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Effects of Virtual Hand Representation on Interaction and Embodiment in HMD-based Virtual Environments Using Controllers

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Επιδράσεις της Αναπαράστασης Εικονικού Χεριού στην Αλληλεπίδραση και την Ενσωμάτωση σε Εικονικά Περιβάλλοντα Βασισμένα σε HMD με Χρήση Χειριστηρίων

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ABSTRACT

Many studies have been conducted in the past few years that focus on interaction and embodiment in the field of Virtual Reality (VR). However, despite the recent widespread use and continuing rise of controller-based head-mounted display (HMD) hardware for VR, there is little research on the use of handheld controllers in this context. To address this shortcoming, we explore the effects of different virtual hand representations on interaction and the user's sense of embodiment, inspired by the work of Argelaguet et al. in 2016, in this case using controllers.

We designed an experiment where users perform the task of selecting and moving a cube from and to specific positions on a table inside an immersive virtual environment. Three representations were selected: the abstract shape of a Sphere, the 3D model of the Controller, which is a one-to-one representation of what the users have in their hands in the physical world, and a human-looking Hand, the most realistic and familiar of the three. For each representation, users were asked to perform the same task with and without obstacles (Brick Wall, Barbed Wire, Electric Current).

A total of 39 participants, belonging to various age groups and having different levels of experience in VR, took part in the study. The design and results of the experiment are presented in this thesis, reporting significant differences in the actual performance of the different representations, the perceived sense of ownership, as well as the users' preferences. Although no significant differences were identified in the sense of agency, the users' performance with the Sphere was significantly worse compared to the other two. Statistical analysis of the results indicates that it is the Hand that generates the strongest sense of ownership, and it is the favorite representation. This makes it the best solution overall when designing interactive virtual environments with controllers, combining good performance with enhanced sense of ownership, with the exception of cases requiring very precise object manipulation in which the Controller is the best option.

SUBJECT AREA: Human Computer Interaction

KEYWORDS: Virtual Reality, Interaction, Virtual Embodiment, Perception

ΠΕΡΙΛΗΨΗ

Τα τελευταία χρόνια, έχουν γίνει αρκετές έρευνες που επικεντρώνονται στην αλληλεπίδραση με και την αίσθηση της "ενσωμάτωσης" σε περιβάλλοντα Εικονικής Πραγματικότητας (Virtual Reality - VR). Παρόλα αυτά, σε αντίθεση με την πρόσφατη ευρεία χρήση και συνεχόμενη άνοδο του υλικού εικονικής πραγματικότητας που είναι βασισμένο σε κάσκες (HMDs) και χειριστήρια, η έρευνα σχετικά με την χρήση αυτών των χειριστηρίων είναι περιορισμένη. Για να αντιμετωπίσουμε αυτήν την έλλειψη, διερευνήσαμε τις επιδράσεις που έχουν διαφορετικές αναπαραστάσεις εικονικού χεριού στην αλληλεπίδραση με την χρήση χειριστηρίων και την αίσθηση ενσωμάτωσης των χρηστών, εμπνεόμενοι από τη δουλειά του Argelaguet κ.ά. το 2016, που όμως δεν χρησιμοποίησαν χειριστήρια στα πειράματά τους.

Σχεδιάσαμε ένα πείραμα όπου οι χρήστες εκτελούν την εργασία της επιλογής και μετακίνησης ενός κύβου από και προς συγκεκριμένες θέσεις πάνω σε ένα τραπέζι, ενώ βρίσκονται μέσα σε ένα εμβυθιστικό εικονικό περιβάλλον. Τρεις αναπαραστάσεις επιλέχθηκαν: το αφαιρετικό σχήμα μιας Σφαίρας, το τρισδιάστατο μοντέλο του Χειριστηρίου, το οποίο αποτελεί ένα-προς-ένα αναπαράσταση αυτού που οι χρήστες έχουν στα χέρια τους στο φυσικό κόσμο, και ένα ανθρωπόμορφο Χέρι, η πιο ρεαλιστική και οικεία αναπαράσταση από τις τρεις. Για κάθε μια αναπαράσταση, ζητήθηκε από τους χρήστες να εκτελέσουν την ίδια εργασία χωρίς και με εμπόδια (Τούβλινος Τοίχος, Συρματόπλεγμα, Ηλεκτρικό Ρεύμα).

Συνολικά 39 συμμετέχοντες, που ανήκουν σε ποικίλες ηλικιακές ομάδες και έχουν διαφορετικά επίπεδα εμπειρίας σε VR, πήραν μέρος στη μελέτη. Η σχεδίαση και τα αποτελέσματα του πειράματος παρουσιάζονται στην παρούσα διπλωματική, αναφέροντας σημαντικές διαφορές στην πραγματική απόδοση των διαφορετικών αναπαραστάσεων, της αντιληπτής αίσθησης ιδιοκτησίας, καθώς επίσης και στις προτιμήσεις των χρηστών. Αν και δεν παρατηρήθηκαν σημαντικές διαφορές στην αίσθηση αυτενέργειας, η απόδοση των χρηστών με τη Σφαίρα ήταν σημαντικά χειρότερη σε σύγκριση με τις άλλες δύο αναπαραστάσεις. Η στατιστική ανάλυση των αποτελεσμάτων δείχνει ότι το Χέρι είναι εκείνο που δημιουργεί την ισχυρότερη αίσθηση ιδιοκτησίας, και είναι η προτιμότερη αναπαράσταση. Αυτό την κάνει την καλύτερη συνολική λύση κατά τη σχεδίαση αλληλεπιδραστικών εικονικών περιβαλλόντων με χειριστήρια, συνδυάζοντας καλή απόδοση και αυξημένη αίσθηση ιδιοκτησίας, με εξαίρεση περιπτώσεις που απαιτούν πολύ ακριβείς χειρισμούς αντικειμένων όπου το Χειριστήριο είναι η καλύτερη επιλογή.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Αλληλεπίδραση Ανθρώπου Υπολογιστή

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Εικονική Πραγματικότητα, Αλληλεπίδραση, Εικονική Ενσωμάτωση, Αντίληψη

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This thesis describes the research that has been conducted as part of my Master studies at the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens. The experiments took place in the course of one week at the university campus, and I would like to thank my supervisor for providing her office for this purpose.

1. INTRODUCTION

This Chapter contains an introduction for this thesis. It begins with a description of the main research problem that is being tackled, followed by the reasons why this subject was selected and what was the main drive for performing this research. After that, the Chapter proceeds with the contributions this study made to the respective field of virtual reality (VR). Lastly, there is an outline of how the rest of the thesis is structured, briefly presenting the contents of each Chapter.

1.1 Research Problem

The role of interaction in a user's sense of embodiment (SoE) when using a virtual environment (VE) is a topic that has been explored only fairly recently. Earlier research focused mainly on the effects of visual stimulation, tactile [53] and motor [44], or changes in the representation of the users' bodies [71]. In 2016, two studies were conducted, one by Argelaguet et al. [2] regarding the effects that the virtual hand representation has on the role of interaction towards the SoE, and another by Lin and Jörg [35] on how appearance affects the virtual hand illusion. These inspired further research including exploring the effects of virtual arm representations on interaction in VEs [60] as a notable example. This body of research focuses mainly on technologies that track the hands coupled with finger tracking capabilities, either using Leap Motion™ or a glove solution. Interestingly, little work has been conducted on the use of handheld controllers; a recent paper studied the effects of hand size and interaction modality on the virtual hand illusion [34], which included both tracked finger motion and handheld controllers as two independent variables of their experiment.

Figure 1.1: In our experiment the users perform the task of moving a cube inside a hole, for different representations of the virtual hand using controllers. (Left) Selection with the Sphere. (Middle) Positioning with the Controller. (Right) After positioning with the Hand.

In this study, we vary and extend the work of Argelaguet et al. [2] by exploring the effects of the virtual hand representation on the SoE when using handheld controllers as a tracking mechanism to interact with the VE (Figure 1.1). Additionally, we explore how the users' performance, their sense of agency and sense of ownership are affected when the virtual representation of their hand is an object (i.e. the controller) that they actually hold in their hands and that is being tracked and represented in the virtual world exactly as it is in the physical world. An experiment was designed where users performed the task of selecting and positioning a cube on the surface of a table. During the task some obstacles were presented, which in some cases posed a "threat" to the virtual hand. Three representations were selected: Sphere, Controller and Hand. The intuition behind this choice was to provide different levels of realism and three different types of connection to the real world. Even though the representations differed, they all had exactly the same control mechanism. The task was repeated many times for all the possible combinations of virtual hand representations and obstacles.

We set out to answer three main research questions:

(**R1**) *Does the virtual representation of the hand alter the sense of agency when using handheld controllers?*

(**R2**) *Does the virtual representation of the hand alter the sense of ownership when using handheld controllers?*

(**R3**) *How are the sense of agency and ownership affected when using handheld controllers compared to existing research results that don't use them?*.

R1 and R2 are the same as in the case of Argelaguet et al. [2] but in this case using controllers, while R3 emerges from the existence of the controllers.

1.2 Motivation

According to a recent article released by RoadToVR [32], the monthly-connected VR headsets on Steam have reached a record high of 1.3 million in December 2019, after it surpassed 1 million for the first time in May 2019, and this number is constantly rising (Figure 1.2). The data used for their analysis were gathered during the period of the last three years from the monthly reports of Steam, the biggest digital distribution platform for video games in the world.

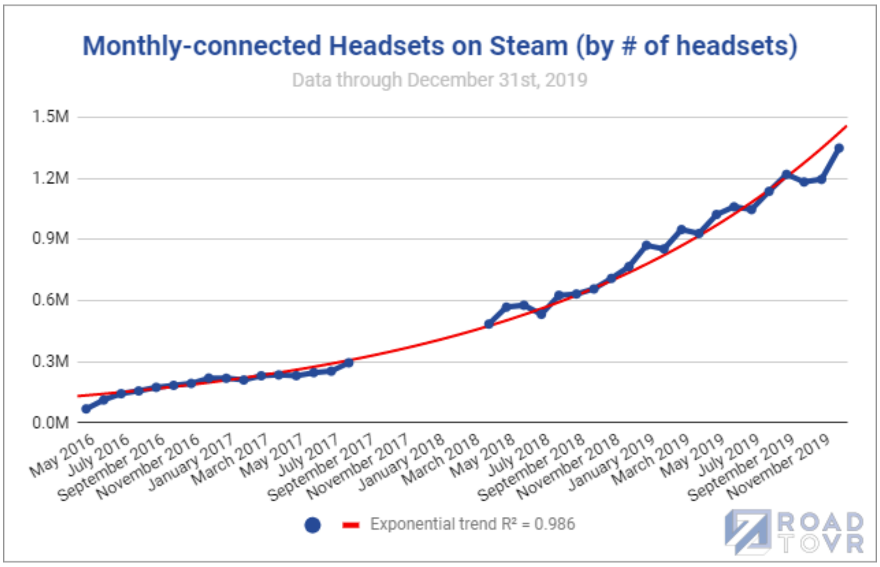

Figure 1.2: The dotted blue line represents the number of connected headsets on Steam, where each dot represents the data collected for that month. There is a gap of seven months due to data misreported by Valve. The image is from the RoadToVR website [32].

The most popular VR headsets providing six degrees-of-freedom (6DOF) and room scale tracking, are Oculus Rift™ and HTC Vive™. Lately more companies, such as HP and Samsung, have started adding their hardware on the VR headset landscape. All these systems have the following setup: a head-mounted display for stereoscopic viewing, two handheld controllers and a tracking mechanism for both the headset and the controllers.

A high-end computer is required to experience VR, something that raises significantly the cost. To overcome this obstacle, the biggest players, namely HTC and Oculus, have announced or released stand-alone headset solutions that do not require a connection to an external machine. Among other things, this is also an attempt to establish VR in the mass market and attract more people to the VR ecosystem. Hence, we can safely assume that in the near future the number of this type of VR headset users will grow even more.

The hardware offered by the various aforementioned companies is similar. There are some differences in the specifications of the different HMDs offered, like the refresh rate and resolution, but the end result is more or less the same with slightly better or worse image quality. Tracking is being achieved either by using inside-out tracking (e.g. Oculus Quest™, renamed to Oculus Insight) or external hardware (e.g. Vive's base stations), both sufficient for smooth and seamless experiences. What all these systems have in common is one of the most important interaction aspects inVEs: hand tracking and the interaction mechanics when using the controllers. The controllers have many similarities in the input and output they offer to the users. All of them have a trigger button where the index finger is placed when holding the controller, additional buttons and a thumbstick (Oculus Touch Controllers) or a touchpad (HTC Vive controllers) where the thumb is placed, and one more button reachable by the rest of the fingers, usually the middle finger. As for the output, all of them support haptic feedback. Having almost identical layout and functionalities offers the advantage that the results of research and experiments performed on controllers made by a company or a research group apply to all of them.

Despite these similarities and the fact that these devices reach a large number of people, almost no research has been published focusing on handheld controllers, during the last three years since they first appeared. On the other hand, there is substantial research regarding hand tracking and interaction mechanics without controllers in VR, especially with the progress of technology and the existence of affordable solutions for this type of input (e.g. Leap Motion). Some of the examples include realistic virtual grasping [6], visual feedback for virtual grasping [47], virtual grasping feedback and virtual hand ownership [10], effects of the virtual hand representation in interaction [2], effects of virtual arm representation on interactivity in virtual environments [60], and realistic hand-object interaction in VR [24]. One would assume that relevant research would also exist for the controllers since there are research questions that could apply to both types of interaction. This is however not the case, exposing a gap in research which is not consistent with the aforementioned importance of the controllers. Furthermore, there are issues identified in the literature for hand tracking and interactions without the controllers that do not apply when using them. The most important one is that due to the fact that there are buttons and explicit input for expressing the intention of a user's action, the "sticking object" problem when exaggerated finger motions are required for release is avoided [48]. The opposite is also true, meaning that there are issues when using controllers that do not apply in hand and finger tracking methods. Nevertheless, the different nature of interaction when holding a controller in your hands versus holding nothing generates a substantial research gap and an open field for exploration and experimentation. Furthermore, there are a couple of recent studies comparing the two interaction modalities that show advantages in user performance and preference when using controllers [20, 9], although more experiments are needed to verify these findings.

1.3 Contributions

As mentioned in the previous section, we first identified an important research gap in comparison to studies that do not make use of handheld controllers. Motivated by this, we then selected to explore the effects that the virtual hand representation has on interaction and embodiment using controllers, since it is a very critical aspect when people interact in VEs. We tackled primarily the three research questions presented in section 1.1, but also examined the performance of each representation, as well as individual user preference.

Analysis of the gathered results indicates that there are some contradictions between the perceived agency and the task efficiency, while the sense of ownership seems to be strongly related to the visual appearance of the virtual hand. Moreover, the use of handheld controllers plays an important role in the differences observed compared to previous work without them. We discuss both quantitative and qualitative results, and offer our interpretations to contribute towards a more effective design of interactive virtual environments for this type of hardware and interaction metaphor. In addition to that, useful insights are provided for the different effects between cases that use handheld controllers and others that don't. Lastly, this work can pave the way for exploring similar cases of missing research, such as visual feedback for virtual grasping using controllers, where the selection of the representation could be based on the conclusions we reached.

