INTERACTION BETWEEN CYBERBODIES AND CYBERSPACE:
THE EFFECT OF AVATAR ABILITIES ON AFFORDANCE PERCEPTION IN VIRTUAL REALITY

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INTERACTION BETWEEN CYBERBODIES AND CYBERSPACE: THE EFFECT OF AVATAR ABILITIES ON AFFORDANCE PERCEPTION IN VIRTUAL REALITY

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DECLARATION OF ORIGINALITY

I, Naciye Tuğçe Akkoç, certify that

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ABSTRACT

Interaction Between Cyberbodies and Cyberspace:

The Effect of Avatar Abilities on Affordance Perception in Virtual Reality

The possible actions that we can perform with an object are determined by the capabilities of the human body. Then, if we could change the body, would it create new action possibilities for us? In this study, we examined the effect of altered abilities on the perception of potential actions for a given object — affordance perception. Objects with handles are known to potentiate the afforded action. Participants tend to respond faster when the handle is on the same side as the responding hand in a bimanual speed response task (Tucker & Ellis, 1986). In the first experiment, we replicated this effect in a Virtual Reality (VR) setting by manipulating the handle orientation and distance of the object with an intermediate level. In the second experiment, we showed that this effect was influenced by the avatar (a 3D representation of the body and its movements in VR) which was manipulated by two different hand types (able hand, i.e., able to grasp vs. restricted hand, i.e., not able to grasp). The division of the data collection into *action planning* and *action execution* created a valuable insight. Specifically, during action planning, the affordance effect was significantly stronger for the restricted hand. One explanation for this is that fewer action possibilities provided the restricted hand an advantage in processing time. During action execution, on the other hand, the affordance effect was reversed. This reversed effect is rarely found in the literature. In this case, it may be due to the ongoing action planning during action execution. The results were examined from a multidisciplinary perspective, together with a discussion on the implications for VR applications.

ÖZET

Siber Bedenlerin Siber Ortamlarla Etkileşimi:

Sanal Gerçeklikte Avatar Becerilerinin Sağlarlık Algısı Üzerindeki Etkisi

Bir objeyle nasıl etkileşime geçeceğimizi insan bedeninin sınırları belirlemektedir. Peki bedenimizi ve bununla beraber sahip olduğumuz becerileri kolayca değiştirebilseydik bu bize yeni aksiyon olasılıkları sağlar mıydı? Bu çalışmada, bedeni manipüle etmenin çevremizdeki potansiyel aksiyonları algılamamız (sağlarlık algısı) üzerindeki etkisi incelenmiştir. Birinci deneyde, hipoteze uygun şekilde katılımcıların kulp yönü ile tepki verdikleri el aynı tarafta olduğunda daha hızlı tepki verdikleri görülmüştür (Tucker & Ellis, 1986). Aynı zamanda uyarıcının katılımcıya olan mesafesi ara bir seviye eklenerek incelenmiş ve tepki süresi üzerinde anlamlı bir etkisi olduğu bulunmuştur. Bu bize sağlarlık etkisinin Sanal Gerçeklik (SG) ortamında ölçümlenebileceğini göstermektedir. İkinci deneyde avatar (SG içerisinde üç boyutlu beden gösterimi) becerilerinin sağlarlık algısını etkilediği bulunmuştur. Avatar becerileri, iki farklı el tipi kullanılarak manipüle edilmiştir (normal eller: kavrama becerisine sahip, kapsül şeklindeki eller: kavrama becerisinden yoksun). Veri toplama aşamasının, aksiyonun planlanması ve gerçekleştirilmesi olarak iki aşamaya bölünmesi değerli çıktılar sağlamıştır. Planlama aşamasında kısıtlanmış ellerde daha güçlü bir sağlarlık etkisi bulunmuştur. Bunun için olası bir açıklama daha az sayıda potansiyel aksiyonun bulunmasının avantaj sağlaması olabilir. Aksiyonun gerçekleştiği sırada ise sağlarlık etkisinin tersine döndüğü bulunmuştur. Kulp yönü etkisinin ters yönde olması literatürde çok nadir rastlanan bir durumdur. Bu durum da hareket sırasında planlamanın devam etmesi ile açıklanabilir. Tüm sonuçlar multidisipliner bir yaklaşım ile incelenmiş ve de çalışmanın sonuçları doğrultusunda SG alanındaki uygulamalarla ilgili olası çıkarımlara yer verilmiştir.

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DEDICATION

To my mom, who called me "the little scientist" when I was a kid

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CHAPTER 1

INTRODUCTION

When we see a mug, we do not consciously think about how to grab it. It happens so naturally that we are not even aware of how that process works. Studies show that there is a direct link between perception and action (Riddoch, Edwards, Humphreys, West, & Heafield, 1998; Rumiati & Humphreys, 1998). Gibson (1966) coined the term affordance, which became a commonly used concept in explaining the interaction between an agent and its environment. Although in the original definition, Gibson defined affordance as what the environment offers to the agent, he also emphasized that the term refers to both the environment and the agent. In this framework, the same object can afford different actions for different agents. A bottle, for example, is graspable for a person, rather climbable for an ant. It is the relationship between the agent and the environment that determines the possible ways of interaction.

Visual features like size, shape, and texture provide critical cues about how to act upon objects. Color, for example, can give a clue about temperature so that the agent can decide whether an object is safely touchable or not. Although in experiments, objects are usually presented in isolation, in real life, they are part of a context. A mug that is by nature graspable, for example, when behind a glass panel becomes unreachable, therefore not graspable, even though the visual information coming from the object is the same. Distance between the object and the agent is another factor that changes the degree to which objects are interactable to agents (Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010).

Although the claim that affordance is formed between the agent and the environment is a well-established one, the role of the agent has mainly been overlooked in the literature. That is to say, affordances have often been taken as being identical for all agents in the environment. Each individual is unique, though, and even the same individual's capabilities may change through time, either temporarily or permanently (Bajcsy, Aloimonos, & Tsotsos, 2018). These changes might also take place in the agents' perceptions, as well as in their physical bodies. An obvious example is a change in the body form during the developmental transformations. As a child gets taller and stronger over time, a chair that used to be higher than his height becomes now 'reach-able' and 'lift-able'. A permanent change in the body might also take place, for instance, after losing a limb in an accident. In these kinds of circumstances, thanks to the brain plasticity, people can adapt to using prosthetics as the brain can modify itself by remapping the representations of the body parts (Ramachandran & Blakeslee, 1998). There are also temporary states that change the abilities of an agent like tiredness, sleepiness, or being under the influence of psychoactive substances. Measuring the effects of these kinds of changes on affordance perception requires controlled manipulation of the body and its capabilities, which is a highly challenging task in experimental design.

Tool-use literature presents examples, where the capabilities of a person can be altered through the use of tools. In Cardinali et al.'s study (2009), for example, even though the body form has been the same, bodily perception was found to be changed via tool use. In another study, it has also been shown that human participants perceive tools as extensions of their own bodies ((Sposito, Bolognini, Vallar, & Maravita, 2012), which in turn changes how they perceive their environment (Berti & Frassinetti, 2000; Farnè, Iriki, & Làdavas, 2005; Witt, Proffitt, & Epstein, 2005; Canzoneri et al., 2013).

VR allows us to manipulate both object properties and agent characteristics while studying the interaction between agents and their environments. An environment could potentially be designed in infinitely many different ways. In a VR setting, the experimenter has precise control over the manipulation of the responses of an object to physical forces, as well as the object's shape, color, size, texture, location, or movement. Since the VR headset completely blocks the visual image coming from the physical world in VR experiment, potential confounding factors such as lighting, context, distances in proportion to the subject's body, and the angle where the participant sees the object can also be carefully controlled. Moreover, the form and capabilities of an agent can be manipulated via an avatar, which is a virtual representation of the body and its movements in a virtual environment. Avatars provide a sense of presence and agency in virtual environments, where the agent can interact with objects by using, for instance, virtual hands or controllers.

Cisek (1999) criticized the field of psychology by claiming that psychologists study human as a segregated organism from its environment and address different segments of the behavior (i.e., perception, action, and cognition) in isolation. Cognitive science studies provide a rather multidisciplinary perspective to the areas of research that are tackled by different fields of studies independently. The purpose of this study is to examine interactive behavior by using the methods of experimental psychology. The potential implications of the results for the VR applications are also discussed. First, I will provide a scientific background for the flexibility of our perception of the body and its capabilities and how that flexibility affects the way we perceive our environment within the context of affordances. I will then present a reliable way of measuring affordances and using VR for this purpose as a research tool.

1.1 Body perception is flexible

Perception of our bodies and their capabilities is flexible and can be altered. Lanier (2006) proposed the concept of homuncular flexibility, which suggests that people can learn how to control novel bodies that are different from their own. This term has originated from Penfield and Boldrey's (1937) homunculus concept, which is a way of presenting the human body with the parts proportional to their representations in the brain. Here, the body is represented based on motor or sensory functions of each body part; for example, hands and lips that occupy more space on the cortex are also drawn as bigger on the homunculus. This map of our body in our brain is known to be not constant but rather flexible and open to change.

The Rubber Hand Illusion (Botvinick and Cohen, 1998) is a phenomenon, where people feel like a rubber hand is their own when they observe it is stroked in the same way as their hidden hand. Slater, Pérez-Marcos, Ehrsson, & Sanchez-Vives, 2008) replicated this effect by using a virtual hand. In both studies, researchers measured the proprioceptive drift by asking participants to close their eyes and nail the spot where they thought their hand was located. Proprioceptive drift was then given by the deviation of the reported position from the original spot. Their results demonstrated that the drift was towards the virtual hand, in other words, when there was a mismatch between the position of the real hand and the virtual hand, participants relied more on the visual information than the proprioceptive one, which is, in this case, was the sensation of the position of the real hand. Recently Aldhous, Hetherington, and Turner (2017) have also replicated the rubber hand illusion by using a VR headset, where they demonstrated a significant proprioceptive drift towards the virtual hand. Overall, these studies showed that it is possible to feel the ownership of a virtual hand as long as the visuo-tactile stimulation is provided in synchrony with the feedback on the hidden real hand.

There is a rich body of literature examining the embodiment of avatars. Synchronous sensory feedback can create a sense of embodiment for the person who is immersed in a virtual environment. With the use of visuo-tactile and/or sensory-motor feedback, people can inhabit avatars that are different from their own body. The embodiment can occur with the avatars of different age (Banakou, Groten, & Slater, 2013), gender (Fizek & Wasilewska, 2011), race (Salmanowitz, 2018), with disproportionate body parts (Kilteni, Groten, & Slater, 2012) or even in the form of different species (Ahn et al., 2016), or abstract representations (Roth et al., 2016).

Avatars in immersive virtual environments provide a tool for manipulating the body and its capabilities. Lanier (2016) started exploring the limits of homuncular flexibility by testing awkward avatars in a series of informal studies. For more than 10 years, they prototyped and tested avatars that are radically different from human body form but still controllable. For instance, they showed that it is possible to get used to the control of a lobster body with eight arms by mapping inputs like wrist rotation onto the movement of extra limbs (Won, Bailenson, Lee, & Lanier, 2015). Day et al. (2019) created avatars with extended arms and gave participants a reaching task. They found that calibration to an avatar with long arms is possible as long as participants receive feedback on their actions. Also, they emphasized the difference between adaptation and calibration. Whereas the former occurs in a longer period of time, the latter occurs rather quickly. In a similar context, Won et al. (2015) also manipulated avatar capabilities. In this study, they switched the mapping of arm and leg movements of avatars in VR. As participants moved their arms, for example, their avatar’s legs moved instead. They showed that the participants could rapidly adapt to the control of their avatar. In a separate experiment, they also demonstrated that participants learned to control an avatar with three arms and performed better than the ones who had avatars with two arms.

