there. These are medical conditions that are directly connected to the disorders of brain’s perception of body.

Furthermore, virtual reality devices are becoming more and more widely available to the public since Oculus Rift and HTC Vive recently released their consumer targeted products. This means that virtual reality based content including psychological experiments will also be on the rise. This paper can be helpful for conducting future studies about changing or extending body schema through virtual reality. It is very likely that new interesting and realistic virtual body-representations will emerge, which may lead to major breakthroughs in prosthetic limbs development or industry of entertainment.

8 Conclusion

In conclusion it can be said that having more arms to operate with does not necessarily mean that one would perform more successfully, especially when their control strategies are still reliant only on one pair of real hands.

However supernumerary hands can still be helpful even when they all move simultaneously to real hands resulting in less total hand movement. In addition to that, increasing the movement scale of hand, enabling it to reach further, makes it more effective when it suits the task better.

Furthermore, the ownership feeling of hands seems to diminish when delay is inserted into the hands. This confirms that synchronous stimulation is really important to achieve body ownership over virtual limbs. Similar effect occurs when hands are put in other position and have different rotation from the real hands.

Therefore, a body avatar extension is a difficult task and needs to be designed carefully for it to feel natural.

Even if the idea of owning supernumerary hands will not turn out to be effective in a practical way in future, it has great potential in the entertainment industry.

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Appendix

I. Unity Project

Thesis is uploaded with “Human_Octopus_Project.zip” file. The file contains the Unity project which includes scenes for each experiment and various prefabs and scripts that were used during development. The project can be opened in Unity after unzipping the containing folder.

II. Short Description

You are about to take part in four different virtual reality experiments which involve operating with various supernumerary hands. The task is to catch the falling object as many times as possible. Experiments are divided into 3 phases, each lasting for 1 minute and there is a 30 second break between each phase. The setup of arms is different in each experiment and you are allowed to catch the object with any of your arms. Catching means that you simply have to touch the object. You are also notified by a sound alert each time you manage to hit the object and when the experiment begins.

Objects are falling from the wooden box that you can see above your head and are returned to the very same box each time you manage to catch it or each time it hits the floor. Object's speed is different in each phase, starting with the slowest and ending with the fastest.

You are also given a short period of time before each experiment to exercise with the current hand setup. When you are ready, the experiment is started. After each experiment you are asked to assess a few statements on a scale of 1 to 5 where 1 stands for strong disagreement and 5 for strong agreement.

You don't have to remember everything stated above as you are instructed through each experiment. You are free to ask questions before and after each experiment and report any anomalies whenever they occur. You are allowed to stop the experiment whenever you feel discomfort.

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