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## Personalized Digital Body: Enhancing Body Ownership and Spatial Presence in Virtual Reality

Sungchul Jung  
*University of Central Florida*



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PERSONALIZED DIGITAL BODY: ENHANCING BODY OWNERSHIP AND SPATIAL  
PRESENCE IN VIRTUAL REALITY.

by

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A dissertation submitted in partial fulfilment of the requirements  
for the degree of Doctor of Philosophy  
in the Department of Computer Science  
in the College of Engineering and Computer Science  
at the University of Central Florida  
Orlando, Florida

Spring Term  
2018

Major Professor: Charles E. Hughes

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## **ABSTRACT**

person's sense of acceptance of a virtual body as his or her own is generally called virtual body ownership (VBOI). Having such a mental model of one's own body transferred to a virtual human surrogate is known to play a critical role in one's sense of presence in a virtual environment. Our focus in this dissertation is on top-down processing based on visual perception in both the visuomotor and the visuotactile domains, using visually personalized body cues. The visual cues we study here range from ones that we refer to as direct and others that we classify as indirect. Direct cues are associated with body parts that play a central role in the task we are performing. Such parts typically dominate a person's foveal view and will include one or both of their hands. Indirect body cues come from body parts that are normally seen in our peripheral view, e.g., legs and torso, and that are often observed through some mediation and are not directly associated with the current task.

This dissertation studies how and to what degree direct and indirect cues affect a person's sense of VBOI for which they are receiving direct and, sometimes, inaccurate cues, and to investigate the relationship between enhanced virtual body ownership and task performance. Our experiments support the importance of a personalized representation, even for indirect cues. Additionally, we studied gradual versus instantaneous transition between one's own body and a virtual surrogate body, and between one's real-world environment and a virtual environment. We demonstrate that gradual transition has a significant influence on virtual body ownership and presence. In a follow-on study, we increase fidelity by using a personalized hand. Here, we demonstrate that a personalized hand significantly improves dominant visual illusions, resulting in more accurate perception of virtual object sizes.



## EXTENDED ABSTRACT

A person's sense of acceptance of a virtual body as his or her own is generally called virtual body ownership. Having such a mental model of one's own body transferred to a virtual human surrogate is known to play a critical role in a person's sense of presence in a virtual environment. That sense of virtual body ownership can be enhanced by *visuotactile* as well as *visuomotor* integration. Our focus in this dissertation is on top-down processing based on visual perception in both the visuomotor and the visuotactile domain, using visually personalized body cues.

The visual cues we study here range from ones that we refer to as *direct* and others that we classify as *indirect*. Direct cues, in our usage, refer to visual cues associated with body parts that play a central role in performing some task. Such parts typically dominate a person's foveal view and generally include their hands. Indirect body cues come from other body parts that are normally seen in our peripheral view, e.g., legs and torso, and that are often observed through mediation, e.g., a mirrored reflection or a shadow, but are not directly associated with the current task. Direct body cues, because they are in our central visual field, are, we assert, the most important factors affecting virtual body ownership.

As hands are central to a human's capability to manipulate physical objects, we focus on them as the primary direct cues in this dissertation. Hands, however, are particularly challenging as humans are intimately familiar with the appearance of their own hands since they are rarely covered by clothing. Moreover, representing an individual's hands involves obvious challenges associated with articulation and subtle challenges associated with uniqueness in appearance due to freckles, scars, and even ornaments such as rings. One goal of this dissertation is to study how and to what degree direct and indirect cues, both personalized and contrived, affect a person's sense of ownership of a virtual body for which they are receiving direct and, sometimes, inaccurate or

even disconcerting visual cues, and to investigate the relationship between enhanced virtual body ownership and task performance. One emphasis here is on reflected images of a person's lower torso and legs. Another is to suggest future work involving a novel algorithm for rendering a personalized hand to assist in ownership.

Our approach is to carefully control each variable and each combination of variables that may influence virtual body ownership. As such, we have carried out experiments that focus on varying the visual realism of direct cues and indirect cues in a manner that investigates each one's unique contribution and each combination's shared contribution to virtual body ownership. Most of our initial studies investigated how realism of indirect cues (legs seen through a virtual mirror) support or detract from a user's sense of ownership of an obviously virtual hand. The hand is static in some of our studies and dynamic (user controllable) in others, and is sometimes even disembodied (not connected to the torso through a corresponding arm). These early experiments support the importance of a personalized representation, even for indirect cues.

The second tier of studies reported in this dissertation investigates the supporting relationship between personalized direct and indirect virtual body cues. Our first study in this phase looked at the effects of gradual versus instantaneous transition between one's own body and a virtual surrogate body, and between one's real-world environment and a virtual environment. Our study demonstrated that gradual transition has a significant influence on one's illusions of virtual body ownership and presence. In a follow-on study, we focused on increasing the fidelity for digital body representation by using a video see-through HMD to capture and display the participant's real hand, with the goal of determining its influence on object scaling precision in a virtual environment. Here, we demonstrated that a personalized hand leads to a significant improvement for the dominant illusions of spatial presence and body ownership, and that the personalized hand resulted in greater accuracy as regards one's estimation of virtual object sizes.

The contributions of the reported research to the computer science discipline are the following. First, we carried out visual perception (direct and indirect) experiments to identify significant factors to improve virtual body ownership and presence in virtual environments, providing statistical evidence and discussions in support of our hypotheses. Second, we developed a human mental model for the immersive virtual environment based on the result that a personalized virtual hand dramatically enhances virtual body ownership and presence, and we showed a positive relationship between the enhanced human perception and task performance in a computer-generated domain. Third, we proposed a novel algorithm for rendering a personalized feature-embodied virtual hand. The proposed algorithm is light-weight and easy to include in game engines such as Unity, but the process is not unique to that engine. Finally, we combined results from five stages of development and experimentation to offer advice to researchers and developers on those combinations of visual body cues that enhance body ownership and a corresponding sense of presence in virtual, augmented and mixed reality worlds.

The biggest challenge is automatically rendering a personalized, fully articulated virtual hand that matches the visual appearance and actions of a specific living person. Because of the complex articulated structure and appearance of an individual's hand, achieving real-time results introduces a complex challenge in the correspondence problem between a user's real and virtual hand. Our proposed method involves warping-based texture mapping between a scanned hand image and a predefined texture for a 3d hand model. The equipment we depend upon is a real-time hand-tracking device and a high-resolution stereo camera. Our solution produces feature points on the contours of both the real and virtual hand textures, warping the captured hand image along the feature points of the predefined texture. One particularly novel contribution in our proposed solution is the way in which we attack the warping problem by solving a series of local problems, building these up successively until a global solution is achieved.

“But as for me and my house, we will serve the LORD”

Joshua 24:15

I give all glory of this tiny fulfillment to my LORD and the Son of Man, Jesus Christ.

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# CHAPTER 1: INTRODUCTION

## 1.1 Motivation

A person's perception of their own body such as proprioceptive sensations, the sense of the relative position of one's own body parts, or somatic experiences, any type of mental or physical traumatic health problem caused by perceived body sensations such as PTSD (post-traumatic stress disorder). This sense of one's consciousness of self-body, is called body ownership. We, normally, have no doubts regarding our own body since we see, move, and feel our body in daily life. However, body parts are often not properly perceived with a virtual human surrogate from a first-person perspective in a computer generated environment. The problem has received a great deal of attention as virtual reality technologies, such as high resolution enabled head-mounted displays (HMDs) and accurate real-time tracking devices, have rapidly evolved in the last few years. Since virtual body ownership (VBO), the sense that a virtual surrogate is our own body, and spatial presence, the sense of "being there," are inherently related, and those are regarded as core factors in a first-person perspective virtual reality (VR) environment such as a video game, a simulation, or a rehabilitation system, a number of studies for virtual body ownership have been conducted.

Historically, researchers in Neuroscience, Cognitive science, Perceptual science, and Psychology have shown that the integration of signals of visual, tactile, proprioceptive, and other senses in humans affect bodily self-consciousness. Based on these findings, VR researchers in the computer science community have studied VBO with spatial presence to further their understanding of how to build computer-generated virtual environments that positively impact a human's sense of immersion. Traditionally, researchers mainly focused on VBO based on tactile and proprioceptive senses; in contrast, visual perception has not been sufficiently studied because of a lack of considering person-specific visual features, even though our perception is closely related to visual



stimulation within an environmental context.

In this dissertation, we describe the effects of visual perception for virtual body ownership and spatial presence using visually personalized body cues. We approach visual perception in two manners: as indirect visual perception and direct visual perception. We conducted several studies using a virtual mirror reflection to observe a personalized body indirectly. We then created a transition effect between the real world and virtual world environment to smoothly advance a user's visual perception. In a final experiment, we rendered a person's actual hand using a combination of a video-see through HMD and a Chroma-key setup to directly increase the participant's sense of body ownership and presence. After we present the various study descriptions and results, we suggest a conceptual framework for an immersive VR system with a rendering algorithm to generate a personalized virtual hand automatically in VR to enhance VBO and spatial presence by eliciting visual perception in a straightforward manner.

## 1.2 Overview of Visual Perception

Human visual perception of the world is a product of the human brain. Through millions of photoreceptors, cones (receptors for Color discerning) and rods (receptors for low levels of light) in the retina of the human eye, we receive light information that is converted to neural pulses in the brain. Early work found that each neural signal influences other neural signals in the neural structure that forms the final visual consciousness, while some information can be missing or emphasized according to context. Based on how the brain works in the human vision system, two types of approaches to understanding human perception have been studied, top-down and bottom-up, respectively. In this dissertation, we developed our research based on the top-down approach. For instance, humans could imagine a triangle in the middle empty area in the picture of Kanizsa geometry or perceive the middle bar in the impossible trident if it exists in Figure 1.1 because

the brain naturally accesses memories that associate the proper geometry according to our prior knowledge, after we observe or watch contextual cues from observed geometries.

With the nature of visual perception, humans can gain contextual information because the human brain recognizes or understands an object with color, size, and shape from familiar visual elicitations in our daily lives. For example, seeing a soccer ball in a picture, it helps to conjecture other object sizes by comparing these with the ball since a ball is a familiar object in our life and we may guess the ball size naturally. We can expand the example to our body. We, generally, know our body features such as skin color, aging marks, creases on palm, scars, shoes, clothes, and accessories that we own because they are stored in our long-term or short-term memory. Even though sometimes we have trouble noticing our body features, seeing our body explicitly triggers recognition of our personal body information, and this enhances the sensation of bodily-self consciousness. Therefore, we emphasize the importance of visual perception on a user's own body to improve VBO and presence. Unfortunately, current experiments for VBO usually use an artist-created virtual human avatar, and so the level of VBO differs depending on the realism of the virtual avatar relative to each individual.

### 1.3 Overview of User Studies and Results

In this dissertation, we present a sequence of novel experiment designs for visual perception that look at the effect of personalized visual cues on VBO and presence, and even on task performance in VR. We categorized the visual perception into two parts, indirect visual perception and direct visual perception. To investigate the effect of the visual perception, we conducted five consecutive experiments under different visual perception conditions.

### *1.3.1 Indirect Visual Perception Experiment*

First, as an indirect visual cue, we employed a virtual mirror to reflect a personalized body that elicits the visual perception of individual participants using a 3D reconstructed model from a point cloud, pure RGBD image or pre-defined model with body continuity (a supportive factor for VBO and spatial presence). Using the experimental design, we conducted two virtual mirror based body ownership and presence experiments.

### *1.3.2 Direct Visual Perception Experiment*

As a third experiment, our experimental design employs a pre-rendered virtual hand that matches that of individual participants when they wear a glove provided by the researcher. This approach provides the visual perception semi-directly. Fourth, as a direct cue, we conducted a study of the relative effects of gradual transition to elicit visual perception when participants entered a virtual environment. In the final fifth experiment, we tested a participant's ability to estimate virtual object scaling when they observed their own right hand that was mediated using a video-see through HMD in a chroma-keyed environment.

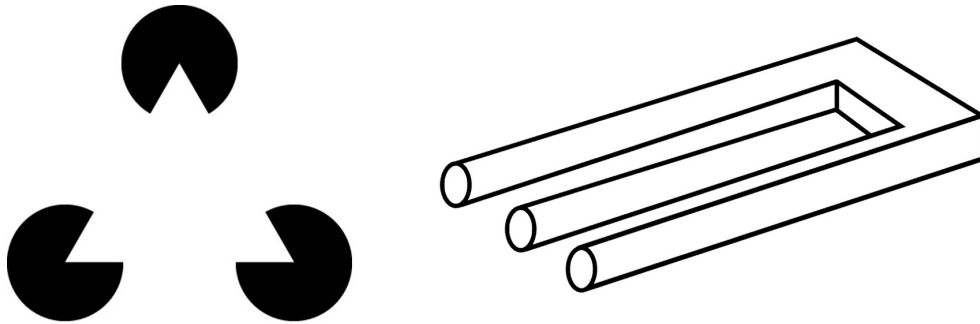


Figure 1.1: Kaniza Triangle(left) and Impossible trident(right)

## 1.4 Proposed Future Work

Since the hand is one of the most frequently used body parts in our daily life, understanding VBO related to a virtual hand is an essential step for immersive presence. Though the hand plays a critical role, it is not easy to employ it correctly in VR because the hand is a complex articulated limb with an appearance and motions that are not easy to model and render. To avoid the rendering problem, a predefined generic virtual hand is generally used for VBO experiments in current VR environments. However, a realistic generic virtual hand is not a perfect solution since it does not match all the different types of individual hands, a deficiency that arouses unexpected impacts that break the illusion of ownership. To resolve this problem, some researchers have used a realistic virtual hand created specifically for each individual by an artist, but manually creating an individual's virtual hand is an expensive and time-consuming process, and it may interfere with the experiment depending on the quality. Otherwise, there have been approaches to render the individual human model with depth cameras, for example, using point clouds based on accurate depth maps such as provided by the Microsoft Kinect. By using multiple cameras to capture humans from multiple viewpoints, we can then reconstruct 3D geometry. Even though the depth camera-based human modeling procedure seems like a good approach, it is still limited in terms of rendering an accurate hand model including articulated fingers because of limited resolution to capture hands accurately and occlusions due to finger movement and overlap. To solve the problem, we describe a method that uses a video see-through stereo camera aided by a Chroma-key environment to create a personalized virtual hand for our VBO experiments. Based on positive results from this approach, we propose a method to render a personalized 3D hand automatically based on a texture warping between a scanned personal hand image using a predefined 3D hand model as a reference. A summary of that approach follows.

With current camera and hand-tracking devices, it is possible to capture personal hand images

with an easy setup in which we attach both an RGB camera and a depth camera to the front of a head-mounted display (HMD). Our method scans both hands of a participant two times: once for the front side and once for the back side of each hand with the fingers totally opened and seen in normal lighting conditions. After calibration between the cameras, we scan a hand image using a traditional background removal setup such as a green screen. Our method uses existing techniques such as a Trimap for smooth matting between the RGB camera and hand tracking camera; thus, the result produces a hand only image with a smooth contour.

We adopted an existing technique to extract feature points from the hand image contour and a predefined texture image. Fortunately, current hand-tracking devices provide anatomical joint points that help to define local regions on the hand. To warp the region locally, we generate feature points around each region in the hand image and the predefined texture, which has manually-defined joint points. Because of anatomically similar geometry between the scanned hand image and the predefined hand texture, we calculate a similarity for each feature point that could be a target point for warping the texture.

Traditional texture warping methods require a pair of points: a target point and a destination point. In our algorithm, we produce the pairs of points from both images automatically using point similarity. The first part, the warping rendering, may produce artifacts on the overlapped region since our warping method processes at each local region. To solve the overlapping problem, we apply current blending solutions based on a gradient domain fuse algorithm using a Poisson blending method.

In this dissertation, we present an efficient algorithm for creating a personalized virtual hand that more dramatically elicits visual perception and visual consciousness than other traditional setups. We believe that the personalized virtual hand with our algorithm will contribute to current VBO experiments and enhance VBO and presence in VR.

## 1.5 Structure of Dissertation

This dissertation has eight chapters in total. The remaining seven chapters are organized in the following manner.

Chapter Two LITERATURE REVIEW: This chapter examines adopted psychological concepts in virtual reality related to bodily self-consciousness, virtual body ownership, body continuity, presence, and visual perception. Also, this chapter explores technologies related to personalized hand rendering, image matting and feature extraction, similarity, warping, and color blending.

Chapter Three INITIAL EXPERIMENT FOR INDIRECT EFFECT ON VISUAL PERCEPTION: This chapter introduces an early stage experiment for the indirect body cue effect on virtual body ownership and presence. In this study, the participants observed their lower body (essentially legs) through a virtual mirror reflection while they performed a specified task in VR. The results from this experimental design support the author's theoretical assumptions regarding the critical role of visual perception.

Chapter Four REALME: INFLUENCE OF ARTIFACT-FREE INDIRECT REPRESENTATION AND CONTINUITY ON VIRTUAL BODY OWNERSHIP In this chapter, we introduce a robustly revised experiment of the previous study. In this study, the artifact-free indirect body representation showed a clear impact on dependent variables, and the statistically strong evidence of the visual perception was suggested as a supportive factor for virtual body ownership and presence in this experiment.

Chapter Five A PILOT STUDY FOR TELEPRESENCE THROUGH A SEMI-DIRECT EFFECT: This chapter introduces a pilot study for the impact of direct body representation for virtual body ownership, presence, agency, and dizziness in a conceptual telepresence system in VR. In this experiment, we ask the participant to wear a special glove and we use a hand model with the glove

texture. Since we mimicked a personalize feature using pre-defined 3D model partly, which is a limitation of the 3D model, we call this study as semi-direct body cue.

Chapter Six IN LIMBO: THE EFFECT OF A GRADUAL VISUAL TRANSITION: Here, we present a novel experimental design for the influence of the direct personalized body representation for virtual body ownership and presence. Based on the top-down human-perception processing, we proposed a human mental model when we entered a virtual space from a physical space and vice-versa. In this experiment, we investigated the impact of a gradual visual transition effect demonstrating a statistically significant result from subjective responses, objective observations, and a direct comparison question.

Chapter Seven OVER MY HAND: THE INFLUENCE OF A PERSONALIZED HAND ON OBJECT SCALING IN VR: In this final experiment, we introduce the possibility of enhanced virtual body ownership for task performance, such as a virtual object scaling estimation. In this study, we used a combination of video-see-through HMD with Chroma-key to enable a fully personalized digital hand representation. To demonstrate effectiveness, we collected each participant's reactions using subjective responses, measured virtual object scaling precision in VR, and a post-questionnaire. Based on the significant impact of the personalized digital body on VBO and presence, and its positive influence on task precision in VR, the author introduces the concept of VR as a next-generation productive workplace.

Chapter Eight CONCLUSION AND PROPOSED FUTURE WORK: In this final chapter, we summarize the contributions of the research associated with this dissertation and provide suggestions for future work, including ones that might improve our virtual body ownership and presence experiment design based on the personalized virtual hand results and those that might result in the development of associated synthetic applications.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Visual Perception

Light rays of the reflection of the world come to human vision system and those chunks of visual information elicit one's brain to recognize the information. This process is called human visual perception M.LaValle (2017). With the mechanical visual perception system, Gregory suggested a scheme, called "ins-and-outs", for representing a relationship between human perception and illusion. Gregory (1997a,c). In his research, Gregory (1997b) suggested a top-down based human perception system that shows how a human could understand given visual information. Basically, the top-down based human perception is affected by prior knowledge of target visual information and this phenomenon produces a significant impact on a human brain. For example, if we see a rotating hollow mask (Figure 2.1) we might notice that we recognize the hollow mask as a normal convex face, which is evidence of strong visual bias. Regardless of the explicit depth information from the reflected rays, our brain recognizes the concave face as a convex face until we see the face at a close distance.



Figure 2.1: We see a hollow mask as convex until we see it up close.



In other words, his research argues that perceptual knowledge (awareness through senses) and conceptual knowledge (abstractions from prior experiences) are combined to produce a meaningful understanding of the current reality. From a similar perspective, Adalberto et al. focused on eliciting human perception by substituting a real object with a similar virtual object in a VR space Simeone et al. (2015).

## 2.2 Virtual Body Ownership Illusion

Regarding the body ownership illusion, Neuroscience, Cognitive science, Perceptual science, and Psychology suggested two type of internal mental models, body schema and body image, which are similar approaches to bottom-up (sensory data-driven processing) and top-down (require prior knowledge) regarding our perception procedures, respectively. Head (1920) described the body scheme as one's own body representation with sensory data such as tactile or proprioceptive, including body movement or body posture. On the other hand, Schilder (1999) suggested the body image as a mental representation of one's own body with a body-specific perception, an approach that informs our focus in this dissertation.

### 2.2.1 *Overview of Body Ownership Illusion*

One famous example of the body ownership illusion is the rubber hand experiment conducted by Botvinick and Cohen (1998). They investigated body ownership using a fake rubber hand, where the experimenter placed the rubber arm beside the participant's real hand and covered the real hand with a cloth or a panel. After the initial study setup, the experimenter gave tactile feedback using a tool on both hands. Surprisingly, the result showed that the participants felt the rubber hand was their own hand. This concept, initially studied in psychology and neuroscience, has been

extensively investigated by the Virtual Reality (VR) community, taking advantage of its ability to create realistic illusions, enabled by high-resolution head mounted displays (HMDs) and accurate tracking technologies, since the dominant illusion could provide an immersive virtual experience. To investigate virtual body ownership illusion, a number of experiments have been conducted by Petkova et al. (2011); Bergstrm et al. (2016); Argelaguet et al. (2016a); Kiltner et al. (2013); Slater et al. (2010); Ye and Steed (2010); Daniel Perez-Marcos and Slater (2012); Jung et al. (2017) from diverse body ownership perspectives. For example, Petkova et al. (2011) conducted a body ownership study using a mannequin body, which is similar to the rubber hand illusion. The participant observed the mannequin body from the first-person perspective through an HMD, while the experimenter gave tactile feedback to the mannequin and the participant simultaneously. Their body ownership study has been moved to a purely virtual environment. Because of more flexible experimental design in VR, researchers could find various components related to virtual body ownership including visuomotor, visuotactile, body positional congruence, anatomical plausibility, resemblance, and contextually appropriate appearance in VR. For example, Sanchez-Vives et al. (2010); Salomon et al. (2016); Pomés and Slater (2013) investigated virtual body ownership with anthropomorphism models such as a robot avatar, a generic avatar, and a human avatar. They found a correlation between human resemblance and the degree of sense of body ownership.

### *2.2.2 Virtual Hand Ownership Illusion*

Because the hand is the most frequently used human part, and was the basis of the Botvinick and Cohen (1998) investigation of body ownership using a fake rubber hand, Slater et al. (2009a) conducted a study for virtual arm ownership to discover a correlation among multi-human sensory systems - visual, motor and tactile in a mixed reality environment. Ye and Steed (2010) conducted an extended version of the rubber hand experiment in virtual reality. In that research, the experiment showed a positive tendency for the role of virtual body ownership in an immersive virtual

environment experience. With the advent of acceptable accuracy and high frame rate hand tracking technology, body ownership using the hand has been a common focus in recent studies. Also Argelaguet et al. (2016a) conducted a study for virtual arm ownership to discover a correlation among multiple human visuomotor systems in a purely virtual environment. Those experiments showed that the morphologically realistic resemblance of the virtual hand is a significant factor for one's sense of virtual hand ownership. (See Figure 2.2)

Researchers have studied virtual hand ownership in three types of hands - abstracted hand, iconic hand, and realistic hand. They have demonstrated that the morphologically realistic resemblance of the virtual hand is a key to the sense of hand ownership. With these results in mind, Hoyet et al. (2016) studied body ownership issues using unnatural hand shapes, which has six fingers, in a similar setup to that of Argelaguet et al. (2016a). The virtual hand with six-fingers showed that the six-finger hand still elicited body ownership despite the explicit structural difference from a user's real hand.



Figure 2.2: Examples of virtual hand ownership experiments

### 2.2.3 *Virtual Mirror*

To investigate the relationship between virtual body ownership and seeing the virtual body from the first-person perspective, the use of a virtual mirror has been addressed from a variety of research

perspectives – González-Franco et al. (2010); Banakou et al. (2013); Kilteni et al. (2013); Bergström et al. (2016). González-Franco et al. (2010) conducted a study using the virtual mirror reflection to observe the relation between motor actions and virtual body ownership. They demonstrated that synchrony of the mirror-reflected avatar with a participant's movement was the most important factor to give a sense of body ownership. On the other hand, Banakou et al. (2013) conducted a virtual body ownership study to show a correlation between the type of avatar body (child body and adult body) and human perception and body ownership. They demonstrated the interesting result that body ownership was elicited for both avatar body sizes without a significant difference. However, the participants reported different perceptions of the virtual world according to their avatars body size. This shows that the implication process, a higher level of cognition, has an effect on a human's perceptual interpretation in a virtual reality environment. Bergström et al. (2016) also conducted the virtual body ownership study with a virtual mirror setting to watch a virtual avatar's posture with two different viewpoints, a first person, and a third person perspective. Kilteni et al. (2013) investigated the relationship between appropriate appearance for the context and virtual body ownership with a virtual mirror. The study asked each participant to play drums with different costumes in the first person perspective. Thus, they could see their body directly by looking at their hand or looking through the mirror. The study showed that cognitive consequence from proper consistency between visual appearance and task context was invoked and suggested the relationship between the appropriate appearance for the context and virtual body ownership. In each case, as in almost all other body ownership studies, the goal is to find a correlation between directly connected variables.

#### *2.2.4 Body Continuity*

Recently, adding on the traditional factors for body ownership, a new component was suggested as a supportive factor for the bodily self, which is called Body Continuity, a term that refers to visually

connected body parts, as in the connection of a hand to its shoulder through a wrist and arm. Pérez-Marcos et al. (2012) experimented with a fully represented hand but no arm to connect it to the rest of the body. The goal was to find the relationship of body continuity to virtual body ownership. Their results suggest that body continuity is a supporting factor for the illusion of virtual body ownership. To further investigate body continuity, Tieri et al. (2015) studied various types of hands – full limb, wire-connected hand, removed wrist, and missing wrist replaced by a pixel glass hand to an arm. They demonstrated that, while the full limb case elicited the strongest sense of body ownership, even an artificial wire connection between hand and forearm elicited an autonomic reaction, e.g., involuntary protective movement, as a virtual body ownership indicator. Also Blanke et al. (2015) studied body ownership in the context of a face, hand, and trunk, and argued that the multi-sensory signals in the space immediately surrounding our trunks are of particular relevance to self-consciousness.

### 2.3 Presence

Because of its ambiguous concept of presence, many researchers tried to define it in various approaches – Slater et al. (2013a). Among them, one of general expressions of presence is the phenomenon of behaving or a feeling like being in a computer generated world, which has a critical role for a level of immersion in a virtual environment Sanchez-Vives and Slater (2005). Presence was categorized into three categories: social presence – the sense of not only sharing space but also sharing an experience with another entity Slater et al. (2013a), co-presence – the sense of being in a shared space with another entity Bainbridge et al. (2008), and spatial (aka physical) presence – the perception of existing in another space Meehan et al. (2002). We focus on spatial presence in this proposal since the presence in a virtual environment is inherently related to one’s virtual body representation Schuemie et al. (2004)

To measure the sense of presence in VR, researchers Heeter (1992); Witmer and Singer (1998); Bailey et al. (2016); Usoh et al. (2000) developed a subjective measurement using a questionnaire that considers various contributing factors, (e.g. reliable, valid, sensitive, controlling, and objective) for presence. In addition to subjective measurement, Slater (2004) argued that objective measurement should be conducted for the dominant illusion in VR, because using only subjective measurement is not sufficient to assess presence. With both subjective and objective measurement, Meehan et al. (2002) designed a presence study which is called "Pit Room" (Figure 2.3).