The evidence for the manipulation of body perception is not limited to VR. Tool-use studies provide real-life examples of altered body perception. Just holding a stick can have a dramatic effect on body perception. It remaps our body form and the environment around us and the interactivity in between. It has been shown that just 15 minutes of tool-use is enough for people to estimate their arm length longer (Sposito et al., 2012). This provides evidence that humans do not perceive their bodies in stable metrics. Instead, our body perception is dynamic and changes through action. Cardinalli and her colleagues (2009) showed that after using a mechanical grabber, the kinematics of normal hand grasping changes. They also showed the after-effects of tool-use can be generalized to pointing, which suggests that what is modified is not just one specific action that is learned through the experiment but the somatosensory body representation.

Both VR studies and tool-use studies provide evidence for the flexibility of body perception. It is possible to control new bodies through the manipulation of sensory feedback. As sensory feedback changes, our perception of ourselves and the world around us changes. Perception of the body and the environment is interdependent (Harris et al., 2015). In the next section, we will present evidence about how the flexibility of body perception and its capabilities affect our perception of the environment.

1.2 Altered abilities, altered perception

Our actual or even perceived abilities play an important role in our perception of the environment. In a study older, heavier or shorter people, and women overestimated the steepness of a staircase (Eves, 2013). Fatigue or being low on physical fitness also altered perception — hills appeared to be steeper to the participants. Also, wearing a heavy backpack created the same effect (Bhalla & Proffitt, 1999). In a similar study, researchers manipulated the jumping ability of the participants by putting ankle weights on them. With the restricted jumping abilities, participants perceived gaps wider (Lessard, Linkenauger, & Proffitt, 2009).

With tool-use people not only start to perceive their arms narrower and longer based on the tool they used during experiments but that their peripersonal space perception was found to be extended after tool-use (Canzoneri et al., 2013). However, the active use of the tool is necessary for these effects to appear. Passive exposure to the same tools was found to create no such effects (Farnè et al., 2005). Along with active use, the functional relevance of the tool is also necessary for these effects to appear. For example, when a shorter tool was used actively for the same amount of time, no functional extension of reachable space was found (Bourgeois, Farnè, & Coello, 2014). Therefore, the embodiment of the tool not only affects how people perceive their bodies but also how they perceive the environment.

In a study (Witt et al., 2005), researchers manipulated reachability by giving a reaching task to individual participants with or without a tool, then measured their depth perception. They found that tool use has a significant effect on depth perception but only when the participant intends to reach. This gives us a clue that our perception of the environment is shaped by our intentions and perceived capabilities.

Through interactions with the environment, the brain constantly modifies itself by updating the neural representation of the body parts and their positions (Sirigu, Grafman, Bressler, & Sunderland, 1991). Researchers trained macaque monkeys to use a tool to reach distal objects and recorded brain activity (Iriki, Tanaka, & Iwamura, 1996). They showed that not only the neural correlates of the hand were modified by tool-use but also that the visual field of the monkeys was altered in a way to cover the new larger accessible area.

Both behavioral (Berti & Frassinetti, 2000; Witt et al., 2005) and neuroscientific data (Iriki et al., 1996) supports the perceptual effects of tool-use in peripersonal space, this effect seems to go beyond changes in visual perception. Researchers tested the changes in the auditory peripersonal space by giving a walking stick (a blind man's cane), to participants (Serino, Bassolino, Farnè, & Ladavas, 2007). They found that with tool-use their peri-hand space, which was limited around their hand before they used the walking stick, was extended. Even though this effect contracted back to normal after a resting period for sighted subjects, it was shown that the extension of the auditory peripersonal space of blind subjects endured. This is evidence that long-term use of tools may create permanent effects. Compared to tool-use effects, as mentioned in the previous section, avatars provide a more direct way to manipulate body perception.

As mentioned in the previous section, being in a new avatar body may make objects look closer or farther away, bigger or smaller. As hypothesized in this thesis, the embodiment of avatars can also affect the way we see and react to the world around us. In a study (Banakou et al., 2013), adults inhabiting 4-year-old avatar bodies in VR felt strong body ownership and also overestimated the size of objects. This provides evidence consistent with our hypothesis that changes in our bodies affect our perception of our surroundings. Testing this hypothesis requires a reliable measurement of affordance perception. In the next section, a background for the selected methodology will be provided.

1.3 How to measure affordance perception

Most studies mentioned above rely on verbal responses of the participants or they decide to execute an action after making a judgment (Banakou et al., 2013; Lessard et al., 2009; Witt et al., 2005). In these studies, participants are making conscious predictions which may be affected by other higher processes. In order to find a better way to measure affordance perception, we give it an operational definition: Affordance perception as used in this thesis means perceiving the action possibilities for a given object. It lies in the interaction between us and the environment. Within the scope of this thesis, it lies in the interaction between the avatar hands and the virtual object.

In a review of the affordance literature (Jamone et al., 2018), researchers provided three conclusive insights from a multidisciplinary perspective. These were "(A) perception of action-related object properties is fast; (B) perception and action are tightly linked and share common representations; (C) object recognition and semantic reasoning are not required for affordance perception." (p. 7). If the process of action related perception is fast, then fast-paced measurement techniques are needed to catch it. Within the context of perceptual-motor behavior, the fastest responses are also thought to be the most accurate (Fitts and Seeger, 1953).

Affordance perception can be measured with a fast-paced response task by using the stimulus-response compatibility paradigm, where the compatibility between the stimulus and given response creates a measurable effect on the speed and/or accuracy of the response (Fitts and Seeger, 1953). Measuring the speed of response allows us to get an understanding of our mental processes and their order. With well-designed behavioral studies, it is even possible to investigate subprocesses that are either serial or parallel.

In the stimulus-response compatibility paradigm, people respond faster and more accurately when the required response is compatible with the stimulus. This allows us to give participants a task that is not directly linked to what is intended to be measured in order to see the potentially subconscious effects of the stimulus on response time. For example, a circle can be presented on the right or the left side of the screen while a participant is responding according to the color of the stimulus. A participant may be responding with the right hand if the stimulus is red and responding with the left hand if the stimulus blue regardless of its location. However, the location of the stimulus affects response time. This is a classic example of the Simon Effect (Simon, 1969) that is based on the spatial relationship between the location of the stimulus and the response. When a part of the object, which is a signifier for action, is used as a stimulus then the compatibility effect is called the affordance effect (Ambrosecchia, Marino, Gawryszewski, & Riggio, 2015).

Instead of the color or shape of an object, Tucker and Ellis (1998) used object inversion as a criterion for the responding hand selection. For example, the subjects responded with the right hand if the object was upright and responded with the left hand if it was inverted. In contrast with a color based task, deciding whether the object is inverted or not requires the processing of the form of the object which carries information about potential actions. For example, handled objects like a mug or a frying pan automatically potentiate a reach-and-grasp response towards their handles (Yamani, Ariga, & Yamada, 2016). In a bimanual response task, the left-hand responses are faster when the handle is on the left side and right responses are faster when the handle is on the right side.

Overall, this methodology allows measuring the affordance effect while participants are engaged in a task. Most importantly, they are unaware of the main purpose of the experiment, unlike answering questions about affordances explicitly. In the methodology section, the implementation of the stimulus-response compatibility paradigm in a VR setting will be presented. Before that, in the following section, VR as a research tool to study interactive behavior will be introduced.

1.4 Virtual Reality as a research tool

This thesis was titled as ‘The Interaction Between Cyberspace[1] and Cyberbodies[2]’ because it intends to investigate interactive behavior by taking both the agent and the environment into consideration. The affordance is the interaction between these two classes of entities.

Affordances are not only invariant properties of the environment as Turvey (1992) suggested, but emerge from the interaction between agent and environment. However, it is not easy to manipulate the agent component of the interaction in perception studies. Perhaps, for this reason, the literature on affordance is heavily based on the studies where the agent component is stable and the properties of the environment and/or objects have been altered in various ways. VR technology allows us to manipulate the body component through the embodiment of avatars, which are experienced as the subject’s own body.

For visual perception studies, VR provides an invaluable tool to design and conduct experiments where we can precisely manipulate potential factors. Compared to traditional methods like using a screen for stimulus presentation and a keyboard for responses, interactions in VR are more natural. Its medium is more likely to become invisible. That is, the participants are more directly immersed within it. Virtual objects can be shown in a 3D environment with realistic textures and lighting where the participant can directly respond with bare hands. This opens up new possibilities for the examination of topics in the field of action and perception.

As well as realistic environments and bodies that can replace and advance lab studies, VR also provides new opportunities where properties of the environment or the abilities of the agent can be manipulated in ways that are not possible in real life.

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[1] Cyberspace is herein defined as the virtual objects that make up the virtual environment. The space itself can be considered an object.

[2] Cyberbodies herein refers to avatars

Even though the virtual objects resemble real-world objects, the way we interact with them can be quite different. VR users can interact with objects out of arm's reach if a programmer has thus designed the environment. Users can inherit magical abilities to pull objects to their hands (in a fashion similar to using the force in the Star Wars franchise) or maybe have arms that can extend — the go-go technique from Bowman, Kruijff, LaViola, & Poupyrev (2004). Enhancing or restricting the abilities of an agent is a powerful technique to understand the limits of human perception.

Ecological validity is a concern for all experiments conducted in a lab environment. VR perception studies raise the question of whether they are generalizable to real-world conditions. However, it has been shown that the perceptual fidelity of the virtual environments can be similar to the real world conditions if realistically designed and scaled. A group of researchers (Geuss, Stefanucci, Creem-Regehr, & William, 2010) measured perceived affordances in the matched virtual and real environments. In order to match the environments, they created a 3D virtual replica of the experimental setting. They measured perceived affordances with judgments of distance and size. They found that affordance judgments were not significantly different for the virtual environment and the real world. Regia-Corte, Marchal, Cirio, and Lécuyer (2012) also found similar results showing that the perception of affordances in virtual environments is possible and comparable to real-world affordances.

In the introduction, we covered the topics of the flexibility of body perception, its effects on affordance perception, the methodology to measure it, and VR as a tool to measure these variables and their effects. In the next chapter, we will present how we accomplished this.

CHAPTER 2

GENERAL METHODOLOGY

2.1 Participants

Sample size for the first and second experiments were 16 and 32, respectively. Whereas in the first experiment, participants were mostly affiliated with Istanbul Technical University, recruited via convenient sampling on a voluntary basis, in the second experiment, the sample was mainly composed of Bogazici University undergraduate students who received 1.5 extra course credits where possible. All observers had normal or corrected-to-normal vision (the VR headset has the required space inside to be worn with eyeglasses) and were naïve to the purpose of the experiments except for the supervisor. The study was compliant with the university research ethics requirements and approved by the Boğaziçi University Ethics Coordinating Committee (see Appendix A). Confidentiality and anonymity were ensured by saving data using subject ID’s. Since all participants were native speakers of Turkish, the consent form, as well as the experimental instructions were given in Turkish.

2.2 Stimuli and apparatus

In both experiments, stimuli were presented using an Acer (AH101-D8EY) Windows Mixed Reality Headset (Model VD.R05AP.002). The VR Headset was connected to an HP OMEN Laptop (Intel Core i7, 7820HK, 32GB, GTX 1080, 17.3") via an HDMI 1.4/2.0 and a USB 3.0 cable. A Sony 310AP Wired Headphones, adjustable to the head size was connected to the VR headset for auditory feedback. A Leap Motion hand tracking device was connected to the same computer and attached to the front part of the VR headset for the first experiment and fixated on a metal stick at the edge of the table for the second experiment. For the second experiment, a second keyboard (HP USB Slim KB, Wired QWERTY Keyboard) was connected to the same computer.

For both experiments, the stimuli and the virtual environment were coded in Unity 2018 3d Game Engine with C# as the programming language. The frying pan for the second experiment was designed in Autodesk Maya 2018. All other 3D models were downloaded from the Unity Asset Store.