1.4 Structure of thesis

The rest of the document is structured as follows. In Chapter 2, the necessary background for the reader is being provided, containing explanations about the VR hardware, interactivity in VEs, and virtual embodiment. Chapter 3 presents the experimental design and hypotheses, followed by a description of the technical aspects of the implementation in Chapter 4. The process of the experiment and details about the methods are presented in Chapter 5. Finally, Chapter 6 contains a detailed analysis of the experimental results, which are then discussed in Chapter 7 where the thesis is concluded.

2. BACKGROUND

The current Chapter contains the most important background information required for the reader to be able to follow the next Chapters. First, virtual reality is briefly described accompanied with some historical context and the progression of the head-mounted displays throughout the years. After the modern VR hardware is presented, a classification of the manipulation techniques in VEs follows. Lastly, we present the concept of virtual embodiment and previous work related to the role of interaction in this context.

2.1 Virtual reality

All of us have probably fantasized of possessing the ability to transfer ourselves in a different world, real or illusory, with the freedom of performing acts outside the limits of our everyday lives. We may fantasize either when we are awake, by using our imagination, or in our dreams while we are sleeping. The first man that wrote a science fiction story about this imaginary ability was Stanley G. Weinbaum [66] in his story Pygmalion's Spectacles [63] in 1935 (Figure 2.1), which is probably the first written description of what Jaron Lanier [31] later coined as virtual reality. His inspiration was drawn by the philosophical ideas that were expressed by George Berkeley [65] 200 years before him, where he argues, among other things, that we do not see, feel, hear, taste the objects, but that we have only the sensation of seeing, feeling, hearing, tasting. A famous quote by him, which sums up very well his ideas about immaterialism is, "The only things we perceive are our perceptions". In Pygmalion's Spectacles the main character met a professor who invented a pair of goggles which enabled "a movie that gives one sight and sound, taste, smell, and touch. You are in the story, you speak to the shadows (characters) and they reply, and instead of being on a screen, the story is all about you, and you are in it." Modern VR experiences can be described in a similar way, where instead of goggles the users wear HMDs and can interact with computer generated realistic worlds.

Figure 2.1: Pygmalion's Spectacles is a science fiction story by Stanley G. Weinbaum (1935) [39].

Unlike the device used in Weinbaum's story which offered a multi-sensory experience, modern VR systems are based primarily on one sense, the sense of sight. Auditory input is also being provided, but only recently has reached the level of fidelity to simulate realistic spatial 3D audio, and is not widely used yet due to its computational complexity. Additionally, even though the sense of touch is currently under research through haptic feedback, there hasn't been a satisfactory solution so far. Other senses, such as smell and taste, are considered the most difficult to recreate and simulate, so very limited research has been conducted on this front. Despite the fact that not all senses are included yet, it is remarkable how VR nowadays can achieve Presence, meaning the feeling of being there in the virtual environment [55], believing that you have been transferred in another world. This is being done mainly using two general characteristics. The first is the illusion of depth, also called stereoscopy. This is a very old technique, first invented by Sir Charles Wheatstone in 1838 [64], where two offset images are presented separately to the left and right eye of the viewer. These two-dimensional images are then combined in the brain to give the perception of 3D depth (Figure 2.2), even though we are looking on a flat screen. The View Master (Figure 2.3) was designed based on the same principle, and 3D movies also work the same way.

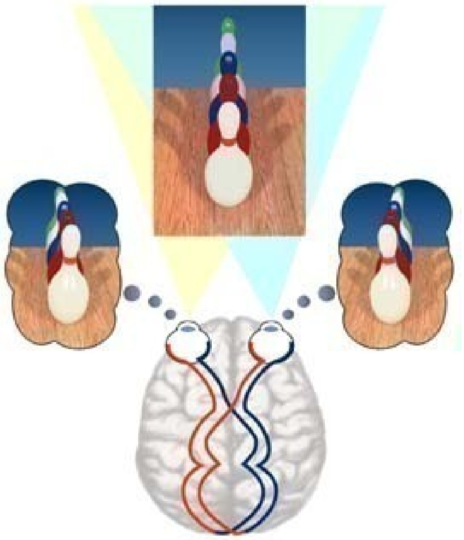

Figure 2.2: Stereoscopic view [37].

Figure 2.3: View Master classic [59].

The second characteristic, which makes modern VR hardware unique, is real-time head tracking. What the users see, which in the present day is sophisticated graphics, changes depending on the movements of the head without a noticeable lag, hence giving the impression of being there. A more detailed and technical explanation follows in the rest of this section where the history of the HMDs is presented as well the state of the art in VR hardware.

2.1.1 Head mounted displays (HMDs)

In our brief overview for the history and evolution of the VR headsets we are going to focus mainly on the ones that are head-mounted and offer 6DOF. For example, cases such as the Sensorama device which was patented [22] and created in 1962 by Morton Heilig some years after publishing his vision of multi-sensory theater in a 1955 paper [23], or even more recent devices like Samsung's Gear VR which offer only 3DOF, will not be considered. Having said that, the first ever HMD that worked with real-time computer generated graphics was created in 1968 by computer scientist Ivan Sutherland and it was called the The Sword of Damocles [62], inspired by its formidable appearance (Figure 2.4).

It was so heavy that a structure attached to the ceiling had to be designed to support it. Although the generated graphics were very simple, limited from the computing power available at the time, the required components to experience virtual reality were outlined very accurately.

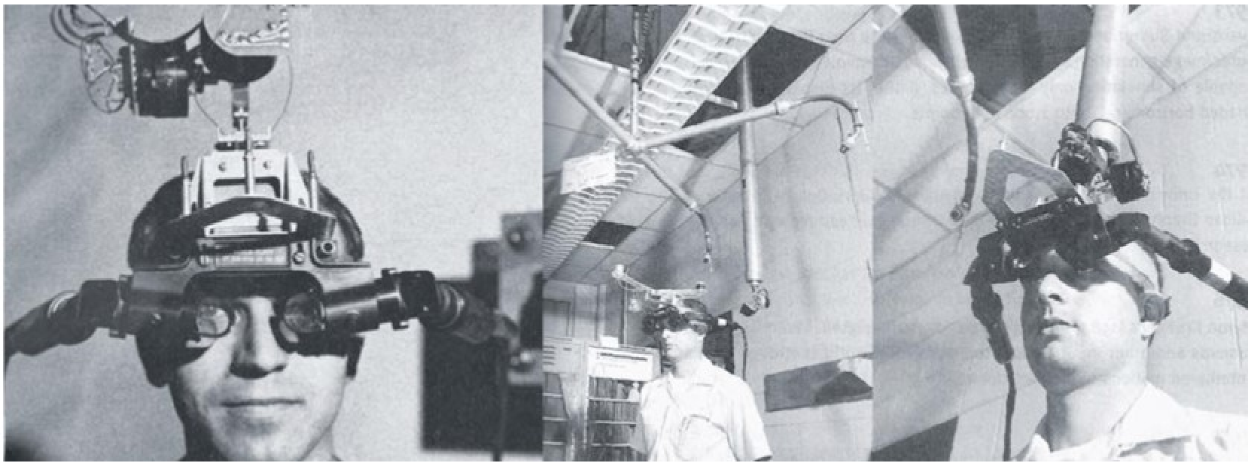

Figure 2.4: Sword of Democles, the first head mounted display (1961) [62].

In the following years from 1970 to 1990, VR HMDs were mainly developed and used by industries and governments for medical, flight, military simulation and training, and automobile design purposes. We have to keep in mind that this was the period that personal computers and home consoles have just started to become available to the mass market. Furthermore, 2D graphics used in games and experiences were at their infancy, let alone 3D graphics. During this period several HMDs were created from different research labs, including the ”The Virtual Interface Environment Workstation” (VIEW) [42] by NASA (Figure 2.5). It was also the period when Jaron Lanier [68], one of the modern pioneers of the field, made the term ”virtual reality” popular.

Figure 2.5: NASA’s VIEW [42].

Figure 2.6: Atari Jaguar VR [8].

Figure 2.7: Virtuality [16].

Many people during the 1990s, especially with the explosion of the personal computer and home consoles, as well as the growth in processing power, expected virtual reality to experience one of its golden ages. A lot of companies emerged that offered their HMD products to the market, either for personal use, like the Atari Jaguar VR (Figure 2.6), or for public use in arcades, like the Virtuality systems (Figure 2.7). The fact though was that the technology wasn’t mature enough to support people’s expectations and make the industry sustainable. The cost of some of these systems was very high, the processing power was still weak to offer very realistic graphics, the resolution of the screens was very low at the time, there were latency problems both on the screens' refresh rates and on the mechanisms used for tracking, most of them offered in the best case only 3DOF, and the list goes on. So we can imagine that the quality of the user experience was very low, experiencing at the same time noticeable motion sickness.

This negative user reception and industrial failure made such an impact, that kept both the users' and the industry's interest away for more than a decade. The situation started to change after the year 2010, when Palmer Luckey designed the first prototype of the Oculus VR headset, which led to a revival in the VR industry and research. The timing was very good because, unlike the 90s, the required technological aspects, each one for different reasons, have matured enough to support a good quality HMD device. As suggested by Moore's law, which was still true at that point in time compared to now, the processors continued getting faster in an exponential fashion through the years 2000 to 2010. Alongside access to greater processing power came also the evolution of more sophisticated 3D graphics. Additionally, the rise of smartphones and touch screens that occurred at the same period, was the reason for a big increase in the need for small responsive screens with high resolutions, as well as the need for small and accurate sensors (e.g. accelerometers, gyroscopes etc.). This led to the creation of very high quality small displays with high resolutions and refresh rates, and very responsive sensors with small form factor, both very helpful for someone who wanted to create a high quality VR HMD.

After having experimented with many prototype HMDs in his garage, Palmer Luckey in 2012 founded a company called Oculus and run a KickStarter campaing with his latest prototype, the Rift. The campaign turned out to be a huge success and many VR enthusiasts help the platform to grow, one of whom was John Carmack, a famous computer programmer, video game developer and engineer, who later joined the company as CTO. In 2014 Facebook acquired the Oculus company, after two development kits have been shipped, and launched a consumer version in 2016 (Figure 2.8). The same year also HTC, who has partnered up with Valve, launched their VR headset called HTC Vive (Figure 2.9). Both headsets did their job really well and the public's opinion about VR started for the first time in many years to shift, which can be observed in the continuous growing number of HMD owners, as mentioned in section section 1.2.

Figure 2.8: Oculus Rift.

Figure 2.9: HTC Vive.

Modern VR headsets have, very close to the eyes of the wearer, a screen divided in half, or two screens - one for each eye, covering the peripheral vision and blocking any information from the outside world. Using the stereoscopy technique, each eye receives the same image with a small offset, just like vision works in our everyday lives due to the distance between them. They provide rotational tracking, through a set of sensors that reside inside the headset, i.e. a gyroscope and an accelerometer. Using these sensors, the three axis rotations of the head are being tracked, namely the pitch, yaw and roll (Figure 2.10). The head movements inside the three dimensions, X, Y and Z position axis, are also tracked, providing a 6DOF setup. To achieve positional tracking two techniques are being used: outside-in tracking and inside-out tracking. Outside-in tracking uses cameras in stationary positions inside a room, which they track with very high accuracy infrared light sources placed on top of the headset (Figure 2.11 Top). Using the detected positions of the light sources and knowing static positions of the cameras, the computer has the necessary data to calculate the exact position of the headset. In contrast to how outside-in tracking works, inside-out tracking doesn't require any additional sensors placed in the physical space. It uses the multiple cameras placed on the headset to look for distinctive characteristics that originally exist in the environment and to determine position and orientation (Figure 2.11 Bottom). Image recognition algorithms are then applied to identify specific images or shapes in order to calculate the device's position in space.

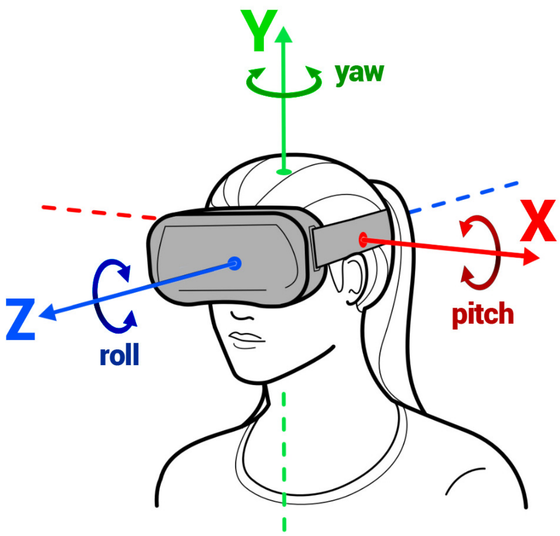

Figure 2.10: The six degrees of freedom. Three positional axis and three rotational [43].

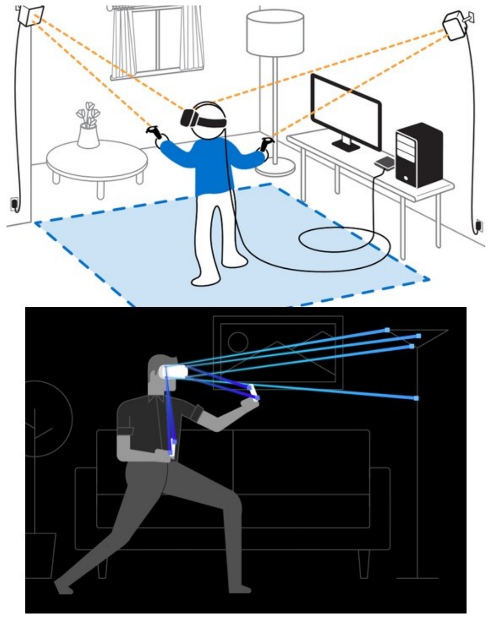

Figure 2.11: Tracking (Top) Outside-in [15]. (Bottom) Inside-out [11].

According to Michael Abrash, who serves right now Chief Scientist in Oculus, in a talk that gave in 2014 while working at the VR research team of Valve [1], to establish Presence you need all the following:

- A wide field of view (80 degrees or better)
- Adequate resolution (1080p or better)
- Low pixel persistence (3 ms or less)
- A high enough refresh rate (>60 Hz, 95 Hz is enough but less may be adequate)
- Global display where all pixels are illuminated simultaneously (rolling display may work with eye tracking.)
- Optics (at most two lenses per eye with trade-offs, ideal optics not practical using current technology)
- Optical calibration

- Rock-solid tracking – translation with millimeter accuracy or better, orientation with quarter degree accuracy or better, and volume of 1.5 meter or more on a side
- Low latency (20 ms motion to last photon, 25 ms may be good enough)

The device we used for our study was the HTC Vive (Figure 2.9) which has the following specifications:

- Screen: Dual AMOLED 3.6'' diagonal
- Field of view: 110 degrees
- Resolution: 1080 x 1200 pixels per eye (2160 x 1200 pixels combined)
- Pixel persistence: 1.9ms
- Refresh rate: 90 Hz
- Global display
- Optical calibration: Interpupillary distance and lens distance adjustment
- Tracking: SteamVR outside-in tracking, G-sensor, gyroscope, proximity
- Latency: 22 ms

2.1.2 Controllers

Apart from the technical requirements mentioned in the previous section, another factor that it is equally important for generating the sense of Presence to the users, is the ability to interact with the virtual environment in a natural way. The most common interactions we perform in the physical world are being done with our hands. Similarly, in VR we use our virtual hands to perform actions and tasks. In order to use our virtual hands in the VEs we either use hand tracking without controllers, or we use hand tracking with controllers. Hand tracking without controllers can be achieved by wearing special gloves or use camera-based tracking, like Leap Motion or Oculus hand tracking which uses the cameras on the headsets empowered by machine learning to represent the virtual hands. Even though these options also offer finger tracking capabilities, they have their limitations, such as that they lose tracking of the hands and fingers when they overlap each other from the camera's point of view. This doesn't apply for the glove solution, but wearing gloves that fit your hands can be tricky and cumbersome. As mentioned in section 1.2, all of them are susceptible to the "sticking object" problem, in contrast to the hand tracking when using controllers that this problem doesn't occur.