Figure 2.3: Side view of the virtual environment. A researcher trains subjects in a training room first, then subjects enter the Pit Room (Left) while they are equipped with HMD and physiological sensors (Right)

They hypothesized that higher physiological responses represent a higher sense of presence, and the physiological responses would be elicited when the virtual environment looks real. To test this conjecture, they designed a virtual room and examined participants' reactions to a stressful virtual height situation, while they wore thin slippers that allowed them to sense passive tactile feedback associated with feeling the end of a raised board that ended right where the virtual pit started.

Recently, researchers focused on a relationship between presence and perception. For example,

Diemer et al. (2015) developed an experiment to observe the effect of conceptual information on fear for presence in VR while Ferretti (2016) suggested that visual representation of a particular space with a given object has a critical role for presence.

## 2.4 Object Size Estimation

A substantial body of literature exists on the topic of distance estimation in VR (e.g., see Loomis and Knapp (2003); Renner et al. (2013) for review articles), which elucidated various factors that facilitate overestimation of close distances and underestimation of longer distances in VEs. Compared to this research on distance estimation, there is only limited research on size estimation in VEs. Overall, this limited research suggested that size is perceived reasonably accurately in VEs Stefanucci et al. (2012); Kenyon et al. (2007); Geuss et al. (2012, 2010) when rich familiar size cues are present in the environment. One type of familiar size cues that could reasonably support size estimation is the user's own body.

To investigate the impact of a given virtual body and its size on the perception of visually perceived objects, Tajadura-Jimenez et al. and Banakou et al. conducted human-subject studies with a virtual mirror to reflect the participant's body size changes Tajadura-Jimenez et al. (2017); Banakou et al. (2013) while Hoort et al. conducted a study with an invisible body condition van der Hoort and Ehrsson (2016). These studies consistently showed that the size of the virtual body has a strong impact on the perception of virtual objects. Moreover, Linkenauger et al. focused on the user's hands and manipulated the size of a virtual hand while a participant was observing a virtual object Linkenauger et al. (2013). Similarly, they also found that the size of the virtual hand of the participant was a critical factor in perceiving the sizes of other virtual objects. In this chapter, we extend this research by investigating the benefits of a high-fidelity personalized hand in VEs.

## 2.5 Personalized Virtual Human Representation

It has been common to use a pre-defined human avatar in VR. Since most of the focus of the human subjects was related to visuomotor, visuotactile and, anatomical resemblance, a generic virtual human was enough for the goal. However, there are many approaches to rendering a personalized virtual human avatar based on computer vision and computer graphics technologies that have evolved along with the advent of commercial low-cost depth cameras such as the Kinect or Primesense, since the fundamental step of avatar creation requires either a set of images or depth range scans. Using depth cameras and 3D human reconstruction technologies, a personalized virtual avatar has been adopted recently in virtual reality environments Achenbach et al. (2017); Latoschik et al. (2017); Shapiro et al. (2014); Malleson et al. (2017); Lucas et al. (2016).

### 2.5.1 *Human Body Rendering*

Zollhöfer et al. (2011) introduced a method to render a human face from a single color image and the corresponding depth map using the Kinect depth sensor. With a similar approach, Tong et al. (2012) presented a 3D reconstruction method using a commercial depth sensor that scanned a human on a turntable. Because of the trade-off between tracking quality and distance, they used three Kinect devices to cover the entire body from top to bottom. With a roughly constructed template, they deformed the model along with corresponding color maps. Because of the number of Kinects required to achieve a virtual human from scanning, Wang et al. (2012) suggested a four key pose-based rendering approach using just one depth camera; however, this approach also showed the adverse effects of low resolution at a distance. To avoid the low-resolution problem at a distance, Li et al. (2013) obtained a super-resolution scan at each of eight key poses at a close distance and stitched them together using multi-view non-rigid registration to produce 3D reconstructed models. Unlike this approach, Shapiro et al. (2014) suggested a system to produce a virtual human



from scanning four static poses at 90° angles relative to each pose with a Kinect. From the scans, their system produced a skeleton of the virtual human and rigged the joints automatically. Unlike previous research, they did not use a stitching algorithm that worked in an iterative fashion, but used Kinectfusion (Newcombe et al. (2011)). On the other hand, some groups still employ 3D human rendering with multi-view reconstruction Starck and Hilton (2003).

Recently, a number of VR researchers presented a system for creating a personalized virtual avatar with less effort than past 3D human reconstruction techniques. Malleon et al. (2017) suggested a system for human scanning and rendering with a single image while the user is in a T-static pose. In their system, they used a combination of multiple stereo RGB cameras with a depth camera. After they took a user body and face, they reshaped the data and fit it to their template of a futuristic astronaut model, since they had a particular scenario. Interestingly, they warped a user face to fit inside a helmet. Similarly, Achenbach et al. (2017) proposes a pipeline to render a personalized virtual human with multiple stereo RGB cameras and a depth camera, while the user sits on a chair in a booth. To generate a virtual human, they also fit the obtained data from the booth to a template modes that already marked nine landmarks manually.

### *2.5.2 Personalize Hand*

Surprisingly, research on developing a fully personalized virtual hand has not been reported yet, even though the human hand is one of the most frequently used body parts and has great potential usage in a computer generated world. In particular, we expect a personalized hand to have great impact on virtual body ownership illusion and spatial presence.

Most virtual hand representations were developed as a supportive factor for gesture recognition, motion analysis, hand tracking, and medical purposes. Thus previous work has focused on a hand model. Wu and Huang (1999); Heap and Hogg (1996); van Nierop et al. (2007) In addition, due to

the complexity of the human hand's shape with its particular skin tone, it is a challenge to render a personalized hand without the aid of an artist. The first approach to generate a personalized virtual hand including accurate geometry and high quality texture was introduced by Rhee et al. (2006)'s research. They introduced creating a high resolution personalized virtual human hand based on an acquired personal hand image and deformed a pre-defined 3D hand model. Using a specialized device setup with a fixed camera, under good lighting condition and in front of a dark background. To ensure the personalized body features of the hand, they divided their method procedure into two steps: First, they used Tensor voting to extract salient geometric features such as creases, or wrinkles on the palm. Second, they deformed the 3D template hand along with an anatomically modeled one after they obtained a feature extracted hand image. Since joint skeletons of the virtual hand are bound to skin geometry, they could automatically deform the skin easily along with the given texture.

#### *2.5.2.1 Warping and Morphing*

In 1988, IndustrialLight&Magic (ILM) introduced a mesh-based morphing technique in the movie Willow. Due to the massive success of the resulting visual effect, the image warping or morphing method has been developed extensively and has been extended to 3D objects as well. Either warping or morphing requires geometric transformation using a set of corresponding features (e.g. points, line segments, mesh nodes, or user specified features) between a set of points in the source, and a set of points in the target Glasbey and Mardia (1998); Wolberg (1996, 1998). Two fundamental warping processes are described in Figure 2.4.

While warping is a transforming process of the geometry of the target using a set of points, 2D morphing is a mixture of image warping with a weighted combination of two images, called a cross-dissolve. This morphing technique has been extended to 3D object transformations, provid-

ing natural shape changes.

A set of features for both source and target is an essential factor for successful warping or morphing. A great number of approaches for feature extraction have been proposed Guyon and Elisseff (2006). For example, Chetverikov (2003) suggested a simple and efficient 2-pass algorithm using a triangle with a specific size and opening angle to detect a corner or a point on a curve. Using the detected feature points, Liu et al. (2004) solved a correspondence problem between two planar shapes by calculating geometrical similarity for each point. With the warping method, Fadaifard and Wolberg (2013) shows a mesh grid based deformation system on 2D images with feature points manually provided by each user. In their system, they showed a 2D image warping system to overlay garments over targeted mannequins in arbitrary poses.

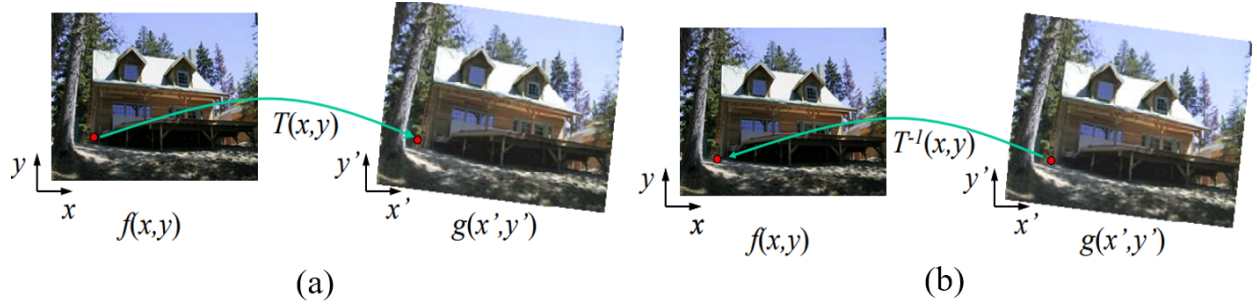


Figure 2.4: (a) Forward warping sends each pixel location to its corresponding target pixel. (b) Using predetermined pixel positions with their correspondence to the source, the pixels in the source move to target locations.

## **CHAPTER 3: INITIAL EXPERIMENT FOR INDIRECT EFFECT ON VISUAL PERCEPTION**

In this chapter, we present our first research experiment for virtual body ownership illusion and spatial presence based on enhanced visual perception that is enabled through indirect cues. Basically, we focus on the virtual hand in various experimental setups and measure each participant's subjective and objective responses in a virtual environment. To arouse enhanced visual perception through a personalized body while participants have a virtual body, we implemented a virtual hand that replicated a participant's hand along with a mirror-reflected personalized lower body.

### **3.1 Overview**

In this experiment, we explore the effectiveness of appropriate indirect visual cues to elicit visual perception from an irrelevant body part using a virtual mirror to provide a personalized real body cue as a component for enhanced visual perception for the illusions. The motivation for this experiment is the fact that there is no prior evidence in the literature of the influence on body ownership of sensory data associated with parts of the user's body that are not directly associated with the task being performed. For example, if arms and hands are the functional parts in a first-person perspective game, do other body parts such as the torso or legs affect the person's sense of illusion in ways that can increase or decrease the sense of body ownership? To observe the effect, we conducted a virtual mirror-based experiment. Specifically, we created a virtual reality system that has four mirror-reflected body conditions in which a participant can see his or her real lower body, a human avatar's lower body, a generic avatar's lower body or no lower body in the virtual mirror (Figure 3.1).



Figure 3.1: The first person perspective of a participant seen in the four cases of mirror reflected body cues in a virtual room during the experiment with logs-on-fire condition. We indicate the mirrors with red color rectangles. (a) Real body reflection on a mirror, (b) No body reflection on a mirror, (c) Human Avatar body reflection on a mirror, (d) Generic Avatar body reflection on a mirror.

The research questions posed here are: (1) “Does the implication of body cues create connectivity between the mirror-reflected real body and the virtual hand even though we know from visual appearance that the hand is not our own hand?” If yes, (2) “Does the indirect use of implicated body cues influence the sense of body ownership of one’s hand and of one’s sense of presence?” In order to investigate these research questions, we designed a simple task-based experiment in a virtual reality system. Since our main focus is the effects of the real body cue, we designed a system to compare these with other conditions - human avatar body cue, generic avatar body cue, and no body cue. To compare them, we prepared four conditions: real body, human avatar body, generic body and no body. To minimize the distraction from repeated tasks, we divided the four conditions into two comparison groups: (1) real body VS generic body VS no body, which we call the Rs set, (2) human avatar body VS generic body VS no body, which we call the Hs set and generic body and no body as a baseline. We also present analysis for comparison from a group: real body vs human avatar, which we call the Ts set. We assume that different levels of virtual body ownership may happen in our study when we use a human avatar, and so we separated the real body case and human avatar body case into different groups to investigate this phenomenon. We conducted a within-subject test for both the Rs set and the Hs set, respectively, and conducted

a between-subject test with the two sets. In this experiment, we hypothesized that the real body cue will give the greatest sense of body ownership and presence; that the human avatar cue and generic cue will give equivalent senses of body ownership and presence; and that no body cue will give the least sense of body ownership and presence to the participants. Here, we summarize our hypotheses.

- **H1.** Observing the mirror-reflected real body will produce a strong connection between a participant's physical body and the virtual hand.
- **H2.** This strong connection gives a sense of body ownership for the virtual hand and presence in the virtual room.
- **H2.1.** The real body cue will give the strongest sense of body ownership and presence.
- **H2.2.** The human avatar body cue and generic body cue will give equivalent senses of body ownership and presence.
- **H2.3.** The no-body cue will have the lowest sense of body ownership and presence.

## 3.2 Experimental Design

### 3.2.1 *Participants*

The total number of participants of the Rs set was 19 – 14 were male and 5 were female. There were 8 Asian, 6 White, 1 Hispanic, 3 Black and 1 unknown. The average age was 23.4 ( $SD = 5.08$ ).

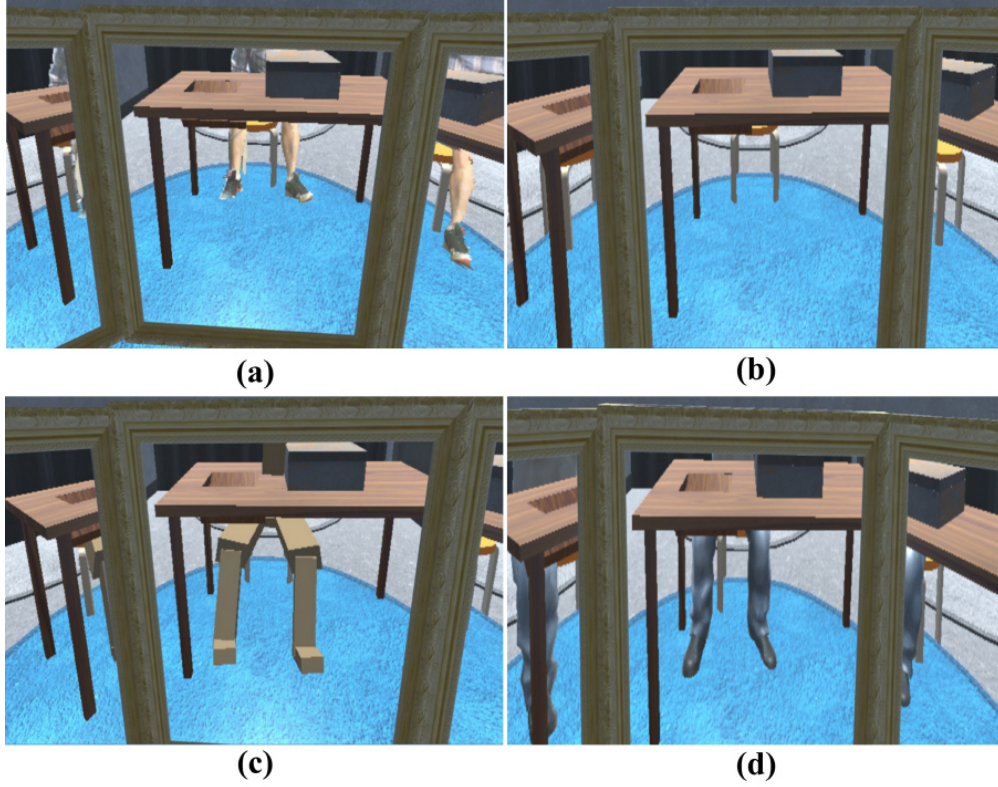


Figure 3.2: Zoom in version of four cases of mirror reflection, (a) shows real lower body reflection, (b) shows no reflection, (c) shows generic lower body reflection and (d) shows human avatar's lower body reflection

### 3.2.2 *Material*

To explore these hypotheses, we created a room with virtual mirrors so the participant could see the mirror-reflected lower body part during the experiment. As our goal was to represent only the participant's legs through the virtual mirror, we removed the body part above the middle of the torso, including the arms of the human generic avatar. However, participants could partially see their own upper parts during the real body case, a situation we will address in the discussion section (Figure 3.2). Participants were asked to do a simple 'pick and drop' based task in a virtual reality environment. We conducted the study with counter-balanced ordering to remove any ordering

effect. The study was approved by the at the University of Central Florida's Internal Review Board Office.

To include a real body in a virtual mirror room with hand interaction, a Leap Motion was attached to an Oculus Rift (DK2) and a Kinect 2 was used. We prepared the participant's interaction room that was isolated with muted lighting to minimize distractions. We used the point cloud from the Kinect 2 to render the real body reflection on the virtual mirrors, having placed the participant's stool 2.5 meters from the Kinect 2. Each participant was asked to sit on a stool to do a task, and they could move their head or upper body with the head tracker provided by an Oculus Rift that was placed in front of the participant's stool at the same 2.5-meter distance as used with the Kinect 2. In a separate room, we call a questionnaire area, participants were asked to fill out questionnaires while sitting on a chair. We prepared six types of hand models to match each participant's race to be reasonably consistent with each individual's skin color. In this study, we prepared realistic virtual hand models for Black, Asian and White females and males. These are selected based on demographic information and are positioned using the Leap motion to properly match the participant's hand. Similarly, we prepared a generic avatar and the human avatar with male and female versions, respectively. Those avatars did not have bodies above the middle of the torso that included arms and head because those body parts were not relevant to our study and interfered with the hand interaction in the virtual environment. We did not measure the end-to-end latency of tracking since the high tracking fidelity of the Kinect 2 for the sitting position allowed participants to see their leg movements via the virtual mirrors without any critical latency problems. On rare occasions, we asked a participant to enter a neutral position for their legs when they crossed their legs, which introduced a tracking problem.

We ran our system using an Intel Core i5 with 8GB DDR memory and a GeForce 970. The virtual environment was developed using the Unity game engine. We prepared three types of questionnaires: demographic, interval and post. We organized the interval questionnaire into two sections,



body ownership related items and presence related items using a 7- point Likert scale, 1 with Not at all, 4 with Neutral, and 7 with A Great Deal. The items for body ownership contain body connectivity related questions as well. We created some of our own questions for body ownership, adopted body ownership related questions partly from Argelaguet et al. (2016a) and adopted the presence related questions partly from Bob G Witmer (2007). We provide the details on interval questions in Table 3.1. The post questionnaire mainly consisted of body ownership and presence related items, with the purpose of comparing three different cases after finishing all tasks. We created the post-questionnaire as a forced choice among three conditions within each Rs and Hs set. The details on post questions are in Table 3.2. Participants were asked to read our informed consent and fill out their demographic information before entering the interaction room in the questionnaire area. After they had filled out their demographic data, we gave them information about our study related to a task and a manipulation of the system. Each participant had three kinds of body cue, and each case had three three-minute tasks. We explicitly told participants that they will have a virtual hand, which is not modeled on their real hand because we wanted to remove any misunderstanding of the virtual hand in their interaction.

After receiving an explanation of the session activity for the study, the participant moved to the interaction room and was equipped with the Leap motion-attached Oculus rift (DK 2) and headphone while sitting on the stool. The participant listened to an announcement of instructions for the study in our virtual mirror room. That announcement was delivered through headphones using a recorded native American speaker's voice. After completing all the tasks in a session, the participant was asked to fill out a questionnaire in the questionnaire area. We repeated this three times with three different cases, respectively. Finally, we asked the participant to fill out a post questionnaire after completing all sessions. We asked each participant to do a pick and drop based simple task that is similar to Argelaguet et al. (2016a); Steed et al. (2016) with different obstacles and different body conditions.

Table 3.1: The question component in the interval questionnaire.

Item	ID	Question
VBOI (Connectivity)	1	You had the feeling that the mirror-reflected legs were part of your real body.
	2	You had the feeling that the virtual hand and the mirror-reflected legs were connected to your own body.
	3	You had the feeling that you observed the mirror-reflected legs and they matched your legs movements during the experiment.
VBOI	4	You had the feeling that the virtual hand was your own hand.
VBOI (Treat)	5	You had the feeling that you were in danger of burning your own hand when you moved or touched the small burning logs.
	6	You had the feeling that the temperature of your own hand was increased when you moved or touched the small burning logs.
	7	You had the feeling that you wanted to avoid the small logs often because they were burning.
	8	You had the feeling of either being amazed or disgusted as if the spiders touched your real hand when you moved or touched the spiders.
	9	You had the feeling that spiders were moving on your real hand when you moved or touched the spiders.
	10	You had the feeling that you wanted to avoid the spiders often because you were either amazed or disgusted.
	11	You had the feeling that you wanted to wash your hand with sanitizer or a tissue after finishing the experiment.
VBOI (Agency)	12	You had the feeling that you could control the virtual hand as if it were your own hand.
	13	You had the feeling that you could pick up and drop objects naturally.
Physical Presence	14	You had the feeling that the virtual environment was a real space
	15	You had the feeling that the spiders existed in front of you.
	16	You had the feeling that you were involved in the virtual environment experience.
	17	You had the feeling that you could observe the virtual room well during the experiments.
	18	You had the feeling that the hand or the legs were on fire in your space.
Dizzy	19	You became dizzy during the experiment.

In the virtual room, the participant had a table that had a hole on their left side and a metal box with a button on their right side. When the participant touched the button, the box lid opened and there were 20 wooden balls in the box. The task was to pick a ball and drop the ball into the hole completing this for at least 15 balls. However, the task purpose was not the task performance but was rather to get them to observe their surroundings in the virtual room. To afford the participants sufficient opportunities to observe the virtual room, we designed the task completion time so the participants would have to spend three minutes on each task.

Table 3.2: The question component in the post questionnaire.

Item	ID	Question
VBOI	1	In which condition did you feel the most realistic sense of using your own hand during the experiment?
Physical Presence	2	In which condition did you feel the most realistic sense of being in a real room during the experiment?
VBOI (Threat)	3	In which condition did you feel the greatest temperature rise when you touched the small burning logs?
	4	In which condition did you feel the most amazed or disgusted when you touched the spiders?
VBOI (Agency)	5	In which condition did you feel most natural control of the virtual hands?
Physical Presence	6	In which condition did you see the mirror-reflected legs most frequently during the experiment?

Actually, most participants had more than one minute to look around the room after their task completion since the task was not hard. In this experiment, the mean value of reported difficulty for the task is 2.684 for Rs set ( $SD = 1.35$ ) and 2.333 for Hs set ( $SD = 1.08$ ) on a 7-point Likert scale. Each task took approximately 10 minutes per case to complete so about 50 minutes were spent per participant, including all steps.

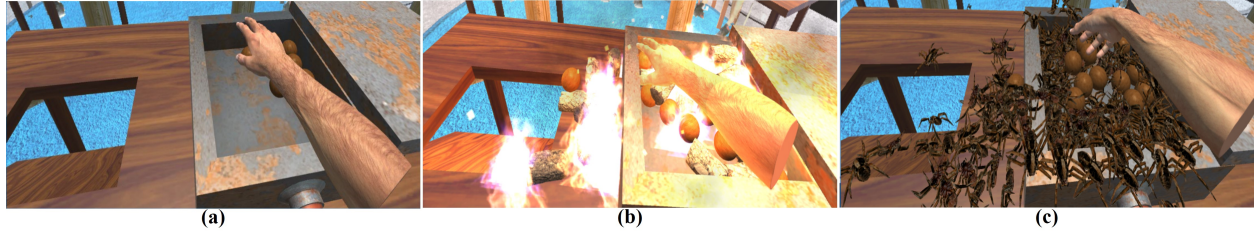


Figure 3.3: Three types of threats while the participant completes a 'pick and drop' task. We asked the participant to grab a ball in the metal box and drop the ball into the hole in the table in 3 minutes per task conditions. (a) Without any interference condition during the task. (b) With logs-on-fire condition during the task. (c) With an animated spider condition during the task.

In this experiment, we designed three different kinds of obstacles: no obstacle, logs on fire and animated spiders (See Figure 3.3). As luc Lugin et al. (2015) showed an influence of stressful event using fire in their virtual environment, we adopted fire and spider for a stressful event based

on a similar concept.

### 3.2.3 *Methods*

We conducted the experiment as a 3x2 mixed design with a within-subject test and a between-subject test. The within-subject factor is the representation of body cue among the three conditions in the Rs and Hs set. The between subject factor is a representation of body cue between a real body and a human avatar body. Since the only variable is the mirror-reflected body condition and the corrected data is a non-parametric data type, we chose to use the Kruskal-Wallis test for the within-subject test and the Mann-Whitney method for the between-subject test. In our interval questionnaire, we had an item to determine if participants had recognized their mirror-reflected body condition. If they had a wrong answer for this item, we considered all answers of that type from the participant to be noise, so we filtered them out. In our experiment, one participant presented extreme arachnophobia, so we stopped the experiment immediately and filtered out that participant's data as well. We did not filter out based on sickness since the measured value for dizziness was low for all cases ( $M = 2$ ,  $SD = 1.455$  for Real body,  $M = 1$ ,  $SD = 0$  for Human Avatar body,  $M = 1.704$ ,  $SD = 1.38$  for Generic body and  $M = 1.64$ ,  $SD = 1.319$  for No body). We present the Rs set within-subject test result first, and the Hs set within subject test result next. Then we show the result from the Ts set between-subject test. Last, we show the result for the post-questionnaire.

### 3.2.4 *Result*

We have an interesting result for the within subject test with the Rs set (Figure 3.4). The strongest connectivity to the virtual hand was aroused with statistical significance when one's real lower body is observed with the results for ID 1, ID 2, and ID 3 ( $p < 0.001$ ,  $p < 0.002$  and  $p < 0.001$ ,

respectively) so we believe that the results support H1. The result for ID 4, which is a pure Virtual Body Ownership (VBOI) question, represents that the Real body condition has the highest score with statistical significance ( $p < 0.042$ ).

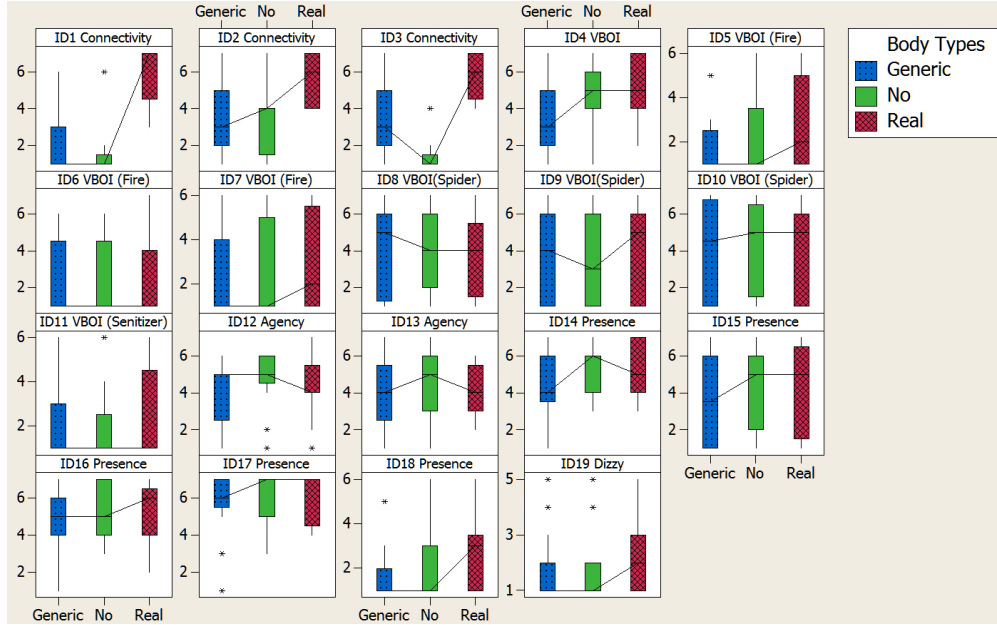


Figure 3.4: We represent a result with median, connected line between median, interquartile range and outlier. We represent all results for all questions.