2.3 Procedure

Participants were given an informed consent form prior to the experiment. Those who read and accepted to take part in the study were then asked some questions from a short questionnaire, where they were expected to provide information about their (i) demographic background, (ii) handedness, (iii) alcohol or substance consumption in the last 12 hours, (iv) night sleep prior to the day of testing, and (v) previous VR experiences. Regardless of their familiarity with the VR and hand tracking technology, participants were given general information about the VR goggles and the hand tracking device. Before the experiment, they were asked to pull up their sleeves and take off their metal accessories (i.e., watch, ring, bracelet) since reflective materials affect hand tracking. They were also instructed to keep their hands in the tracking area during the testing.

In the first experiment, in a virtual room environment, participants were presented with a mug on a table that appeared either in an upright or upside down orientation across different trials. The handle orientation was also randomized so that it was either on the left or right-hand side of the mug. The task of the participants was to report whether the mug is upright or upside down as quickly as possible by rotating their wrist and making a grasp action using their left (i.e., for upside down decisions) or right (i.e., for upright decisions) hands. Thus, in different trials, the hand with which participants reacted could either match with the handle orientation or not. This compatibility between the reacted hand and the handle orientation was the first independent variable. In blocked trials, the distance between the participant and the mug was also manipulated - as a second independent variable - such that the mug could appear in 3 different locations—at a near, middle or far distance from the participant. The response times of the participants were recorded from the moment when the stimulus had first appeared until the grasping response was finalized.

In the second experiment, the mug stimulus was replaced by a frying pan, the position of which was fixed at a single coordinate (the middle position used in the first experiment). In two different conditions of the independent variable, the avatar hand was either a realistic hand with both grasping and pushing abilities or a capsule-like restricted hand, which lacked any grasping abilities. Response times were recorded using two indices, namely the lift-off and movement times. Lift-off time was the time it took for participants to lift their hands off a rest-state-key on a keyboard following the presentation of the stimulus on the screen Movement time, on the other hand, was recorded from the lift-off time until the hand model contacted the invisible, virtual object detection box on the target location. Recording the lift-off time, as well as the movement time increased the reliability of the reaction time measure.

2.4 Data analysis

After each session of the experiments, a text output file was automatically created in comma-separated values format. Raw data were combined and processed in Jamovi (2019), where outlier detection and individual mean calculations for each condition were performed using the Rj Editor module (R Core Team, 2018). Data points, which are above or below two standard deviations from the individual means were discarded. Only the trials where participants responded correctly were taken into the reaction time analyses. In the first experiment, data were analyzed using a 2 (Handle Orientation: Compatible and Incompatible) x 3 (Distance: Near, Middle, and Far) repeated measures factorial ANOVA, using response time measure as the dependent variable. Because the two dependent variables, lift-off- versus movement time, were highly correlated, for the second experiment, two dependent variables (lift-off time and movement time) were analyzed over two separate 2 (Handle Orientation - Reacted Hand: Compatible and Incompatible) x 2 (Hand Type: Able Hand, Restricted Hand) repeated measures ANOVA rather than a single MANOVA analysis.

2.5 Methodological suggestions

Leap Motion provides a fluent experience where people can interact with the virtual objects directly with their bare hands, but the tracking is not perfect. The common practice is to attach the device in front of the head-mounted display because this provides more mobility and better tracking. In our setup, this arrangement worked well with the first experiment since the participant's head and hands were stable during the experiment. For the second experiment, on the other hand, participants performed a reaching behavior, which rather required the Leap Motion device to be stable and completely independent of the head movements. Because the source codes provided by Leap Motion update hand positions relative to the direction of the head, we had to find our own workaround to dissociate hand movements from the head movements. Our solution was to add an extra object in Unity and set it as a reference point for the movement of hand models relative to the position of the actual device in the real world. Thus, possible asymmetries that could be caused by slight head movements were avoided and the movement trajectory was standardized across participants.

A study reported the inconsistent sampling rate of the Leap Motion device and the problems of positional tracking when there is movement involved (Guna, Jakus, Pogacnik, Tomažic, & Sodnik, 2014). Therefore, for reaction time and position measures, it might be better to use physical buttons or extra measurement devices. Despite these limitations, Leap Motion can still be of valuable use in academic research to understand hand-object interaction in virtual environments. On the other hand, using standard VR controllers are more similar to tool-use experience and are not as natural. Day et al. (2019) compared reaching in the real world and VR. He found that participants made more errors while reaching in the real world. The estimated distance was found to be more accurate for the targets in VR compared to the ones in the real world. Here, in our second experiment, participants were asked to reach a specific target and their movements were restricted with the tracking area of Leap Motion device for the sake of standardization.

In the first experiment, response time was measured from the beginning of object appearance until the end of the grasping action. This process includes many different subprocesses, including action planning and action execution. While measuring the process as a whole, it is hard to understand what might be the main cause of the difference in reaction time. Dividing this measurement into two parts as the lift-off time and movement time provided making conclusions about action planning and actual movement in separation. In the discussion section, the advantages of dividing data collection into substeps will be discussed more in detail.

CHAPTER 3

EXPERIMENTS

3.1 Experiment one

Objects with handles were found to potentiate the afforded action. Participants tend to respond faster when the handle is on the same side as the responding hand in a bimanual speed response task (Tucker & Ellis, 1998). This effect, also known as an affordance effect, is found to be affected by the reachability of the object (Costantini et al., 2010). The purpose of this experiment was to see (1) whether the affordance effect can be replicated with the current experimental setup in VR and (2) whether the affordance effect is modulated by the distance of the object relative to the agent. In the literature, the distance is usually divided into two categories: peripersonal and extrapersonal space. In this experiment, a mid-range position was added in between the two in order to see whether the effect is categorical (i.e., reaction times clustering around two categories — the effect is present or absent) or gradient-like.

3.1.1 Participants

Sixteen graduate and undergraduate students (13 male, 3 female) from Istanbul Technical University participated in Experiment One. The mean age of the participants was 25 ranging from 22 to 33 years old. Fifty-six percent of the subjects had previously tried VR at least once. Seventy-five percent of the participants were right-handed and the rest were left-handed.

3.1.2 Stimulus and apparatus

The hand tracking device was connected to a laptop and physically attached to the front of a head-mounted display. Participants saw the stimulus via the head-mounted display. Since the VR goggles physically covered their eyes, they did not see the real experimental room but rather the virtual room from the first-person perspective. Both in the real and virtual experimental rooms, participants were sitting on a chair in front of a table. A red mug with a handle on the right-hand or left-hand side was used as a stimulus that randomly appeared in different orientations (upright or inverted). In blocked trials, the mug was presented either at a Near (30 cm), Middle (60 cm) or Far (150 cm) distance from the observer.

3.1.3 Procedure

First, the experimenter demonstrated the resting position of the hands. In the default resting position, participants held both of their hands open (in front of the tracking device) with their palms facing away from them. They were then shown the required hand movement to respond to the stimulus: rotating the wrist inward and grasping. The experimenter then presented the upright and inverted orientations of the stimulus with a real physical red mug which was similar to the virtual mug (which acted as the stimulus) in the virtual environment.

Participants initiated the experiment by pressing the space bar on the keyboard. They were instructed to fixate their eyes on a black cube (with the side length of 10 cm) that appeared in one of three positions (at the near, middle or far distance) for 500 milliseconds. Right after the cube disappeared, the red mug appeared at the same location. Participants responded according to the vertical orientation of the mug, independent of the handle orientation (see Figure 1). After each grasp response, faint auditory feedback marked the end of an individual trial. This stereo sound always originated from the location of the responding hand. This was technically achieved in Unity by attaching audio source objects to the hand models. After every trial, participants returned their hand back to its default position.

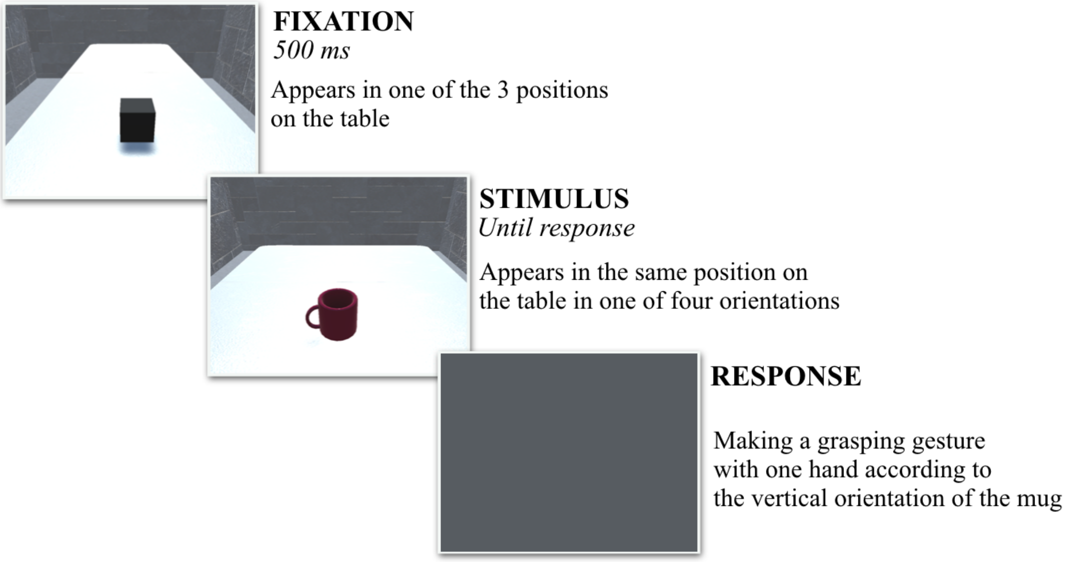

Figure 1. Outline of experiment one

Note: At the beginning of each trial, a black cube appeared in one of the three locations on the long table. After 500 milliseconds, the cube disappeared and the stimulus randomly appeared at the same location in one of four different orientations (Right-Up, Right-Down, Left-Up, or Left-Down). Up and Down represent the vertical orientation of the stimulus, while Right and Left represent the handle orientation. The handles were rotated 15° towards the participant. Participants responded according to the vertical orientation of the stimulus by making a grasping gesture either with their right or left hand.

For the first part of the experiment, participants completed a practice session with 25 trials during which they were given auditory error feedback (for the general procedure[3] of the practice session go to the given video link[4]). Participants who made errors in more than 10% of the trials repeated the practice session. At the beginning of the experimental session, participants were instructed to respond as quickly and accurately as possible. They then completed 60 test trials. Subsequently, the instruction was changed and in the second part of the experiment, the participants

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[3] The grasping gesture was updated after this video was taken

[4] https://www.youtube.com/watch?v=urmPo3wRQNw

completed another 25 practice and 60 test trials. Participants completed 120 trials in two blocks. Each test trial took approximately two minutes. In each block, the mug appeared at every location and in every orientation (right-up, right-down, left-up, left-down) 5 times. The order of these states was randomized.

Immediately after the completion of the experiment, participants were given two post-experimental questions which were: ‘Was it tiring to hold your hands up like that?’ and ‘Do you think the orientation of the handle affected you? If so, in what way do you think it affected you?’. Finally, the participants were debriefed and a copy of the informed consent form was given to the participants if requested.

3.1.4 Results

Two-by-three repeated measures analysis of variance (ANOVA) was conducted with the Handle Orientation (compatible and incompatible) and Distance (near, middle, and far) as within-subject factors. The main effect for both Handle Orientation and Distance was significant, as yielded by $F(1, 15) = 7.690, p = .014, \eta^2 = .339$ and $F(2, 15) = 7.290, p = .003, \eta^2 = .327$ respectively. No interaction effect was found $F(1, 31) = 0.435, p = .651, \eta^2 = .028$ between Handle Orientation and Distance.

With this experiment, the effects of handle orientation and distance of the object on reaction time were replicated (Costantini et al., 2010). Finding a significant handle orientation effect in VR with hand tracking supported the idea that the stimulus-response compatibility paradigm can be used to understand the interaction between the object (a component of cyberspace) and the agent (a cyberbody within this thesis).