Modern hand tracking with controllers works the same way the head tracking works, as described in the previous section. Depending of whether the system uses outside-in tracking or inside-out tracking, the controllers are being tracked the same way as the headset. In the case of outside-in tracking the controllers have on them some infrared light sources that are detected by the static sensors that are placed in the area. On the other hand, inside-out tracking tracks the controllers using the cameras that are placed on the headset itself. We can easily notice that this introduces a limitation for this hand tracking technique since the controllers are only tracked when they are inside the field of view of the headset cameras. This is not the case in outside-in tracking, but then again in this case if something gets between the sensors and the light sources they also have problems. Although there isn't yet a perfect solution, both work very well without breaking the users' experience.

For the purposes of our experiment, hand tracking using controllers was used for the reasons described in section 1.2. The HTC Vive we used offers outside-in tracking and comes with two HTC Vive Controllers (Figure 2.12) for hand tracking, that have the button layout shown in Figure 2.13. The participants of our study had to use only the trigger button to interact with the objects of the VE.

Figure 2.12: The Vive controllers.

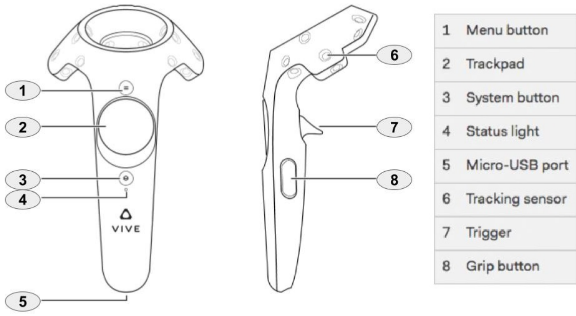

Figure 2.13: The Vive controller layout.

2.2 Interactivity in virtual environments

The meaning and correct usage of interactivity has been widely debated for many years. Most of the times, it is heavily dependant of the context and the type of medium we are using. According to Steuer, interactivity is the extend to which users of a mediated environment can participate real time in modifying its form and content [58]. But this definition, as Roussou correctly points out [50], does not entail any form of response. In terms of VR, a more accurate description is the same as Talin gave for making a distinction between the more interactive systems who they adapt to the user's actions and allow varied degrees of freedom [27].

In the rest of the section you will find a list of the main interaction tasks that can be performed in VR, a taxonomy of the manipulation techniques that are used to perform these tasks, and lastly we present the most common action both in the real world and virtual reality, i.e. grasping.

2.2.1 Interaction tasks

Poupyrev et al. suggest that tasks we perform in the real world when we make positioning movements, are the same as the basic VR manipulation tasks [46]. In the same paper they have gathered all these main interaction tasks proposed by previous studies, and they are the following:

- Position: the task of positioning an object.
- Selection: the task of identifying an object (also referred as a target acquisition task).

- Orient: the task of orienting an object.
- Text: the input of a string of characters.
- Quantify: the input of a numerical value.

As presented in the next Chapter which contains the experimental design details, our design includes two of these tasks, selection and positioning.

In one hand, the selection task requires users to select, whatever that means depending on the interaction metaphor, a target object that is located in their field of view. According to the same study by Poupyrev et al. [46], it can be described based primarily on five parameters: number of objects to be selected, distance to the target object, size of the target object, direction to the target object and occlusion of the target object.

The positioning task, on the other hand, requires the users to place the selected object from its initial to a final target position, usually with a specific precision. It depends mainly on the following five parameters: initial distance to the manipulated object, initial direction to the manipulated object, distance to the terminal object, direction to the terminal object and required precision of the positioning.

2.2.2 Manipulation techniques

The interaction techniques that take place between the users and VEs in order to perform the tasks listed in subsection 2.2.1, can be separated in some basic, most general metaphors as suggested by Poupyrev et al. [45] (Figure 2.14). They present two different categories of manipulation techniques in regards to their basic interaction metaphors, one called exocentric and another called egocentric. With the exocentric interaction, users interact with the VEs from the outside, known also as the God's eye viewpoint. With egocentric interaction, the users are interacting from inside the VEs, which is the most common kind of interaction in immersive environments. For egocentric manipulation there are two basic metaphors: virtual hand and virtual pointer.

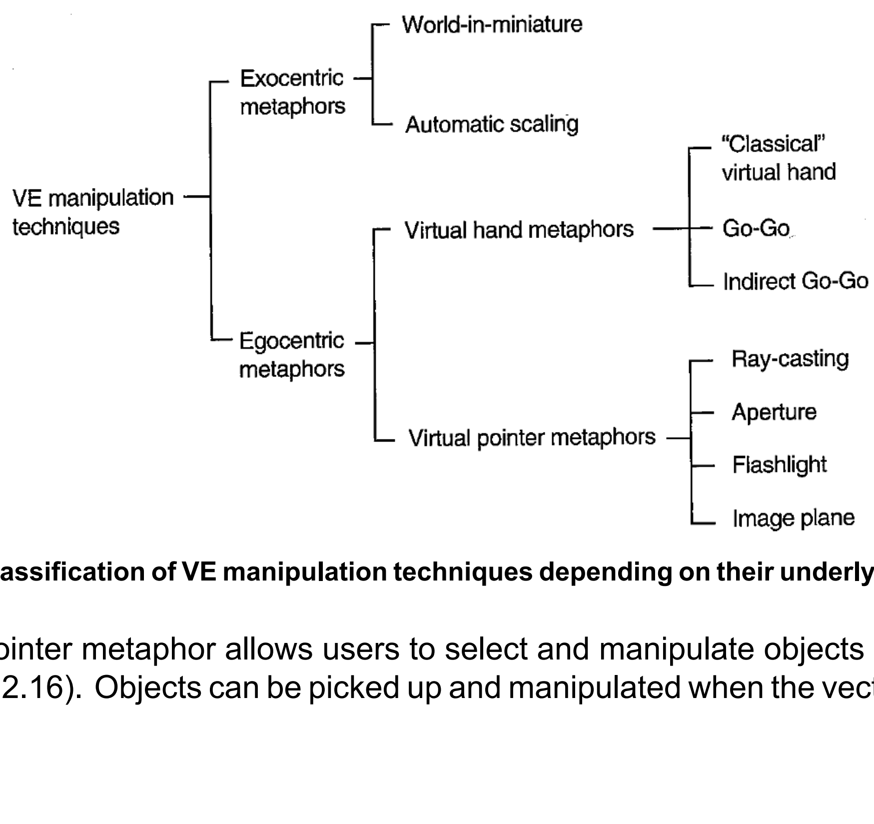

Figure 2.14: Classification of VE manipulation techniques depending on their underlying metaphors.

The virtual pointer metaphor allows users to select and manipulate objects by pointing at them (Figure 2.16). Objects can be picked up and manipulated when the vector emanating from the virtual pointer intersects with it. With the virtual hand metaphor, users control the virtual representation of their real hand to grab and position objects by touching and picking them (Figure 2.15). The different virtual hand techniques are distinguished by the input devices and the mapping between the real hand's rotation and position, and the respective properties of the virtual hand. The "classical" virtual hand technique provides one-to-one mapping between the real and virtual hands. Although this technique doesn't offer great user's area of reach, since it is limited by the reach of the actual hand, it simulates the way we manipulate objects in the real world with great accuracy [45]. For this reason, and because it has been studied as an effective tool for interacting with objects in VEs [3, 26, 21], we selected to use the "classical" virtual hand manipulation technique for our experiment.

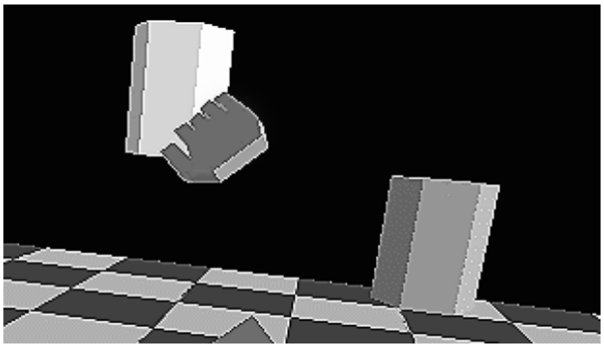

Figure 2.15: Virtual hand metaphor.

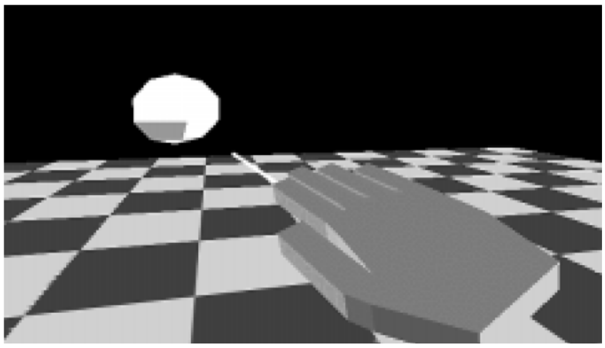

Figure 2.16: Virtual pointer metaphor.

Even though object grasping is one of the most common interactions performed in everyday life, and the most common task in VEs, the simulation of realistic grasping in VR still requires special input devices and specific algorithms [6]. In this work we focus only on the virtual hand technique not requiring physically-based simulations. In the "classical" virtual hand manipulation technique, users' hand movements are translated to a virtual representation of the hand, in which objects typically stick to the virtual hand when they touch and after the user presses a button. Additionally, in order to provide visual feedback, the interactive objects can be altered to express contact, valid grasping status [40] or use illumination effects [57].

2.3 Virtual embodiment

Embodiment is a complex multi-parameter phenomenon that could be described as the mental representation of the parts of our body and reachable space, which effectively extends their normal area of influence with real or artificial body parts, habitually used tools, or prostheses [19]. The capability of our brain of having a representation of our body results in a mental construction composed of perceptions and ideas about the dynamic organization of our own body, involving vision, touch, proprioception, interoception, motor control, and vestibular sensations [38]. In this regard, embodiment is defined as the sense of having a body.

Nowadays, in the field of applied neuroscience the replacement of a subject's real body with a virtual one is possible using modern VR systems, allowing the person to feel embodied in a virtual representation of his or her body. Virtual embodiment can be defined as "the physical process that employs the VR hardware and software to substitute a person's body with a virtual one" [56]. It has received a lot of attention in the VR research community in regards to virtual hand representation [2, 25, 28, 52] and avatar body representations [38, 41, 54]. Virtual characters driven by human behavior that represent a user are defined as avatars [4].

A more detailed description of the Sense of Embodiment (SoE) follows, presenting the three different constitutive components of embodiment that were identified based on previous research. Next, there is a brief mention to the body ownership illusions, and more specifically the virtual arm illusion. Lastly, we present a study on the role of interaction in virtual embodiment and the effects of the virtual hand representation [2].

2.3.1 Sense of Embodiment

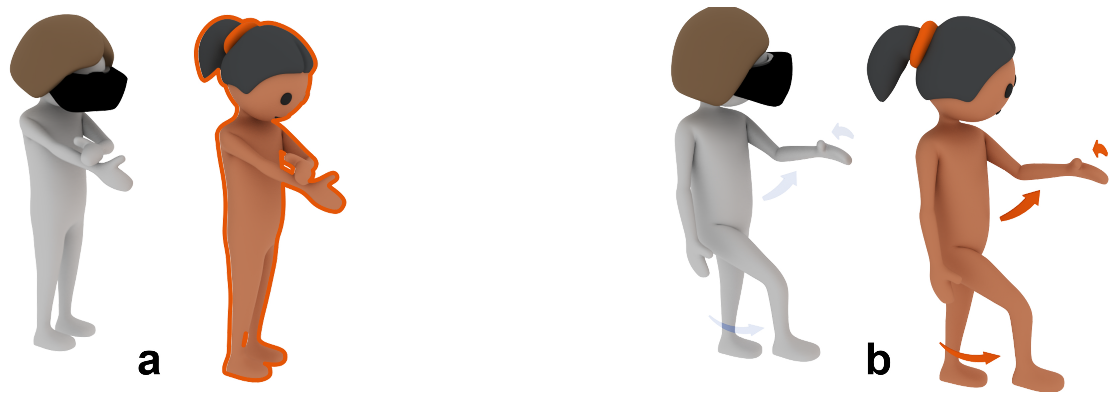

Figure 2.17: Virtual body ownership (a), agency (b). The user is depicted in grey; the virtual avatar is depicted in orange [49].

Kilteni et al. [30] presented a review and clarification of the concepts and mechanisms involved in body ownership illusions, focusing on the phenomenology of embodiment and offering an overview of existing definitions for these senses as well as of the variety of instruments that can be employed to measure them. In their paper, they propose an underlying structure, consisting of three components:

Sense of self-location - it alludes to the sense of being in the place where one's body is [33]. It can be defined as the space in which we perceive the self to be located.

Sense of agency - The sense of agency is defined as the sense of having "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" [5]. It refers to the sense that one can move and control one's own body.

Sense of body ownership - The sense of body ownership refers to one's self-attribution of a body [18, 61] and has a possessive character. It can be defined as the sense that the body that one inhabits is one's own.

For the purposes of this thesis, we examined the last two components, namely the sense of agency and the sense of ownership.

2.3.2 Virtual arm illusion

The rubber hand illusion (RHI) is the illusion of ownership when visual and tactile stimulation are provided synchronously on a visible rubber arm and on the hidden real arm. In the original version of the RHI [7], participants see a rubber hand located in front of them in a similar posture to their corresponding but hidden real hand (Figure 2.18 A). Both rubber and real hands are stroked by the experimenter. When the strokes on the real and rubber hands are delivered synchronously and in the corresponding spatial locations, most participants experience the rubber hand as if it were their own and feel the touch as originating from the rubber hand itself; the same does not happen, or to a much lesser extent, when the stroking is asynchronous, or when there are other inconsistencies (such as spatial) between the stroking on both hands.

Studies have shown that the RHI can also be achieved in a virtual environment, called the virtual arm illusion [53]. Instead of a rubber arm, participants saw a completely virtual arm projecting out of their right shoulder (Figure 2.18 B). The real hand was hidden behind a screen in a darkened room. When the experimenter touched the real hand of the subject with a small yellow ball, that was tracked in real space and its movement was replicated in the 3D virtual space, the subject would see the virtual ball touch the virtual hand, registered in the same place on the virtual hand. In this way synchronous visual and tactile stimuli could be applied to the virtual and real hand. The asynchronous stimulation in the control condition was achieved by using prerecorded movements of the virtual ball. The illusion produced was significantly greater for the synchronous condition compared with the asynchronous.