However, we did not find clear results with statistical significance in the threat-based VBOI. We provided two types of threats using the fire and the spiders. Most of participants did not show any phobia with our threats, except the one person who had arachnophobia. Although no phobia were exhibited, most participants received a strong emotional effect from the spiders, with a weak emotional effect associated with fire. So the average Likert value for ID 4 to ID 11 were located in similar ranges. Therefore, we could not find distinguished results for our participants' sense of VBOI using a Likert scale method. Even though there was a problem of scale, we can see a tendency that one's real body arouses a sense of VBOI by observing that the Real body condition has highest value or higher median than other conditions in ID 5, 7, 9, and 11. Thus, one's real legs

had an effect on body ownership to the virtual hand under the connectivity perspective and direct VBOI perspective, but not under the traditional threat-based VBOI. We did not find statistical meaning for presence perspective, but participants seem to have more presence in the No body condition. We observed that the noise introduced by the point cloud from the Kinect 2 distracted the participants' sense during the Real body condition. Even though we tried to prevent the noise by adjusting the Kinect 2 position, some participants observed the noise when they tried to bend their upper body extremely. We feel that this distracted their sense of presence and VBOI as well. Interestingly, participants have more Agency when they have no body since they feel it is harder to control their virtual hand even though the hand condition was identical for all cases. Thus, we could say that the consecutive hypotheses, H2.1, H2.2 and H2.3, are supported only partially for VBOI (note that we do not include connectivity in VBOI) and are not supported from a presence perspective.

The total number of participants of Hs type was 12 – 9 were male and 3 were female. There were 3 Asian, 8 White and 1 Hispanic. The average age was 22.8 ( $SD = 4.03$ ). From this experiment, we noticed that the human avatar body did not support body ownership sensations as we hypothesized (Figure 3.5). For connectivity, the Human Avatar body condition shows the highest value with ID 1 and ID 3 with statistical meaning ( $p < 0.005$  and  $p < 0.001$ , respectively). However, there is no statistical significance for VBOI and presence in the Hs set. Also, there is no clear tendency for VBOI among the three conditions. We hypothesize that this phenomenon might have happened because of the low personalized visual cue from the all conditions in the Hs set, so the Human avatar body couldn't represent strong VBOI even though it has strong connectivity relative to the other conditions. From the presence perspective, the Human Avatar body did not show a dominant tendency in the result. On the contrary, the generic body condition or no body condition shows more sense of VBOI and presence. Also, it is unclear that one can distinguish the difference for Agency among the conditions from our results.

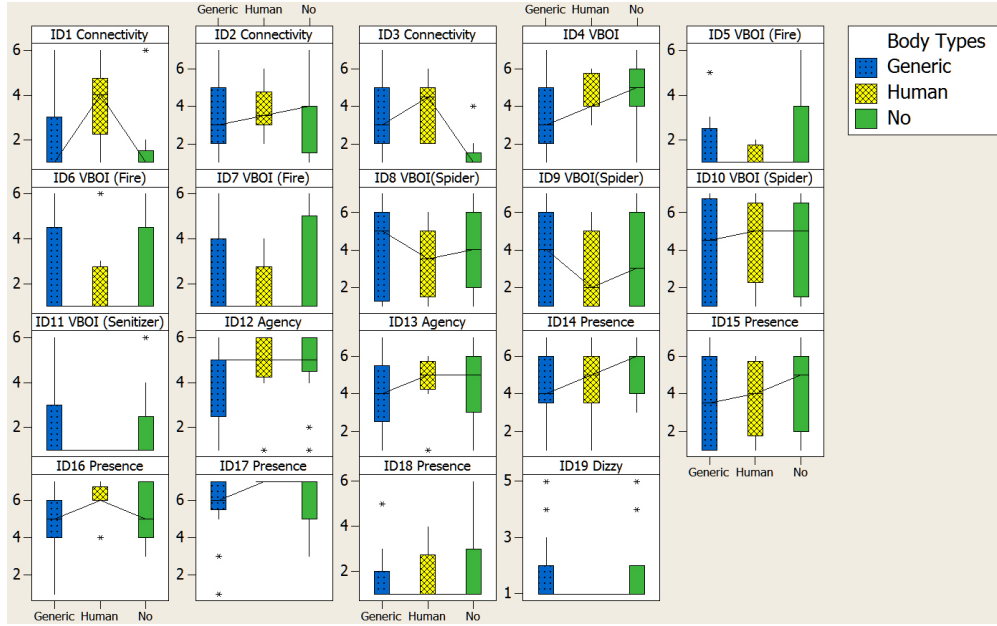


Figure 3.5: We represent a result with median, connected line between median, interquartile range and outlier. We represent all result for all questions.

As a result, the Human Avatar body partially supports H1, but the generic and Human Avatar conditions fail to support H2. Thus, we did not find support for the consecutive hypotheses H2.1, H2.2 and H2.3.

As we mentioned above, we expected this result because of the low personalized visual cue from the human avatar and generic body. Neither body condition with mirror reflection produced connectivity as strong as we expected with the real body, so our results failed to support VBOI and presence clearly. However, we still have an unclear result for presence. Also, the participants felt more comfortable when they controlled their virtual hand in the Human Avatar body condition. In conclusion, we could say that the Real body condition strongly supports H1 and H2 in comparison to the Human Avatar condition.

Finally, we conducted the between-subject test with the Real body and Human Avatar body condi-

tion using the Mann-Whitney method (Figure 3.6). Explicitly, the result shows that the real body condition has stronger connectivity compared to the Human Avatar body condition with statistical significance in ID1, 2 and 3 ( $p < 0.008$ ,  $p < 0.01$  and  $p < 0.02$ , respectively). From the result, we conclude that there is a clear tendency for the Real body condition to induce more VBOI than the Human Avatar body. To provide a direct comparison among the types in the within test sets, we asked participants to fill out the post questionnaire after they had finished all the sessions. We present the questions in Table 3.2 in the previous section and the result chart in Figure 3.7 and Figure 3.8. In the post-questionnaire, we asked participants to choose their best sensation among conditions. In both graphs, the bar represents the number of participants who selected each condition. Even though the questionnaire consisted of a forced choice set, some participants failed to mark or decide. So the number is not equal to the total number of participants in both sets, respectively. The figure 3.7 graph shows an accumulated value of the participants's choices in the Rs set and the figure 3.8 graph shows results in the Hs set. We observed a dominant tendency that most participants were satisfied with the Real body condition for VBOI and presence compared to the Generic body or No body cases in the Rs set. The ID 1 and ID 2 sets show strongly differences, which are core questions for body ownership and presence, respectively.

However, there was not a clear difference in the Hs set. An interesting phenomenon was observed from ID 5 in the Rs set that indicated Agency. A result from the interval question in the Rs set indicated that the real body condition did not give the highest sense of Agency so the results seem conflicted. We believe that the participants recognized the ID5 as a preference for their control environment, not only a functional control. Therefore, they recalled that the real body condition was most natural to control the hand because it gives greater visually correct body information than the other conditions.

In conclusion, the result is not supported by statistical values, but we can observe the participants' preference in our experiment.



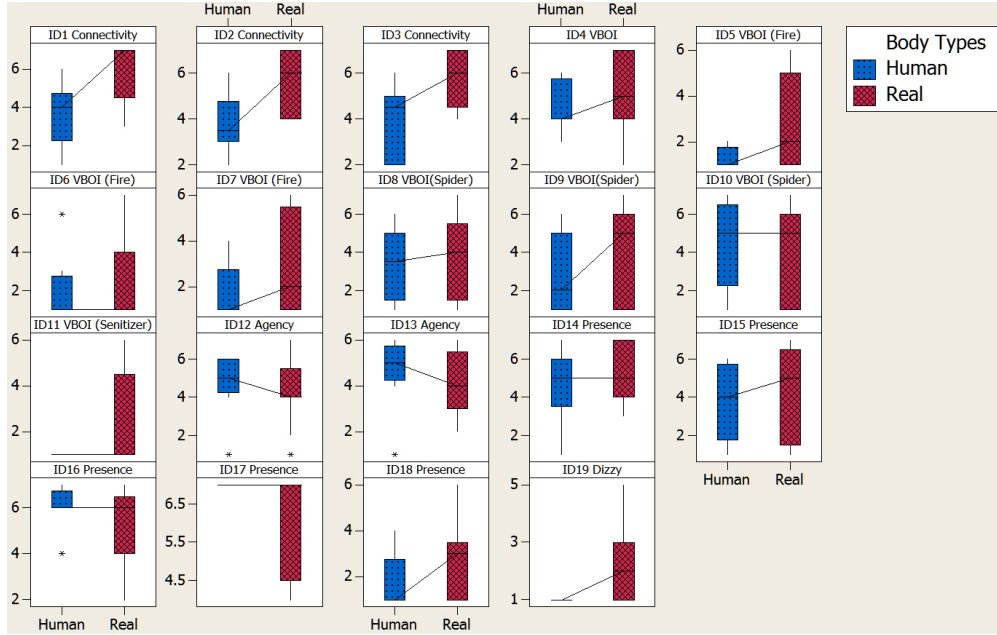


Figure 3.6: We represent a result with median, a connected line between median, interquartile range and outlier. We represent all result for all questionnaire items.

The results represent a tendency that a real body cue elicits more sense of body ownership effects rather than other body cues with statistical difference support for some parts.

However, we did not see the tendency in all statistical data, especially in presence. We conjecture the reasons that some participants did not recognize the changes in their mirror reflection was, perhaps, because the mirrors were located a little too far from the participants. Also, as we conducted the study in the summer, some participants wore shorts so that they had trouble recognizing their real legs because they could not see their skin color well since we use the point cloud from the Kinect 2. In comparison, the participants who wore long pants recognized their legs well. The other problem of the point cloud from the Kinect 2 was its artifacts which worked as a deal-breaker for body ownership and presence when participants see these artifacts. Because our focus was real body cue, we began the study with the Rs set first, so the total number of participants was different between the study groups, which may affect the accuracy of analysis of the experiment.

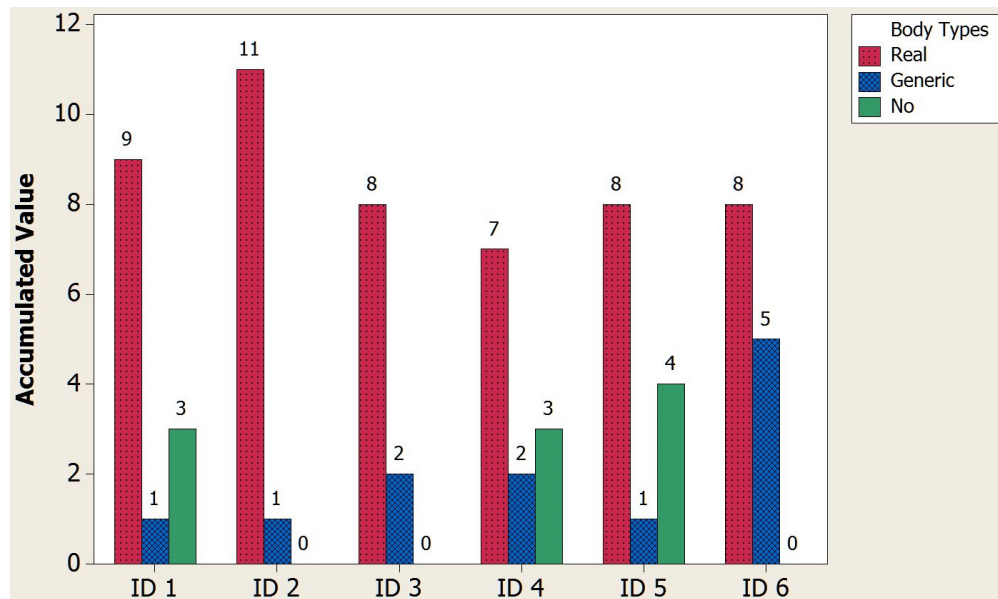


Figure 3.7: In the Rs set, the Real body shows a dominant difference compared to the Generic and No body conditions.

Also, some participants tried to see their upper body part by bending their bodies into extreme positions, but they may have felt weird when they saw the invisible upper body in the generic and human avatar cases.

Otherwise, they could see their upper body part in the real body case so that it may create a bias for the result as well. Finally, the study task was more stimulating than our intention so it was hard to detect a difference among the body conditions for the sense of illusion. For example, most participants had a strongly disgusted sensation with the animated spiders; they had similar answers with our Likert scale-based questionnaire under all conditions as we mentioned.

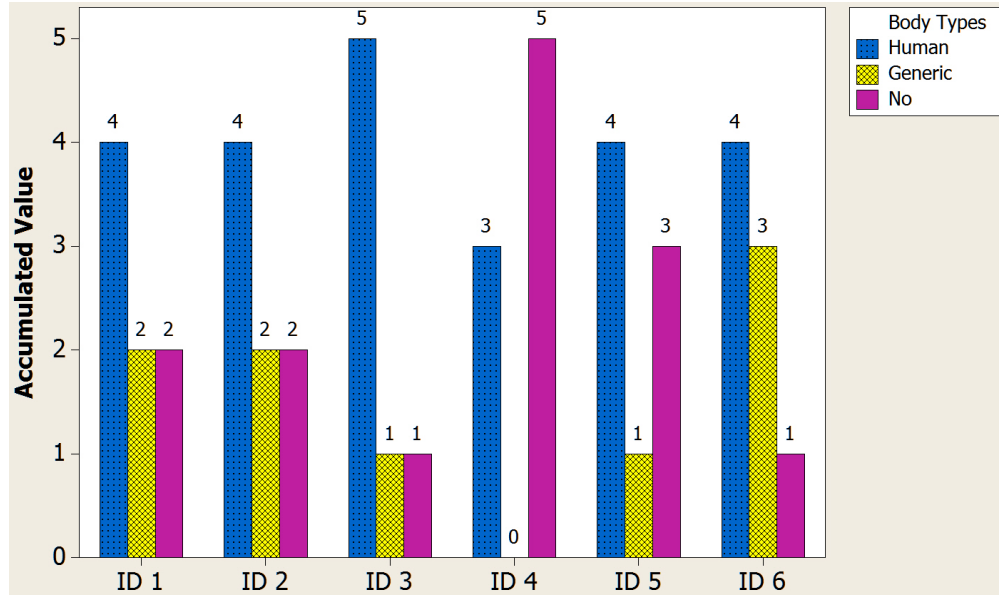


Figure 3.8: In contrast to Rs set, ID 1 and ID 2 in Hs set, significant difference was not shown

### 3.2.5 Discussion

In the next chapter we apply lessons learned from the experiments discussed here. In particular, the experiment described in Chapter 4 avoids the artifacts we encountered when using the Kinect, while still focusing on indirect cues, and investigating factors related to body continuity and agency.

# **CHAPTER 4: REALME: INFLUENCE OF ARTIFACT-FREE INDIRECT REPRESENTATION AND CONTINUITY ON VIRTUAL BODY OWNERSHIP**

## **4.1 Overview**

Even though we had a positive effect of personalized real body cue from mirror reflection for the dominant illusions, our prior research showed limitations such as artifacts from point cloud rendering. Therefore, in this experiment, we developed a revised artifact-free experimental platform for the personalized real body cue effect on virtual body ownership illusion and spatial presence. Since our perception is closely related to visual stimulations in the human brain Velmans (1998), we could show the effect of visual perception more explicitly in this study. In fact, a human can notice realistic body features (color, texture, etc.) because our brain forms the connection based on explicit and implicit memory associated with the actual body, Fuchs (2012). Based on this insight, we began to measure the effect of real body cues for virtual body ownership, Jung and Hughes (2016). In the study reported here we extend those earlier experiments to investigate the interplay between arm-hand continuity, freedom of hand movement in the presence of a threat, and realism of a lower body reflection that is personalized but not directly relevant to the user's central focus. Our goal is to see how combinations of each of these influence illusions of virtual body ownership and presence.

## 4.2 Experimental Design

### 4.2.1 *Participants*

For this experiment, we conducted an a priori power analysis to determine our sample size before recruiting participants. Using G\*Power to detect a medium effect size with a power of 0.80, we needed a minimum total of 24 participants, Franz et al. (2007b). We recruited participants with normal to corrected-to-normal vision using on-campus fliers. Most participants had higher education backgrounds and were studying in diverse majors, but mainly in computer science. We conducted our experiment with 21 participants (15 male, 6 female,  $M = 21.1$ ,  $SD=2.92$ ) for personalized visual body representation and 20 (15 male, 5 female,  $M = 21.65$ ,  $SD=2.50$ ) for avatar body representation. Because of a data logging problem, we omitted one person's data (male) from the personalized body cue group. Therefore we conducted the experiment with 40 participants total. Most of participants had a small number (under 5 times) of experiences wearing an HMD. We gave each a \$10 gift card for their participation.

### 4.2.2 *Material*

In this research study, we investigate the effect of personalized body cues on body continuity, testing two levels of detail. Also we examine agency, Tsakiris et al. (2007), which is a sensation for controlling the virtual body, because the coordination of movement and visual perception, visuo-motor, has been shown to be a significant factor for virtual body ownership, Sanchez-Vives et al. (2010). In our experiment we not only focused on virtual body ownership but also spatial presence, the sense of "being there" Slater et al. (2013a), since the sense of presence in a virtual environment is closely related to virtual body representation, Schuemie et al. (2004). We designed our experiment to provide either a visually personalized body cue or a generic avatar body cue, always

seen as a reflection of one's lower body in the absence of artificial tactile sensory stimulation. To investigate the effect of a visually personalized body cue, we placed a virtual mirror in front of the participants so they could see their lower body reflections (Figure 4.1 (a)). A virtual mirror was also used in previous research by Jung and Hughes (2016); Kilteni et al. (2013). Those studies showed that seeing a reflected avatar body from the first person perspective helps to elicit a greater illusion of body ownership than if there is no visual representation. The study reported here builds on those previous experiments by comparing the influence of a personalized visual body cue versus that of a generic avatar body cue. The virtual mirror was positioned so participants could observe their reflected lower body, mainly their legs, while performing a specified task with a virtual hand. To prevent a bias from rendering artifacts as described in Chapter 3 and Jung and Hughes (2016), we used the RGB pixel values and the depth information from an RGBD camera to render the participant's lower body. Because of the low resolution of our RGBD camera, the reflected image on the virtual mirror seemed relatively fuzzy, but most participants easily recognized the personalized body rendering as their own body. While participants looked at the virtual environment involving the mirror reflection, we provided two levels of virtual arm/hand representation – fully rendered from shoulder to hand, and arm removed disconnected hand (Figure 4.2 (a) and (b)) with two types of motor action – a movement-enabled hand and a movement-disabled hand. Each participant experienced one of two body reflection types with all two hand levels and both motor action conditions, so the total combinations of conditions experienced by a participant were four. We clearly asked each participant to occasionally look at the body reflection while they were performing the given task, which means that, except for the visual difference, all conditions were identical for all participants.

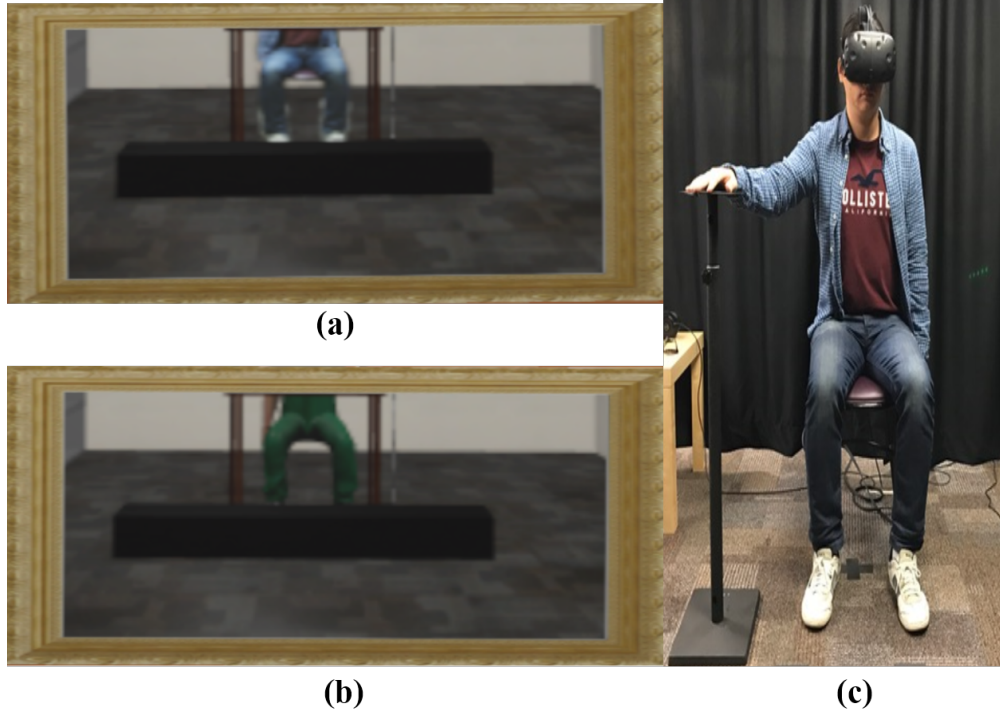


Figure 4.1: We provided two types of body reflection through a virtual mirror while the participants looked at a virtual hand and arm from a first person perspective. (a) Visually personalized body reflection where the clothes and shape are identical to those of the participant seen in (c). (b) Generic Avatar body representation.

#### 4.2.3 Method

To investigate the effect of a personalized visual body representation, we developed a virtual office space that includes a virtual mirror to reflect a personal body or avatar body as a visual cue. In this experiment, we examined virtual body ownership including body continuity and agency, and presence as dependent variables. For independent variables, we chose varying body representations, levels of hand representation, and motor action capabilities. We used a subjective measurement based on a questionnaire with a 7-point Likert scale. Our experiment is a 2x2x2 mixed Within-Between factorial design intended to show the effect of a personalized body representation.

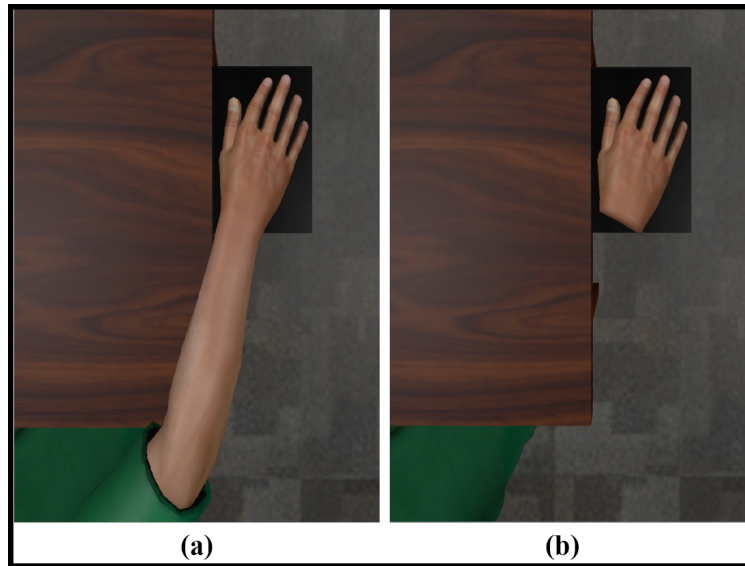


Figure 4.2: (a) Fully modeled limb from shoulder to hand. (b) Arm removed resulting in disconnected hand.

We divided the participants into two groups, one for personalized visual body representation, and one for generic avatar body representation (Between factor with two levels). Each group experienced both hand representations (Within Factor with two levels) and motor actions (Within factor with two levels). To prevent an ordering effect, we used a counter-balanced ordering. Our experiment was approved by the Internal Review Board Office at the University of Central Florida. Starting with results from our previous research, we conducted our experiment to find answers for the following research questions: (1) “Do the personalized visual body cues create psychological continuity between a participant’s real body and their purely virtual hand?” If yes, (2) “Do the personalized visual body cues influence the sense of body ownership of one’s hand and of one’s sense of presence?” The following hypotheses are based on our previous research results and our beliefs concerning the effect of a personalized visual body representation. For each of the first three cases, we expect to elicit significantly higher levels of perceived a) Body Continuity, b) Body Ownership, c) Presence, and d) Agency for the first of the two options specified.



- **Body Representation** Using a personalized visual body reflection will be more immersive than having a generic avatar body reflection.
- **Body Continuity** A virtual body with a continuous, full arm will be more immersive than a hand-only virtual body.
- **Body Motion** Allowing users to move their hand will be more immersive than requiring them to keep their hand in a static position.
- **Combination** The combination of personalized body representation with a full hand, enabled with dynamic motor action, will give the highest levels of VBOI, BC, agency and presence.

We designed a physical experiment space isolated from any visual interference. To reduce fatigue for the participants during the experiment, we had them sit on a stool and rest their right hand on a stand. We used an HTC Vive to provide the virtual environment, and the HMD was tracked using the Vive's tracking system. To render each participant's lower body, we placed an RGBD camera in front of the stool so we could capture their lower body. We created a virtual office model similar to the physical experiment space except for the presence of a table and small foot occluder in the virtual space (Figure 4.3). In the virtual office, we included a table in front of the participants and a prop to their right side that mimics the stand present in the real space. To represent the personalized visual lower body part seen on the virtual mirror, we rendered the RGB pixel value with matched depth value on a plane and reflected the image onto the virtual mirror. Because of limited fidelity of the depth value for thin body parts, the feet were not rendered correctly so we hid that part with a block cube occluder located on the floor. To elicit a protective reaction, we dropped a photorealistic rock five times onto the participant's virtual right hand (See Figure 4.4). As a subjective measurement, we created an instrument that consisted of questions about virtual body ownership, body continuity, agency, and presence using a 7- point Likert scale – 1 for

strongly disagree, 4 for Neutral, and 7 for strongly agree. For virtual body ownership, including body continuity and agency, and presence questions, we used questions adapted from Witmer and Singer (1998); Pérez-Marcos et al. (2012); Jung and Hughes (2016); Argelaguet et al. (2016a); Tieri et al. (2015) with modifications appropriate to our study. We provide the details on interval questions in Table 4.1.