We could not find a significant interaction effect between handle orientation and distance $F(2, 30) = 0.435, p = .651, \eta^2 = .028$. However, as shown in Figure 2, the observed trend in the data was worth mentioning. In the compatible conditions, participants reacted faster only when the object was in a reachable region (Near and Middle). This difference was the largest in the middle distance where the participants needed to move their hand to interact with the object as compared to near (11 ms) and far (3 ms) conditions.

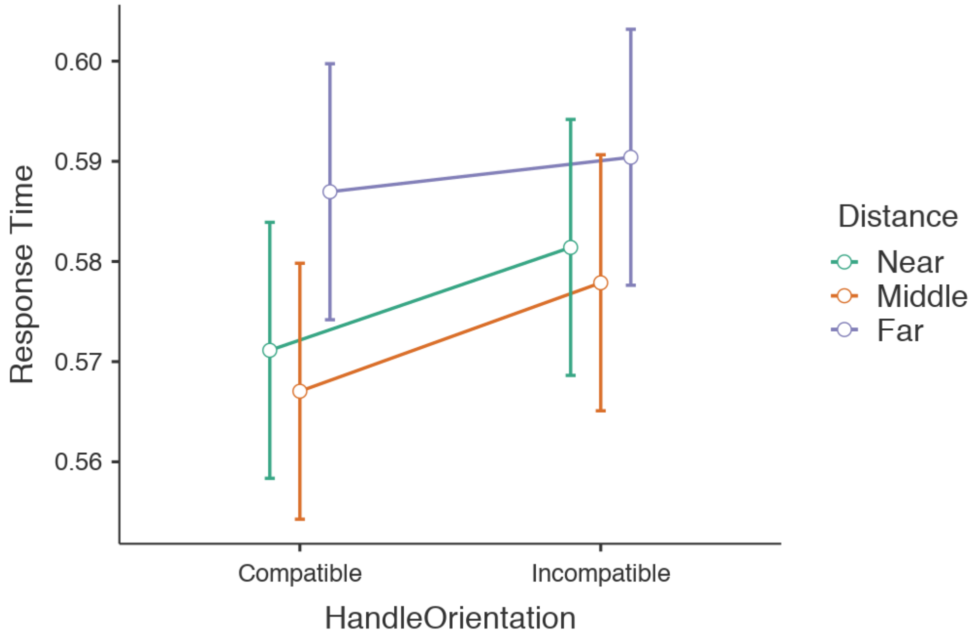

Figure 2. Overall results of experiment one

Note: Response time is represented on the y-axis in seconds. On the x-axis, two levels of the handle orientation effect (the compatible and incompatible conditions) are shown. The purple, orange, and green lines represent the conditions where the stimulus was shown at near, middle, and far distances respectively. Error bars indicate the standard errors of the mean (+/- 2 SEMs).

In this experiment, response time was interpreted as the time required to perform motor actions. However, measuring response time at the end of a grasping action involves different subprocesses, including action preparation and action execution. In the second experiment, we divided response time measures into two parts (as lift-off time and movement time) to further investigate these subprocesses of interaction.

3.2 Experiment two

The results of the first experiment showed that the affordance effect can be created in VR. The purpose of the second experiment was to see if this effect is modulated by body representation. Previous studies showed that avatar abilities can be changed in VR (Won et al., 2015; Day et al., 2019). In this study, we manipulated the avatar hands and measured the affordance effect in the same way as in Experiment One. However, the methodology was upgraded. The counterbalancing of the instruction was changed from within subjects to between subjects. Response time measurement was divided into two steps and measured by using buttons instead of Leap Motion's grasp detection for the sake of precision in data collection. The stimulus was changed from a mug to a frying pan to eliminate wrist rotation during action execution. Also, the accuracy of the hand tracking was improved. The changes in the methodology will be given in more detail in the following sections.

3.2.1 Participants

Thirty-two undergraduate students (14 female, 18 male) from Boğaziçi University participated in Experiment Two. The mean age of the participants was 23 ranging from 19 to 35. Sixty-two percent of the subjects had previously tried VR at least once. Ninety-four percent of the participants were right-handed and the rest were left-handed. None of them participated in the first experiment.

3.2.2 Stimulus and apparatus

The VR headset and the hand tracking device were connected to a computer in the same way as the first experiment. The methodology and setup were upgraded. In this experiment, the hand tracking device was attached to a metal stick rather than the VR headset. An extra keyboard was connected to the same computer to measure lift-off time. ‘X’ and ‘2’ on the numeric keypad were used as response keys. All the other keys surrounding them were pulled out of the keyboard to prevent possible interfering inputs during the experiment. The response keys were physically enlarged by fixing larger buttons onto them. These buttons were made by cutting and shaping a styrofoam material and covered with a soft rubber fabric, where participants rested their palms during the experiment. The same materials were used to raise the keyboard to a point where it was aligned with the handrests where participants placed their wrist. This helped hand tracking and device stabilization (for the upgraded version of the experimental setup see Appendix B).

For the stimulus object, a frying pan was designed in Autodesk Maya, 2018. The bottom texture was chosen to be different so that it would be easier for the participants to tell the upright oriented pan from an inverted pan. For the placement of the object the base-centered approach (Cho & Proctor, 2010 as cited in Kiril, 2017) was used by placing the pivot of the virtual object at the center of the body of the pan.

The pan always appeared at the same distance from the participant, which is the same as the ‘middle’ distance (in cm’s) in Experiment One. In Unity, two invisible boxes were placed to the right and left sides of where the pan appeared. These boxes were used to detect the contact of the hand models. Two audio source objects were placed in the same locations for audio feedback to mark a successful reaching response.

The main difference between Experiment One and Experiment Two was the second independent variable – the hand type. Two types of hands were used in Experiment Two. One was the able hand, which is a standard hand model with full finger tracking (same as the one that is used in the first experiment), and the restricted hand, which is a capsule-shaped 3D model. The restricted hand was the same size, texture, and color as the normal hand. The able hand was designed to allow grasping behavior as opposed to the restricted hand, which was not able to grasp. Thus, different abilities were provided to the participants. There were no physical restrictions to the real hand movements of the participants, but when they grasped with their real hands, the visual feedback from the virtual hands and their ability to grasp were restricted for the capsule hand model.

Prior to every experimental session, participants spent time with the respective hand model for adaptation. The stimuli in these sessions were red squares that appeared exactly where participants were supposed to reach their hands during the test sessions. Red cubes that participants can push forward appeared and two cubes (one red and one black) appeared near each other for pick and place task. All stimuli in the adaptation session appeared in succession either on the left-hand or right-hand side. The experimenter controlled the appearance and disappearance of the stimuli by pressing the required keys on a separate keyboard.

3.2.3 Procedure

Participants initiated the experiment by pressing both response keys simultaneously. In a manner similar to Experiment One as both keys were pressed down, a black cube appeared for 500 ms. Participants were told to fixate their eyes on the location of the black cube. Right after the fixation object disappeared, the stimulus (the frying pan) appeared with the handle on either on the right or left-hand side. Participants responded according to the vertical orientation of the object (see Figure 3). Responses were given by lifting the responding hand off the response key and reaching forward.

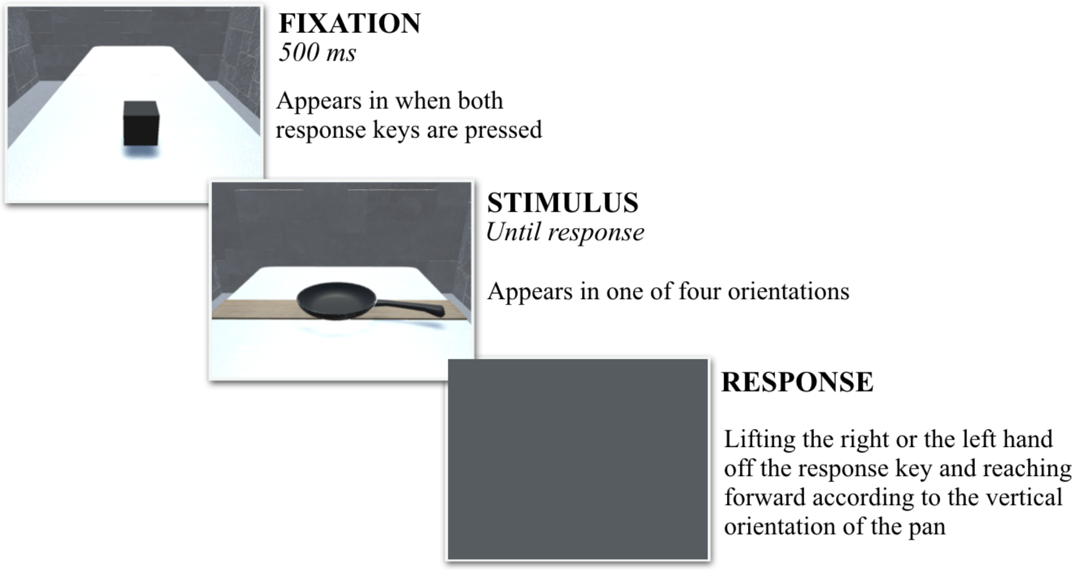

Figure 3. Outline of experiment two

Note: At the beginning of each trial, a black cube appeared at the same location on the table. After 500 milliseconds, the cube disappeared and the stimulus appeared at the same location in one of four different orientations randomly (Right-Up, Right-Down, Left-Up, or Left-Down). Up and Down represent the vertical orientation of the stimulus, while Right and Left refer to the handle orientation. The handles were rotated 15° towards the participant. Participants responded according to the vertical orientation of the stimulus by lifting their right or left hand off the response key and reaching forward until the target point, represented by the wooden areas on the table.

Counterbalancing the instruction across subjects caused confusion and increased the error rates in the second part of Experiment One. Therefore, in Experiment Two, the instruction was counterbalanced between subjects. Half of the participants were given instruction A only, which was ‘Respond with your right hand if the pan is upright and respond with your left hand if the pan is inverted’ and the other half of the participants received the instruction B only, which is ‘Respond with your right hand if the pan is inverted and respond with your left hand if the pan is upright’.

At first, they completed the first adaptation session wherein they performed four simple tasks as instructed by the experimenter sixteen times each. The adaptation part is composed of 4 different tasks. Adaptation Task 1A is Open and

Close Hands: Palms facing inwards (opening and closing hands while looking at the palms and counting out loud). Adaptation Task 1B is Open and Close Hands: Palms facing outwards (opening and closing their hands sixteen times while looking counting out loud). Adaptation Task 2 was Reach and Touch (reaching and touching the red squares that appeared either on the right-hand side or left-hand side with the corresponding hand and bringing the hand back to its default position). Adaptation Task 3 was Push Forward (pushing the cubes forward with the back of their hands). Adaptation Task 4 was Pick and Place (picking red cubes up and placing them on the black cubes).

Participants first completed 24 practice trials with error feedback as in Experiment One. Once the practice session was completed, they started the first test session, which was composed of 24 trials without error feedback. Participants completed six blocks of 24 trials. In each block, the pan appeared at every location and in every orientation (right-up, right-down, left-up, left-down) two times. The order of these states was randomized. Overall the experiment had seven sessions: one practice and six test sessions in two parts composed of three sessions for each hand type. Prior to each test session, participants completed an adaptation session. Depending on the pace of the participant, each adaptation session took three to five minutes. Each test session took approximately one and a half minutes. Between the two parts of the experiment, participants were allowed to rest as long as they needed. They were allowed to talk to the experimenter, and drink water but they were not allowed to have screen time or engage in cognitively or physically demanding tasks. The order of hand type was counterbalanced among the participants (for the experimental setup and procedure go to the given video link[5]).

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[5] https://youtu.be/eyru1BVJShU

After every session, data including lift-off time and movement-time for each trial automatically saved as a text file. Lift-off time starts as the object appears and ends as the subject lifts one hand off the key. At that moment, the movement time counter starts and it stops when the hand of the subject touches the invisible detection box over the stimulus.