The remarkable thing about the virtual arm illusion is that it can also be achieved even in the absence of any tactile stimulation [51]. In this experiment, they extended the results of previous research by exploiting a virtual reality system, and hand tracking with a data glove (Figure 2.18 C), showing that the illusion of ownership of the virtually presented hand occurs on the basis of visuomotor synchrony between movements of the real hand and the virtual hand. When there is asynchrony the illusion does not occur.

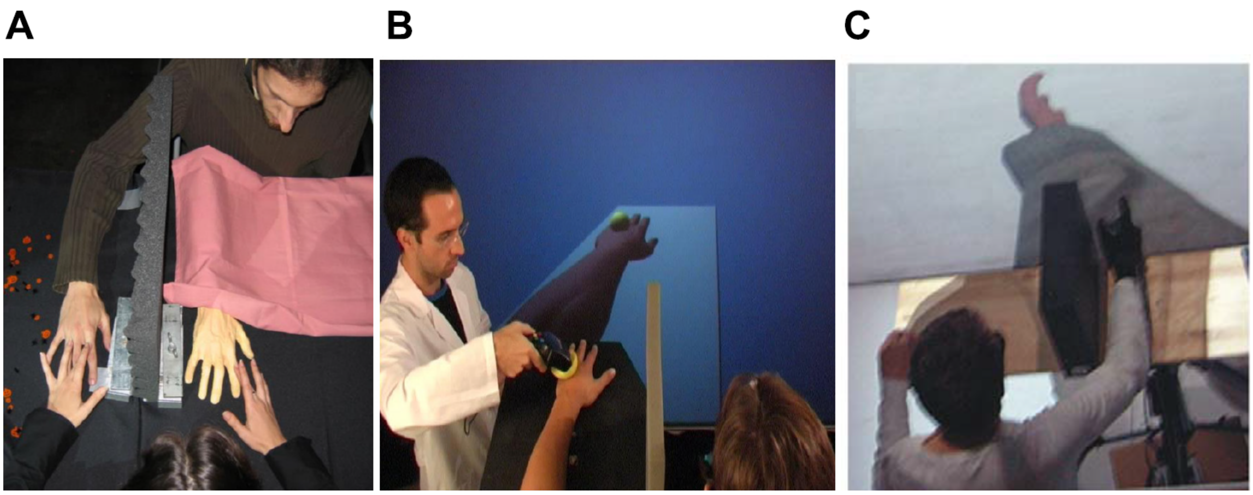

Figure 2.18: Experimental setups for (A) the rubber hand illusion (RHI), (B) the virtual hand illusion with visual and tactile stimuli, and (C) the virtual hand illusion visuomotor stimuli.

2.3.3 Virtual hand representations

Although, as we have seen in the previous sections, there is evidence that the virtual representation of the user has an impact on the sense of ownership, only a few studies have explored how the virtual body and its interaction capabilities alter the user's behavior. Argelaguet et al. [2] argue that "existing studies have focused on constrained interactions with the virtual environment, limited to pushing virtual buttons [17], touching landmarks [36] or drumming [29]". Their work goes one step further and evaluates the effects of the avatar representation in a realistic setup when believable interaction with the environment is provided.

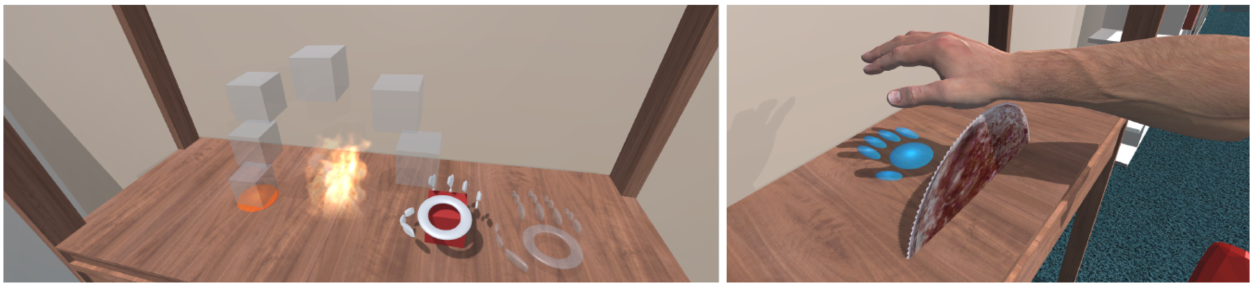

Figure 2.19: The tasks participants performed on the experiment of Argelaguet et al. [2]. (Left) The positioning task. (Right) The spinning saw task.

In their study, they explored the effects of the virtual hand representation on the sense of embodiment when actively interacting with the virtual environment (Figure 2.19). The goal was to grow the existing knowledge on how the representation of the user alters the perception of the virtual environment. They designed an experiment in which participants performed a number of positioning tasks in which, sometimes, obstacles were present that could be threatening to their virtual hand (Figure 2.19 Left). The considered virtual obstacles were the following: brick - a tangible and non-threatening obstacle, barbed wire - a tangible threatening object, fire - intangible but threatening. Additionally, they designed a second task in which participants were asked to place their virtual hand in a predefined virtual location which could potentially endanger their virtual hand (Figure 2.19 Right). Three different visual representations of the virtual hand were selected, offering three respective degrees of realism, from an iconic virtual hand to a fully animated one (Figure 2.20). However, all of them provided the same interaction capabilities, sharing the same control scheme. The study focused on two components of the sense of embodiment: the sense of agency, and the sense of ownership. Their results show that the sense of agency is related to the virtual hand control and the task efficiency, while the sense of ownership is mainly related to the visual appearance of the virtual hand. By observing the different hand realisms with direct control, they found that the virtual human hand generated the strongest level of ownership, but the less realistic hands generated higher levels of agency.

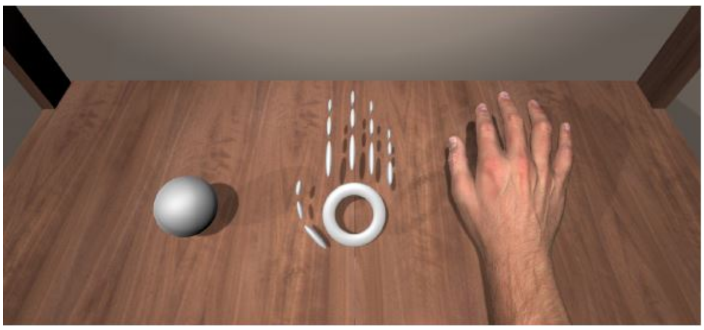

Figure 2.20: Virtual hand representations. Abstract (left), iconic (center) and realistic virtual hands (right).

Figure 2.21: Experimental setup. User wearing HMD, Leap motion on top.

Participants were immersed in the VE using an Oculus Rift (DK2 - 2nd development kit), in which head tracking was provided by the Oculus Rift and the participant's dominant hand was tracked using a Leap Motion. In order to provide optimal tracking conditions for the Leap Motion, the physical setup of Figure 2.21 was constructed. The experiment of the current thesis reproduces some of the main aspects of their work, using the same interaction metaphor and the ”classical” virtual hand technique, while performing a task that requires grasping, but in this case with handheld controller tracking instead of Leap Motion. In the next Chapter, more details about the design decisions and the setup of our experiment are presented, highlighting also the other modifications, apart from the tracking mechanism, that we made compared to the experiment of Argelaguet et al. [2].

3. EXPERIMENT DESIGN

The goal of this thesis is to investigate how the performance, the sense of agency and the sense of ownership inside an interactive virtual environment are affected for different virtual hand representations while performing a simple task using handheld controllers. In addition, we examine how the aforementioned attributes change when virtual obstacles are present, that sometimes can be threatening to the virtual hand. For this purpose, an experiment was designed where users perform the task of selecting and positioning a cube on top of a table. This task is repeated many times, adopting a multi-factorial 3×4×9 design based on the three virtual hand representations, the four obstacle conditions, and the nine cube positions. These are designed with a 6DOF HMD-based VR setup that supports hand tracking and input-output capabilities of handheld controllers.

Our design is based on the work of Argelaguet et al. [2], as briefly mentioned at the end of the previous Chapter. Another work that influenced our experimental design is the study by Poupyrev et al. [46], where the authors have gathered the main interaction tasks suggested by previous studies, including selection and positioning, and where they define the “virtual cubit”, a user-dependent unit of measurement that is the length of the user’s maximum reach in a virtual environment. The rest of this Chapter describes in detail the virtual environments and task of our experiment, and then our hypotheses for the expected results are listed.

3.1 Virtual environment and tasks

The virtual environment designed for the experiment is a spacious rectangular room without a ceiling, to make users feel more comfortable and avoid causing any sense of claustrophobia. Additionally, the walls are white and without any textures, as simple as possible, to not distract from the task at hand. Yet, the environment is realistic, with natural lighting features and shadows. The users start out at the center of this virtual room, which is empty at first. Features of the environment are adjusted according to the biometric characteristics of the users, as recorded through questions and measurements. These include their height and arm’s reach. The experiment is then ready to begin.

After a fade-out and fade-in effect, a table with a square surface is placed in front of the users. The height of the table and the width of its surface are automatically calculated, set to 65% of the user’s height and 125% of the user’s arm’s reach respectively. On top of the table rests a 3x3 grid of semi-transparent cubes, placed according to Figure 3.2 (left). These cubes are non-interactable and their purpose is to indicate the possible positions of the cube the users are going to interact with. In contrast with the experiment design of Argelaguet et al. [2], we decided to have more than one starting positions for the cubes, to minimize the effect of the repeatability of the exact same task on the user, and to collect user data for a wider range of hand movements.

Placed in front of the table is a virtual button. When the button turns green the users have to press it in order to start the task (Figure 3.1a). The moment they press this button one of the cubes becomes non-transparent and all the others disappear (Figure 3.1b). Their task is to select and move the cube from its current position, and place it in a hole (Figure 3.1c-g), on the left or right of the table, following the user’s handedness. The hole has a rectangular shape, almost at the same width as the cube, thus it requires accuracy to successfully place the holding cube inside it. In this way, information about accuracy is

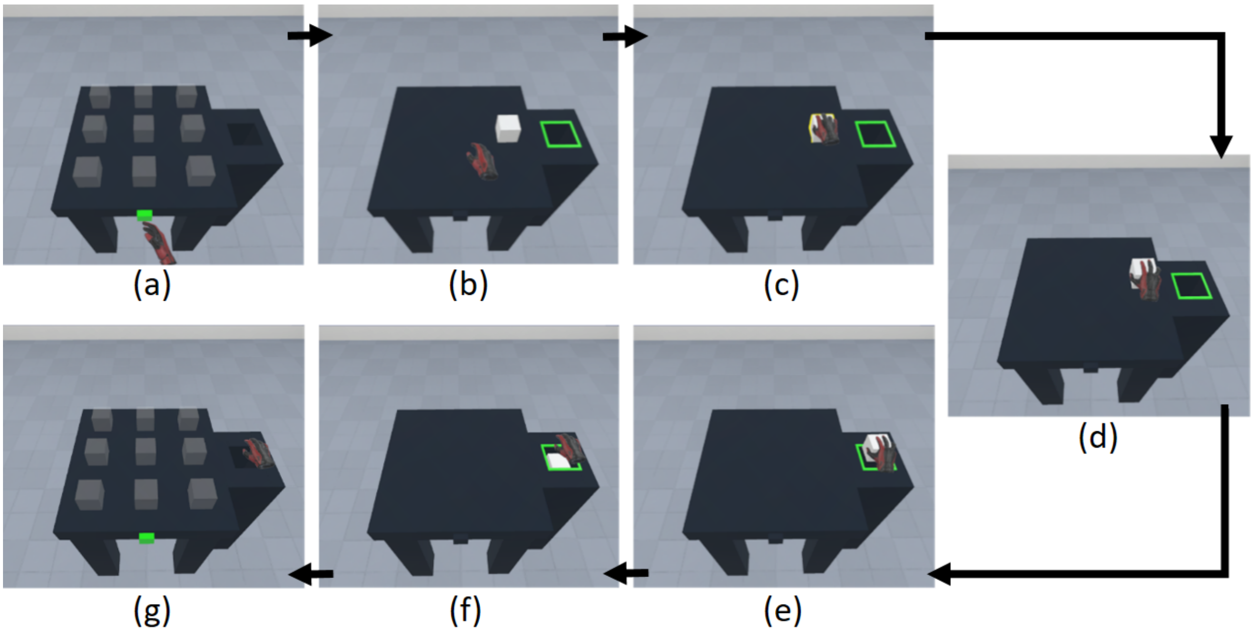

Figure 3.1: The steps of the task are (a) users push the green virtual button, (b) one cube becomes non-transparent, (c) they approach and touch it, (d) they grab it by pressing the trigger, (e) they position it to the hole, (f) they place it inside the hole, (g) table gets reset for the next task.

included in their time performance of the positioning part. The users' goal is to perform the task of selecting and moving a cube as fast as they can for all possible combinations of the following variables: virtual representation of hand, obstacle and cube position. They are able to use only their dominant hand for completing the task. Even though the other hand is visible, it cannot be used to interact with the environment.

The main independent variable of the experiment is the virtual hand representation. Three representations were selected: an abstract shape of a sphere, a one-to-one controller representation, and human-looking hands wearing gloves (Figure 3.3). The idea behind the selection was to provide different levels of realism and three different types of connection to the real world.

Sphere: it provides a non-realistic and completely unfamiliar to real life experience, hand representation. Two spheres are placed in the position of the hands, one for each. The sphere is the simplest possible abstract shape, resulting in a visible change only when altering its position, not its rotation.

Controller: this is an exact representation of what the users have in their hands in the physical world. The controllers are represented using the default SteamVR 3D models of them. This means the users see a highly detailed model of the actual object they are holding, which is being tracked in space with absolute accuracy in terms of position and rotation, and with the same scale.

Hand: a realistic and familiar representation of human hands. The 3D models used are the default human hands wearing leather gloves that SteamVR provides. There are two slightly different versions of them, a slimmer and more delicate version, and a thicker and more bulky version. The users select between the two at the beginning. Animations are applied on the virtual representation depending on button presses, that are translated to fingers closing in a grabbing motion depending on the degree the button is being pressed, and on grabbing/releasing the cubes, applying a predefined pose to the model.

Even though the representations differ, they all have exactly the same control mechanism.