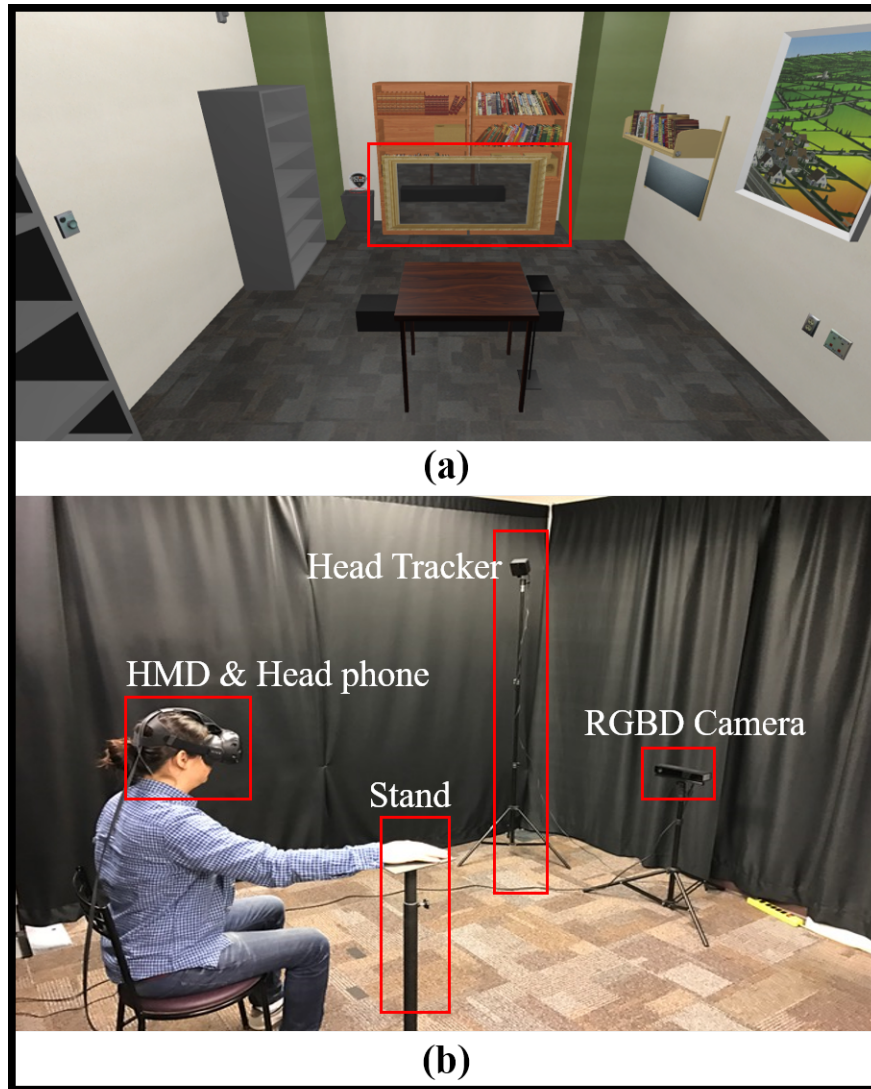


Figure 4.3: (a) Virtual office. (b) Physical setup

Table 4.1: The questionnaire of a second indirect visual perception experiment

Item	Question
VBOI	You felt as if the virtual hand was your own.
	You felt that your hand was endangered by the falling rock.
	You felt as if the virtual hand started to look like your own.
BC	You felt as if the virtual hand was connected to your body.
	You felt as if the virtual hand was a part of your body.
Agency	You felt as if you could control the virtual hand.
Presence	You felt as if you were physically present in the office room.
	You felt as if you were in a virtual setting.

Prior to starting the experiment, we asked each participant to read our informed consent and fill out their demographic information. After they had filled out demographic data, we asked them to sit on a stool in the experiment room and gave them information about our study related to a task and manipulation of the system. We were especially insistent that their initial pose had them sitting on the chair in a normal forward facing position and that they placed their right hand on the physical stand. We then placed the Vive HMD and headphones on the participant and asked them to look at their right arm, from the shoulder to hand, at least once, and to look at the virtual mirror as well. The participant listened to an announcement of instructions for the study in our virtual office. That announcement was delivered through headphones using a recorded native American speaker's voice. Each participant had two kinds of hand representations with two motor action capabilities and one of two body reflections, so four sessions were conducted with each participant. For each session, we gave the participant one minute to look at the environment, including the arm and hand, and the mirror reflection. After the participant had observed the virtual setting, we began to drop a photorealistic rock onto the virtual hand five times, randomly distributed over a one-minute interval with a corresponding hitting sound effect (Figure 4.4). We provided a 30-second break time for their right hand and refreshing their sense. During the rest time participants were still wearing the HMD in turned off mode (black screen) before beginning the next session. When in the static motor action condition, participants were not allowed to move their hand and fingers. They could,

however, move their legs and head. Therefore they passively observed the rock dropping events on the virtual right hand that was fixed in position.

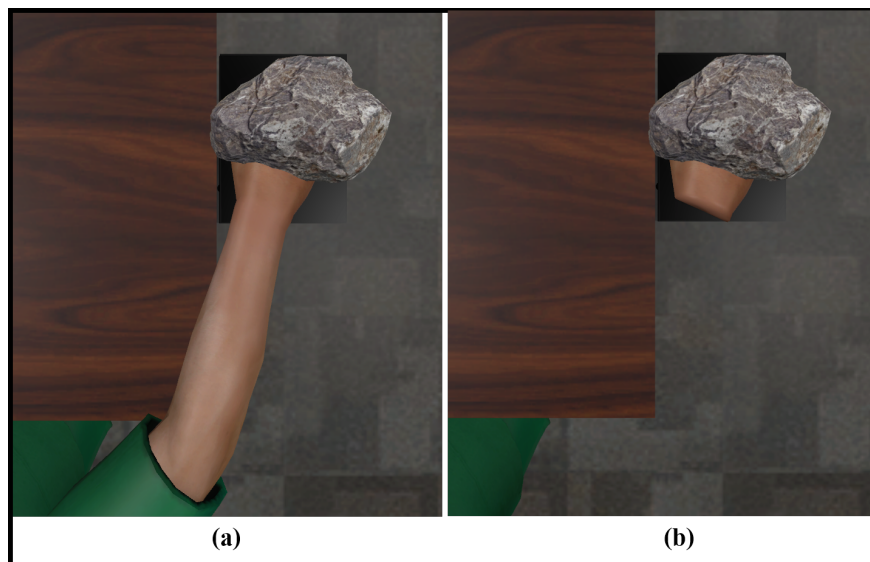


Figure 4.4: We dropped a photorealistic rock onto participant’s right virtual hand five times. (a) Dropped rock onto a fully represented hand. (b) Dropped rock onto arm removed hand.

#### 4.2.4 Result

In the dynamic motor action condition, participants were allowed to move their real hand, resulting in a corresponding movement of the virtual right hand. Thus, in the dynamic condition, they could actively avoid the dropping rock. After finishing each task, whether static or dynamic, we asked participants questions through the headphone, and participants answered these verbally. After finishing two sessions with each of the hand representations, we gave the participants a three-minute break and resumed with the other two sessions with a different motor action condition. After completing all tasks, we asked the participants whether they noticed the different hand representations and their recognition as regards the reflected body representation. We present our results for the effect of the personalized visual body cue as the dominant virtual illusion. As we described in the

experiment section, we ran our study as a 2x2x2 mixed Within-Between factorial design. Before we analyzed the data, we clustered the measured data into identical categories. Our two presence question were slightly modified versions of pre-validated ones from Witmer and Singer (1998), with the first of these having an explicit reference to the office setting we used. Participants gave higher ratings to the second presence question (See Table 4.1); we assume that they thought the question's use of the phrase virtual setting had a stronger influence on their answers than their reporting an actual sense of presence. However, we still have a significant difference for body representation (user versus avatar reflection) in both presence questions, ( $p<0.002$ ) and ( $p<0.015$ ), respectively, without any interaction effect. To analyze the subjective measurement, we used general Multivariate Analysis of Variance(MANOVA) for all dependent variables. Our results show that body representation had more of an effect on VBOI than any other independent factors from the main effect result (Figure 4.5).

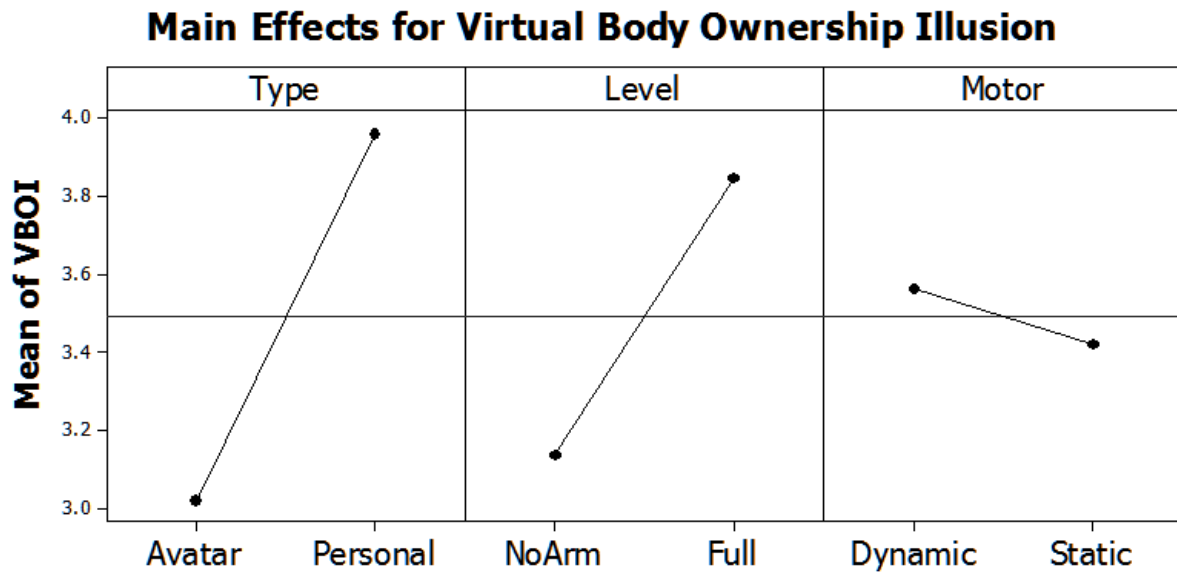
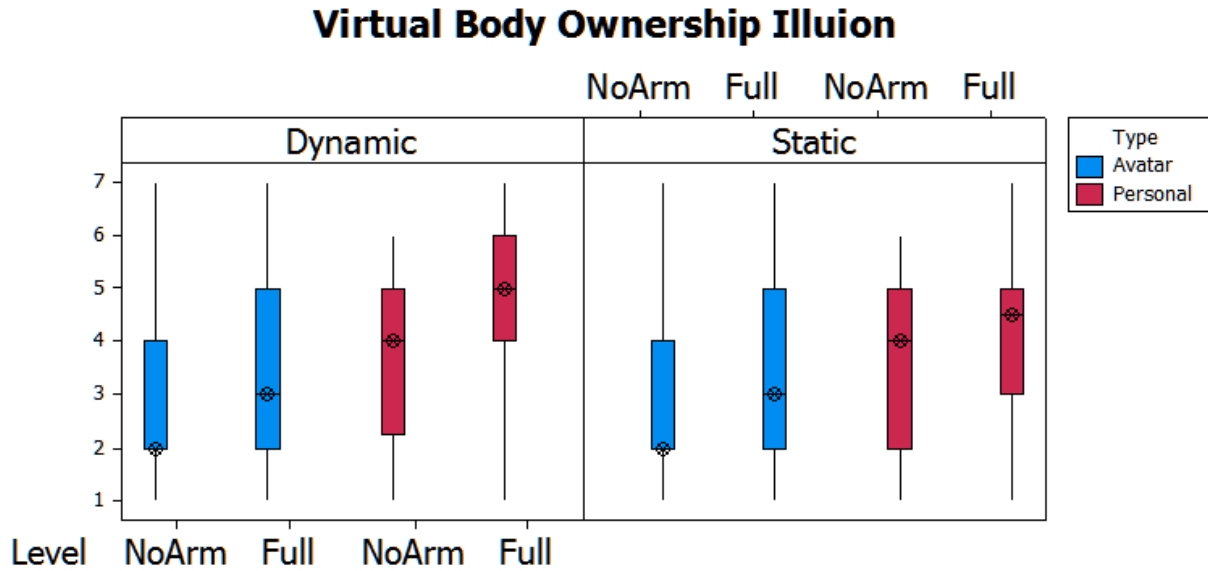


Figure 4.5: Body representation type and hand representation level show a significant difference in virtual body ownership.

As we expected, the fully modeled arm and hand gave a higher sense than the hand-only condition. The motor action did not show any significant difference between the dynamic and static conditions for VBOI. We did not find a significant interaction effect between body representations and hand representations, and between hand representations and motor conditions, but we found a small significant interaction effect between the motor conditions and body representations. Specifically, we found a significant difference between body representations ( $p < 0.001$ ) and hand representations ( $p < 0.001$ ) for virtual body ownership. We confirmed that all dependent measures were normally distributed before analyzing these data. Using mean values, we confirmed that the personalized visual body representation elicited a higher sense of VBOI ( $M = 3.958$ ) than the avatar body representation ( $M = 3.025$ ). Also, the fully modeled arm and hand ( $M = 3.846$ ) elicited a higher sense of VBOI than the hand-only condition ( $M = 3.138$ ). Consequently, the personalized visual body representation with fully represented arm and hand in the dynamic motor condition showed the strongest effect on virtual body ownership (Figure 4.6). We provide statistical results for VBOI in Table 4.2.

Similar to virtual body ownership, we observed an interesting result explicitly seen in the main effect result (Figure 4.7). The personalized visual body representation shows a significant difference in body continuity in comparison to the avatar body representation. Also, the result shows that hand representation had more of an effect on body continuity than any other independent factor. As we expected, the personalized body representation gave a higher sense of body continuity than did the avatar body representation. The motor action did not show any significant difference between the dynamic and static conditions for body continuity as well. We did not find a significant interaction effect between body representations and hand representation, and between body representations and motor conditions, but we found a slight interaction effect between the hand representations and motor conditions. We found a significant difference of body representation ( $p < 0.001$ ) and hand representation ( $p < 0.001$ ) for BC, which is identical to the virtual body ownership result.



between body representations and hand representations, but we found an interaction effect between the hand representation and motor conditions.

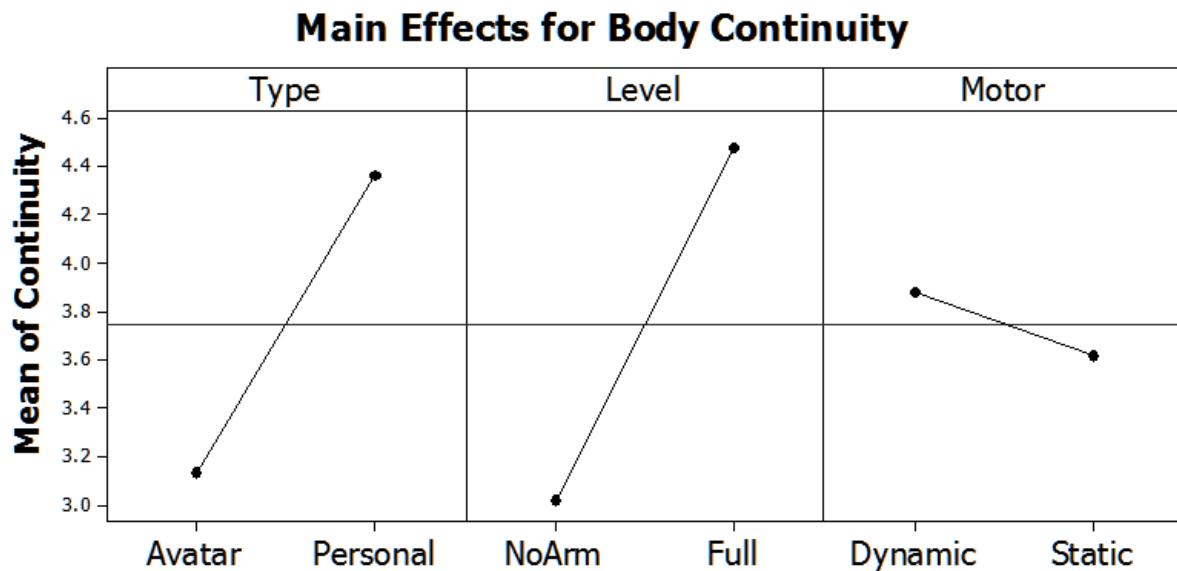


Figure 4.7: Body representation type and hand representation level shows a significant difference in body continuity.

We found a significant difference in motor condition ( $P < 0.001$ ) only for a sense of agency. We confirmed that all dependent measures were normally distributed before analyzing the data. Using mean values, we confirmed that the dynamic motor condition showed a higher sense of agency ( $M = 5.038$ ) than the static motor condition ( $M = 3.150$ ). Not surprisingly, the choice of motor condition showed a significantly higher effect on agency than any other variation (Figure 4.9). We provide statistical results for a sense of agency in Table 4.2. We observed interesting main effect results regarding body representation type and sense of presence (Figure 4.11). The personalized visual body representation shows a significant difference in presence compared to the avatar body representation.



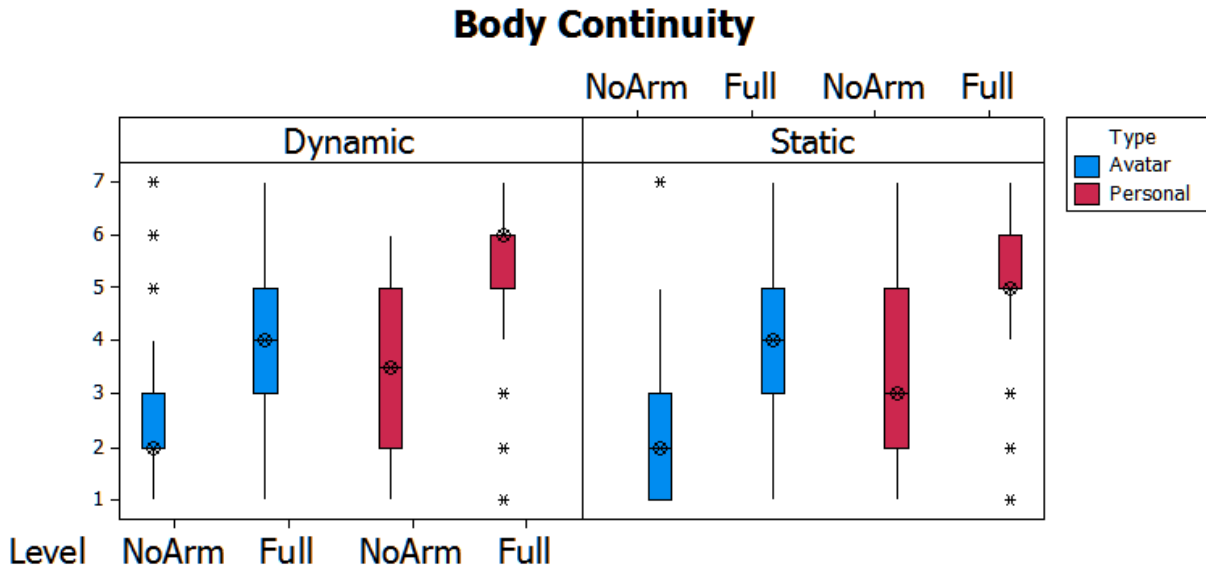


Figure 4.8: Personalized visual body representation shows higher sense of body continuity than avatar body representation in all identical conditions. We represent the interquartile range box with outlier and median symbol.

The hand representation did not show any significant difference between the full arm and hand and hand-only representations.

The motor action did not show any difference between the dynamic and static conditions for a sense of presence. We did not find a significant interaction effect among independent factors. We found a significant difference of body representation ( $P < 0.001$ ) for presence. We confirmed that all dependent measures were normally distributed before analyzing data. Using mean values, we confirmed that the personalized visual body representation showed a higher sense of presence ( $M = 5.619$ ) than the avatar body representation ( $M = 5.056$ ). Also, the personalized visual body representation shows a higher effect on presence than the avatar body representation in identical condition (Figure 4.12). We provide statistical results for presence in Table 4.2. As we expected, the illusion effects of a personalized visual body representation were supported by full body con-

tinuity and vice versa but, surprisingly, motor capabilities did not have any effect on either. This interplay between body representation and body continuity can be seen in the box plots (Figure 4.12).

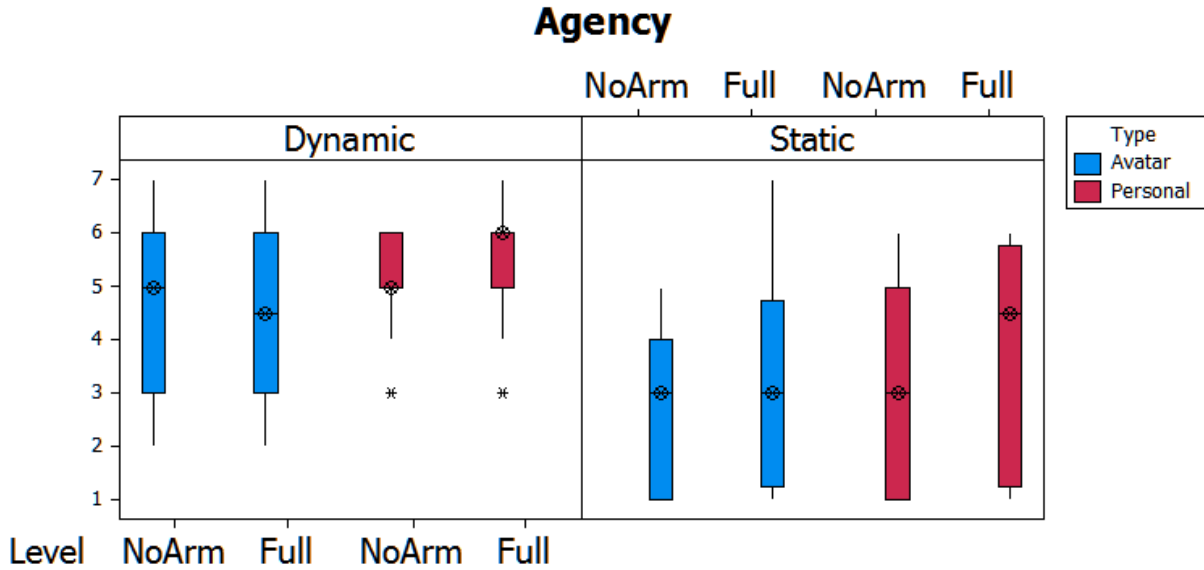


Figure 4.9: Dynamic motor condition shows a higher sense of agency than does the static motor condition in identical situations. We represent the interquartile range box with outlier and median symbol.

We also investigated the effect of personalized visual body representation on one’s sense of presence. Of interest, we found a statistical difference between personalized visual body representation and avatar body representation regarding the presence, a result that was not shown in Jung and Hughes (2016). We believe this is because artifacts were produced in the earlier experiment from the point cloud that rendered a participant’s mirror reflection. These artifacts distracted participants, resulting in a decreased sense of presence. In the experiment reported here, we did not use the point cloud data for rendering the participant’s mirror reflection; rather we used a 2d image based on the RGB and depth values from the RGBD camera. This latter approach removed the unexpected artifacts around the participant’s sitting location.

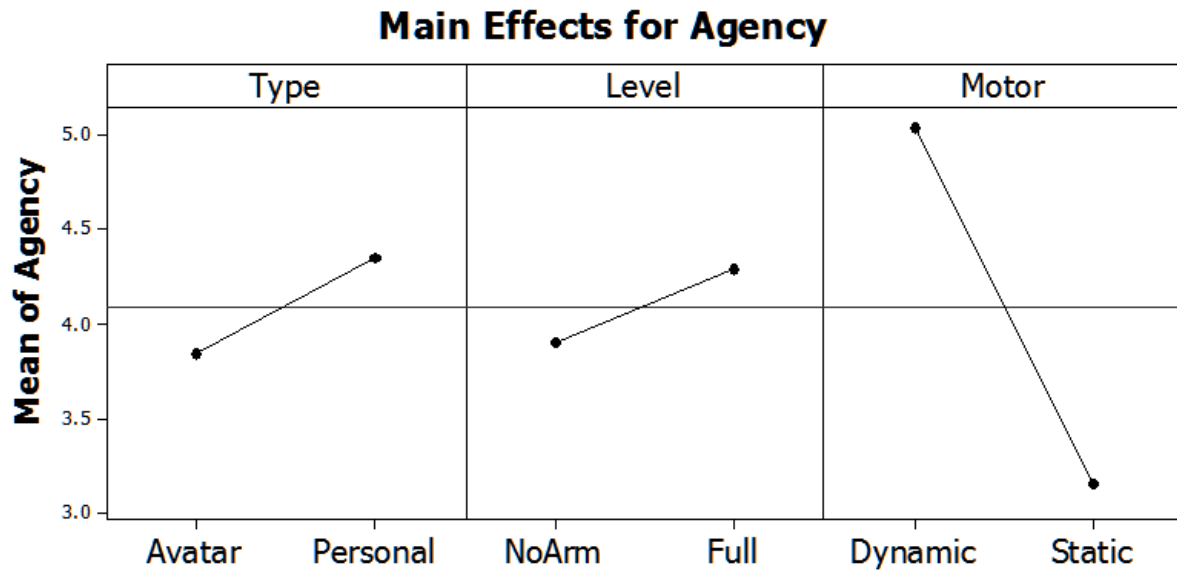


Figure 4.10: Only motor status shows significant difference in sense of agency.

Table 4.2: Descriptive Statistics with mean value

		VBOI	BC	Agency	Presence
Body	Personal	3.958	4.363	4.350	5.619
	Avatar	3.025	3.131	3.838	5.056
Hand	Full	3.846	4.475	4.288	5.431
	NoArm	3.138	3.019	3.900	5.244
Motor	Dynamic	3.563	3.875	5.038	5.344
	Static	3.421	3.619	3.150	5.331

With this more precise experimental environment, participants reported that a personalized visual body representation gave them a higher sense of presence.

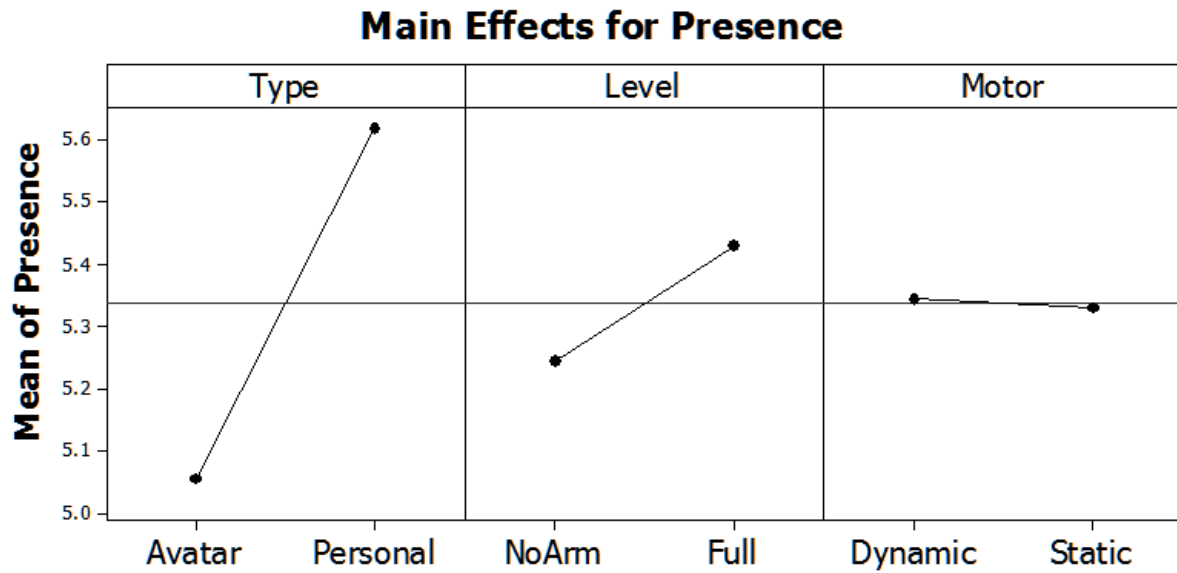


Figure 4.11: Only the body representation type shows significant difference in presence.