Immediately after the completion of the experiment, participants were given a post-experimental question which was: ‘Do you think the orientation of the handle affected you? If so, in what way do you think it affected you?’. Then they filled out two Body Ownership Questionnaires, one for able hand (see Appendix C and Appendix D) and one for restricted hand (see Appendix E and Appendix F). The questionnaire was prepared by modifying the questions that are used in three different VR studies (Argelaguet, Trico, Hoyet, & Lécuyer, 2016; Day, 2019; Sikström, de Götzen, & Serafin, 2014). The questionnaires were given in the same order of the given hand type. Finally, the participants were debriefed and a copy of the informed consent form was given to the participants if requested.

3.2.4 Results

For two different dependent variables (Lift-off Time and Movement Time), two Repeated measures analysis of variance (ANOVA) were conducted with the Hand Type (able vs. restricted) and Handle Orientation (compatible vs. incompatible) as within-subject factors.

3.2.4.1 Lift-off time

A significant handle orientation effect was found for Lift-off time, $F(1,31) = 34.456$, $p = .001$, $\eta^2 = .547$. Participants lifted their hand off the response key faster in the compatible conditions than in incompatible conditions (897 vs. 947 ms). There was no significant main effect of hand type, *F*(1,31) = 0.769, *p* = .387, η^2 = .024. This means that participant lifted their hands off the response keys at similar times with both able (930 ms) and restricted hand (914 ms).

There was a significant interaction effect between Handle Orientation and Hand Type, *F*(1,31) = 7.129, *p* = .012, η^2 = .187. This means the Handle Orientation effect was modulated by Hand Type. The difference in the lift-off times between compatible and incompatible conditions was higher when participants used the restricted hand compared to able hand (66 ms vs. 34 ms). As shown in Figure 4, in incompatible conditions, it takes a similar amount of time for participants to respond (947 vs. 947 ms). However, participants reacted significantly faster with the restricted hand than with the able hand in the compatible conditions (881 vs. 913 ms).

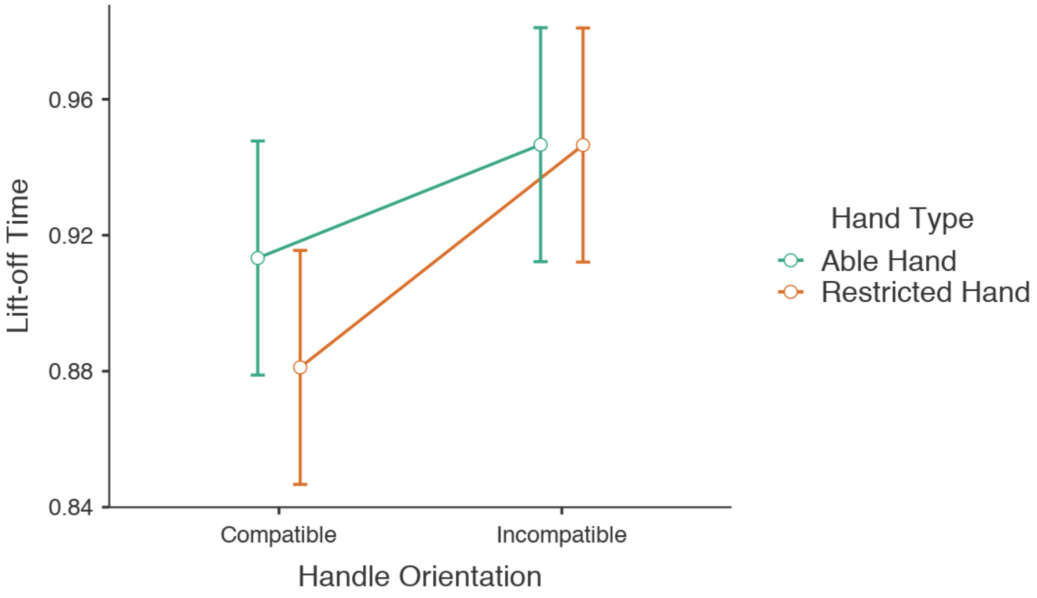


Figure 4. Results of experiment two (lift-off time)

Note: Lift-off time is represented on the y-axis in seconds. On the x-axis, two levels of the handle orientation effect (the compatible and incompatible conditions) are shown. The green and orange lines represent the conditions where the participants have able or restricted hands respectively. Error bars indicate the standard errors of the mean (+/- 2 SEMs).

3.2.4.2 Movement time

Handle orientation was also significant for Movement Time *F*(1,31) = 9.414, p = .004, η^2 = .233. However, the direction of the effect was found to be reversed (see Figure 5). After the participants lifted their responding hand off the response key, they moved their hand to the target point faster in the incompatible conditions than in the compatible conditions (566 vs. 581 ms).

There was no main effect for hand type for Movement time as well *F*(1,31) = 1.561, p = .221, η^2 = .048. And no significant interaction effect was found *F*(1,31) = 0.572, p = .455, η^2 = .018.

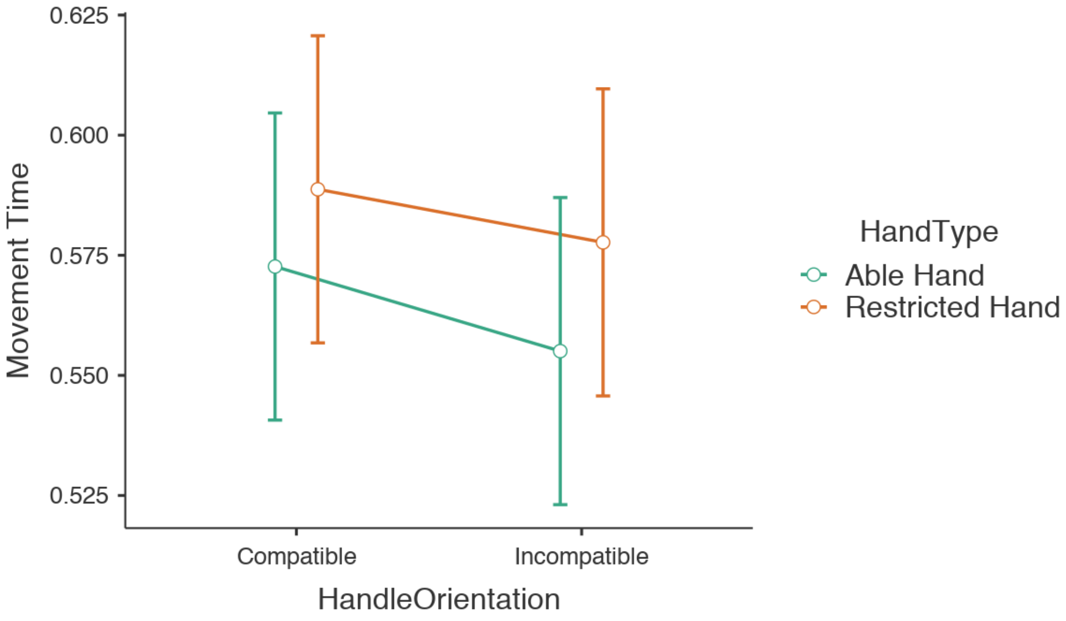


Figure 5. Results of experiment two (movement time)

Note: Movement time is represented on the y-axis in seconds. On the x-axis, two levels of the handle orientation effect (the compatible and incompatible conditions) are shown. The green and orange lines represent the conditions where the participants have able or restricted hands respectively. Error bars indicate the standard errors of the mean (+/- 2 SEMs).

3.2.4.3 Body ownership

Participants answered the same questions for able hand and restricted hand on a Likert scale from 0 to 10 corresponding to ‘completely disagree’ and ‘completely agree’. Before entering the questionnaire data into Jamovi, the scores of the negative questions were reversed. For instance, if the participant answered this question ‘I felt like the virtual hand movements were independent of me.’ as 2, the number was translated into 8, which corresponds to stronger body ownership. The results showed that both restricted hand and able hand provided a sense of ownership. A paired-samples t-test was conducted to compare the sense of ownership created by different hand types. The able hand with full finger tracking created significantly more ownership (M = 7.99, SD = 1.14) compared to the restricted hand (M = 5.67, SD = 1.74) conditions $t(31) = 7.70$, $p = .001$, $d = 1.36$.

Since participants answered the questionnaires at the end of the experiment, they may have thought that they were supposed to compare the two hands and answered questions relative to the other hand type. This difference between the hand types may not have appeared if it was a between-subject design, where participants complete the task with only one hand. Although participants reported that the able hand felt more like their own, the movement time results do not reveal a difference between different hands. Also, in lift-off time results, there is no difference between the able and restricted hands in the incompatible conditions. The difference only appears in the compatible conditions, where the hand is approaching a handle. Therefore, the difference created by the hand type should be related to the relationship between the virtual hand’s capability (able to grasp or not able to grasp) and object affordance (graspability) rather than the sense of ownership created by the hand type.

In order to see whether the level of ownership has an effect on the significant interaction result in lift-off time measures, a median-split analysis was conducted. Participants were divided into two groups (the ones who felt strong ownership and the ones who felt less strong ownership). Later this is given the repeated measures ANOVA as the between-subject factor. No significant effect of the level of ownership was found $F(1, 30) = 3.03, p = .092, \eta^2 = .092$.

3.3 Summary and the overall conclusion

In the first experiment, we replicated the handle orientation effect with the experimental set up that we created in VR. We showed that distance might have a significant effect on reaction time. Even though we could not show a significant interaction effect, the trend in this result indicated that further exploration of the interaction between affordance and distance could be worthwhile. However, as the main purpose of this study was to investigate the effect of avatars, we focused our energy on designing a better experiment based on the lessons learned during Experiment One.

In Experiment Two, handle orientation was again significant for both the lift-off time and movement time measures. Interestingly, the effect was reversed after the participant started moving their hand (movement-time). It appears that when there is a handle on the opposite side, it increases planning time. In other words, it took the participants longer to start the action in the incompatible condition. However, after they started the response, they completed the trial even faster than they do in the compatible conditions.

The most important result is the interaction effect that was found between the handle orientation effect and hand type. This result supports the main hypothesis that avatars affect affordance perception. Finding a stronger affordance effect with the restricted hands, the hands that cannot provide the afforded action, was counterintuitive. These results show that manipulating the agent rather than the object properties may reveal a different story. In the next chapter, we will discuss the findings of the experiments in the light of the literature and try to provide possible explanations.

CHAPTER 4

GENERAL DISCUSSION

Our results provide further support for the affordance effect such that participants respond more quickly when the handle of an object is on the same side as the response key on a keyboard. That the orientation of the handle triggered faster responses for the compatible condition in Experiment One and that the lift-off times of the avatar hands were shorter when the handle was on the responding hand side in Experiment Two may support the view that the sight of an object might automatically potentiate possible actions, shortening response times. Interestingly, though, we also found that the reaction times were smaller for the restricted hand than those for the normal hand avatar, an unexpected effect which will be further discussed.