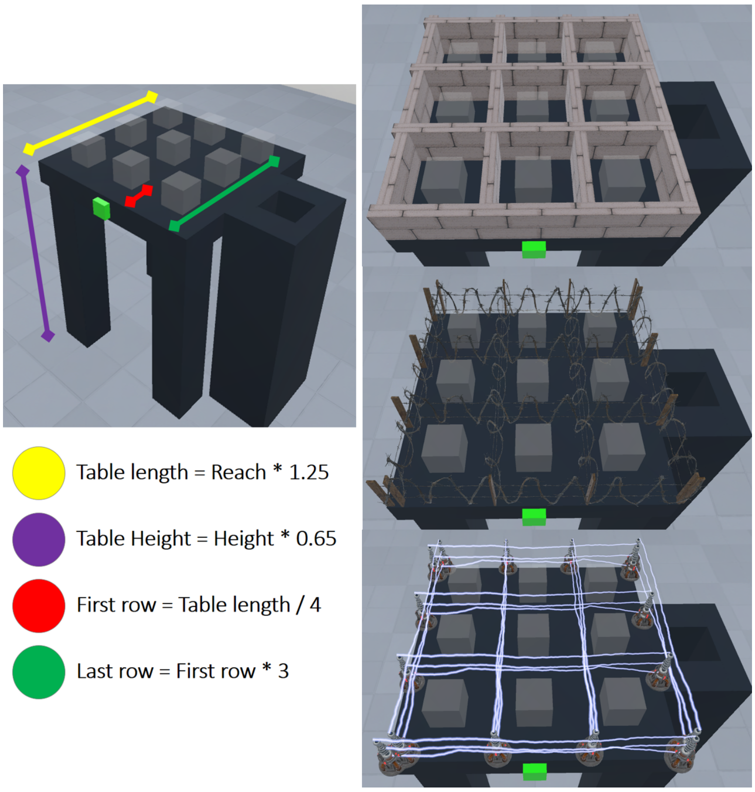

Figure 3.2: (Left) Table dimensions and cube distances. No obstacle. (Right, from top to bottom) Brick Wall obstacle, Barbed Wire obstacle, and Electric Current obstacle.

Figure 3.3: Three different virtual hand representations. (Top) Sphere (Middle) Controller (Bottom) Hand.

To perform the actions needed for the experiment, only the trigger button on the back of the controller, accessible with the index finger, is required. To grab the target cube the users approach it, and when it gets highlighted they press the trigger button. The distance a representation has to have for grabbing is the same for all of them, and that is the size of the Sphere. Until they place the cube in the hole, it stays attached on their virtual hand, but when they place it in, it gets detached from their virtual hand automatically. This design decision was made to ensure that the users will not lose time by accidentally dropping what they are holding. The virtual button on the table does not require any button presses on the controller to interact with it, it can be pushed by the virtual hand representations.

The experiment consists of three sessions, one for each virtual representation. To avoid the ordering effects as much as possible, a Latin-square design was used to counterbalance the order of the sessions. In each representation, one of the obstacles or no obstacle is randomly selected and placed on the table, again to minimize the ordering effect.

The obstacles designed were based on two properties: solid or not, and threatening or not. Apart from the case where no obstacles (not solid and not threatening) are placed on top of the table, the others are the Brick Wall (solid and not threatening), Barbed Wire (solid and threatening) and Electric Current (not solid and threatening), covering all combinations of these two properties. Only the latter was animated, giving a very good sense of realism to it, something that was also stated by the users during the runs. We followed the same logic as Argelaguet et al. [2] for the design of the obstacles, except we replaced fire with the Electric Current. Both of them are non-solids but threatening obstacles, but fire gives you the impression that if you do it fast enough the threat can be ignored, whereas this is not the case of the Electric Current. The obstacles are placed between the cubes as shown in Figure 3.2 (right), affecting in that way the whole task, both the selection and the positioning part. We opted for this set up to take better advantage of the effects of the obstacles in relation to the senses of agency and ownership, and the user's performance in both parts of the task.

At the beginning of each session the users practice the task four times for different random cubes and with no obstacle, in order to familiarize themselves with the process and the new virtual representation they are presented with. After the end of the practice part, they repeat the task nine times, one for each cube position in random order, until all are selected exactly once. With the current virtual representation, this process gets repeated for each of the four obstacle conditions. That means that for each session, without counting the practice part, the task is performed 4x9 times, which results in a total of 108 tasks throughout the experiment.

Every representation and obstacle change is introduced after a fade-out and fade-in effect, to and from black, to prevent confusion. Additionally, there is audio feedback for some of the interactions or from the environment, such as electricity sound for the electric current obstacle, impacts of cubes with the virtual objects and obstacles, and lastly, presses of the virtual button on the table.

3.2 Hypotheses

Taking into account our research questions, presented in section 1.1, we defined a set of seven hypotheses to examine during this experiment. We present them in this section, along with our rationale.

H1: Faster selection time for the sphere. Since the sphere is a very simplistic object with no corners and without any changes when it is being rotated, we believed it would let the users make the selection of target cubes a little faster than the other representations. We assumed that not having to think about the angle of the representation would give a slight advantage to the sphere, at least for the selection part of the task.

H2: Faster positioning time with the controller. For the positioning part, this hypothesis was based on the difference of the controller to the other two in terms of its one-to-one connection with the real world and the fact that the users see exactly what they are holding. We believed that this would help with the accuracy of movement needed for the positioning part, thus resulting in faster time performance than with the others.

H3: Faster overall time for the controller. Based on the previous two hypotheses and taking also into account that the positioning part is more time consuming than the selection part, we believed that the representation that would perform faster for the whole task, was the controller.

H4: Reduced number of collisions and collision duration for the hand. To measure the actual impact the obstacles had on the movements of the virtual hand representations, apart from collecting information related to time, we also kept some data related to collisions, as mentioned in section 5.2. We believed that the hand would result in less collisions and also in less collision time in total. The reason for this is that, as mentioned also in the following paragraph, we assumed that the hand will generate a stronger sense of ownership to the users, leading them to be more careful and avoid touching the obstacles, especially the threatening ones.

H5: Greater sense of agency with the controller, H6: Greater sense of ownership with the hand. Concerning the perceived sense of agency and ownership, our assumption was that in the same way as Argelaguet's et al. study [2], where the simplified virtual hands provided a better sense of agency, and the realistic hand a better sense of ownership, here we were going to report similar results. More specifically, we believed that the controller, for the same reasons we discussed for H2, would lead to a stronger subjective sense of agency, and the hand, because it is the most realistic and familiar to the users, would lead to a stronger subjective sense of ownership.

H7: Preferred representation overall, the hand. Lastly, we believed that the latter would be so strong that there would also be a general preference for the hand by the users when asked.

4. IMPLEMENTATION

For developing and running the experiments, we used an HTC Vive tethered to a Windows 10 desktop (Intel Core i7-7700K Processor, Nvidia GeForce GTX 1070 GPU, 32GB RAM). The technical details of the implementation of the VE and the interaction system are presented in this Chapter. Unity 3D game engine was the platform that the experiment was developed on, where the C# language is supported for scripting, accompanied by some assets downloaded from the Unity asset store. The code editor for the development was Visual Studio Code with some extensions found in its marketplace. All the above are described in more detail in the following sections.

4.1 Unity

Unity is a game engine developed by Unity Technologies, released in 2005. It is a cross-platform development tool that can be installed in all major operating systems (Microsoft Windows, macOS, Linux). Unity can be used to create three-dimensional, two-dimensional, virtual and augmented reality games, as well as simulations and other interactive experiences for more than 25 platforms, including mobile, desktop, consoles, and VR headsets. Apart from the video game industry, the engine has been adopted by other industries as well, such as film, automotive, architecture, engineering and construction [69].

The user friendly development interface that Unity provides, is suitable for creating 3D environments, levels, menus, doing animation, writing scripts, and organizing projects (Figure 4.1). The users can assemble assets into scenes, add lighting, audio, special effects, physics and animations, through an iterative process of editing, testing and playing that are happening seamlessly inside Unity's editor. The tool's intuitive structure and quick, productive workflow helps users produce interactive content lowering the required time, effort and cost.

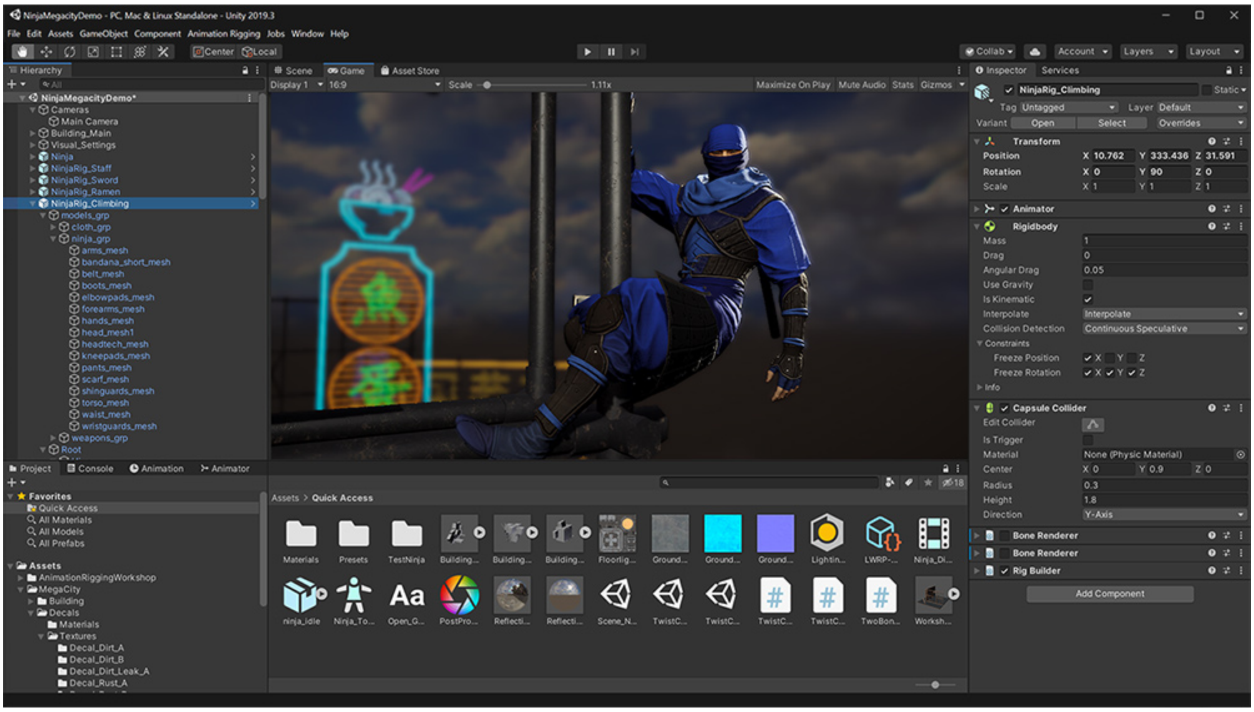

Figure 4.1: The editor of the Unity game engine.

4.1.1 Scripting

Scripting is an essential ingredient in all applications made in Unity. Scripts are written to respond to input from the player and manage events, that are part of the interaction and gameplay design, to happen when they should. Beyond that, scripts can be used to create graphical effects, control the physical behaviour of objects or even implement a custom AI system for characters in the game [13]. The behavior of GameObjects, which are entities in the virtual environment, is controlled by the scripts, called Components, that are attached to them. Although Unity's built-in Components can be very versatile, in order for the users to go beyond what they can provide and implement unique features, the creation of Components is possible using custom scripts. These allow users to trigger game events, modify Component properties over time and respond to user input in any desired way [12].

For scripting, Unity supports the C# programming language natively. C# (pronounced C-sharp) is an industry-standard language similar to Java or C++. Prior to C# being the primary programming language used for the engine, it previously supported Boo, which was removed with the release of Unity 5, and a version of JavaScript called Unity-Script, which was deprecated in August 2017, after the release of Unity 2017.1, in favor of C# [69]. This is a general-purpose, multi-paradigm programming language encompassing strong typing, lexically scoped, imperative, declarative, functional, generic, object-oriented (class-based), and component-oriented programming disciplines. It was developed around 2000 by Microsoft as part of its .NET initiative, and later approved as an international standard by Ecma (ECMA-334) and ISO (ISO/IEC 23270:2018). C# was designed originally by Anders Hejlsberg, and its development team is currently led by Mads Torgersen [67].

4.1.2 Assets

Creators can develop and sell user-generated assets to other game makers via the Unity Asset Store. This includes 3D and 2D assets and environments, as well as packages of libraries that contain custom scripts offering a specific functionality or mechanism. Unity Asset Store launched in 2010. By 2018, there had been approximately 40 million downloads through the digital store [69]. Below we mention the assets that were downloaded through the Unity asset store during the development of our VE and our interaction mechanics, followed by their brief description:

- **SteamVR Plugin.** Valve maintains a Unity plugin to smoothly interface SteamVR with Unity. With SteamVR developers can target one API that all the popular VR headsets can connect to. The modern SteamVR Unity Plugin manages three main things for developers: loading 3d models for VR controllers, handling input from those controllers, and estimating what the hand looks like while using those controllers. On top of managing those things they have an Interaction System example to help get the development of VR applications off the ground, providing concrete examples of interacting with the virtual world and their APIs [14]. This was the library that all the interaction mechanics were built upon, by extending what already offered with custom functionality through scripting.

  Link to the asset store:
  https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

- **Original Bricks Textures.** This asset contained the textures that were used for the Brick Wall obstacle.

  Link to the asset store:
  https://assetstore.unity.com/packages/2d/textures-materials/brick/15-original-bricks-textures-72427

- **Lightning Bolt Effect for Unity.** Lightning Bolt Effect for Unity is a fast, easy and high performance way to get simple lightning and electricity effects into a Unity app or game. There are options to control the chaos factor and the duration of the lightning bolt, and set the start and end point where it will be placed. Animated lightning is even supported via a sprite sheet. The Electric Current obstacle was created using this asset.

  Link to the asset store:
  https://assetstore.unity.com/packages/tools/particles-effects/lightning-bolt-effect-for-unity-59471

- **JSON .NET For Unity.** JSON .NET brings the power of Json and Bson serialization to Unity with support for 4.7.2 and up and is compatible with both .NET and IL2CPP backends. It was included to our project in order to create a saving and logging mechanism for the experiment data in JSON format.

  Link to the asset store:
  https://assetstore.unity.com/packages/tools/input-management/json-net-for-unity-11347

There were also two 3D models that were downloaded outside the Unity asset store, at the Sketchfab store:

- **Barbed-Wire.** This was the 3D model that was used to represent the Barbed Wire obstacle.

  Link to Sketchfab store:
  https://sketchfab.com/3d-models/alambre-de-puas-576a6a487ee44b3e9707d5b5b68a6c8c

- **Tesla coil.** This was the 3D model that was used to be the source of electricity for the Electric Current obstacle.

  https://sketchfab.com/3d-models/tesla-coil-5a2c8c1ac0a44efca9500af608af710e

4.2 VS Code

Visual Studio Code is a source-code editor developed by Microsoft for Windows, Linux and macOS. It includes support for debugging, embedded Git control and GitHub, syntax highlighting, intelligent code completion, snippets, and code refactoring. The source code is free and open source, released under the permissive MIT License. It is highly customizable, allowing users to change the theme, keyboard shortcuts, preferences, and install extensions that add additional functionality [70].

Out-of-the-box, Visual Studio Code includes basic support for most common programming languages. This basic support includes syntax highlighting, bracket matching, code folding, and configurable snippets. Visual Studio Code also ships with IntelliSense for JavaScript, TypeScript, JSON, CSS, and HTML, as well as debugging support for Node.js. Support for additional languages can be provided by freely available extensions on the VS Code Marketplace. This includes additions to the editor and language support. A notable feature is the ability to create extensions that add support for new languages, themes, debuggers, perform static code analysis, add code linters, using the Language Server Protocol and connect to additional services [70].