#### 4.2.5 Discussion

The experiment discussed in the next chapter no longer uses virtual mirror reflections (indirect) but rather shifts focus to direct or, more appropriately stated for this first such experiment, to a semi-direct effect.

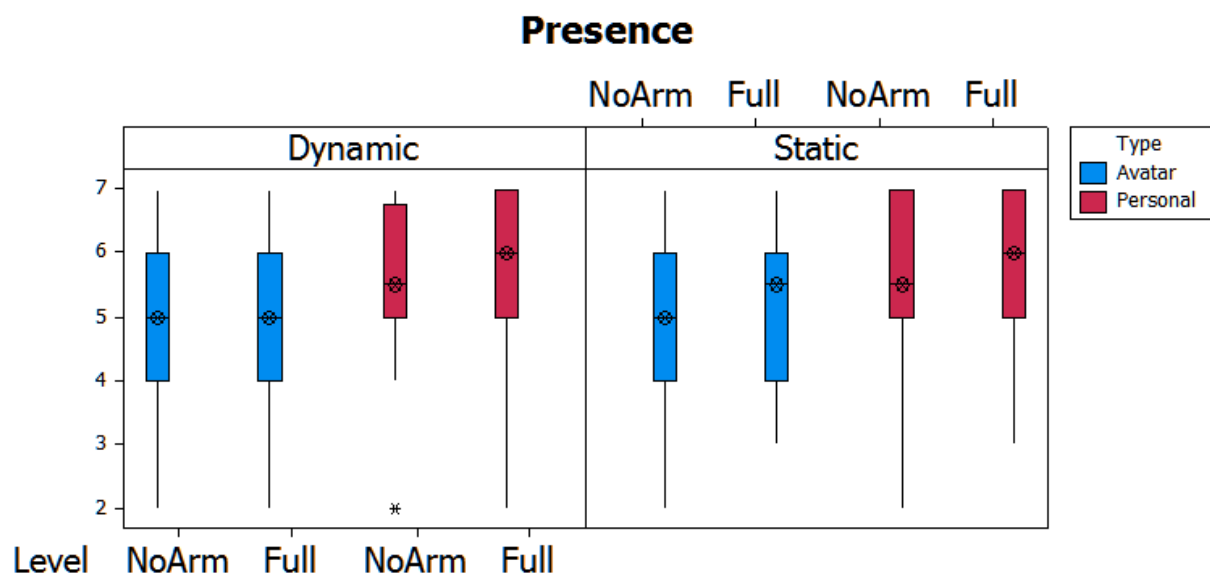


Figure 4.12: Personalized visual body representation shows a higher sense of presence than avatar body representation in identical conditions. We represent the interquartile range box with outlier and median symbol.

## **CHAPTER 5: A PILOT STUDY FOR TELEPRESENCE THROUGH A SEMI-DIRECT EFFECT**

### **5.1 Overview**

As preliminary research for VBO under the effect of direct visual perception, we conducted a pilot study in a mixed reality environment using a predefined virtual hand model. For this part, we present the results of an experiment investigating a participant's sense of presence by examining the correlation between visual information and physical actions in a mixed reality environment. We designed and conducted our experiment to examine the sense of telepresence a person has with a partner in a mixed reality environment. We hypothesize that the reasons a user will not experience the sensation of telepresence are, at least in part, due to constraints on visual information and a disagreement between a user's visual information and his or her actions. First, the visual information provided must give the user a sensation of actually being in a particular environment, which is called place illusion or spatial presence. Moreover, a user will likely have a diminished sense of telepresence if their physical actions such as moving their arms do not result in an appropriate visual changes as this disagreement breaks situational plausibility. Finally, even when users perform physical actions, they will feel less present if these actions do not result in corresponding physical changes in their partner's location. To test these assumptions, we designed the following experiment (Figure 5.1).

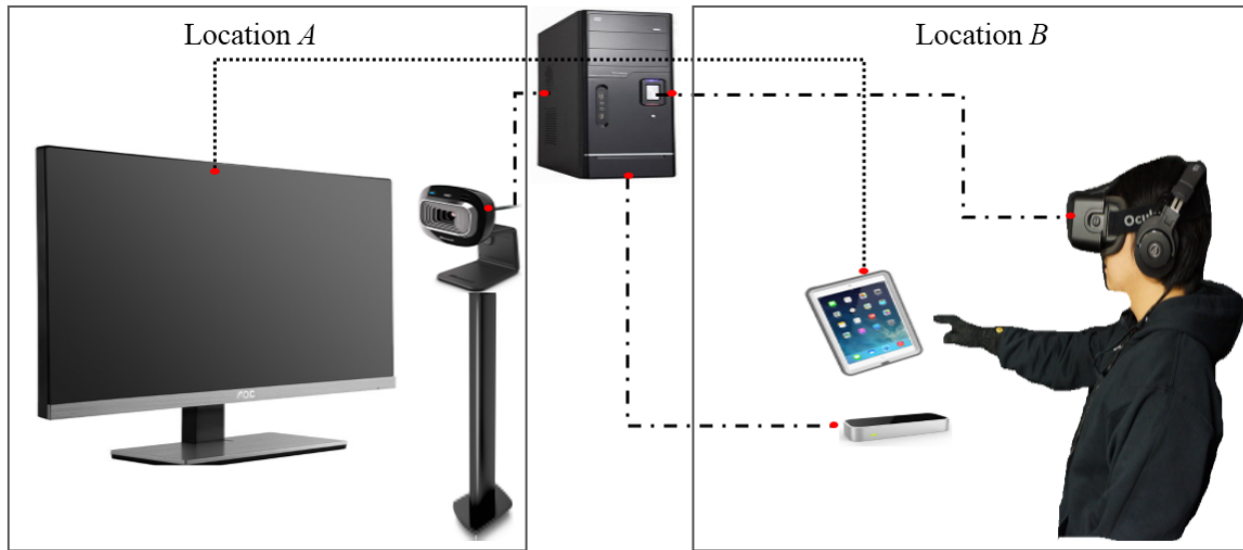


Figure 5.1: Overall experiment system

## 5.2 Experimental Design

### 5.2.1 Participants

Since the purpose of this section is to report on the formative phase of a more extensive study associated with enhancing telepresence through an increased sense of body ownership, we conducted the experiment with only a small number of people. The participants we recruited had different background knowledge on computers, virtual reality, and the concept of telepresence.

### 5.2.2 Material

In this experiment, we used a hand tracking device attached to a head-mounted display (HMD). A camera in the collaborator's room was connected to the participant's HMD. We asked the participant to perform simple cooperative tasks with the collaborator using a control device in his or her

location to control a screen located in the collaborator's room (Figure 5.2).

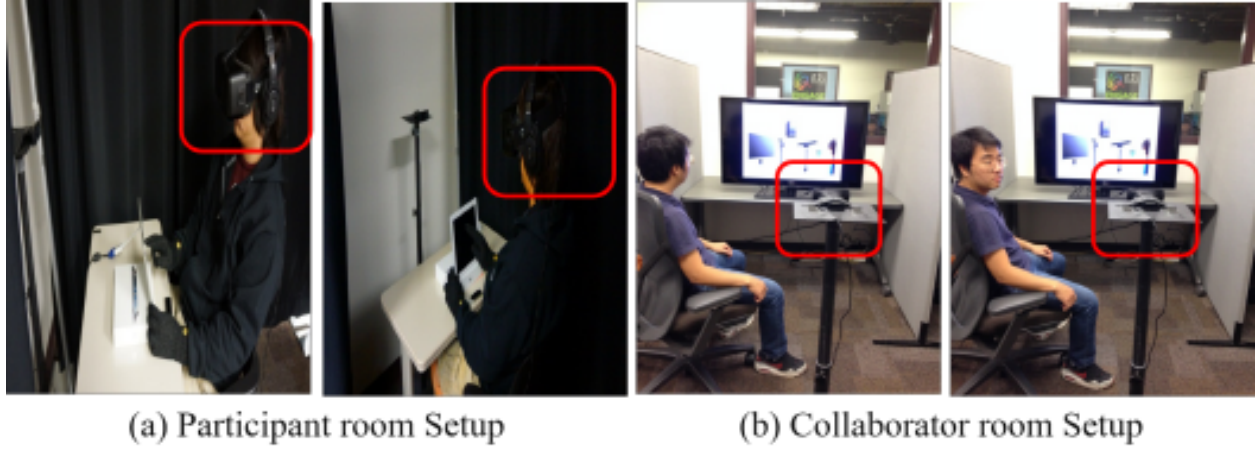


Figure 5.2: (a) The participant dons a hand tracker attached HMD while wearing a black color glove and controlling an iPad that is connected to a screen in a collaborator room. (b) The collaborator helps the participant to complete a given task. Through the web camera, the participant observes the collaborator's room.

We hypothesized that participants will feel a higher degree of presence if they see their own hands and fingers during these interactions. To verify this hypothesis, we carried out an experiment with three cases. In the first one, we used a virtual model of the participant's hands to mimic his or her actions and displayed the model on the HMD. In the second case, we used a generic hand model that looks like a skeleton. Finally, we conducted one case using no displayed hand model (Figure 5.3).

### 5.2.3 Method

Before starting the experiment, we asked the participant to fill out a demographic questionnaire. We also had the participant fill out simple experience questionnaires during each of the three experimental cases. A final questionnaire following the experiment asked the participant to compare



these three cases.

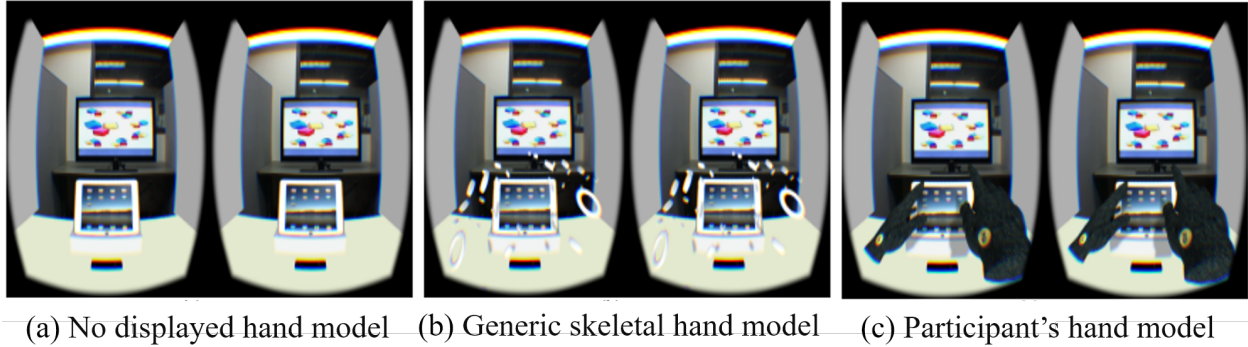


Figure 5.3: (a) While a participant conducts a task, they do not see any hand. (b) The participant conducts a task with a generic skeletal virtual hand. (c) A virtual hand model that wears a glove was used while the participant completes a task. The glove texture is from the real glove that the participant is wearing in the real environment.

In this study, we assumed that participants will experience a greater sensation of presence when they see their own body parts on the HMD corresponding to their actions. We asked participants to perform a simple task: counting a number of objects and solving math problems with small numbers. During the task, the participant answered the questions on each slide displayed on a remote screen seen through the HMD and controlled by the participant's hands. While the participant controls the display screen and answers the questions, the collaborator interacts with the participant, providing verification for the participant's answer. For instance, the collaborator might ask the participant how many blue cubes do you see? or what is the result of the equation? and then the collaborator verifies or corrects the answers. We used only simple and easy questions because the performance was not our focus in this experiment. We designed a set of questionnaires similar to those in Jane Lessiter and Davidoff (2001). The set is composed of four parts: a sense of physical space, engagement, control and negative effect. Each category has two or three questions with answers selected on a five-point Likert scale. Before beginning the experiment, we asked participants to fill out a demographic form; after the end of each experiment, we asked participants to fill out an

experience questionnaire consisting of interval scale questions. After finishing the last experiment, each participant completed a final questionnaire consisting of comparison questions between the three types of experimental conditions. This final questionnaire uses a five-point scale as well.

#### *5.2.4 Result*

From the study, we show results that include graphs of the interval questions, categorical questions and final questions for comparison and discussion. To show only the preference of each different experimental condition, we did not apply an analytical method but used a simple tally. To create the preference chart, we counted the number of one to five Likert score responses for each question for each of the three cases. Figure 5.4 displays the questions we asked. We conjecture that a personal model gives the most sense of telepresence as indicated by the results depicted in the first graph item that is associated with the interval question 'You had the feeling that you were in a different room'. Also, having no model has the most negative effect: dizzy and unnatural control (tenth and eleventh bar in (Figure 5.4)). These results make sense because the participants felt they were in the collaborator's room, communicating with the collaborator using an iPad to control the screen, but they did not see any part of their own body in that context. However, there were no significant differences between each of the three cases in the remaining questions because we had so few participants. To address this weakness, we represent the categorical graph, which is a summation of each question in four categories to show participant preferences concisely (Figure 5.5). As one can see, in the graph of the first category, 'Sense of Physical Space (Being there)', our participants perceived that using the personal model, the generic model, and no model ranked high to low, respectively. Surprisingly, though, using a personal model has the lowest score in the third category, 'Ease of Control'. This may relate to the fact that participants sometimes saw uncontrolled finger or hand movement when they tried to manipulate the iPad screen by touch since the Leap motion does not detect hand motion very well.

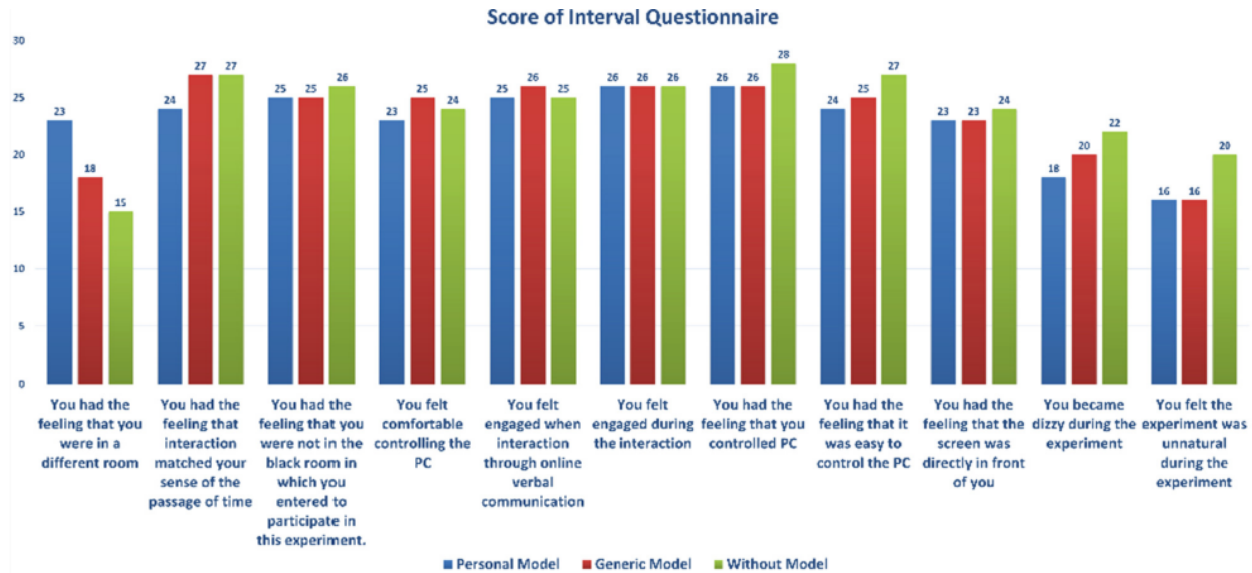


Figure 5.4: Result for each questions.

After finishing all experiments, participants mentioned the personal model case was not working correctly to control the hand, making it confusing to control the iPad screen. Actually, since we used the same skeleton model for the personal model as the generic model but with a different texture, it should have had similar tracking and rendering performance. However, participants did not perceive control to be weak with the generic model, perhaps because the model consisted of only a simple skeleton whereas the personal model had an explicit hand model with texture, so the lack of control was more obvious to the participants. The fourth category graph shows an interesting result: the total score is relatively low since we have two questions for the fourth category while the others have three questions each. The lack of a model caused the participants to experience negative effects while controlling the physical screen via an iPad; these included feeling dizzy or perceiving unnatural movement, as seen in (Figure 5.4). To enhance the sense of telepresence, any disagreement between a user's visual information and his or her actions is an important factor because of its negative effects. However, we did not encounter a remarkable distinction in the second category of (Figure 5.5), 'Engagement (involvement and interest in the content)'. We assume the

reason is that, in all cases, the participants felt a presence in the collaborator room.

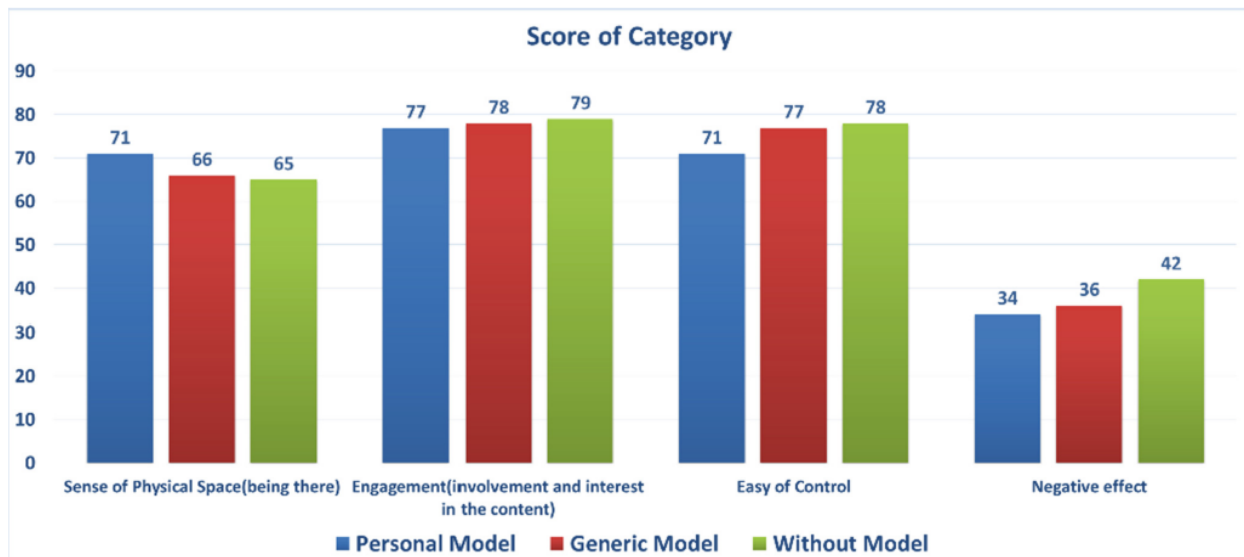


Figure 5.5: Categorically summed result.

Finally, we provide a comparison among the three cases (Figure 5.6). According to these results, we conclude that using the participant's personal model enhances presence in a remote context. This is supported by our participants' responses to most questions, which indicate that a personal model is preferred and feels most natural. There is, however, a contrary indication in the ratings of ease of control where the absence of any model achieved the highest score (Figure 5.5). Because the answers displayed in (Figure 5.6) were provided by participants after all experiments were completed, some graphs do not agree with (Figure 5.5), especially when one looks at the second and third graphs in (Figure 5.6).

### 5.2.5 Discussion

However, we still believe that participants have more sense of telepresence when they use their personal model to interact with a collaborator if they have a significant agreement between visual

information and the user's action. Unfortunately, the visual information we provided was not always synchronized with reality resulting in a reduced sense of telepresence. In addition, we hypothesize that a high degree of visual fidelity in the human model and better performance, e.g., less latency, provide a greater sense of telepresence.

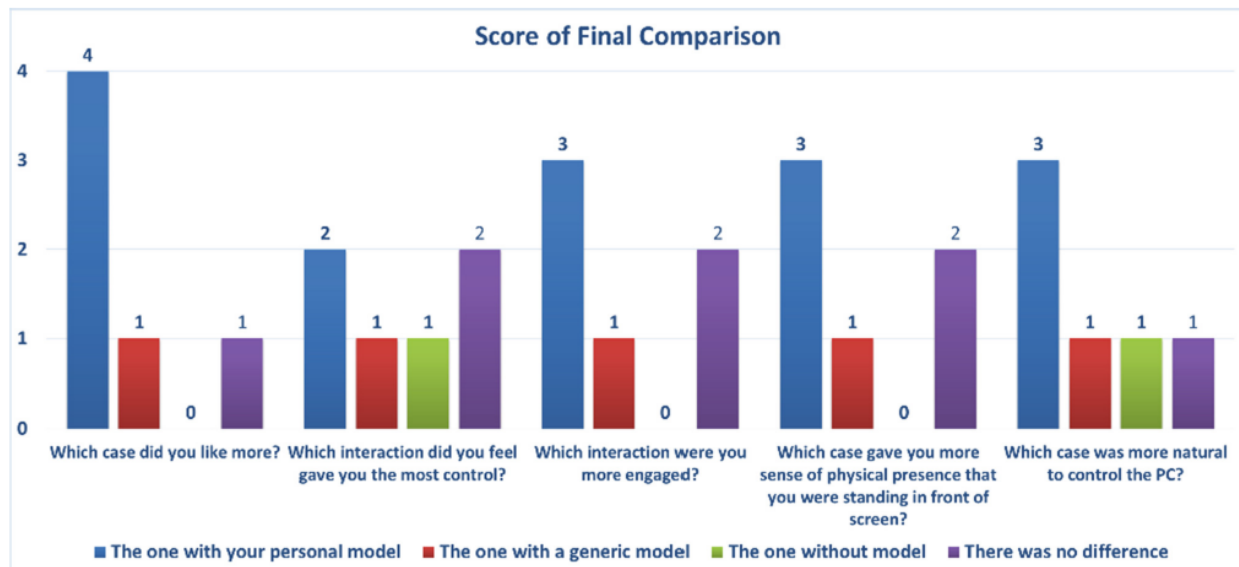


Figure 5.6: Comparison result among three conditions.

The next chapter presents a direct effects study that studies the effect of a gradual versus and instantaneous transition between a real and a virtual context.

## CHAPTER 6: IN LIMBO: THE EFFECT OF A GRADUAL VISUAL TRANSITION

### 6.1 Overview

In contrast to our prior indirect and semi-direct studies, The experiment reported here looks at the effect of directly enhanced visual perception with the introduction of a gradual visual transition between a personalized real body in the real world and a virtual body in the virtual world (See Figure 6.1). In this research, we also provide a mental model of how the effect of direct visual perception could enhance the dominant illusions.

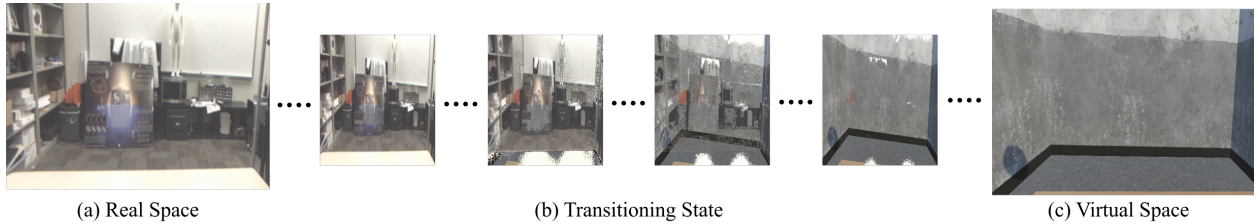


Figure 6.1: A series of view frames to show the gradual transition from real space to virtual space (a) A video see-through view of real room from a first-person perspective; (b) Video data gradually disappeared according to time elapse until the virtual world completely appeared; (c) A view of virtual room from a first-person perspective

In contrast to the traditional VR research approach that focuses inside the VR space, we include elements from outside the VR space, as observed before the user enters the VR scenario completely. Here, we assume that human perception is sensitive to real-world information and this sensitivity affects our perception of the VR experience. For example, prior to wearing and during the donning of the HMD, we still visually perceive real-world information, including our body and the surrounding environment. However, after we have secured the HMD completely over our eyes, we

feel as if we have been instantly transported to VR space, which is normally a disconnect because the virtual environment is visually different than the place where we were just located. Also, there is a disconnect when we have a virtual agent body that is different than our own body.

Regarding gradual transition, there has been some prior related research. To investigate the transition effect for virtual illusion, Steinicke et al. designed a virtual space that mimics a real world office where a participant conducted their experiment. The participants experienced a transition while they move to a virtual space through a virtual portal, Steinicke et al. (2009), by the action of walking. Similarly, Valkov and Flagge proposed a smooth transition concept to increase immersiveness. Using a similar approach to that employed by Steinicke et al. (2009), they started the study from a virtual replica of their real laboratory. While the participants were walking around in the virtual laboratory with HMD, the laboratory began to change a bit at a time to the virtual world, passively, without the participant's intentional behavior, Valkov and Flagge (2015).

Building on these earlier studies and based on Gregory's top-down approach for a visual perception illusion model, Gregory (1997a), we implemented a visual transition system with a gradual transition (GT) mode to adjust the human perspective gap between the two visual contexts (real and virtual) and compare it to a traditional instant transition (IT). With the GT, we refer to the transition as a Limbo stage according to a conceptual proposal by Sproll et al. (2013). With this system, we conducted a study of the dominant illusions. In this experiment, we hypothesize that a gradual transition will enhance the IVE experience, including VBOI (SP) and P, compared to a traditional VR setup with its instant transition. Our study suggests that GT leads to an enhanced immersive virtual environment design with strong statistical support for our hypotheses using subjective and objective measurements for a participant's behavior.

When we enter a computer generated world using an HMD-based VR system, we pass through three physical-mental transition stages (or changes in perceptual data): donning the VR devices

(physical), transitioning (mental) to VR while seeing the computer-generated world for the first time, before we completely enter VR space (physical/mental), which are similar to three of the five stages discussed in Proll et al. Sproll et al. (2013). In this section, we focus on the transitioning stage that exists between two definite places (real and virtual), a stage where a user is conjecturing about the appearance of the emerging VR environment including their virtual body. We call this space Limbo. To arouse the Limbo state, we stimulate the participant by visually transitioning to a virtual right hand with the same pose, from a first-person perspective, as the participant's real right hand. We include a haptic sensation by using an HTC Vive controller to tap the user's hand where the controller is accurately modeled controller in VR, so the tapping position, visual appearance and tactile feedback are the same for both the real and virtual hand.

## 6.2 Experimental Design

### 6.2.1 *Participants*

Before recruiting the participants, we conducted an a priori power analysis to determine the required sample size using G\*Power with a power of 0.80. This determined that we needed a minimum of 18 participants, Franz et al. (2007a). We recruited voluntary participants with normal to corrected-to-normal vision using on-campus fliers. Most participants had higher education backgrounds and were mainly in computer science. We conducted our experiment with 20 participants. We divided the participants into two groups, one for gradual transition as an experimental group with 10 participants (6 Male, 4 Female, Mean Age=29.5), and one for instant transition as a control group with 10 participants (8 Male, 2 Female, Mean Age=31.7). Our experiment was approved by the University of Central Florida's Internal Review Board Office.