In the first experiment, our initial hypothesis was to find a significant affordance effect in conditions where the object was reachable (at the near and middle distances), whereas no such effect was hypothesized for the far distance condition, as this distance is out of the peripersonal space, where interaction with objects takes place. Although the interaction effect between the handle-response key compatibility and the distance was found to be insignificant, though, the expected trend was still observed in the data. Similarly, in the second experiment, we had expected to find a significant affordance effect only with the able-hand-avatar and not with the restricted-hand-avatar, as the restricted hand had no grasping abilities. We thought that if the object is not graspable in the context of an interaction with a particular hand (i.e., restricted hand), then it would not potentiate the graspability affordance, which would reduce the strength of the affordance effect. However, the results showed that the affordance effect was rather strengthened using restricted hands. In other words, the difference between the compatible and incompatible conditions was larger in the restricted hand condition. These results may be explained within the context of Cisek's Affordance Competition Hypothesis. The Affordance Competition Hypothesis (Cisek, 2007) proposes a new model wherein brain functions are classified as either action specification or action selection. As suggested with the affordance effect, objects automatically trigger an afforded action. However, Cisek (2007) argues that the sight of an object activates not only one final act, but also all the currently available actions simultaneously. In other words, when we look around, we create a list of internal representations. These representations are made of the potential "competing" actions, which were defined as affordances by Gibson (1966). Cisek (2001) presented that the two different affordances used in this study, reaching and grasping, are represented in different areas in the brain, as "the dorsal stream diverges into separate systems concerned with different classes of actions" (p. 37) (see Appendix G). Grefkes and Fink (2005) reviewed electrophysiological studies investigating different areas in macaque brain, which specialized in different sets of actions including arm movements and object manipulation. They compared these areas with relevant findings from functional magnetic resonance imaging studies with humans. They provided evidence for the equivalence of the functionality of these areas both in monkeys and humans. They concluded that various distinct areas are involved in goal-directed arm movements, including reaching and grasping. Cisek and Kalaska (2005) recorded neuronal activation in the dorsal premotor cortex of monkeys while they engage in a reaching task. They showed that when there are two potential reaching actions, both of them are specified and activated simultaneously. However, their response time results showed that having more potential actions caused a delay in the action execution. They suggested that this delay may be caused by the temporal integration of the evidence to reach the decision threshold. Similarly, in Experiment Two, we found that when the handle is on the responding hand side, the able hand providing multiple action possibilities (both reaching and grasping) was significantly slower than the restricted hand.

Using the movement time measures, the handle orientation effect was still significant but interestingly, reversed. The reverse compatibility effect, which is very rare in the literature (Kostov, 2015), is thought to arise due to the stimulus selection or the placement of the stimulus (i.e. when the stimulus is a saucepan with a large body part, and centralized according to this body mass which renders the handle insignificant, or the body of the object contains more task-relevant information compared to the handle). In this study, however, we found the reverse compatibility effect using the same stimulus and procedure but with a different response measure. This discrepancy may have been caused by two response measures having been collected at different phases of action: Whereas the affordance effect is visible in the action planning part of the experiment, such that participants lift their hands off the response key faster in the compatible conditions, the effect is reversed once they initiate action and they complete it faster in the incompatible conditions. This is in agreement with Cisek's (2007) argument that action planning is never complete. He argues that reaching a certain information threshold is enough to start an action. However, "even in the cases of highly practised behaviours" (p. 1586), an action begins without a complete trajectory. That is, there is ongoing planning during the action execution, with continuous feedback loops, which allows fine motor adjustments while interacting with objects. Within this theoretical framework, in our experiment, no such adjustments were needed in conditions where the handle orientation was not corresponding to the target location. If the handle was on the side where they were reaching, however, action planning may still have continued to adjust the hand to the handle during the execution phase, even though the initial plan was not to grasp it. This may explain why we found approximately 14 milliseconds of slow-down in the movement time for compatible compared to incompatible conditions.

In the Introduction, we mentioned how we rely on the sensory feedback to perceive our bodies and the environment around us, which makes it possible for us to control novel bodies in VR (Lanier, 2006). The results of the second experiment supported this idea of flexibility in body perception. It is known that it is possible to embody a completely virtual hand via synchronous visuo-tactile feedback (Aldhous et al., 2017). Here, for the first time, we demonstrated that synchronous visual feedback, even in the absence of haptic input, is enough to create such embodiment effects.

There is an ongoing debate about using the stimulus-response compatibility to measure the affordance effect. Whereas the motor account views the stimulus-response compatibility effect as an affordance effect, following the tradition of Tucker and Ellis (1998), the attention account views the stimulus-response compatibility effect as a spatial alignment effect caused by the attentional shift towards the salient feature of the object, following the tradition of Anderson and his colleagues (2002). If the handle orientation effect was in fact caused by the attentional shift towards the handle of the frying pan (the visually salient part of the object), however, then we would not expect this effect to be modulated by the different hand avatars that provide different affordances in our paradigm. Therefore, our results support the motor account side of this compatibility effect debate; thus, we prefer to label the compatibility effect as the affordance effect within the scope of this thesis.

In a series of experiments, Costantini and his colleagues (2010) manipulated the distance of an object to a participant, while keeping visual saliency under control, and measured the handle orientation effect. The handle orientation effect was only found when the object was at a reachable distance from the participant. This effect disappeared when the object was far away from the participant. In the first experiment, with a very similar design, we replicated their results for the main effects of handle orientation and distance. Even though we could not find a significant interaction effect between the affordance effect and distance, we found a similar trend in the data.

This study provided evidence for the effects of avatar abilities on affordance perception with a reliable experimental methodology. However, the abilities of the avatar were only manipulated by changing the visual feedback. In future studies, the effect of physical restrictions on real hands could be compared to restricted virtual hands. If similar results were to be found, then it could be interpreted that only visual feedback from restricted virtual hands could create similar effects as real physical restrictions on hands. The effect of introducing multiple sensory feedback can also be investigated in this paradigm. For example, the physical restriction could be a capsule-shaped foam around the hand that looks like the virtual representation of the restricted hands. In this case, the haptic feedback together with visual feedback could possibly create a stronger effect on affordance perception compared to having only visual feedback. Another thing that could be worth further investigation would be having no feedback of any kind. In other words, the identical task could be done by rendering the hand model invisible. Since the human brain is good at filling in the blanks, the subject may imagine a hand similar to his hand in the absence of feedback. Therefore, having no hand may result in response times similar to those found with the able hand virtual representation (normal hand with finger tracking) in the present study. Yet another study could be done by manipulating the virtual hands by enhancing the user’s avatar abilities instead of restricting them. For instance, virtual hands that could interact with distal objects could eliminate the effect of distance on affordance perception. In other words, the handle orientation effect could be found in the objects that are far away from the subject, since the avatar hands will potentially enhance the perception of the reachable space. These abilities could also be rendered in a full body avatar, instead of using virtual hands only. This would allow the investigation of different affordances when the whole body interacts with space (i.e., navigation).

CHAPTER 5

IMPLICATIONS FOR VIRTUAL REALITY APPLICATIONS

The findings of the experiments presented two significant outcomes: (1) Virtual objects can potentiate the affordance effect in VR and (2) affordance perception is affected by the avatar representation (i.e., either normal or restricted). In our experiments, less than 5 minutes was enough for participants to adapt to the virtual hands. The virtual hand representation affected the way participants interacted with the virtual objects. These findings provide potential implications for VR applications in the areas of interaction design, digital sports, health, and psychophysics research.

Designing interactions in VR is a challenging task. First of all, users need to know what is interact-able and how to interact with it. In order to improve user experience in VR, designers mostly use objects that users are already familiar with such as a kettle and a mug. In VR, users try to mimic similar gestural inputs and expect similar behaviors from virtual objects. Just like visual representations of these virtual objects drive their use, the visual representation of the hands determines the available actions with which these objects can be interacted. Thus, changing virtual hands and their capabilities can make it easier for the user to understand potential actions in a virtual environment. In other words, altering the body form might be a way to tell users what is possible in a VR setting.

Depending on the available tasks that need to be accomplished by the user in a virtual environment, hand representation can also be changed while the user is interacting with an object. For example, giving the correct shape to the hand when grasping something is still a complex technical challenge in VR. It requires not only the detection of the shape of the object but also a proper animation of the hand grasping the object, which becomes particularly complicated and computationally expensive given the varying morphology of different objects. A common solution for this problem is to make the hand disappear while grasping an object so that the hand becomes the object itself. Interestingly, this has been reported to be neither noticeable nor disturbing to VR users. In other words, seeing the hand in unfamiliar shapes was less acceptable than seeing no hand at all. Thus, in VR settings, omission of feedback might sometimes be less obtrusive than unexpected or uncanny feedback in terms of the user experience.

In VR, the avatar / representation of a hand can potentially be anything such as a frying pan, a gun, or a paintbrush (Welker, 2006). When full finger tracking becomes available, it may even be possible for each finger to act like a different tool. The variety of tool options changes the affordance such that far objects can now become reachable, heavy objects liftable, small objects stretchable or big objects scalable. Therefore, the idea of having shape-shifting hands provides potentially infinite affordances for virtual objects in VR. Enhancing the ways of interaction by giving users magical abilities provides creative freedom for developers, designers, and users. Having multiple action possibilities, however, can also distract users, make the application hard to learn and use, and make the decision making harder (as shown by the results of the second experiment). Therefore, virtual interactions can sometimes be enhanced by restricting potential actions to direct users to perform a task in a certain way. Restricting action possibilities may also provide precise results with imprecise actions. Unlike real object interactions, a user can interact with virtual objects by making actions in the vicinity of the object that is expected to be interacted on. For example, in VR, the detection of contact between any part of the user’s hand with a virtual object can be enough to grasp the object. In real life, on the other hand, grasping an object requires a complex sequence of actions and proper positioning of the fingers. This difference may provide advantages in some tasks for VR over the real-world tasks.

Our results showed that when multiple actions are available, action planning takes longer time, a difference in the range of milliseconds. Although not perceived consciously, however, these brief temporal delays may still be critical in some applications, for example, in competitive gaming. Today, games are the most widespread use case of VR technology (“Newzoo Report”, 2019, p.17). Some VR games have been already recognized in the digital sports category by Electronic Sports League (2019) and have become a part of international tournaments. In non-VR digital sports, players compete by controlling a game character with a keyboard and a mouse or other traditional controllers. By contrast, in VR games, players control the character by their body movements that are tracked in 3D space. These games have the potential to better reflect the experience of real-world sports and can broaden our understanding of the capabilities of the human body. For example, in the VR game Echo Arena, users control robotic avatars and compete in a disk throwing game in a zero-gravity virtual environment, reminiscent of the 2010 movie Tron. In this game, players’ avatars fly and their arm movements affect the direction of their overall flight path. These novel affordances are critical to game performance. This is an example of how controlling new avatars with new abilities can be turned into a competitive sport. Competitors can adapt to new abilities and master them via practice to become professional players. Therefore, changing the abilities of a person in VR can open new possibilities in digital sports where we can enhance and explore the limits of the human body and its capabilities.

Our abilities are already enhanced with personal devices we use. Digital affordances introduced by new technologies like copy and paste, drag and drop, pinch to zoom in have become a part of everyday activities. New abilities that come with potential new affordances can redefine the way we interact with the media. For example, VR is a powerful platform to visualize multidimensional data. Visualizing complex data in three dimensions can bridge the gap between "the quantitative content of data and human intuition" (Donalek, C. et al., p. 609). The way we understand, interpret, and interact with data can be enhanced via new representations of data and the body of the agent who interacts with it.

The implications of the interaction between body perception and environment perception can extend beyond the interaction between virtual bodies and virtual space. VR technology has the potential to be used as a way to remotely control real-world machines. The applied areas of this concept include but not limited to military solutions (Kumar, Kumar, Kumaran, & Valarmathy, 2014), space exploration (Stoll, Wilde, & Pong, 2009), submarine robots (Hine et al., 1994), all of which are examples of operational fields beyond human reach. Even for the accessible places, being able to do things remotely brings tremendous advantageous. Telepresence surgery (where a surgeon controls a robot for remote operation on a patient) is a possible renaissance in technology wherein experts can suddenly be accessible from all around the world. The idea of telepresence extends to simple tasks. Workers in the future may control factory robots from the comfort of their homes. In these scenarios of remote control, instead of seeing a camera view on a flat screen and controlling the machinery with buttons and controllers, the operator can use his own body movements that are mapped onto a purposefully designed avatar. For instance, if a robot arm has a vacuum gripper, then many objects that are naturally not graspable by a human can be potentially graspable and liftable. A proper representation of the avatar hands may provide a sense of embodiment and better control of the robot arm, which results in precise control of the machinery. Future easy-to-learn / intuitive interfaces and close-to-real presence in distant places could act as an extension of virtual abilities into the real world.