The extensions used in our case were:

- C# for Visual Studio Code (powered by OmniSharp).
- Unity Tools for Visual Studio Code.
- Unity Code Snippets.
- Unity Debugger Extension for Visual Studio Code.
- Git History.

5. STUDY

5.1 Participants and Procedure

A total of 39 participants, 22 women and 17 men, between the ages of 21 and 63 were recruited to take part in the experiment. We aimed for a variety of expertise in VR, ranging from 12 users with no experience, 18 users with little experience (1-3 times), 7 users with moderate experience (4-10 times) and 2 users with considerable experience (more than 10 times). All of them except 3 were right handed. Invitations were sent out to the participants to arrive at the experiment location at scheduled times. The study was approved by the institutional ethics review committee and followed all standard processes. The procedure lasted 55 minutes on average and was divided into the following phases (Figure 5.1):

Phase 1 - Preparations (15 min.). A member of the team welcomed each user and offered refreshments, while explaining briefly the objective and nature of the experiment, as well as the risks in using VR (Appendix D). The user was provided with an experiment information sheet and a consent form (Appendix C). After consenting to be photo-, video-, and audio-recorded, a member of the research team helped the user wear the VR equipment.

Phase 2 - Experiment (25 min.). The experimenter controlling the experiment asked the user a set of questions, including which is their dominant hand and guided them through the calibration phase, measuring their height through the VR equipment and asking them to extend their arm in front of them, to calculate their arm's reach. This phase set the dimensions of the surface and the height of the virtual table. The goal was to adjust dynamically different aspects of the experiment to fit each user and prevent the deterioration of the experimental data. The main experiment then started, structured in three iterations of the participant performing the set of tasks for each representation, as described in section 3.1, and then answering questions for the specific representation. The questionnaire presented in section 5.3 was filled in by the experimenter, while the participant answered the questions remaining immersed in the virtual environment.

Phase 3 - Conclusion (15 min.). The experimenter helped the participant remove the VR equipment and asked a set of concluding interview questions, to assess the representations comparatively.

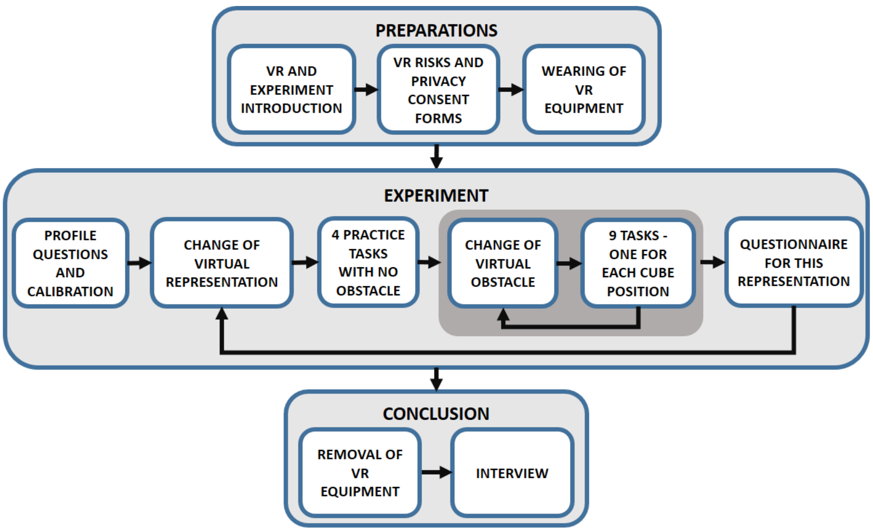

Figure 5.1: The procedure that was followed with each participant.

Additionally, during the experiment, an observation sheet (Appendix E) was used by one of the experimenters to write down interesting details about the participants' behavior and comments. A detailed description of the flow of the procedure can be found in Appendix A.

5.2 Data logging

The data gathered during the runs of the experiment included the time needed to complete the whole task, and the selection and positioning tasks individually, with an accuracy of a millisecond. The start time of the whole task as well as the start time of the selection sub-task are the same, and they are "marked" by the press of the green virtual button by the users. In that way, the starting position for the virtual hand representations of the users is always the same and can serve as reference for recording the start of the task. Accordingly, the end time of the selection sub-task and the start time of the positioning sub-task are the same and are "marked" by the grabbing of the target cube. Lastly, the end time of the positioning sub-task and the end time of the whole task are the same and "marked" by the successful placement of the cube inside the hole.

Another measurement logged in each session is collision time and collision count for each obstacle. Collision time is the total number of milliseconds that the virtual hand representation kept colliding with this obstacle. Collision count is the total number of times that the virtual hand representation collided with this obstacle. The colliders of each representation work as one and have the same structure as their 3D model. The colliders of all the obstacles are exactly the same and also work as one. Every time the collider of one of the representations starts touching the collider of an obstacle, and after it stops touching it for this time, the collision count is increased by one and the elapsed time is added to the collision time. Compared to the experiment of Argelaguet et al. [2], instead of having a separate task for examining the users' perception regarding the sense of ownership, we decided to keep the data about collisions because we felt they will produce more natural results since they are being logged at the same time as the task itself.

5.3 Questionnaire

The questionnaire employed for the purposes of this experiment is divided in three parts:
- A user profile section aiming to record basic information including participant's height, reach, gender and experience with VR.
- Sense of agency and ownership for each representation.
- A concluding section, administered as an interview, aiming to discuss in more detail the users' impressions of the representations in terms of effectiveness and personal preferences, focusing on the user's perceived advantages and disadvantages of each one.

Kilteni et al. [30] discuss questionnaires as one of the methods to measure the sense of agency and body ownership. These are designed to measure, in the case of the sense of agency, the users' subjective sense of control over the virtual representation and their perceived effectiveness. In the case of the sense of body ownership, the questions are designed to record, directly, whether the virtual representation felt as an extension of their body and, indirectly, through the perceived sense of danger to the threats and the perceived possible physiological responses to those threats.

The questionnaire combined closed and open ended questions and statements with which

Table 5.1: The questionnaire that was used after the completion of each virtual hand representation.

A1	I felt that selecting the cube after hitting the button was easy.
A2	I felt that placing the cube I had grabbed in the hole was easy.
A3	I felt like I had control over my actions with the sphere/controller/hand.
O1	I felt as if the sphere/controller/hand was an extension of my own body.
O2	I thought that the sphere/controller/hand could be harmed by the virtual obstacle.
O3	I felt that my physical body was endangered during the experiment.
O4a	I tried to avoid the electricity obstacle while performing the task.
O4b	I tried to avoid the brick obstacle while performing the task.
O4c	I tried to avoid the barbed wire obstacle while performing the task.
O5	I felt a tingling sensation in my physical body when the sphere/controller/hand approached or touched an obstacle.
O6	I felt that the sphere/controller/hand was able to pass through the virtual obstacles.

the users should mark their level of agreement. The statements for each representation marked with A and a number refer to the sense of agency, whereas those marked with an O and a number to the sense of ownership (Table 5.1). The whole questionnaire, which was created using the Google Forms platform, can be found in Appendix B.

6. ANALYSIS AND RESULTS

This Chapter presents the results of the statistical analysis of the experimental data and the questionnaires. In each case, the analysis approach is briefly described, followed by a presentation of the main findings. First the user performance is examined, in terms of duration and collisions, and then the perceived sense of agency and ownership of the users, as well as the users' preferences, based on their answers. After presenting the results of each analysis, there are conclusions about the rejection or confirmation of the related hypotheses.

6.1 User performance

In this section we present the results of the analysis of the logged data of the experiment, which includes the task duration as a whole and for the selection and positioning tasks in particular, as well as the total collision duration and number of collisions per representation.

6.1.1 Task duration

As discussed in section 5.2, we timed every task's duration for each user, recording the following time durations in milliseconds:
• Selection duration; the duration from the start, when they press the virtual button on the table, until the selection of the cube.
• Positioning duration; the duration from the end of the selection part until the positioning of the cube inside the hole.
• Task duration; the duration of the whole task.

We had a total of three factors: the sessions, the obstacles and the positions of the cube. Our first step was to proceed with a three-way ANOVA method. We aimed for at least 10 participants for each of the three representations, to attempt for a sample following the normal distribution. In order to use ANOVA, the samples must satisfy normality of both samples and residuals, and they must also satisfy the Homogeneity hypothesis, meaning the equality of the variance. We examined different approaches to satisfy these requirements, including logarithmization of the samples; however, the tests we applied, including Kolmogorov-Smirnov test for normality of samples and residuals and Levene test for equality of variance, were not positive for the use of ANOVA.

We thus proceeded with Friedman-Wilcoxon non-parametric tests. As shown in Table 6.1, the Friedman test rejected the hypothesis for equality of means with $p<0.001$. The pairwise comparisons revealed significant differences in their mean values for all the three tasks. These results are presented in Table 6.2. We conclude from these results that the Sphere is the slowest of the three representations, for the whole task (Figure 6.3) and for the selection task in particular (Figure 6.1). In both these cases, the Controller and the Hand are the fastest, with no significant difference. For the positioning task, the Sphere shares the second place with the Hand, showing that the Controller in this case is significantly faster than the other two (Figure 6.2).

The analysis of the experimental data, using Chi square tests for dependence, concluded that the effect of the obstacles and cube positions is the same across all three representations. It is interesting to note that for the Barbed Wire the participants were significantly

Table 6.1: Mean and Standard Deviation for the durations.

	Selection	Positioning	Whole task
Friedman	χ^2=66.361	χ^2=21.456	χ^2=39.032
Sphere	M=1437.5 SD=910.55	M=1861.50 SD=1025.89	M=3298.9 SD=1505.63
Controller	M=1276.4 SD=687.42	M=1795.4 SD=1051.72	M=3071.8 SD=1371.85
Hand	M=1286.1 SD=743.41	M=1830.1 SD=1028.21	M=3116.3 SD=1422.39

Table 6.2: Results of the Wilcoxon tests for the durations.

	Selection	Positioning	Whole task
Sphere-Controller	Z=-8.061 p<0.001	Z=-4.234 p<0.001	Z=-6.201 p<0.001
Sphere-Hand	Z=-7.023 p<0.001	Z=-1.894 p=0.058	Z=-4.755 p<0.001
Controller-Hand	Z=-0.465 p=0.642	Z=-2.085 p=0.037	Z=-0.796 p=0.426

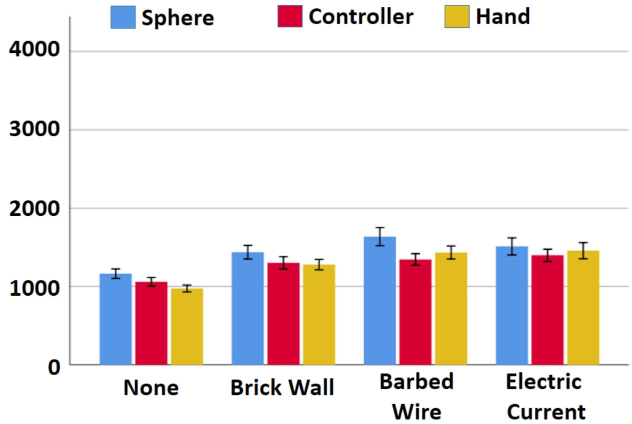

Figure 6.1: The mean selection durations.

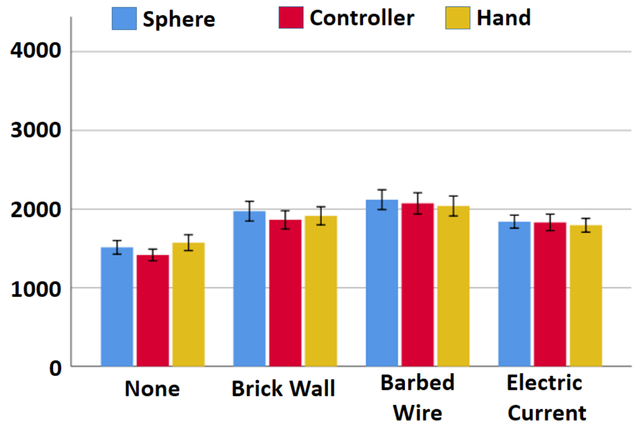

Figure 6.2: The mean positioning durations.

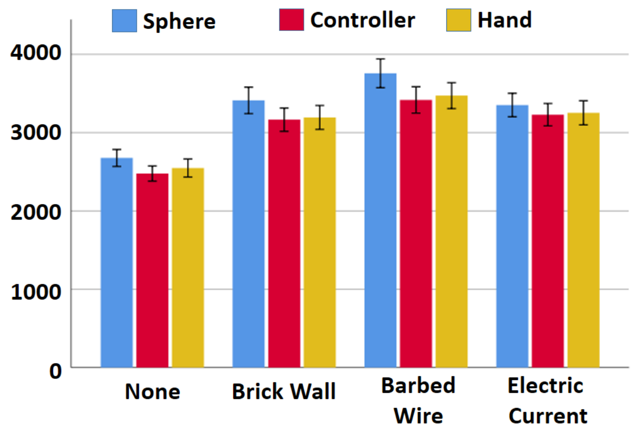

Figure 6.3: The mean whole task durations.

slower compared to the other obstacles, followed by the Brick Wall and the Electric Current obstacles which share the second place without a significant difference between them. This result is not surprising, taking into account that the Barbed Wire is both solid and threatening, whereas the Brick Wall is solid but not threatening and the Electric Current threatening but not solid.

The aforementioned results lead us to the following conclusions concerning our initial experimental hypotheses on task duration:

H1: Faster selection time for the Sphere - Rejected. The Sphere had the slowest selection, and overall time.

H2: Faster positioning time with the Controller - Confirmed. The Controller was the fastest representation for positioning the cubes in the hole.

H3: Faster overall time for the Controller - Rejected. The Controller was the fastest for the positioning, but for the selection and the whole task it shares the first place with the Hand since they do not have significant statistical difference.

6.1.2 Collisions

For the obstacle collision time, the Friedman test rejected the similarity (of the distributions) of the representations with p-value<0.001 (Table 6.3). The Wilcoxon pairwise tests revealed that the shortest collision time was exhibited by the Hand, whereas there was no significant difference between the Controller and the Sphere (Table 6.4).

For the obstacle collision count, the Friedman test rejected the similarity with p-value<0.001 (Table 6.3). The Wilcoxon pairwise tests revealed that the Hand exhibited the largest collision count, followed by the Controller and then the Sphere (Table 6.4).

Table 6.3: Mean and Standard Deviation for the collisions.

	Collision Time	**Collision Count**
Friedman	χ^2=37.675	χ^2=92.648
Sphere	M=10851.86, SD=13051.121	M=7.35, SD=2.811
Controller	M=9671.49, SD=9623.488	M=8.39, SD=3.35
Hand	M=9731.04, SD=12361.929	M=14.46, SD=7.790

Table 6.4: Results of the Wilcoxon tests for the collisions.