### 6.2.2 Material

In our experiment (Figure 6.2), the transition begins while a participant is donning the VR equipment, a step which is generated by a human’s physical actions. Once the HMD is in place, the transitioning to the virtual space may be triggered actively through human behavior, or passively without the human’s choice. The passive approach is adopted in the study reported here. Regardless of the transition trigger mode, the user experiences a transition. However, the Limbo stage requires cues as we mentioned above to anticipate the VR environment while in transition to a completely computer generated space. Interestingly, we experience the de-transitioning in the inverse order while exiting the virtual world but that is not the focus here.

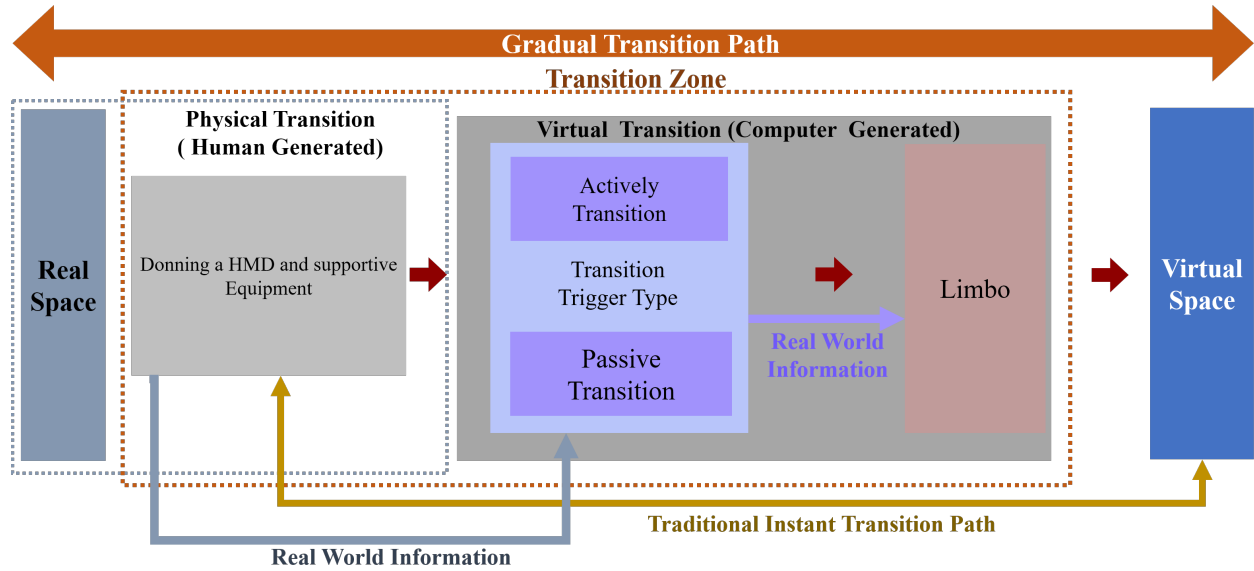


Figure 6.2: Transition Model for both gradual transition and traditional instant transition. The key concept for gradual transition to arouse Limbo is incorporating real world information.

Generally in VR, the transition stage occurs without a critical impact on a user since rendering of the VR environment begins immediately after donning the HMD, while visually disconnecting from the real world. However, in our study we elongate the Limbo stage noticeably to give time

for the user's mind to adjust to the mismatched visual information between real and virtual spaces. As previously noted, we expect a higher sense of virtual illusion from the GT approach.

To investigate the effect of the gradual transition for virtual body ownership and spatial presence, we implemented a visual blending method using a stereo camera with a virtual body in VR. Before we conduct the experiment, we posed the following hypotheses regarding the dominant illusions:

- **VBOI:** Using a gradual transition will provide a higher sense of virtual body ownership illusion than having an instant transition.
- **Spatial Presence:** Using a gradual transition will provide a higher sense of spatial presence than having an instant transition.

We used multiple measurements including questionnaires with a 7-point Likert scale and observed behaviors in this study. Our experiment is a 2x1 Between subject design intended to show the effect of a gradual transition. Based on a VR extended version Slater et al. (2009b) of a traditional rubber hand experiment Botvinick and Cohen (1998), we designed our study with a gradual transition effect. In the real experiment space, we placed a desk and a chair with the HMD tracker behind the participant as seen in Figure 6.3 (a). The participants wore a stereo camera attached HMD during this study while placing their right hand near a black colored mark on a table. To collect the participant's objective response, we installed a web camera for recording their behaviors.

In this study, a primary experimenter gave tactile feedback by tapping a participant's hand and forearm using a Vive controller (Figure 6.3 (b)). In the VR space, the participant has a virtual body that is in a pose similar to that of the participant who is placing their right hand near black color tape on the table, from a first person perspective. Also, the participant sees the virtual surrogate of the Vive controller that is tapping the virtual hand. While a participant is located in VR space, we arouse their sensation with two kinds of treats: one is a virtual knife attempting to stab the right

virtual hand, and the other is a virtual spider walking on the right virtual hand (Figure 6.4 (a-b)).

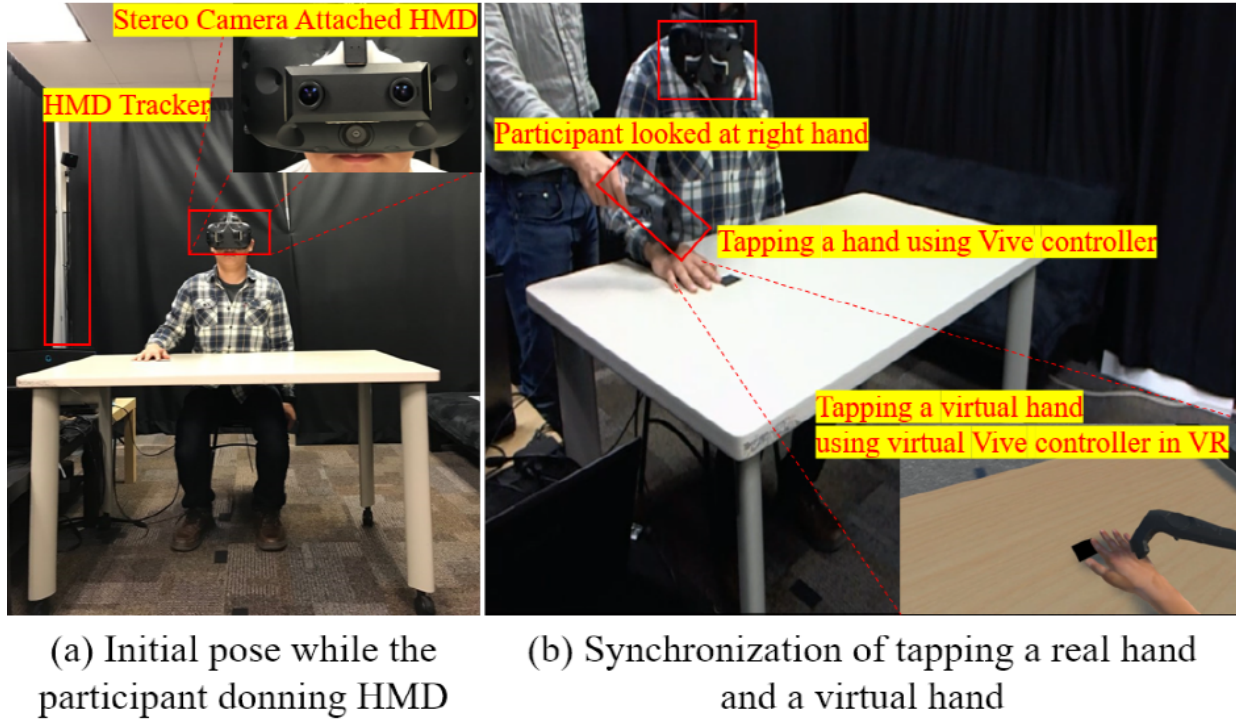


Figure 6.3: Experimental platform based on rubber hand study

We rendered a real world environment using a stereo camera attached to the HMD to provide a video see-through platform for the participant to observe the real world. The stereo camera offers 45 frame per second(fps) with 1280 by 960 screen resolution for each eye.

### 6.2.3 Method

For a visually convincing transition effect, we blended a camera view plane between the real and virtual worlds while controlling HSL (hue, saturation, and luminance) model-based color components using a simple equation (Equation 6.1-2).

$$p = (ElapsedTime)/(FixedTimeDuration) \quad (6.1)$$

$$(h, s, l) = (Lerp(h, p) * e1, Lerp(s, p) * e2, Lerp(l, p) * e3) \quad (6.2)$$

According to the time elapsed, we calculated a percentage for the current value for each color component using linear interpolation multiplied by constants  $e1$ ,  $e2$ ,  $e3$ , respectively. We iteratively calculated the color value until the percentage reached zero, which means a totally transparent video stream so the participant sees only the virtual world behind the video data plane (Figure 6.1). We fixed the gradual transition effect to take 30 seconds in our experiment.

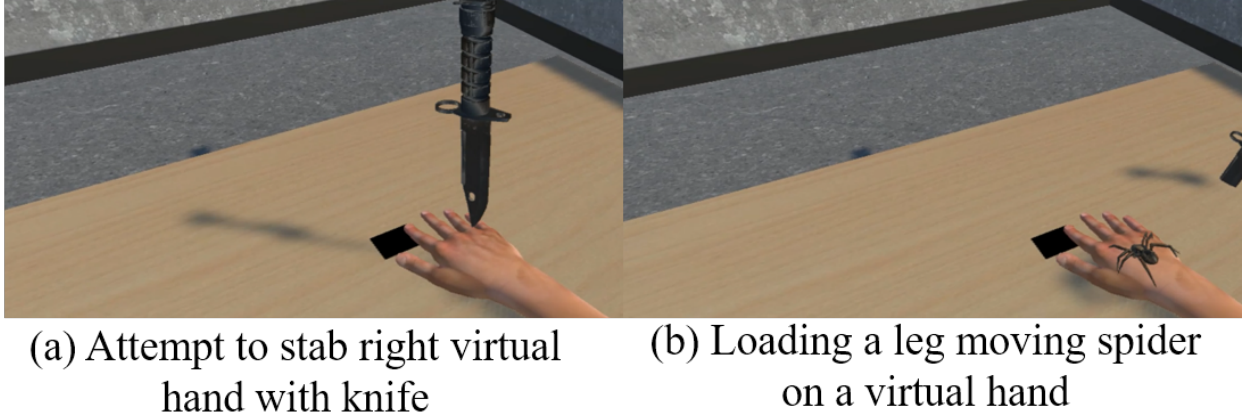


Figure 6.4: Virtual threats, one for a knife stabbing and the other one for a moving virtual spider, to arouse a participant illusion in VR space

According to Slater et al., using only a subjective measurement is not sufficient to assess dominant illusions in virtual environments, Slater (2004). Thus we assessed virtual body ownership and spatial presence using subjective measurements based on questionnaires, and objective measurements based on each participant's behaviors. For the subjective measurements, we adopted pre-validated questionnaires called spatial-presence (P), and self-presence (SP) by Bailey et al. (2016).

Table 6.1: The question component for the subjective response

Item	Question
P	To what extent did you feel like you were really inside the virtual room?
	To what extent did you feel surrounded by the virtual room?
	To what extent did you feel like you really visited the virtual room?
	To what extent did you feel that the virtual room seemed like the real world?
	To what extent did you feel like you could reach out and touch the objects in the virtual room?
SP	To what extent was the avatar an extension of yourself?
	To what extent did you feel if something happened to the avatar it felt like it was happening to you?
	To what extent did you feel that the avatars body was your own body?
	To what extent did you feel that the avatar was you?
	How much did the avatars actions correspond with your actions.
VBOI	I felt as if the virtual representation of the hand was part of my body.
	I thought that the virtual representation of the hand could be harmed by the virtual danger.
	Sometimes I had the feeling that I was receiving the hits in the location of the virtual arm.
	During the experiment there were moments in which it seemed as if what I was feeling was caused by the black controller that I was seeing in the virtual space.
	During the experiment there were moments in which I felt as if the virtual arm was my own arm.

Even though they use the term self-presence instead of virtual body ownership, we determined the set of questions represents the body ownership property. For comparison purposes of self-presence, we adopted VBOI questionnaires from Slater et al. (2009b) and Argelaguet et al. (2016b) with slight modifications based on our study context. Before analyzing the corrected data, we ran Cronbach’s alpha test as a validation, Tavakol and Dennick (2011). Lastly, we created a set of post questions for comparison purposes between the gradual transition effect and the instant transition effect. We provide our subjective measurement items for VBOI in Table 6.1. Objective responses were collected by recording all behaviors with a web camera.

Before we conducted our study, each participant read an informed consent and filled in demographic data while in a waiting area. After completion of the demographics, the participant entered the experiment room, which is an isolated space to avoid distractions. We verbally provided overall instructions for the experiment and required actions to conduct the study before they actually participated. After the instruction, we asked the participants to close their eyes while sitting on a stool because we wanted to prevent any visual transition while the participants were donning the

HMD. Up to this step, both GT and IT employ the same procedure. After donning the HMD with their eyes closed, we asked participants to enter into an initial pose and to open their eyes, look around the environment, and look at their right hand. For a GT, we tapped the participant's real hand and forearm using the Vive controller for about 20 seconds, and asked them to look around the environment again, while the transitioning was taking place. After finishing the transition, we asked the participant to look at their hand (we did not mention real or virtual) while we kept providing the tactile feedback with the same tapping interval in the VR space. After about 35 times tapping, we suddenly changed the black Vive controller to a knife. We held the knife in the air for five seconds and we then attempted to stab the participant's virtual hand, but we did not actually touch the participant's hand. After the event, we placed the knife on a virtual table, and a virtual spider suddenly showed up, moving its legs on the virtual hand with tactile feedback using the experimenter's fingers to give a sense that mimics the spider walking on the hand. We ran each event only one time, and for just over five seconds. After the second event, we asked the participant to look at the environment and ran the inverse transition effect to return to the real world. After the change to the real world, we asked the participant to close their eyes and take off the HMD.

For IT, we conducted the same procedure as for GT except we rendered a black screen during the transition. The participant entered the virtual world instantly right after they donned the HMD and opened their eyes. After finishing the experiment, each participant filled in a subjective questionnaire while in a waiting place. For a comparison between the two types of transitions, we asked participants to enter the study again like a Within-subject test that this is used to get a response to three questions only but that this is not the focal point of the study. After the second experience, the participant responded to a comparison question, which ended their involvement in the study.

#### 6.2.4 Result

Before we analyzed the collected subjective data, we assessed construct validity of multiple items in the same categories using Cronbach's alpha, and all four items were satisfied with  $\alpha > 0.7$ . To analyze the subjective measurements, Mann-Whitney test was used for all items, since our data did not show a normal distribution with the Anderson-Darling method, which means they were non-parametric data. We observed the explicit outcome that GT (Blue bar) is more influential on VBOI and presence as seen in Figure 6.5. We provide the interquartile range box with outlier and median symbol in all box-plot graphs along with median confidence interval box at the 95% level with the white colored dotted box inside each bar. Along with the graph, we found a significant difference for all dependent variables: spatial-presence ( $p < 0.006$ ), self-presence ( $p < 0.012$ ) and VBOI ( $p < 0.001$ ) respectively.

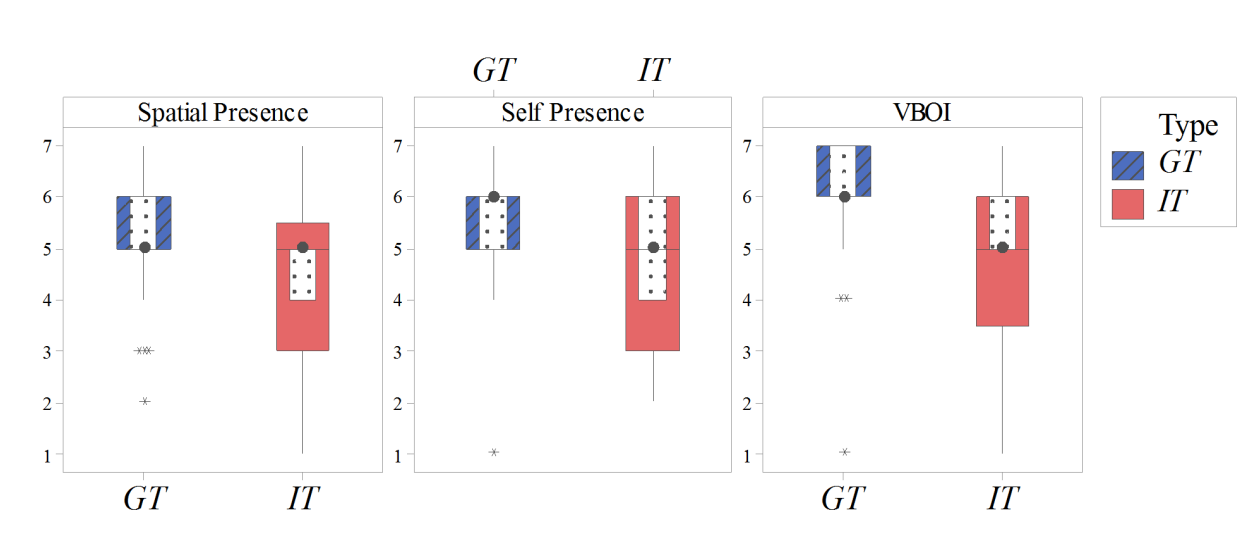


Figure 6.5: Gradual transition shows a significant difference for spatial presence and virtual body ownership illusion

Interestingly, both self-presence and VBOI showed a positive impact when a Pearson's product-moment correlation was run to assess the relationship between them as one construct.

Table 6.2: Descriptive Statistics with mean value(SD) and median

Item	P-Value	GT $\mu(\sigma)$ , Mdn	IT $\mu(\sigma)$ , Mdn
Spatial Presence, $\alpha=0.92$	$P<0.006$	<b>5.32(1.19), 5</b>	4.42(1.70), 5
Self Presence, $\alpha=0.89$	$P<0.012$	<b>5.62(1.18), 6</b>	4.7(1.75), 5
VBOI, $\alpha=0.78$	$P<0.001$	<b>6.12(1.14), 6</b>	5(1.81), 5.5

Since the test shows  $r(18) = .40$ ,  $p<0.005$ , which is a moderately positive correlation, and Cronbach's alpha confirmed a strong relation of  $\alpha > 0.92$ , we assume we can treat these as one dependent variable in this study. Through our open question, only one participant reported any discomfort and that was in the GT condition. We provide a numerical result in Table 6.2. We calculated P value at the 5% significance level for all classes.

We also collected qualitative feedback from participants to triangulate our quantitative results from the post comparison question, seen in the pie chart (Figure 6.6).

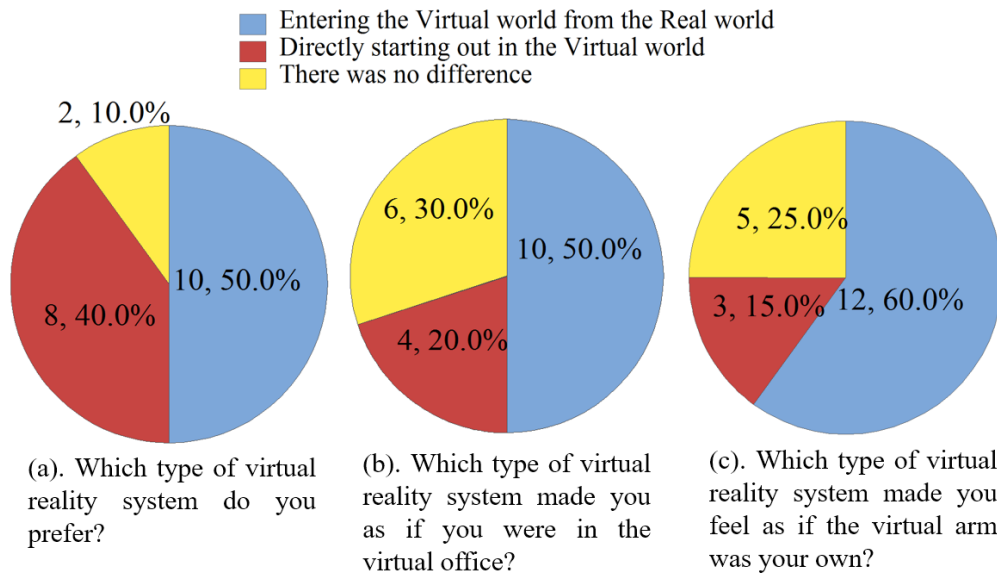


Figure 6.6: We represent the result with a pair (number of votes, percentage). When asked directly, more participants preferred the gradual transition overall, stating that it made them feel as if they were in the virtual office (spatial presence) and as if the virtual arm was their own (VBOI).



Regarding system preferences, it seems there was not a significant difference, though 10 participants (50%) voted for gradual transition. However, even though there was no reported differences between the transition methods, 10 participants (50%), felt more spatial presence in the gradual transition scenario, and 12 participants(60%) voted for gradual transition regarding a higher sense of VBOI.

To analyze a participant's behavior, we reviewed recorded videos from this study. Because of a recording error, we dropped one data entry from the instant transition, so we observed 10 recordings for gradual transition while we observed only 9 recordings for instant transition. Since emotion is ambiguous to classify accurately, we simply coded the behavior based on three categories: audible noise, physical body movement, and no observed reaction. For example, if a participant made any verbal or non-verbal noise after the event was triggered, we coded it as a response. Similarly, if a participant showed body movement even slightly after the threat happened, we coded it as their response. We present the graph with accumulated number of behaviors in each category (Figure 6.7).

From the recording results, we found there were a greater number of audible noises and body movements aroused with gradual transition, though the number of participants who reacted at some point was similar for GT and IT. Because both conditions are enough to arouse a sensation, participants exhibited behavioral responses in all cases since we provided the known critical elements for the sensation, such as visuotactile, resemblance, and positional congruence for both conditions. However, we conclude that gradual transition gave a stronger illusion than instant transition. We will explain this conclusion in detail in the discussion section.

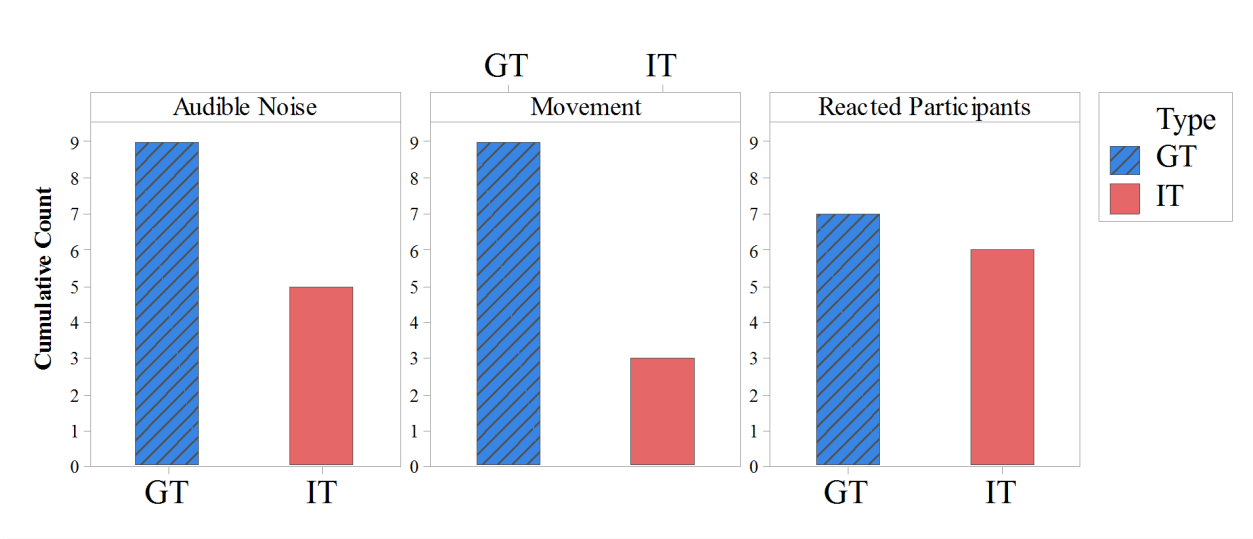


Figure 6.7: Gradual transition case shows higher number of behavioral reactions compared to Instant transition case

### 6.2.5 Discussion

We conducted a virtual hand study focused on the effects of a gradual transition on virtual body ownership illusion and spatial presence, using multiple measurements questionnaires and recorded behaviors. From the results, we found a statistically positive effect of the GT for VBOI and spatial presence explicitly in comparison to IT. We also confirmed that self-presence and VBOI were similar constructs with correlation analysis and Cronbach's alpha, allowing us to combine these constructs into one. Thus, our results support our research hypothesis that gradual transition will provide more VBOI and spatial presence in comparison to traditional instant transition. Along with these results, we are confident that our implementation provided a useful Limbo status during which the participants could adjust to the conflicting information between the real and virtual worlds. One more noticeable feature of this study was the Vive controller, since we gave a continuous tactile feedback using the controller, and the participant felt the same tapping feedback while they saw the same shape of the controller in both the real and virtual spaces, a connection

that might have worked as a mental-physical link or cue between the distinct spaces. Interestingly, the question “Sometimes I had the feeling that I was receiving the hits in the location of the virtual arm.” shows a significance difference between GT and IT with ( $p < 0.021$ ) and GT achieving a higher mean value, even though we tapped on the identical location with the same regular time interval in both cases.

In contrast with the positive effect, we found that there is no difference regarding system preference as seen in the first chart based on a post questionnaire. From these results, we guess that our gradual transition system is not effective as a convenient interface to entering virtual space, perhaps because the video see-through might arouse some confusion because of its relatively low frame rate and narrow field of view. In addition, HSL color component based gradual transition is quite sensitive to light conditions in the real world, so this might not be applicable to the transitions required in all VR applications. Finally, we had some trouble rendering the virtual hand in the exact location of the participant’s real hand, so we asked our participants to look at the environment instead of looking at their right hand during the gradual transition. However, we still conjecture that the real world information from the gradual transition would greatly help to give a more dominant illusion even though our statistical results were limited, since these did show a strongly positive effect compared to the traditional instant transition method.

In summary, we found a positive effect of the gradual visual transition from real to virtual with statistical support in both subjective and objective measurements. With the result of this study, we could argue that adopting real world information could elicit positive human perception and increase dominant illusions compared to the traditional instant transition. Thus, we would recommend the adoption of a Limbo transition stage employing real world information when researchers or developers design VR environment using virtual agents.

In the next two chapters, we extend this study to include a personalized body, with a highly detailed

and accurate virtual hand and surround environment, during the transition to the virtual environment. The next chapter provides preliminary results and the following one provides an extended design.

## CHAPTER 7: OVER MY HAND: THE INFLUENCE OF A PERSONALIZED HAND ON OBJECT SCALING IN VR

### 7.1 Overview

As immersive virtual reality (VR) technologies evolve, transformative virtual experiences are now becoming possible with effective means to observe and interact with computer-generated worlds. For example, when experiencing a virtual environment (VE) from a first-person perspective while wearing a head-mounted display (HMD), we can be a different person; we can move with our virtual body to another virtual place; or we can use our virtual hands to touch and manipulate the virtual objects around us. To understand such embodied virtual experiences, VR researchers have studied the concept of *presence* Slater et al. (2013b), i.e., the sense of being in the virtual world, as well as *virtual body ownership illusion* Kilteni et al. (2015), i.e., one's self-consciousness of one's own body regarding a given self-representation in the VE. Moreover, VR researchers have investigated how a virtual body changes our perception of sizes and distances in VEs.