There are also real-world applications of VR in the field of health. The flexibility of body perception and the embodiment of avatars are already commonly used in the rehabilitation of stroke patients (Shin, Ryu, & Jang, 2014) and the treatment of phantom pain (Ambron, Miller, Kuchenbecker, Buxbaum, & Coslett, 2018). In these studies, patients are trained with virtual limbs in game-like VR activities to either increase the functionality of limbs or reduce pain caused by the remaining sensation of a lost limb, called phantom pain. This indicates that improvements in real-world affordances can be induced from activities in VR with realistic virtual objects. For example, a patient with a lost limb can practice interacting with objects using many different prosthesis designs in VR before the most optimized model is produced as a mechanical limb. Best-fit artificial limbs could be selected according to performance measures (i.e., the level of adaptation of the patient to a specific design can help to determine the ultimate version of the prosthesis). VR technology can also provide a training environment for the patients with neural prostheses, with which they control the prosthetic arm with nerve signals.

The findings also have implications for the future of psychophysics research. Instead of passive observation of the stimulus, the relationship between stimulus and sensation can be examined during the interaction with the stimulus. Traditional input methods like mouse and keyboard, joystick, or controller could be improved via hand and body tracking. Multiple inputs from participants such as position and rotation of the body parts, gaze, pupil dilation, head direction, and many more could be gathered during experiments. This would provide valuable insight from multiple sources of data and their relations. Sensation and perception can also be studied in relation to body representation with a systematic variation of the body and the object simultaneously. For example, changing the proportions of the sensory organs and incoming sensory information like smaller eyes of the avatars could result in blurry vision.

Applications of VR are projected to spread to all areas of life as presented with some examples above. Since the dawn of civilization, human capabilities have been evolving with technology. This effect has been accelerating during the information age with increasing computational power. Virtual Reality represents a new frontier for extending representations of the human form, creates new areas of application, and open new perceptions of reality. This will, in turn, create new horizons of research in perception, blurring the lines between the real and the virtual.

APPENDIX A

ETHICS COMMITTEE APPROVAL

T.C.
BOĞAZİÇİ ÜNİVERSİTESİ
İnsan Araştırmaları Kurumsal Değerlendirme Alt Kurulu

Sayı: 2018-30

26 Haziran 2018

Naciye Tuğçe Akkoç
Bilişsel Bilim

Sayın Araştırmacı,

"Siber bedenlerin siber ortamlarla etkileşimi: Sanal gerçeklikte avatar becerilerinin sağlarlık algısı üzerindeki etkisi" başlıklı projeniz ile ilgili olarak yaptığınız SBB-EAK 2018/38 sayılı başvuru İNAREK/SBB Etik Alt Kurulu tarafından 26 Haziran 2018 tarihli toplantıda incelenmiş ve uygun bulunmuştur.

…………………………
Dr. Öğr. Üyesi Nur Yeniçeri

…………………………
Doç. Dr. Gül Sosay

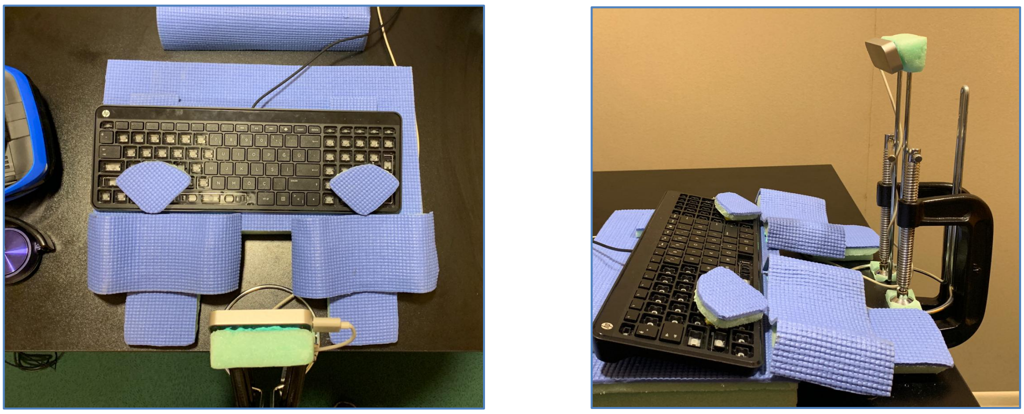
…………………………
Doç. Dr. Ebru Kaya

…………………………
Dr. Öğr. Üyesi İnci Ayhan

…………………………
Dr. Öğr. Üyesi Bengü Börkan

APPENDIX B

UPGRADED EXPERIMENTAL SETUP



Experimental setup for experiment two:

The two response keys were physically enlarged. The keyboard was raised and aligned with the handrests (left). The Leap Motion hand tracking device was fixed at the edge of the table (right).

Left-hand response in experiment two:

In experiment two, the response was given by lifting the responding hand off the response key and reaching forward.

APPENDIX C

BODY OWNERSHIP QUESTIONNAIRE FOR ABLE HANDS

1. I felt as if the virtual hands that I saw during the experiment were part of my body.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

2. I felt as if the virtual hands were moving independently of my movements.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

3. I felt as if my body was immersed in the virtual environment.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

4. I felt as if the virtual hands were someone else’s hands.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

5. I felt as if I was the one who is controlling the virtual hands.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

6. During the experiment, I felt as if was watching a scene from third person perspective.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

APPENDIX D

BODY OWNERSHIP QUESTIONNAIRE FOR ABLE HANDS

(ORIGINAL TURKISH VERSION)

Beden Aidiyeti Anketi

1. Deney sırasında gördüğüm sanal eller bedenimin bir parçasıymış gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

2. Sanal eller benden bağımsız hareket ediyor gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

3. Kendi bedenimle sanal ortamın içindeymişim gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

4. Deney sırasında gördüğüm sanal eller, başka birine aitmiş gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

5. Sanal ellerin hareketlerini kendim kontrol ettiğimi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

6. Deney sırasında kendimi dışarıdan bir sahne izliyormuş gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

APPENDIX E

BODY OWNERSHIP QUESTIONNAIRE FOR RESTRICTED HANDS

1. I felt as if the virtual capsule hands that I saw during the experiment were part of my body.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

2. I felt as if the virtual capsule hands were moving independently of my movements.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

3. I felt as if my body was immersed in the Virtual Environment.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

4. I felt as if the virtual capsule hands were someone else’s hands.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

5. I felt as if I was the one who is controlling the virtual capsule hands.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

6. During the experiment, I felt as if was watching a scene from third person perspective.

Strongly Disagree 0 1 2 3 4 5 6 7 8 9 10 Strongly Agree

APPENDIX F

BODY OWNERSHIP QUESTIONNAIRE FOR RESTRICTED HANDS

(ORIGINAL TURKISH VERSION)

Beden Aidiyeti Anketi

1. Deney sırasında gördüğüm sanal kapsül eller bedenimin bir parçasıymış gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

2. Sanal kapsül eller benden bağımsız hareket ediyor gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

3. Kendi bedenimle sanal ortamın içindeymişim gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

4. Deney sırasında gördüğüm sanal kapsül eller, başka birine aitmiş gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

5. Sanal kapsül ellerin hareketlerini kendim kontrol ettiğimi hissettim.

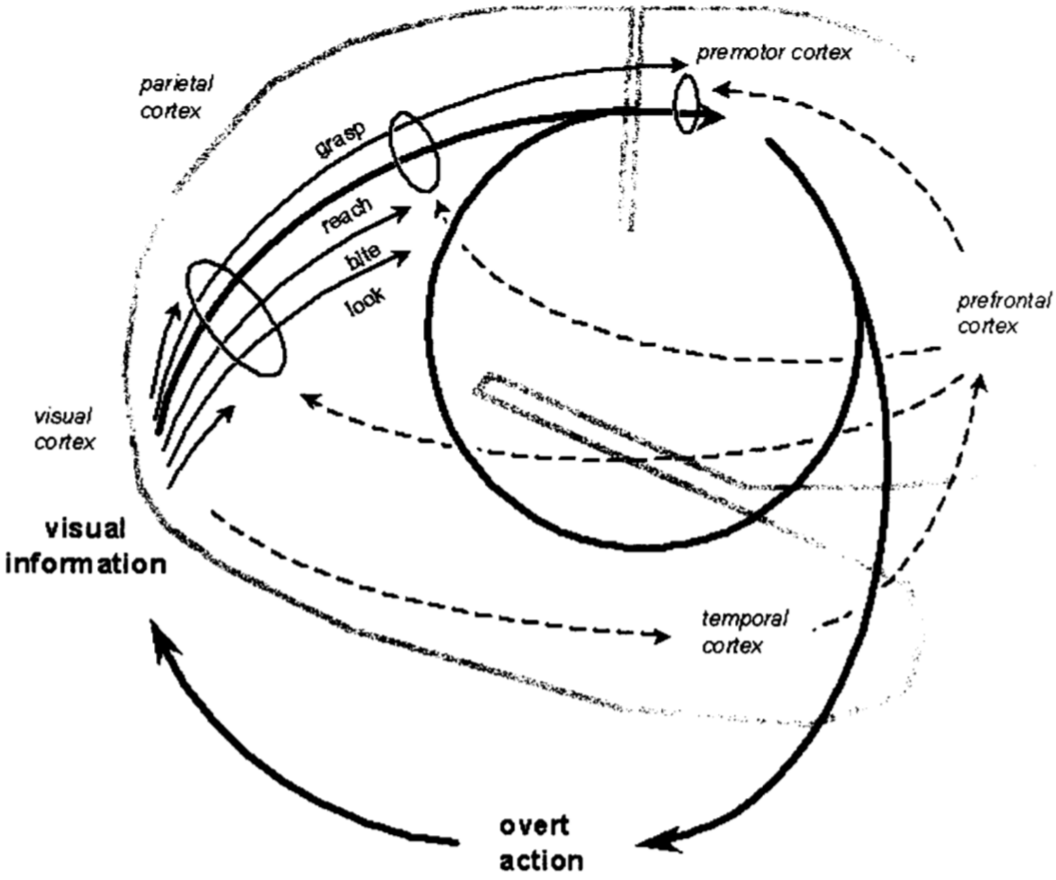
Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

6. Deney sırasında kendimi dışarıdan bir sahne izliyormuş gibi hissettim.

Kesinlikle katılmıyorum 0 1 2 3 4 5 6 7 8 9 10 Kesinlikle katılıyorum

APPENDIX G

THE SPECIFICATION-SELECTION MODEL



Cisek's drawing showing *the specification-selection model*:

In this model dorsal pathway in the brain is shown to diverge into different systems that are involved in different action classes, including reaching and grasping. Solid lines represent the potential actions that are activated in parallel. Dashed lines represent the pathways where the information needed for decision making are carried (Cisek, 2001).

REFERENCES

Ahn, S. J. G., Bostick, J., Ogle, E., Nowak, K. L., McGillicuddy, K. T., & Bailenson, J. N. (2016). Experiencing nature: Embodying animals in immersive virtual environments increases inclusion of nature in self and involvement with nature. *Journal of Computer-Mediated Communication*, *21*(6), 399–419. doi: 10.1111/jcc4.12173

Aldhous, J., Hetherington, R., & Turner, P. (2017, July 3-6). *The digital rubber hand illusion*. Paper presented at the 31st International BCS Human Computer Interaction Conference (HCI 2017: Digital Make-Believe Conference). doi: 10.14236/ewic/HCI2017.59

Ambron, E., Miller, A., Kuchenbecker, K.J., Buxbaum, L.J., & Coslett, H.B. (2018). Immersive low-cost virtual reality treatment for phantom limb pain: Evidence from two cases. *Frontiers in Neurology, 9*(67), 1-7. doi: 10.3389/fneur.2018.00067

Ambrosecchia, M., Marino, B.F., Gawryszewski, L.G., & Riggio, L. (2015). Spatial stimulus-response compatibility and affordance effects are not ruled by the same mechanisms. *Frontiers in Human Neuroscience*, *9*(283), 1-11. doi:10.3389/fnhum.2015.00283

Argelaguet, F., Trico, M., Hoyet, L., & Lécuyer, A. (2016, March 19). *The role of interaction in virtual embodiment: Effects of the virtual hand representation.* Paper presented at Virtual Reality (VR) 2016, IEEE. doi: 10.1109/VR.2016.7504682

Bajcsy, R., Aloimonos, Y., & Tsotsos, J.K. (2018). Revisiting active perception. *Autonomous Robots*, *42*(2), 177-196. doi: 10.1007/s10514-017-9615-3

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, *110*(31), 12846-12851. doi: 10.1073/pnas.1306779110

Berti, A. and Frassinetti, F. (2000) When far becomes near: Re-mapping of space by tool use. *Journal of Cognitive Neuroscience*, *12*(3), 415–420. doi: 10.1162/089892900562237

Bhalla, M. & Proffitt, D. R. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology: Human Perception and Performance, 25*(4), 1076-1096. doi: 10.1037/0096-1523.25.4.1076

Botvinick, M. & Cohen, J. (1998). Rubber hands ‘feel’ touch that eyes see. *Nature 391*(6669), 756. doi: 10.1038/35784

Bourgeois J, Farnè A, & Coello Y. (2014). Costs and benefits of tool-use on the perception of reachable space. *Acta Psychologica*, *148*, 91–95. doi: 10.1016/j.actpsy.2014.01.008

Bowman, D., Kruijff, E., LaViola, J., & Poupyrev, I. (2004). *3D user interfaces: Theory and practice.* Boston, MA: Addison-Wesley.