	Collision Time	Collision Count
Sphere-Controller	Z=-1.372, p=0.17	Z=2.78, p=0.005
Sphere-Hand	Z=-5.131, p<0.001	Z=8.71, p<0.001
Controller-Hand	Z=-3.321, p<0.001	Z=7.579, p<0.001

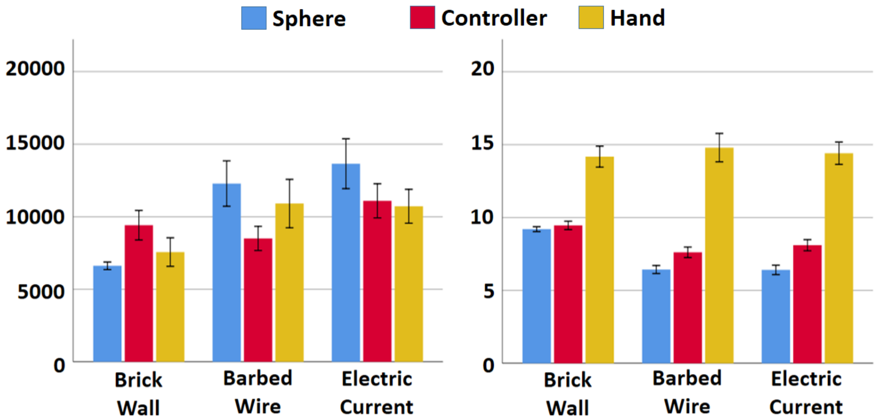

Figure 6.4: (Left) Mean collision time. (Right) Mean collision count.

In terms of our initial relevant hypothesis, **H4**: Reduced number of collisions and collision duration for the Hand, we conclude that it is partially confirmed. Although the Hand exhibited the shortest collision time, at the same time it also exhibited the greatest collision count (Figure 6.4).

6.2 User perceived sense of ownership and agency

To analyze the questionnaire data, we performed non-parametric tests, Friedman and Kendall's W for related variables, in order to compare the score of the statements the users gave to each representation. The analysis did not reject the equality in the means of these scores in all statements except the following three: "*O1 - I felt as if the representation was an extension of my own body*" (p-value<0.001, χ^2=26,824, Kendall's W = 0.344), "*O2 - I thought that the representation could be harmed by the virtual obstacle*" (p-value=0.001, χ^2=13,118, Kendall's W = 0.168), "*O4a - I tried to avoid the electricity obstacle while performing the task*" (p-value=0.011, χ^2=8,951, Kendall's W = 0.115).

Table 6.5: Mean, Standard Deviation and Mean Rank for the statements.

	O1	O2	O4a
Sphere	M=2.05 SD=1.297 MR=1.56	M=0.92 SD=1.345 MR=1.71	M=2.44 SD=1.334 MR=1.88
Controller	M=2.28 SD=1.45 MR=1.87	M=1.21 SD=1.436 MR=1.94	M=2.28 SD=1.395 MR=1.83
Hand	M=3.26 SD=1.044 MR=2.56	M=1.82 SD=1.43 MR=2.36	M=2.82 SD=1.374 MR=2.28

In all three cases the Mean Rank for the Hand was higher (Table 6.5). We performed

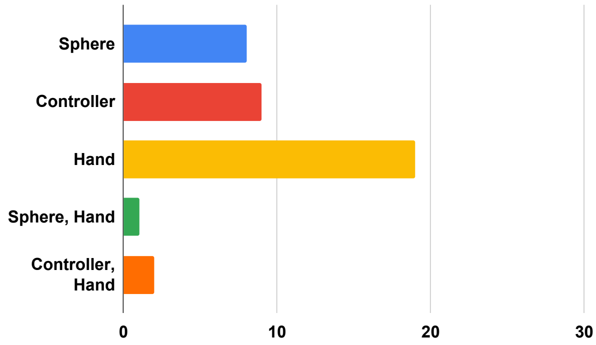

Figure 6.5: The users' answers when asked about their favorite representation(s).

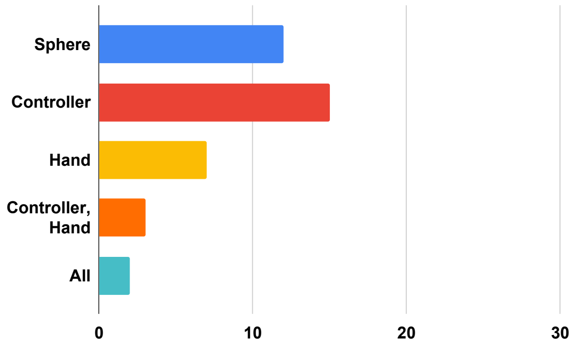

Figure 6.6: The users' answers when asked about the most effective representation(s).

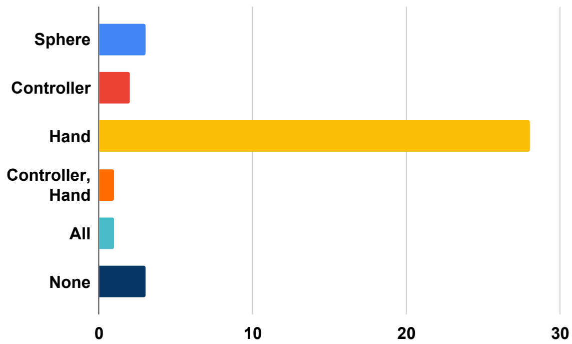

Figure 6.7: The users' answers when asked about the most vulnerable representation(s).

pairwise comparisons for the Wilcoxon Signed Ranks for the Sphere-Controller pair and for all the three statements there was no significant difference (O1:Z=-1.323, p=0.186, O2: Z=-1.216, p=0.224 and O4a: Z=-0.8, p=0.424). This analysis concludes that the Hand had significantly higher score in comparison to the other two representations for these three statements. More graphs with the responses of the users can be found in Appendix F.

In terms of comparative user preferences, concerning the representations, the Hand seems to be the favourite one, for the 49% of the participants, with the Controller and the Sphere sharing second place with 23% and 20% respectively (Figure 6.5). Interestingly, although the Hand was the favourite, it was considered the most effective only for 18% of the participants (Figure 6.6). The Controller in this case has the first place with 38%, followed by the Sphere with 31%. There is an 8% of the participants that considers the Controller and Hand equally more effective than the Sphere. In terms of perceived vulnerability, the Hand was considered the most vulnerable by 74% of the participants (Figure 6.7).

The perceived difficulty of the obstacles seems to follow a similar trend for all the representations, with the Electric Current considered the most difficult and the Brick Wall and Barbed Wire sharing second place (Appendix F). This result is different compared to the actual time measurements, where the Barbed Wire slowed down the participants the most, suggesting that the users felt more threatened by the Electric Current, most probably because of the continuous audio effect and animation.

Taking into account the aforementioned results, we conclude for our initial relevant hypotheses the following:

H5: Greater sense of agency with the Controller. - Inconclusive. Although the Controller was considered the most effective of the three by 38%, the agency related questionnaire statements did not exhibit any significant difference in its favor.

H6: Greater sense of ownership with the Hand. - Confirmed. The Hand indeed exhibited higher score in the related questionnaire statements and at the same time it was considered overwhelmingly “the most vulnerable” representation.

H7: Preferred representation overall: the Hand. - Partially confirmed. The percentage of participants who favored the Hand representation, even though numerous, were not enough to fully confirm this hypothesis.

7. DISCUSSION

An interesting outcome of our experiment was the underperformance of the Sphere for the task duration. The Sphere, being smaller and more compact as a representation, allowed better view of the cubes. Also, the simplicity of the Sphere led us to form the hypothesis that it would have an advantage in terms of efficiency for the selection part in comparison to the other two representations. So why were the users slower with the Sphere? Perhaps an explanation for these results can be found on the users outlook of the Sphere, as recorded in the interview questions. It was the most removed virtual hand representation from the physical world and this seemed to affect most users, some in a positive and others in a negative way. The Sphere was considered “aesthetically pleasing”, “fitting to the virtual environment”, “playful” or “fun” but also “unnatural” and “alien”. Some of the users tried to find familiar metaphors for this “neutral” interaction paradigm of the Sphere, thinking that it works “like a magnet” or “like a pirate’s hook”. Further investigation is needed to understand if this lack of familiarity with the Sphere was indeed the reason for its underperformance. Another possible reason could be that the Sphere as a shape is so different from the physical controller. The controller is longer and its center of mass is not the same as that of a sphere. The hand, however, has a center of mass which is closer to that of a controller.

The Controller was considered the most promising representation in terms of agency while designing the experiment, especially for the positioning task, due to the higher sense of control its one to one relation with the physical world would offer. Indeed, this relation to the physical world was very positively commented by about 30% of the participants, along with the sense of control it offered. The fact that it felt like a tool in an obvious way, and not like an extension of the user’s body, helped when facing the obstacles and threats as it provided a greater sense of safety. It also had greater reach, although for the selection task some felt they had to hold it “at a weird angle”. Some participants felt that the use of this representation was “like playing a game” and it was “fun”.

The Hand, not so surprisingly, proved to be a favourite representation for the majority of the users, generating a significantly greater sense of ownership. Although the users performed well with the Hand and they liked it, it did not feel as the most effective to many of them. Maybe the answer for this lies in how the Hand performed in comparison to the user’s expectations. The Hand was the most “realistic” and most “familiar” representation in terms of interaction, as more than half of the users explicitly stated. We use our hands everyday to grab objects in the physical world. These hands however, being in this case avatars of the controllers, did not behave exactly as expected. For example, the fingers were moving but the user could not fully control their movements. In addition, the Hand had a predefined animation pose, when a cube was grabbed, in order to be realistically placed in it. So when the users grabbed one it was automatically rotated to fit this pose, and that seemed to give them the impression that it reacted at times on its own. The user was holding controllers but looking at a pair of hands. These sensations possibly created a slight sense of unease, a sense that they could not fully control these virtual limbs. This lack of full control could also be the most probable explanation for the greater collision count of the Hand with the obstacles, which is not consistent with its low collision time and its greater reported sense of vulnerability. Additionally, perhaps the fact that the hand is the most complicated shape of the three, and the only one with animation, played a significant role on the results related to the collision count.

Based on the results from the analysis presented in chapter 6 and the aforementioned observations, we attempt to answer the research questions posed at the outset. (**R1**) The perceived sense of agency does not seem to be affected by the virtual representation, even though the user performance indicates that there is a significant difference between the Sphere and the other two. In terms of actual efficiency the Controller is the best option for object manipulation with accuracy, although the Hand is on par with it in respect to the performance for the selection sub-task and the whole task.

(**R2**) The sense of ownership is definitely altered depending on the virtual representation; this claim can be supported by both the qualitative and quantitative data gathered. The Hand generated the strongest perceived sense of ownership, significantly imprinted on users' answers, and suggested also by the total collision time with obstacles. The stronger sense of ownership wasn't reflected much in performance drops when threatening obstacles were present, and the reason, we believe, is the great capability of control that the handheld controllers offer, avoiding some of the problems of the finger tracking hardware, as described in section 1.2.

(**R3**) The biggest difference that the use of controllers seems to make is in the perceived sense of agency as well as the efficiency of the abstract shape of the Sphere. In the case of Argelaguet et al. [2], the sense of agency was stronger in the less realistic representations, and also they provided better performance results. In our experiments, the Sphere had the worst performance on both sub-tasks and the whole task, with the Hand performing significantly better than the Sphere for the selection and the whole task, all of which is in direct contrast with their work. Additionally, none of them stood out in terms of the sense of agency. The different nature and control mechanism of the controllers, compared to finger tracking, could explain why all provide the same sense of agency. Being able to grab an object precisely with a single press of a button and move your virtual hand accurately and without any lag, probably gives a great sense of control regardless of representation. Efficiency-wise the most promising proved to be the new condition that was introduced compared to related research, i.e. the Controller, especially when accuracy was required. For the sense of ownership, our results are in agreement with the work of others in that, the Hand was without any doubt the most effective.

7.1 Limitations and future work

One factor that may be responsible for the Sphere's underperformance, apart from what has been already discussed earlier, is its smaller form factor. Even though this was also the case for Argelaguet et al. [2], there is a possibility that when using controllers the difference in size affects the perceived sense of reach, and consequently the overall performance. A similar study to Lin et al. [34], where the effects of the virtual hand size were analyzed, could provide a better insight into this subject. An improvement to the current study would be to develop a more natural grabbing mechanism with the Hand that doesn't make automatic adjustments to objects, to avoid the sense that it has a will of its own. As a final note, this study could be extended with more representations, especially a representation containing both the Controller and the Hand. Such a representation was considered at the initial stages of the design process but we decided against it so as to not mix the basic representations in the scope of this work.

7.2 Conclusion

This thesis presents the design, analysis and results of an experiment focused on the comparative performance of different virtual hand representations for handheld controller-based immersive VR settings. None of the representations stood out in terms of the perceived sense of agency. The abstract representation of the Sphere doesn't appear to be suitable for use with controllers, since it had the worst performance and didn't generate a strong sense of ownership to most of the users. Although in previous research without controllers the Hand had the worst performance, it seems to be the better solution when using them, since the perceived sense of ownership is significantly better than the others and it performs almost as good as the Controller representation. The only occasion where this is not the case is on precise positioning tasks, where the Controller outperformed the others. The specific interaction paradigm of the handheld controllers, and how it is perceived and used by the users, merits further research to explore and produce results similarly to existing research on virtual hand representation where hand tracking and no controllers were used.

ABBREVIATIONS - ACRONYMS

HMD	Head Mounted Display
VR	Virtual Reality
3D	Three Dimensional
SoE	Sense of Embodiment
VE	Virtual Environment
RHI	Rubber Hand Illusion
ANOVA	Analysis of Variance

ANNEX I: EXPERIMENT FLOW

A.1 Preparation

1. Make sure the controllers are charged beforehand!!
2. Have water, juice and cookies available.

A.2 Welcome and introduction

1. Welcome and thank users!
   (a) "Hello and welcome! Thank you very much for coming to participate in this study. I hope it will be as interesting to you as it is to us."
2. Offer refreshments.
3. Explain the objective and flow of the experiment.
   (a) Explain briefly what is VR.
      i. "First of all let's start with some basic introduction to virtual reality called VR in short. Maybe you will know most of these information but let's refresh them in any case. The goal of VR is to make the users feel that they are part of an immersive virtual environment where ideally they cannot tell the difference between what is real and what not. The current state of technology does not offer something so groundbreaking, but at least it can make you forget for a while that you are in a virtual world. What is remarkable about this, is that it is achieved only by tricking the brain while seeing 3D and by changing what the users see depending on their movements and the position and rotation of their head. In other words, the user is being tracked in the physical space and every movement is translated to the virtual world changing what the user sees, like it would happen if the user was physically in this environment."
   (b) Explain what is the objective of the experiment.
      i. "Apart from tracking the movements of the head, in order to give the ability to the users to interact with the environment around them, the modern VR systems offer two controllers, one for each hand. These controllers are being tracked in the same way the head does, and they are visible to users when they are inside a virtual world. Most of the times they are represented as they are exactly or as human hands, and other times they are represented by some other 3D model, even abstract shapes. The goal of this experiment is to investigate how the performance, the sense of agency and the sense ownership of the virtual representation of the hands inside a virtual environment are affected, depending on the different representations they can have, while performing a simple task. In our case the virtual representations are the abstract shape of a sphere, the controllers as they are and a pair of human hands. The task is to select and place a cube in a specific place. In addition to that it is investigated also how the placement of different obstacles can affect the above. Any questions?"