Object size perception depends on various cues from our surrounding environment, such as depth cues, familiar object sizes, shadows, viewing angles, and more. Although, object size estimation integrates multiple factors, this procedure is very sensitive and prone to estimation errors, as documented by the fact that size and distance estimation in VEs often differs from the real world – Loomis and Knapp (2003); Renner et al. (2013). In the real world, an invariant in this process is our own body, which thus lends itself as a reliable metric; this process is called *body-based scaling* Ogawa et al. (2017). For example, we can use the known shape and size of our hand as a relative size cue when estimating the size of an unknown physical or virtual object. However, in VEs with different forms of one's body representation, such cues from our body can differ from what our

perceptual system is trained on, which might be a cause of some of the observed differences.

Kilteni et al. (2015) noted that semantic memory and knowledge help to shape generic human body information regarding posture, and structural properties of our body, if specific body information is given. In this scope, we hypothesized that not only the overall shape and size of our own body but also subtle *personalized body cues* and features on our hands such as scars or even temporary changes such as paint applied to our hands are important cues that can facilitate improved size estimation in virtual worlds.

In this chapter, we investigate a *personalized hand* as a supportive factor to increase not only the subjective feelings regarding virtual body ownership illusion and spatial presence but also the objective perception that allows users to estimate the relative size of virtual objects in the VE. Therefore, we compared two conditions: we created a highly-personalized hand by combining temporary personalizations with an augmented virtuality hand approach Jung and Hughes (2016); Jung et al. (2017); Jung, Wisniewski, and Hughes (Jung et al.); Bruder et al. (2009), and we compared it against a generic virtual hand as a baseline condition denoting the most common use of a virtual body in VR.

## 7.2 Experimental Design

### 7.2.1 Participants

Before recruiting participants, we conducted an a priori power analysis to compute the required sample size using G\*Power Franz et al. (2007a). For a medium effect size with a power of 0.8, we determined the need for a minimum of 24 participants. We recruited participants using on-campus fliers at the local university. We conducted our experiment with 17 male and 7 female participants (age  $M = 26.6$ ,  $SD = 9.3$ ).

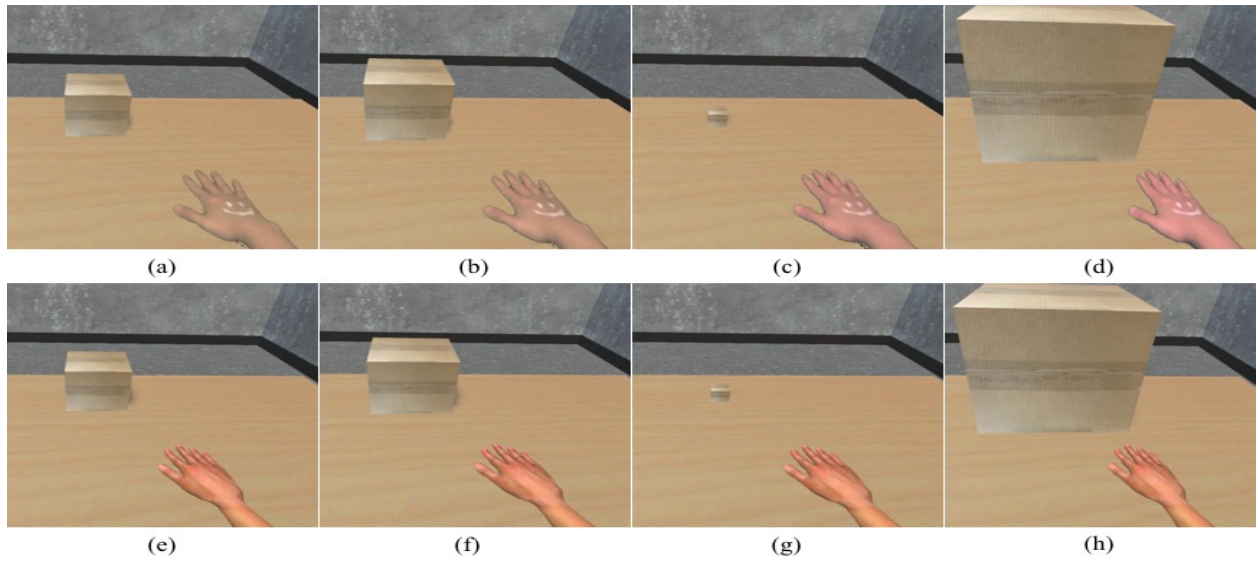


Figure 7.1: Series of screenshots depicting a participant in the experiment scaling a virtual box on a table in front of them, while receiving supporting size cues from their hand resting on the table. The top row shows the personalized hand condition, whereas the bottom row shows the generic virtual hand condition. The left two columns show the perceptual matching task in which participants scaled the virtual box to match a previously seen physical box. The right two columns show the corresponding tasks where they matched the virtual box size to a verbally communicated absolute value of 5 cm or 38 cm.

We had to exclude one participant’s data from the analysis due to a strong feeling of dizziness during the experiment. All participants had normal or corrected-to-normal vision. Most participants had a higher education background and were studying in diverse majors, but mainly in computer science. We assumed that object size estimation performance would be sensitive to the participant’s hand size in this experiment. Hence, we measured the width ( $M = 5.9$  inches,  $SD = 0.55$ ) and height ( $M = 7.1$  inches,  $SD = 0.6$ ) of the participants’ right hand. Participants received a small monetary compensation for their participation.

### 7.2.2 Material

In this experiment, we used an experimental setup consisting of an HTC VIVE HMD, to which we attached and calibrated an Ovrvision Pro stereo camera rig (see Fig. 7.2b). The HMD and Ovrvision Pro were hooked up to an Intel computer with core i7 CPU and NVIDIA GeForce GTX 1080 GPU and 16GB of RAM. The computer was used for rendering using the Unity 3D engine, system control, and logging. Hence, the HMD was capable of either rendering a fully immersive virtual environment or could integrate the video feed from the front-facing stereo cameras into the view to the virtual world. Participants were seated in front of a desk, which was covered in a green material for use as a Chroma Key (green screen) background (see Fig. 7.3b). Using this approach, all green pixels in the Ovrvision Pro camera images were identified as background pixels and only those pixels that corresponded to foreground objects were overlaid over the participant's rendered view of the virtual world in the HMD. As a result, the participants were able to naturally see their actual hands in the VE, although the visual appearance differed slightly due to the video representation. This form of virtual body feedback is sometimes called an *augmented virtuality (AV) body* and stands in contrast to the traditional form of a *virtual reality (VR) body*. In Milgram's reality-virtuality continuum Paul Milgram (1995), *augmented virtuality* denotes such environments in which the predominant virtual space is enhanced with real-world objects. In contrast, *augmented reality* denotes environments in which the predominant real space is enhanced with virtual objects.

Furthermore, for the experiment, we prepared two physical boxes with different sizes, which had a uniform color and a uniform size in width, height, and depth (see Fig. 7.2a). The boxes had a size that was either slightly smaller (15.5 cm) or larger (20 cm) relative to a participant's typical hand size.

Once the participants donned the HMD and were immersed in the VE, they could not see the physical boxes, but they saw a virtual box in front of them, which had a variable size (see Fig. 7.1).



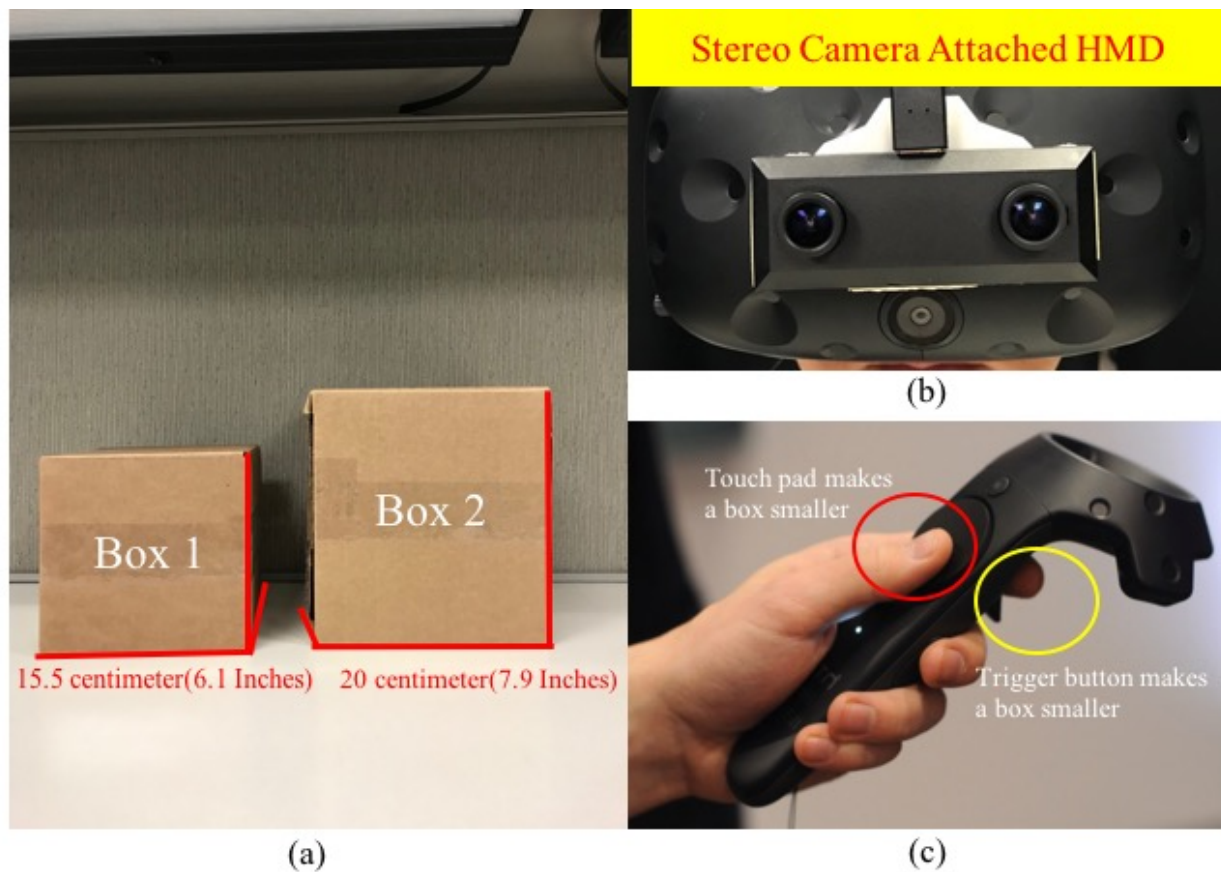


Figure 7.2: : (a) Two different sizes of physical boxes for observation. (b) Stereo cameras attached to an HTC VIVE HMD for rendering a video see-through hand in the virtual environment. (c) An HTC VIVE controller to manipulate the virtual object size using two buttons.

They could manipulate the size of the virtual box using an HTC VIVE controller with their left hand. To minimize the learning curve for the experiment, we designed the system with only two buttons that made the box larger with the touch-pad button (see Fig. 7.2c, red circle) or smaller with the trigger button (see Fig. 7.2c, yellow circle).

### 7.2.3 Method

In this experiment, we used a within-subject design with the three independent variables *Hand Representation* (Personalized AV Hand, Generic VR Hand), *Perceptual Matching Task* (Relative Size Matching, Absolute Size Matching), and *Box Size* (relative: 15.5 or 20 cm, absolute: 5 or 38 cm). We used a Latin-square order to avoid any ordering effect. The experiment was approved by our at the University of Central Florida’s Internal Review Board Office.

We designed the following two conditions for the independent variable *Hand Representation*:

- **Personalized AV Hand:** In this condition, the participants could see their own personal hands via the stereo cameras using the augmented virtuality approach described above. Furthermore, they could see any temporary personalized effects such as paint on their hands (see protocol below).
- **Generic VR Hand:** This condition did not use the stereo cameras and instead presented a virtual hand model to the participants at their own hand’s physical pose. This baseline condition matches the common procedure in VR to use generic virtual hands without any personalization for users.

We deliberately chose these two experimental conditions even though they combine multiple factors, including the type of hand representation (AV and VR) and the ability to represent temporary personalized effects. We made the decision to combine these two factors to create the strongest personalized hand we could. Our rationale is that if we can show a significant benefit of this personalized AR hand over the most common representation, i.e., a generic VR hand, we would thus have shown the importance of these cues, while the detailed contributions of each of the involved factors could be investigated in future work.

For the *Perceptual Matching Task*, we chose two conditions. Participants were instructed to manipulate the size of the virtual box in front of them either to reproduce the relative size of a (previously seen) physical box or an absolute size that was communicated verbally (i.e., not previously seen):

- **Relative Size Matching:** In this condition, the participants were instructed to scale the virtual box to match the size of one of the two physical boxes (sizes: 15.5 or 20 cm) that they previously saw before they were immersed in the VE.
- **Absolute Size Matching:** Here, the participants had to scale the virtual box to match an absolute width, height, and depth of the box (sizes: 5 or 38 cm). This absolute size was communicated verbally to them without a physical reference that could be used as a relative cue.

The rationale for using these sizes was that the user's similar familiar hand size could provide benefits in estimating the sizes of the boxes. We arbitrarily chose frequently used one hand lifting-enabled packing boxes in our daily life for relative size matching condition, while we chose less common box sizes for absolute size matching condition. Before we conducted our study, each participant gave their informed consent and filled in demographic data while in a waiting area. After completion of the demographics questionnaire, the participant entered the experimental room. As discussed in Section 7.2.2, we designed the personalized hand condition to encompass temporary personalization effects as well. Hence, we asked participants to decorate their right hand with washable paint at the beginning of the experiment. We left it up to the participants to decide on the type of decoration. As shown in Figure 7.1, one participant decorated their hand with a smiley face. After participants decorated their hand, they were instructed to observe and memorize the sizes of two physical boxes, shown one at a time, while they placed their right hand on a table in a static pose (see Fig. 7.3a). The smaller box was displayed first and the larger box second.

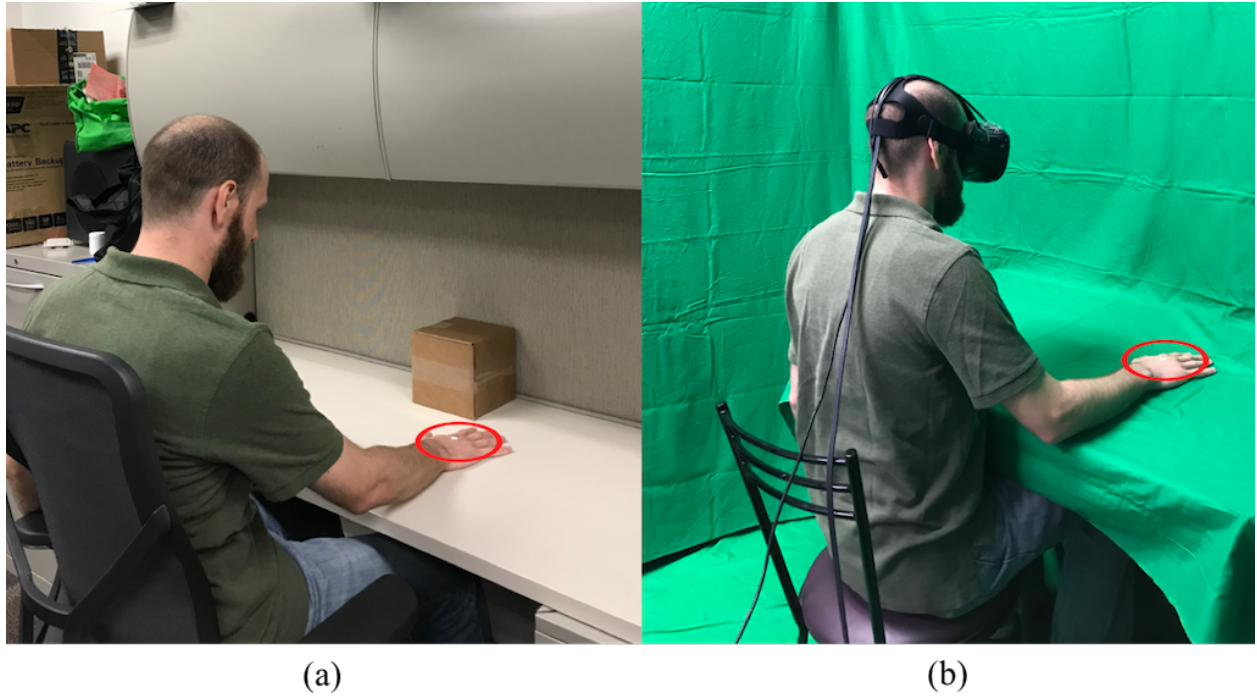


Figure 7.3: : (a) Participant observing a physical box, and (b) participant manipulating a virtual object in the VE. Participant were asked to decorate their right hand using washable paint (red colored circle), and place their right hand on the table in a static pose.

After the observation of these physical boxes, the participants were guided into the Chroma Key (green screen) environment, where the participants were instructed to resume the same pose as before (see Fig. 7.3b). The participants were then informed of the perceptual matching task for which they could change the size of the virtual box that was presented in front of them. After a short instruction on the use of the controller, the participants donned the HMD with their eyes closed. After we launched the VR system, the participants opened their eyes and we confirmed that they could see their hand within their visual range without any head movement. Then, they were asked to manipulate the sizes of the given virtual boxes using the HTC VIVE controller with their left hand. Depending on the condition, participants could then see one of the two hand representations (Personalized AR Hand or Generic VR Hand).

Table 7.1: The questionnaire for the subjective response

Item	Question
P $\alpha < 0.8972$	<p>To what extent did you feel like you were really inside the virtual room?</p> <p>To what extent did you feel surrounded by the virtual room?</p> <p>To what extent did you feel like you really visited the virtual room?</p> <p>To what extent did you feel that the virtual room seemed like the real-world?</p> <p>To what extent did you feel like you could reach out and touch the objects in the virtual room?</p>
SP $\alpha < 0.9375$	<p>To what extent was the digital representation an extension of yourself?</p> <p>To what extent did you feel if the virtual object size manipulation happened to the digital representation it felt like it was happening to you?</p> <p>To what extent did you feel that the digitally represented body was your own body?</p> <p>To what extent did you feel that the digital representation was you?</p> <p>How much did the digitally represented hand position correspond with your commands?</p>
VBOI $\alpha < 0.9713$	<p>I felt as if the digital representation of the hand was part of my body.</p> <p>During the experiment, there were moments in which I felt as if the digital hand was my own hand.</p>

Moreover, depending on the condition, they were then asked to manipulate the virtual box size to either match the size of one of the physical boxes (15.5 or 20 cm) they had just seen, or to manipulate the virtual box size to match the size of one of two boxes (5 or 38 cm) that were not observed prior to this experiment. The latter box sizes were communicated verbally to the participants in their preferred unit (e.g., centimeters or inches). Hence, in these conditions, they could not rely on relative size comparisons with previously seen boxes. We provided a short break to the participants after they completed one of the box conditions. After finishing the experiment with one of the hand conditions, each participant filled in a subjective questionnaire. We show our subjective measurement items in Table 7.1.

#### 7.2.4 Result

After they completed all conditions of the experiment, we asked them to fill in a post-questionnaire. As discussed before, participants were asked to manipulate the size of a virtual box in front of them to match either a previously seen physical box size, or match a verbally communicated size. The virtual box was a cube with the same length on all three axes, to keep the box manipulation task simple. After scaling the virtual box to the size that the participants perceived to match the communicated size, we recorded the final size of the virtual box. We then computed the vector distance, *L2 norm Euclidean distance*, since it enables us to effectively determine the level of similarity. A value that converges on zero means that participants were highly accurate in their object size estimation. We assessed the dependent variables, virtual body ownership and spatial presence, using subjective measurements based on questionnaires. In this experiment, with slight modifications based on our study context, we adopted pre-validated questionnaires called *spatial presence (P)* and *self-presence (SP)* by Bailey et al. (2016), as well as *virtual body ownership illusion (VBOI)* by Argelaguet et al. (2016b). We handled the self-presence and the virtual body ownership as a single construct since they had similar contexts. Finally, we created a set of post questions for comparison purposes between the Personalized AV Hand and the Generic VR Hand.

In this experiment, we considered the following research hypotheses:

- H<sub>1</sub> Using a Personalized AV Hand results in more accurate object size estimation than a Generic VR Hand.
- H<sub>2</sub> Using a Personalized AV Hand provides a higher sense of virtual body ownership illusion than a Generic VR Hand.
- H<sub>3</sub> Using a Personalized AV Hand provides a higher sense of spatial presence than a Generic VR Hand.

In this section, we show results for the objective responses of estimated virtual object size accuracy and subjective questionnaire responses for spatial presence and virtual body ownership illusion. For the analysis, we used a total of 23 participant data sets. As discussed before, we had to remove one of the original 24 participants from the analysis due to a strong feeling of dizziness.

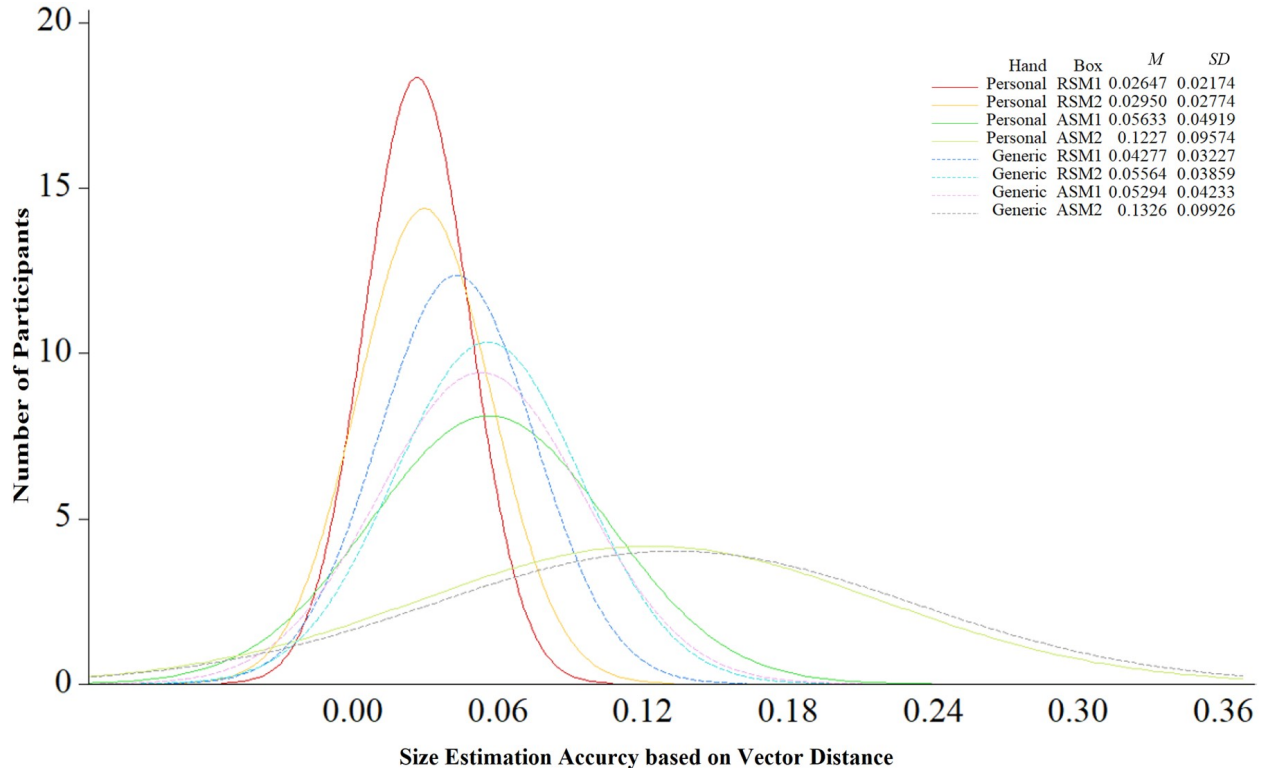


Figure 7.4: Pooled results for the perceptual matching task in which participants manipulated the size of the virtual object. Each line represents a histogram of the computed vector distance between the actual and estimated size. For example, the red line indicates the highest accuracy in size estimation among the experimental conditions.

Figure 7.4 shows the pooled results in the form of a histogram for the perceptual matching task in which participants had to manipulate the size of the virtual box to match the size of a previously seen physical box (relative) or match the size to an absolute verbally communicated size (absolute). We used solid lines for the Personalized AV Hand conditions and dotted lines for the Generic VR Hand conditions. The figure further shows the results for the vector distances in the form of means

and standard deviations for the experimental conditions.

We confirmed the assumptions of the repeated measures ANOVA with a Shapiro-Wilk test and Mauchly's sphericity test at the 5% significance level. We found a significant main effect of box representation on the size estimation accuracy,  $F(3, 179) = 25.01, p = 0.001, \eta_p^2 = 0.295$  while the hand representation showed  $F(1, 179) = 2.05, p = 0.154, \eta_p^2 = 0.0113$ , with an overall higher accuracy for the Personalized AV Hand ( $M = 0.058, SD = 0.067$ ) compared to the Generic VR Hand ( $M = 0.07, SD = 0.068$ ). Since we conjectured that the significant value difference in absolute size data produced noise in hand representation, we conducted a Post-hoc test. The test revealed that the Personalized AV Hand resulted in significantly higher accuracy than the Generic VR Hand for the relative matching task ( $p = 0.001$ , Cohen's  $d = -0.842$ ) but not for the absolute matching task ( $p = 0.854$ ).

Due to the different box sizes in the relative and absolute matching conditions, we could not compare these results directly. Instead, we compared the box sizes within these conditions using paired t-tests. The results showed that, for the relative matching task, the size estimation accuracy between the two box sizes did not show a significant difference ( $p = 0.241$ , Cohen's  $d = -0.253$ ), with a higher relative accuracy for the physical box with a size of 15.5 cm ( $M = 0.034, SD = 0.028$ ) compared to the box with a size of 20 cm ( $M = 0.042, SD = 0.035$ ). However, we found that for the absolute matching task, the size estimation accuracy differed significantly between the two box sizes ( $p = 0.001$ , Cohen's  $d = -0.974$ ), and revealed a higher accuracy for the task to match a box of 5 cm ( $M = 0.054, SD = 0.045$ ) than a box of 38 cm ( $M = 0.127, SD = 0.096$ ). Since we adopted a set of questions to measure subjective responses, we assessed the construct validity of multiple items in the same categories using Cronbach's alpha before we analyzed the collected subjective data from each questionnaire. All four items were satisfied with  $\alpha > 0.8$ , and so we were able to analyze the data from the subjective questionnaires.



Figure 7.5 shows the subjective questionnaire results. We provide the interquartile range with outliers and median symbols in all box plots along with median confidence intervals at the 95% level with a white colored dotted box inside each bar. To analyze the effects, we performed Mann-Whitney U tests for all items at the 5% significance level, since our data did not show a normal distribution with the Anderson-Darling test. Table 7.2 shows the results of these tests. As shown in Figure 7.5 and Table 7.2, we found a significantly ( $p < 0.001$ ) higher virtual body ownership illusion for the Personalized AV Hand condition compared to the Generic VR Hand condition. Since the items, VBOI and Self-Presence represented similar features we tested them with Cronbach's alpha to see if we can confirm them as one construct and it showed a strong relation with  $\alpha > 0.96$ . Thus, we assume we can treat these as one dependent variable in this study.

Similar to the results for the virtual body ownership illusion, we found a significantly higher rating of Spatial Presence ( $p < 0.001$ ) and Self-Presence ( $p < 0.001$ ) for the Personalized AV Hand condition compared to the Generic VR Hand condition.