Canzoneri E., Ubaldi S., Rastelli V., Finisguerra A., Bassolino M., & Serino A. (2013). Tool-use reshapes the boundaries of body and peripersonal space representations. *Experimental Brain Research*. *228*(1), 25– 42. doi: 10.1007/s00221-013-3532-2

Cardinali, L., Frassinetti, F., Brozzoli, C., Urquizar, C., Roy, A.C., & Farne, A. (2009). Tool-use induces morphological updating of the body schema. *Current Biology*, *19*(12), 478 – 479. doi: 10.1016/j.cub.2009.05.009

Cho, D.T. & Proctor, R.W. (2010). The object-based Simon effect: Grasping affordance or relative location of the graspable part*? Journal of Experimental Psychology: Human Perception and Performance*, *36*(4), 853-861. doi: 10.1037/a0019328

Cisek, P. (1999). Beyond the computer metaphor: Behaviour as interaction. *Journal of Consciousness Studies, 6*(12), 125-142.

Cisek, P. (2001). Embodiment is all in the head. *Behavioral and Brain Sciences*, *24*(01), 36–38. doi: 10.1017/S0140525X0124391X

Cisek, P. & Kalaska, J. F. (2005) Neural correlates of reaching decisions in dorsal premotor cortex: specification of multiple direction choices and final selection of action. *Neuron, 45*(5), 801–814. doi: 10.1016/j.neuron.2005.01.027

Cisek P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1485), 1585–1599. doi:10.1098/rstb.2007.2054.

Costantini, M., Ambrosini, E., Tieri, G., Sinigaglia, C., & Committeri, G. (2010). Where does an object trigger an action? An investigation about affordances in space. *Experimental Brain Research*, *207*(1-2), 95–103. doi: 10.1007/s00221-010-2435-8.

Day, B., Ebrahimi, E., Hartman, L. S., Pagano, C. C., Robb, A. C., & Babu, S. V. (2019). Examining the effects of altered avatars on perception-action in virtual reality. *Journal of Experimental Psychology: Applied*, *25*(1), 1-24. doi: 10.1037/xap0000192

Donalek, C., Djorgovski, S. G., Cioc, A., Wang, A., Zhang, J., Lawler, E., ... Drake, A. (2014, October 27-30). *Immersive and collaborative data visualization using virtual reality platforms.* Paper presented at IEEE International Conference on Big Data. doi: 10.1109/BigData.2014.7004282

Electronic Sports League: ESL Play VR League (2019, April 28). Retrieved from https://play.eslgaming.com/echoarena/global

Eves, F. (2013). Is there any Proffitt in stair climbing? A headcount of studies testing for demographic differences in choice of stairs. *Psychonomic Bulletin & Review*, *21*(1), 71-77. doi: 10.3758/s13423-013-0463-7

Farnè A, Iriki A, Làdavas E. (2005). Shaping multisensory action–space with tools: Evidence from patients with cross-modal extinction. *Neuropsychologia*. *43*(2), 238–248. doi: 10.1016/j.neuropsychologia.2004.11.010

Fitts P. M. & Seeger C. M. (1953). SR compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*(3), 199-210. doi: 10.1037/h0062827

Fizek, S. and Wasilewska, M. (2011). Embodiment and gender identity in virtual worlds: Reconfiguring our 'Volatile Bodies'. In A. Ensslin and E. Muse (Eds.), *Creating Second Lives. Community, Identity and Spatiality as Constructions of the Virtual*, (pp. 75-98), Oxon: Routledge.

Geuss, M., Stefanucci, J., Creem-Regehr, S., & William B. (2010, July 23). *Can I pass? Using affordances to measure perceived size in virtual environments.* Paper presented in the 7th Symposium on Applied Perception in Graphics and Visualization (APGV'10). doi: 10.1145/1836248.1836259.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

Gray, R. (2013). Being selective at the plate: Processing dependence between perceptual variables relates to hitting goals and performance. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(4), 1124-1142. doi: 10.1037/a0030729

Guna, J., Jakus, G., Pogacnik, M., Tomažic, S., & Sodnik, J. (2014). An Analysis of the Precision and Reliability of the Leap Motion Sensor and Its Suitability for Static and Dynamic Tracking. *Sensors*, *14*(2), 3702–3720. doi: 10.3390/s140203702

Harris, L. R., Carnevale, M. J., D'Amour, S., Fraser, L. E., Harrar, V., Hoover, A. E. N., … Pritchett, L.M. (2015). How our body influences our perception of the world. *Frontiers in Psychology*, *6*(819), 1-10. doi: 10.3389/fpsyg.2015.00819

Hine, B., Stoker, C., Sims, M., Rasmussen, D., Hontalas, P., Fong, T., … Steele, J. (1994, May 3-6). *The Application of Telepresence and Virtual Reality to Subsea Exploration.* Paper presented at the 2nd Workshop on Mobile Robots for Subsea Environments, Monterey, CA.

Iriki A., Tanaka M., & Iwamura Y. (1996). Coding of modified body schema during tool use by macaque postcentral neurones. *NeuroReport*, *7*(14), 2325–2330. doi: 10.1097/00001756-199610020-00010

Jamone, L., Ugur, E., Cangelosi, A., Fadiga, L., Bernardino, A., Piater, J., & Santos-Victor, J. (2018). Affordances in psychology, neuroscience, and robotics: A survey. *IEEE Transactions on Cognitive and Developmental Systems*, *10*(1), 4-25. doi:10.1109/TCDS.2016.2594134

The Jamovi Project (2019). Jamovi. (Version 0.9) [Computer Software]. Retrieved from https://www.jamovi.org.

Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, *21*(4), 373-387. doi: 10.1162/PRES_a_00124

Lanier, J. (2006, January 8). Homuncular flexibility [Web log comment]. Retrieved from https://www.edge.org/response-detail/11182

Lessard, D. A., Linkenauger, S. A., & Proffitt, D. R. (2009). Look before you leap: Jumping ability affects distance perception. *Perception*, *38*(12), 1863-1866. doi: 10.1068/p6509

Newzoo Report: The new reality for mobile gaming: The VR/AR opportunity. (2019). Retrieved from https://artillry.co/wp-content/uploads/2019/04 /Newzoo-VR-and-AR-in-Gaming.pdf

Ramachandran, V.S. & Blakeslee, S. (1998). *Phantoms in the brain: Probing the mysteries of the human mind.* New York, NY: HarperCollins Publishers.

R Core Team (2018). R: A language and environment for statistical computing. [Computer Software]. Retrieved from https://cran.r-project.org

Regia-Corte, T., Marchal, M., Cirio, G., & Lécuyer, A. (2012). Perceiving affordances in virtual reality: Influence of person and environmental properties in perception of standing on virtual grounds. *Virtual Reality*, *17*(1), 17-28. doi: 10.1007/s10055-012-0216-3.

Riddoch, M. J., Edwards, M. G., Humphreys, G. W., West, R., & Heafield, T. (1998). Visual affordances direct action: neuropsychological evidence from manual interference. *Cognitive Neuropsychology*, *15*(6-8), 645–683. doi: 10. 1080/026432998381041

Roth, D., Lugrin, J., Galakhov, D., Hofmann, A., Bente, G., Latoschik, M., & Fuhrmann, A. (2016, March 19). *Avatar realism and social interaction quality in virtual reality.* Paper presented at Virtual Reality (VR) 2016, IEEE. doi: 10.1109/VR.2016.7504761.

Rumiati, R. I. & Humphreys, G. W. (1998). Recognition by action: Dissociating visual and semantic routes to action in normal observers. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(2), 631-647. doi: 10.1037/0096-1523.24.2.631

Salmanowitz N. (2018). The impact of virtual reality on implicit racial bias and mock legal decisions. *Journal of Law and the Biosciences*, *5*(1), 174–203. doi:10.1093/jlb/lsy005

Serino A., Bassolino M., Farnè A., & Ladavas E. (2007). Extended multisensory space in blind cane users. *Psychological Science*, *18*(7), 642–648. doi: 10.1111/j.1467-9280.2007.01952.x

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, *81*(1), 174-176. doi: 10.1037/h0027448

Sirigu, A., Grafman, J., Bressler, K., & Sunderland, T. (1991). Multiple representations contribute to body knowledge processing: Evidence from a case of autotopagnosia. *Brain, 114*(1), 629–642. doi: 10.1093/brain/114.1.629

Shin, J.H., Ryu, H., & Jang, S.H. (2014). A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: A usability test and two clinical experiments. *Journal of Neuroengineering and Rehabilitation*. *11*(1), 32-42. doi: 10.1186/1743-0003-11-32

Sikström, E., de Götzen, A., & Serafin, S. (2014, October 1-3). *The Role of Sound in the Sensation of Ownership of a Pair of Virtual Wings in Immersive VR*. Paper presented at the 9th Audio Mostly: A Conference on Interaction with Sound. doi: 10.1145/2636879.2636912

Slater, M., Pérez-Marcos, D., Ehrsson, H., & Sanchez-Vives, M. V. (2008). Towards a digital body: The virtual arm illusion. *Frontiers in Human Neuroscience*, *2*(6), 1-8. doi:10.3389/neuro.09.006.2008

Sposito, A., Bolognini, N., Vallar, G., & Maravita A. (2012). Extension of perceived arm length following tool-use: Clues to plasticity of body metrics. *Neuropsychologia*. *50*(9), 2187–2194. doi: 10.1016/j.neuropsychologia.2012.05.022

Stoll, E., Wilde, M., & Pong, C. (2009, October 20-22). *Using virtual reality for human assisted in-space robotic assemb*ly. Paper presented at the World Congress on Engineering and Computer Science. San Francisco, CA.

Turvey, M. T. (1992). Affordances and prospective control: An outline of an ontology. *Ecological Psychology*, *4*(3), 173-187. doi: 10.1207/s15326969eco0403_3

Welker, S. [Google Developers] (2006, May 19) Daydream Labs: Lessons Learned from VR Prototyping - Google I/O 2016 [Video File]. Retrieved from https://www.youtube.com/watch?v=lGUmTQgbiAY

Witt, J.K., Proffitt, D.R., & Epstein, W. (2005). Tool use affects perceived distance but only when you intend to use it. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(5), 880–888. doi: 10.1037/0096-1523.31.5.880

Won, A.S., Bailenson, J., Lee, J. & Lanier, J. (2015). Humuncular Flexibility in Virtual Reality. *Journal of Computer-Mediated Communication, 20*(3), 241–259. doi: 10.1111/jcc4.12107

Yamani, Y., Ariga, A., & Yamada, Y. (2016). Object affordances potentiate responses but do not guide attentional prioritization. *Frontiers in Integrative Neuroscience*, *9*(74), 1-6. doi: 10.3389/fnint.2015.00074