(c) Explain the task they have to perform.

i. “You are asked to perform the aforementioned task of moving a cube as fast as you can for all possible combinations of the following parameters: virtual representation of hand and obstacle. For each one of them you will have to perform the same task 9 times. Also you are going to have some practice sessions and some sessions for answering questions between the representation changes. Any questions?”

(d) Let them know of the VR risks.

i. “During the experiment you may feel dizzy or uncomfortable, if that happens let us know and we will stop the experiment immediately. More information about the risks of using virtual reality equipment can be found on this document.”

ii. Hand them the “RISKS OF USING VIRTUAL REALITY EQUIPMENT” document.

(e) Explain what data will be kept.

i. “The personal data that will be kept for each user are the sex, handedness, calibrated height and hand reach when wearing the equipment and VR experience level. During the experiment the data that are being logged are chronological data of your performance and spatial data of your movements, which we are going to use later to do our analysis. All the above are going to be kept anonymously. Your name or other personal identification information is not kept with this data”

(f) Explain that photos and video will be taken.

i. “In addition to that some photos and videos are going to be taken during the experiment. You can read the details about that on the consent form I will give you now.”

4. Ask them to fill the consent form. Explain first what this is and why we use it.

(a) “In this consent form you will find the rules of agreement on how your data are going to be collected and used and you can select the options you like. We use this to have your consent on if and how your data can be used in the future.”

5. Introduce them to the VR hardware.

(a) “This is the VR equipment: A headset that is connected to the PC and two controllers. When you are ready and if you don’t have any questions we can move on and wear the VR equipment.”

A.3 Familiarization with the equipment and calibration

1. Help them wear the protective masks, then the headset and give them the controllers. Don’t forget to add the straps of their controllers on their hands. Make sure they are placed on the right spot on the floor at the center looking towards the windows.

2. Start the video recording. Make sure sound is also recorded properly.

3. Run the application.

4. Select on the application the desired gender of the user. Then ask them about their handedness.
5. After that tell them to stay straight, look forward and stay still. When this happens click the button that sets the head height.
6. While remaining straight and still ask them to raise their dominant hand forward and keep it stretched in front of them. Then click the button that sets the reach.
7. Last step before the experiment begins, is to ask them about their VR experience level in a scale from 1 to 4, expressed as it is written on the questionnaire.
8. Start the experiment by clicking the appropriate button.

A.4 The main experiment

1. Explain to the users the flow of the experiment. Their main objective is to move the cubes that appear on the table inside a hole placed on the side of the table. Ask them to do the task without moving in space, e.g. by walking. Each time to indicate that they are ready they have to press the green button, and when that happens only one cube is going to appear on the table. By reaching in the cube, touching it and after it gets highlighted, they must press the trigger button to grab the cube. While grabbing the cube they must place it inside the hole and it will fall down. They repeat this task as many times as needed, but while they are doing that they will notice that some obstacles are going to appear and their virtual representation of their hand/controller will change. At the beginning of each different representation of their hand/controller they will have some practice tries in order to get used to this representation.
2. At the end of each session they will have to answer some questions (the respective ones for the current representation) without removing the HDM and leaving the virtual environment.
3. After all questions have been answered the experiment continues to the next session by clicking the continue button until all the tasks of all representations have been completed.

A.5 Conclusion

1. At the end of the experiment close the application.
2. Then help the users take off the HMD and get the controllers.
3. Fill the rest of the questions, the general ones, of the questionnaire to complete it (don't forget to fill the user id in the form).
4. Thank the users once again and wrap things up.
5. CHARGE the controllers!!

ANNEX II: QUESTIONNAIRE

VR hands representation questionnaire

* Required

1. C1 - Gender *

   Mark only one oval.

   - Woman
   - Man
   - Other

2. C2 - Dominant hand *

   Mark only one oval.

   - Left
   - Right

3. C3 - Height *

   ____

4. C4 - Reach *

   ____

5. C5 - Experience in VR *

   Mark only one oval.

   - None (0 times)
   - Little (1-3 times)
   - Moderate (4 - 10 times)
   - Considerable experience (more than 10 times)

Abstract representation

Figure B.1: Page 1 of the questionnaire.

6. Please state your agreement with the following statements

Mark only one oval per row.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Fully agree	N/A
A1 - I felt that selecting the cube after hitting the button was easy.						
A2 - I felt that placing the cube I had grabbed in the hole was easy.						
A3 - I felt like I had control over my actions with the sphere.						
O1 - I felt as if the sphere was an extension of my own body.						
O2 - I thought that the sphere could be harmed by the virtual obstacle.						
O3 - I felt that my physical body was endangered during the experiment.						
O4a - I tried to avoid the electricity obstacle while performing the task.						
O4b - I tried to avoid the brick obstacle while performing the task.						
O4c - I tried to avoid the barbed wire obstacle while performing the task.						
O5 - I felt a tingling sensation in my physical body when the sphere approached or touched an obstacle.						
O6 - I felt that the sphere was able to pass through the virtual obstacles.						

7. Which obstacle was the most difficult with the sphere?

Check all that apply.

- [ ] Electricity
- [ ] Brick
- [ ] Barbed wire

8. Notes

Controller representation

Figure B.2: Page 2 of the questionnaire.

9. Please state your agreement with the following statements

Mark only one oval per row.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Fully agree	N/A
A1 - Selecting the cube after hitting the button was easy.						
A2 - Placing the cube I had grabbed in the hole was easy.						
A3 - I felt like I had control over my actions with the controller.						
O1 - I felt as if the controller was an extension of my own body.						
O2 - I thought that the controller could be harmed by the virtual obstacle.						
O3 - I felt that my physical body was endangered during the experiment.						
O4a - I tried to avoid the electricity obstacle while performing the task.						
O4b - I tried to avoid the brick obstacle while performing the task.						
O4c - I tried to avoid the barbed wire obstacle while performing the task?						
O5 - I felt a tingling sensation in my physical body when the controller approached or touched an obstacle.						
O6 - I felt that the controller was able to pass through the virtual obstacles.						

10. Which obstacle was the most difficult with the controller?

Check all that apply.

- [ ] Electricity
- [ ] Brick
- [ ] Barbed wire

11. Notes

Hand representation

Figure B.3: Page 3 of the questionnaire.

12. Please state your agreement with the following statements

Mark only one oval per row.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Fully agree	N/A
A1 - Selecting the cube after hitting the button was easy.						
A2 - Placing the cube I had grabbed in the hole was easy.						
A3 - I felt like I had control over my actions with the hand.						
O1 - I felt as if the hand was an extension of my own body.						
O2 - I thought that the hand could be harmed by the virtual obstacle.						
O3 - I felt that my physical body was endangered during the experiment.						
O4a - I tried to avoid the electricity obstacle while performing the task.						
O4b - I tried to avoid the brick obstacle while performing the task.						
O4c - I tried to avoid the barbed wire obstacle while performing the task?						
O5 - I felt a tingling sensation in my physical body when the hand approached or touched an obstacle.						
O6 - I felt that the hand was able to pass through the virtual obstacles.						

13. Which obstacle was the most difficult with the hand?

Check all that apply.

- [ ] Electricity
- [ ] Brick
- [ ] Barbed wire

14. Notes

General questions

Figure B.4: Page 4 of the questionnaire.

15. C1 - What would you consider as the main positive aspects of each representation?

16. C2 - Which representation/s was your favourite?

    Check all that apply.

    - [ ] Sphere
    - [ ] Controller
    - [ ] Hand

17. C2b - Why?

18. C3 - Which representation/s was the most effective?

    Check all that apply.

    - [ ] Sphere
    - [ ] Controller
    - [ ] Hand

19. C3b - Why?

20. C4 - Which representation(s) felt more vulnerable to the threats of the obstacles?

    Check all that apply.

    - [ ] Sphere
    - [ ] Controller
    - [ ] Hand

Figure B.5: Page 5 of the questionnaire.

21. C5 - What were the main problems you faced with each representation?

22. C6 - Did you experience motion sickness or any type of discomfort when you performed the experiment?

23. User ID *

Figure B.6: Page 6 of the questionnaire.

ANNEX III: CONSENT FORM

User ID:

GDPR-COMPLIANT CONSENT FORM (ADULT)

Consent Form: VR Hands representation experiment

PARTICIPANT NAME:

PARTICIPANT EMAIL ADDRESS:

Please read and tick each of the square boxes to indicate your agreement:

☐ I have understood the project information that were provided to me and have had the opportunity to ask questions about the research.

☐ I understand my participation is voluntary and I may withdraw at any time without consequence.

☐ I understand my data will be retained in secure storage for use in future academic research and publicity.

☐ I have read and understood the "RISKS OF USING VIRTUAL REALITY EQUIPMENT" info sheet that was provided to me and have had the opportunity to ask questions about it.

I give consent for my data (including photos, video or other visual records) to be used in research, presentations, publications and other media and publicity arising from this research, both print and online.

I agree to the following condition of anonymity - **TICK ONLY ONE OF THE CIRCLES BELOW**:

○ **Option 1**: I agree that my data are used even though I might be recognisable in photo, video and other visual and audio records.

○ **Option 2**: I agree for my data to be used under condition of anonymity. I understand that my identity will be altered/obscured in photo, video and other visual and audio records.

○ **Option 3**: I ask to be consulted further before my data are used in any way in this research.

DATE: /09/19

RESEARCHER SIGNATURE

PARTICIPANT SIGNATURE

Lougiakis Christos

HELLENIC REPUBLIC
National and Kapodistrian University of Athens

DEPARTMENT OF INFORMATICS & TELECOMMUNICATIONS

Figure C.1: Form that was filled by the participants to express their privacy preferences.

ANNEX IV: RISKS OF VR

RISKS OF USING VIRTUAL REALITY EQUIPMENT

This experiment will involve wearing and operating the HTC Vive, a virtual reality (VR) headset. Generally, the use of a VR headset has been associated with known risks, including emotional or mental distress, physical discomfort, and the potential for physical harm or injury. The following information will explain these risks.

Wearing a VR headset detaches one's senses from the physical world, both visually and auditorily, making it possible for a user to:

- become disoriented or nauseous
- accidentally fall
- trip over a cable
- come into contact with a nearby person or object
- feel anxious or nervous

Additionally, using a VR headset may present a risk for individuals with serious pre-existing medical conditions, psychiatric conditions, or are pregnant or elderly. Use of VR headsets can trigger epileptic seizures, fainting, or severe dizziness, even in people who have no history of such conditions.

You may withdraw from the experience at any time. To do so, you may remove the VR headset at any time or ask for assistance. All minors must have a guardian's signature on a consent form and be accompanied by an adult at all times.

Keep in mind the following:

- Follow the instructions on safe equipment handling.
- Ask for clarifying questions if any instructions are unclear.
- Communicate any potentially negative reactions to experiment leaders.

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Figure D.1: Document that informed the participants about the risks of using VR equipment.

ANNEX V: OBSERVATION SHEET

User ID: Observer:

Facial expressions, emotional state	Hand movement	Body movement	User Comments	Observer Comments

Notes: Add to each note when it happened by using the following format = XY: “note” where X = {A, C, H} for abstract, controller and hand representations, Y = {N, B, W, E} for none, brick, wire, electricity obstacles respectively. For example, HB: the user laughed a lot when the cube dropped. In that way we can track when it happened and search for more information on the video data.

Figure E.1: Observational notes were filled in this sheet by one of the experimenters.

ANNEX VI: ADDITIONAL GRAPHS

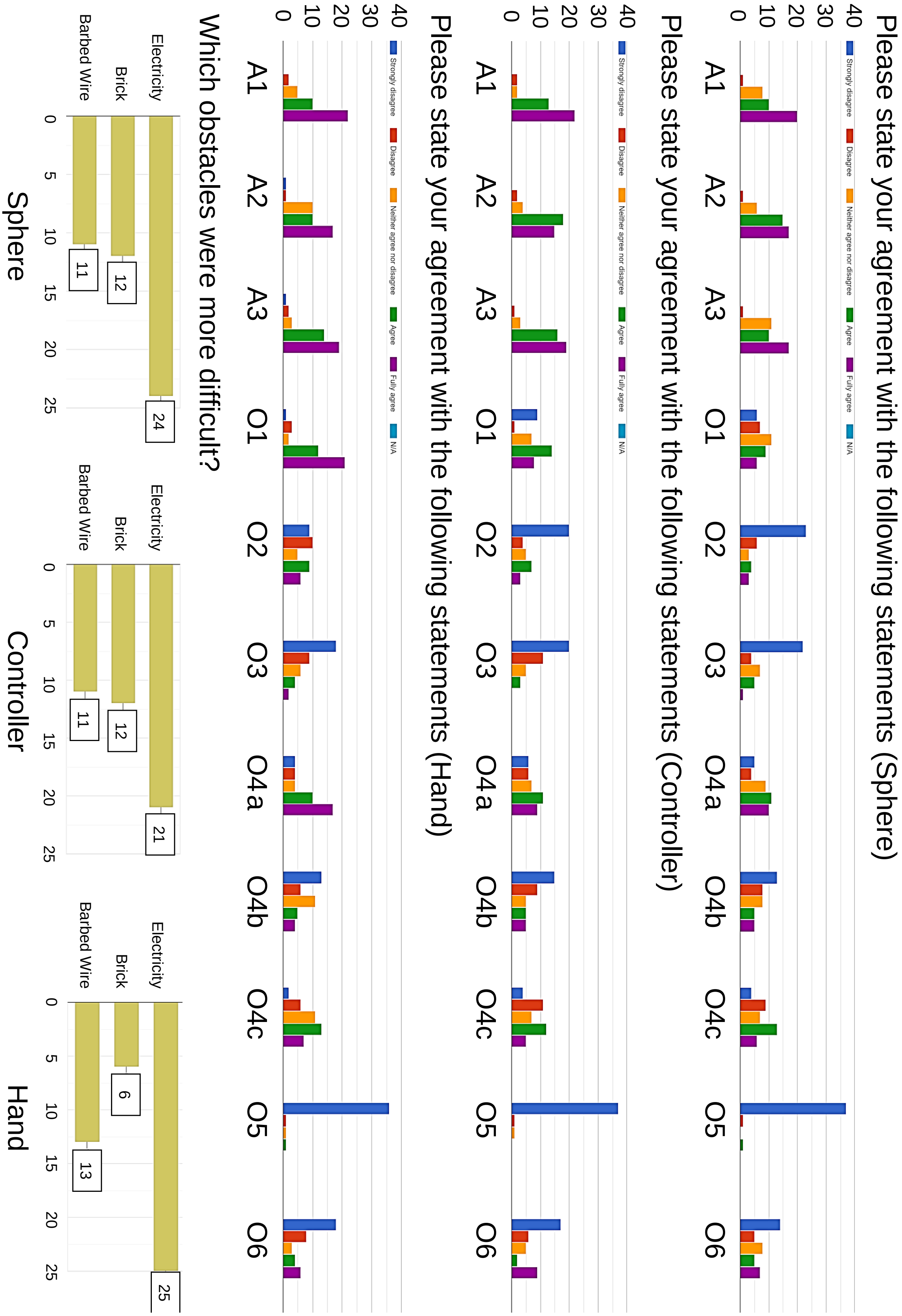

Figure F.1: Graphs containing the complete responses by the participants.

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