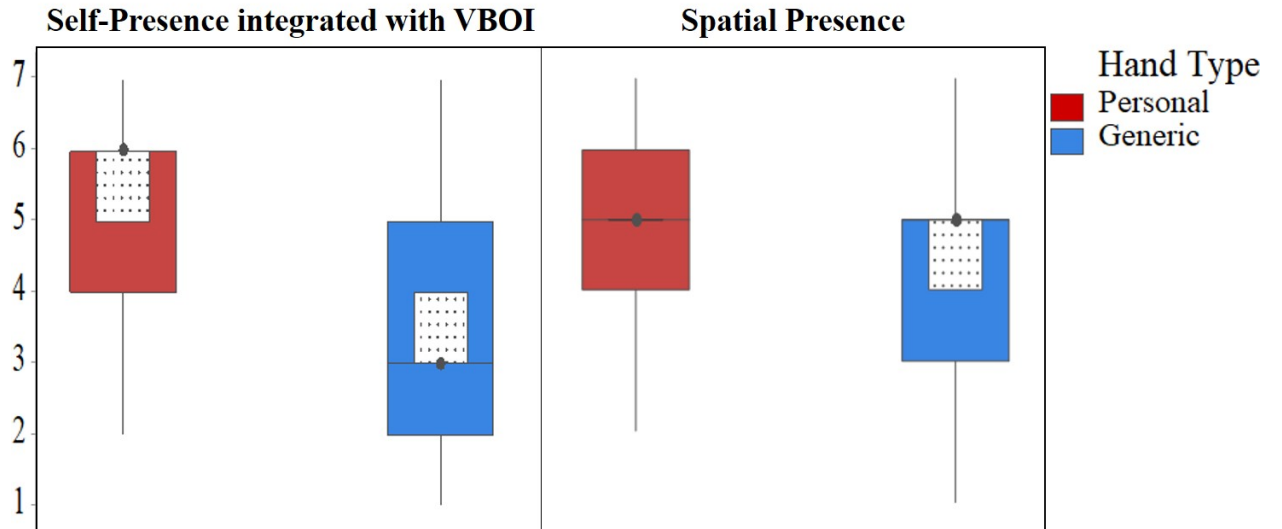


Figure 7.5: Plots showing the subjective questionnaire results for self-presence and spatial presence.

Table 7.2: Statistical results for the subjective measures.

		Spatial Presence	Self- Presence	VBOI	SP+VBOI
Cronbach's $\alpha$		0.8972	0.9375	0.9713	0.9624
Anderson-Darling Test		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
$p$ -Value		$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
Personalized	Hand	<b>(5.1, 1.2)</b>	<b>(5.3, 1.3)</b>	<b>(5.3, 1.6)</b>	<b>(5.3, 1.4)</b>
$(M, SD)$					
Virtual	Hand	$(M, (4.5, 1.5))$	$(3.5, 1.8)$	$(3.3, 1.8)$	$(3.4, 1.4)$
$(M, SD)$					

Figure 7.6 shows the results of the post comparison questionnaire, which comprised of a direct forced choice between the two hand representations, seen in the pie charts. Most of the participants stated that the Personalized AV Hand made them feel as if they were in the virtual office (Spatial Presence), as if the observed hand was their own hand (Self-Presence and VBOI), and as if they could estimate object sizes more accurately. Regarding system preferences, 21 participants (91.3%) preferred the Personalized AV Hand while only 2 participants (8.7%) preferred the Generic VR Hand.

### 7.2.5 Discussion

In this experiment, we found support for all three of our research hypotheses, which showed the benefits of the personalized hand over the generic virtual hand. In support of our Hypothesis  $H_1$ , we found that the object size estimation accuracy was significantly higher for the personalized hand condition compared to the generic virtual hand. Specifically, we found a significantly higher accuracy for the relative size matching tasks in which participants had to scale a virtual box to the size of a previously seen physical box, whereas we did not observe a significant difference in the results when they had to scale the virtual box to a verbally communicated size that they had not previously seen in the real world.

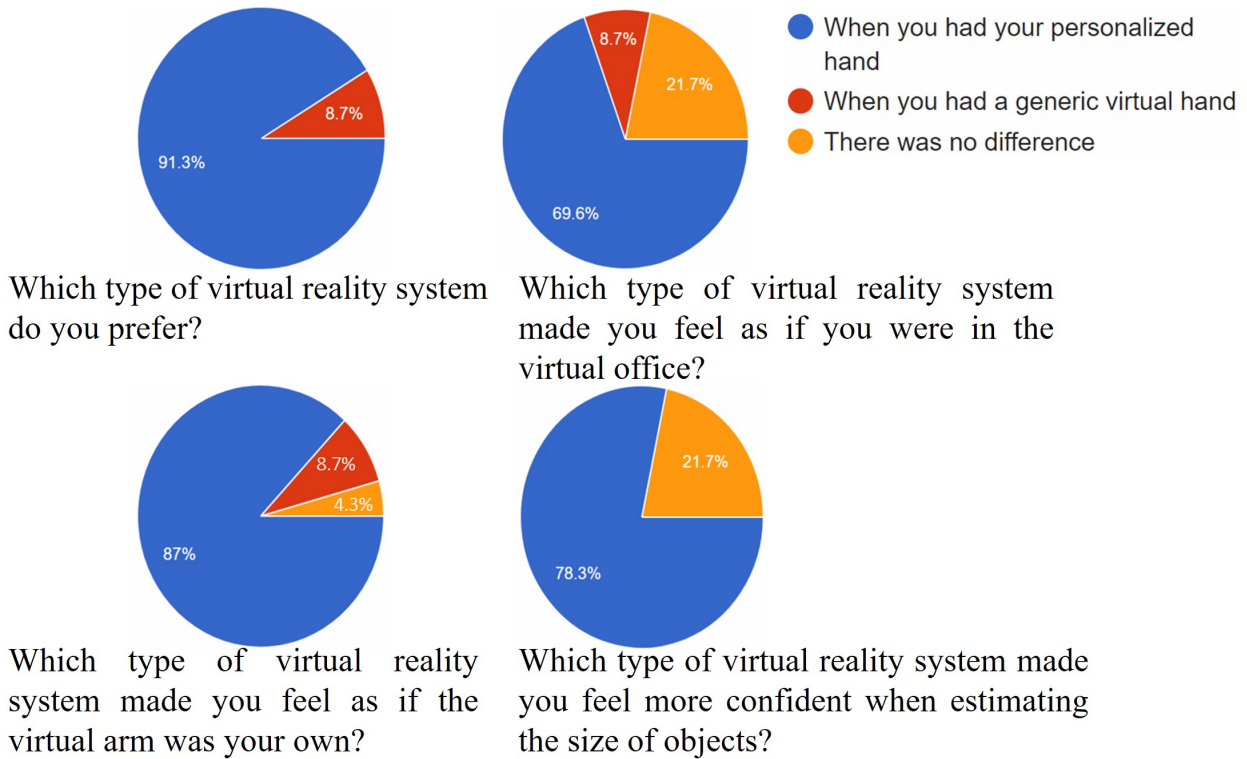


Figure 7.6: We represented the results with a pair (number of votes, percentage). When asked directly, almost all participants indicated a strong preference for the personalized hand.

The subjective questionnaire responses showed a significant effect that the personalized hand elicited a higher sense of spatial presence and virtual body ownership illusion compared to the generic hand condition. These results support our Hypotheses  $H_2$  and  $H_3$ . Moreover, when asked for their preference, most participants indicated that they preferred the personalized hand over the generic hand in the experiment.

Based on results from this experiment, we would recommend that VR developers adopt the personalized hand in areas that require size-sensitive tasks, such as simulation of surgical procedures or usability tests that include activities influenced by product sizes. Even in scenarios that do not involve size-sensitive tasks, personalized body parts increase presence and VBOI, illusions that can

increase the effectiveness of a scenario, especially one that involves training that needs to transfer to the real world. To render the personalized hand, a green screen is not always necessary; one may use a commercial depth camera combined with a stereo camera. The choice of green screen versus depth camera depends on other aspects of the environment, e.g., do we want the hand to be seen in the context of nearby real objects or virtual content? The former is best done with a depth camera and the latter is easier with a green screen.

In this study, we found some technical limitations. First, the stereo camera's color accuracy dropped and noise increased after about one minute, such that two participants observed an increased reddish tinge in their hand as can be seen in Figure 7.1(a-d). We believe that the color change did not have an impact on our experiment since only two participants reported it, and they also stated that it did not influence them. Second, two participants reported a "floating hand" effect while they performed the task. Since we rendered the hand on the stereo camera's view plane, dropped frames or the participant's head movement (though we asked participants not to move) could have caused the floating effect. While this effect might have had a negative effect on how the personalized hand was perceived, our results show an overall strong preference of participants for the personalized hand, such that the impact of this effect probably was not very strong. Further, three participants reported difficulty controlling the virtual box size, even though we designed the manipulation to be very simple by using only two buttons. Overall, we believe that none of these limitations had a noticeable effect on the results.

In this chapter, we investigated the effects of a personalized hand on spatial presence, virtual body ownership, and object size estimation in a virtual environment. We implemented a high-fidelity personalized hand based on an augmented virtuality approach and we enhanced it with temporary personalizations by applying washable paint to their physical hand. We compared this personalized hand condition with a generic virtual hand as a baseline condition, which denotes a common type of virtual body in VR. We found a significantly higher accuracy in object size

estimation for the personalized hand in a perceptual matching task in which participants had to scale a virtual object and match its size to a previously seen physical object. We further found a significantly higher spatial presence and virtual body ownership illusion, as well as a general preference of our participants for the personalized hand compared to the generic virtual hand.

In future work, we plan to perform an experiment to understand whether our temporary personalizations, such as a smiley face drawn on the user's physical hand before being immersed in VR, could be used as a general-purpose method to support virtual body ownership with arbitrary virtual hand representations.

## **CHAPTER 8: CONCLUSIONS AND PROPOSED FUTURE WORK**

### **8.1 Completed Research**

In this dissertation, I presented the importance of the role of visual perception for virtual body ownership illusion and spatial presence in a computer-generated environment. Traditionally, most researchers focused on finding a relationship between dominant illusions and physical aspects such as visuotactile, visuomotor and body posture. In contrast to these traditional approaches, I suggest a visual perceptually enhanced mental model for the dominant illusions with multiple experiments to support the mental model using personalized real body cues in virtual environments. With positive or statistically strong supporting evidence from five independent experiments, I studied the effectiveness of the visual perception effect on virtual body ownership illusion and spatial presence.

### **8.2 Goal and system overview**

In the previous chapters, we explained the importance of enhanced visual perception as the dominant illusion through five individual experiments that showed either indirect or direct use of real-world information with real body parts or the real environment in VR. In this chapter, we focus on developing a personalized virtual hand (PVH) as a direct approach to virtual body ownership illusion and spatial presence. To keep a sense of body ownership from a virtual hand model, we hypothesize the need for a method that is sensitive to skin color, hand shape and artificial features such as nail color, tattoos, aging marks, scars, and accessories. In particular, we feel that the hands and their finger movements are the most important articulated body parts that need to be accurately represented to retain a sense of body ownership. However, it is a challenge to create a virtual hand

that represents personal features as humans could represent their personalities with various types of hand features (See Figure 8.1). Also, depending on their age, race and gender, we will need to have different types of hand.

Here, we extend this work by discussing a proposed method for representing a personal feature-defined virtual hand without breaking the virtual environment context. *This does not mean a precisely identical personalized hand.* For example, we might be playing the role of a character who has a tattoo on his palm and that tattoo must be retained for the character to be recognized by his teammates, so it cannot be altered. In another, we may be playing a character that has long, evil fingers with pointed nails and a powerful ring on its left ring finger. While we may want to alter the skin texture to ours and even the color of the nails, we don't want to change the shape of the fingers and we don't want to replace the ring, even if the user has a ring on that finger. Although we recognize the importance of accessories, and assert that they can be handled in a convenient way by using existing 3D models, here we consider only features like human skin or nails excluding detachable items like jewelry or a watch, .

Figure 8.2. represents an example of a virtual hand that has its own unique features. As we previously showed the effect of visual perception with real body information indirectly, providing a personalized feature of the body is enough to arouse visual perception in VR. Thus, our primary goal for this future research design is to suggest a practical system to produce a personalized feature-represented virtual hand without using bulky specialized devices, expensive computing power, or long preprocessing time in VR. We present the outline of a technique that represents a user's hand and fingers with the virtual avatar's corresponding hand and fingers. To address the problem, we describe a system with a warping based novel algorithm for rendering a personalized virtual hand (PVH) without a specialized photo booth for scanning hands, so our output is a lightweight and a game-engine-ready 3D model in virtual reality.



Figure 8.1: A human could represent his or her personal identity with various features including accessories, tattoos, or nail coloring and more. Also, a person's hand shape, color and features could be different depending on age, race, and gender. Images were taken from open access internet sites

For scanning a hand without a specialized device setup, we place a depth sensor, e.g., the Leap Motion, and a stereo camera, e.g., the OvrVisionPro, onto the front of an HMD. After calibration between the two cameras, we can easily detect the hand position, including its natural gestures in any context (See Figure 8.3).

Instead of an RGBD sensor based 3D reconstruction scheme with its many challenges for long processing time, expensive computing power, bulky physical setup and low details of hand representation, our algorithm adopts an MLS-based texture warping method which was introduced by Schaefer et al. (2006) (Figure 8.4 (a-b)) to apply a personal real hand image using a combined setup of a hand tracker and stereo camera.





Figure 8.2: (a) "The Last of Us 2", a heroine, Elli, has unique tattoos on her arm and hand. Courtesy of Naughty Dog, Inc. (b) "Call of Duty 4: WW2", The character's hand was painted with blood. Courtesy of Activision Publishing, Inc. (c) "Uncharted 4: A Thief's End", The hand has a ring and a watch while showing veins. Courtesy of Naughty Dog, Inc. (d) "The Elder Scrolls V: Skyrim", a character has pink colored nails. Courtesy of Bethesda Softworks LLC.

In our method, we assume that a predefined 3D hand model with its texture is already given while an artist will not only annotate the primary correspondence points, but also the features that must be preserved. After the texture warping, we composite the warped texture with the pre-defined texture and map it onto a pre-defined 3D hand; we apply morphing to the 3D model along with the captured hand image's shape (Figure 8.4 (c)).

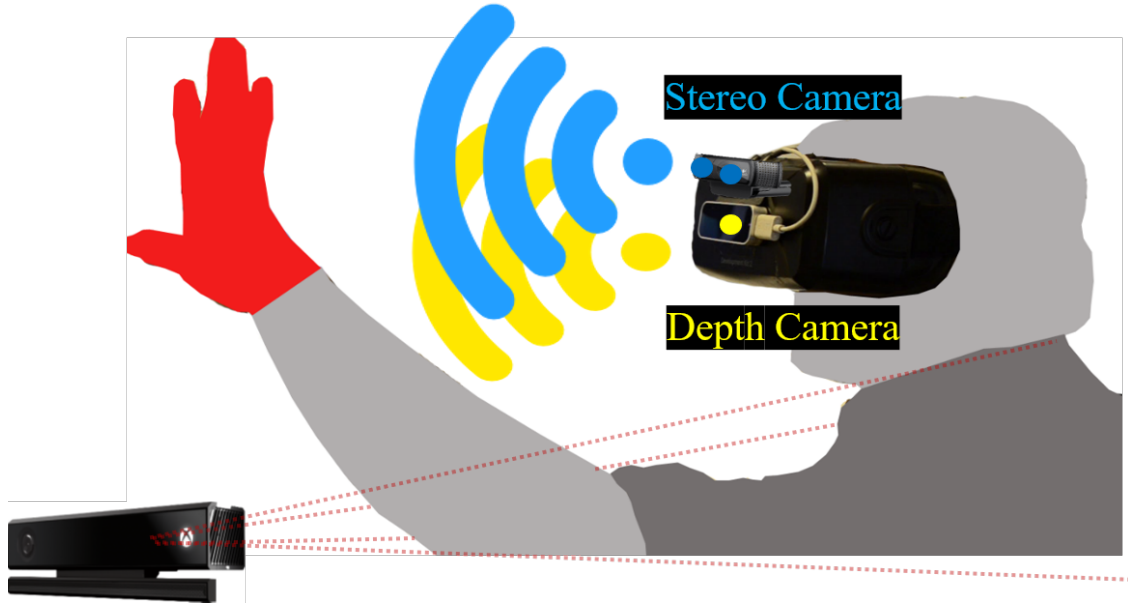


Figure 8.3: A human operator is tracked with three sensors, Leap Motion and Kinect 2. Data from the Leap Motion and stereo camera are fused to find the hand of the operator. The operator's hand is then morphed to conform to the virtual avatar hand.

Using this technique, we create a personalized virtual hand that represents each individual's personal features (skin tone, aging spots, scars and nail color) of a hand using two hand images, palmar and dorsal based on an image composition method. Because of the high resolution of the camera, 2560 by 1920, a highly detailed real hand texture can be acquired. With the PVH, we expect to increase the sense of virtual body ownership illusion and spatial presence, as we believe the PVH will enhance visual perception.

### 8.2.1 Segmentation for local to global mapping

A novel contribution of the design introduced herein is a localization method for successful representation of a personalized virtual hand without long processing time and computing costs. We propose a texture warping method that solves the correspondence problem locally, successively

building up to global correspondences. To carry out this scheme, we find the accurate position and region of each hand and its articulated fingers, a challenging problem in the computer vision domain. For implementation, the depth camera easily provides the position of the hand and fingers with regional joint positions according to an anatomical human hand structure.

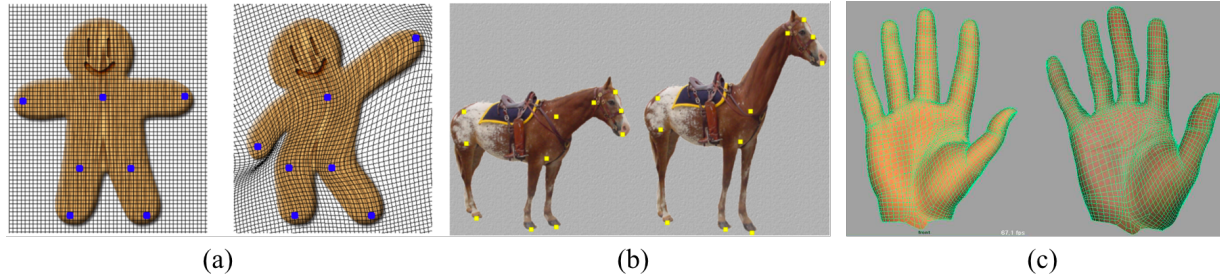


Figure 8.4: (a) Left is an original image that they warped into the right image with MLS deformation using bilinear interpolation in each mesh quad. (b) Left is an original image, and right is its deformation using the rigid MLS method. (c) Shows attained 3D hand model morphs along with real hand image.

Since the depth sensor and RGB sensor were calibrated before scanning, we attain the hand only image easily with simple image processing. With the given joint positions, we produce a segmented hand image using a general classifier such as a K-nearest or Naive Bayes classifier algorithm (See Figure 8.5).

Also, this localization provides benefits from a VR perspective. For example, a personalized virtual hand might actually decrease immersion in certain virtual reality contexts. Some examples are an environment designed to support users developing a sense of empathy for others with different skin colors; a game where the participant's avatar wears a game-specific ring; or an experience where the avatar has a Michael Jackson style partial glove that covers the palm and back of hand, but not the fingers. In these cases, we could keep critical features of the original virtual hand while we selectively enhance certain personal features, since we handle our hand as segmented areas.

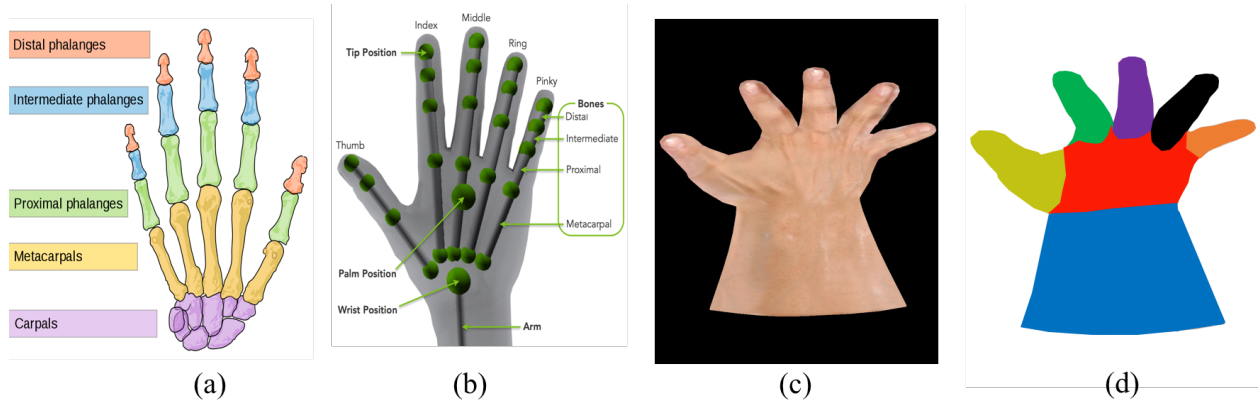


Figure 8.5: Segmented hand image using an anatomical hand structure from the depth camera. (a) A reference hand structure. (b) Leap Motion provided joints position according to the reference hand structure. (c) Example of captured hand image. (d) A result of segmented image using the joint positions.

### 8.2.2 *Warping with corresponding points*

Because we have the texture for a generic 3D hand model, we refer to the texture as a reference image. Due to the size and shape difference between a captured hand image and a reference image, we need to determine the correspondences between the two images to make composition be a one to one mapping between features. We assume that the reference image was annotated with the joint positions manually by an artist. To map an image of the user's hand and fingers onto the reference texture, we apply a warping algorithm to the captured data associated with the hand and fingers. To warp the hand and fingers, we find feature points on the contours for both hand images and find corresponding points between the image of the user and a texture of the virtual avatar hand. This requires us to solve the correspondence problem using techniques similar to those previously reported in Liu et al. (2004); Chetverikov (2003); Sederberg et al. (1993). For example, Liu et al. (2004) suggest a method to calculate a similarity measurement between two points based on a geometric feature, discarding a point, and using an error minimization scheme between the two

points. To solve the problem, they applied a Dynamic Programming technique, and we do so as well based on the segmented region as we described previously. Figure 8.6 shows the robust result of the correspondence algorithm using the geometric similarity value.

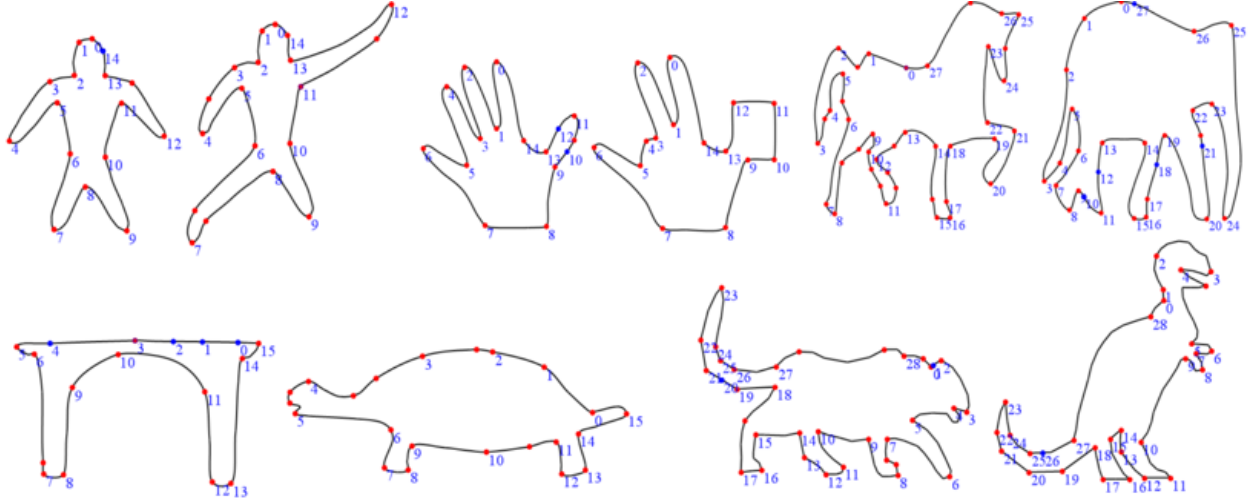


Figure 8.6: Correspondence results using Liu et al. (2004) approach

Fortunately, because we know joint features, we can start to solve the correspondence problem locally, and stitch the solved area to global correspondences while warping each area. Since we have anatomical image data for the hand and fingers based on correspondence features between the image of a user's hand and the texture of a virtual avatar hand, it is easy to apply warping to the texture information Schaefer et al. (2006). We run the warping process for both hand images, palmar and dorsal, we blend them seamlessly using color interpolation after completely warping both sides, respectively. With the description of our algorithm, we provide our scheme with an illustration (Figure 8.7).

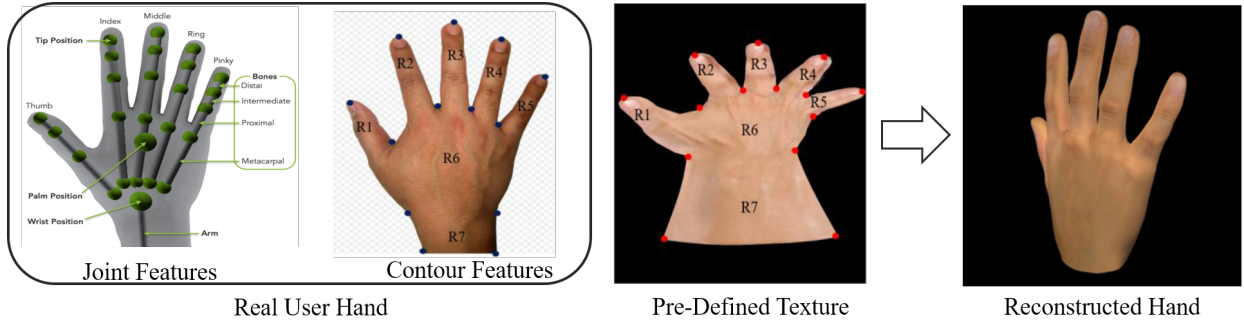


Figure 8.7: Reconstructed hand using joint points and contour feature points from real user hand photo. Warping the photo image to reference image. Left photo from user's upper hand with its feature points. Middle photo is a reference texture with its feature points. Right photo is an example reconstructed personalized hand

### 8.2.3 Feature composition using Convolutional Neural Networks

To enhance the visual perception regarding personal body information, artificial features such as hair, accessories, nail color, and tattoos have critical roles that should be applied to create a new and appropriate texture. Since we segmented the hand region along the anatomical structure as a preprocessing step, we know the location of the artificial features based on a general color salience algorithm. A human hand has a relatively uniform color range under a constant lighting condition, so that a combination of the segmentation information and an image color-based salience algorithm could label the features as accessories. However, even though we have a high resolution hand image, a relatively small size error of the detected feature area for certain accessories or tattoos could create a problem in saliency. Also, complex shapes of tattoos or physical accessories makes the detection problem more challenging. To overcome these problems, we adopt Deep Convolutional Neural Networks to recognize the saliency of an artificial feature. After we determine the salient area, we propose to composite the stored features using the segmented area from our own hand to the generic virtual hand with Laplacian Pyramid blending or a machine learning method (See Figure 8.8).



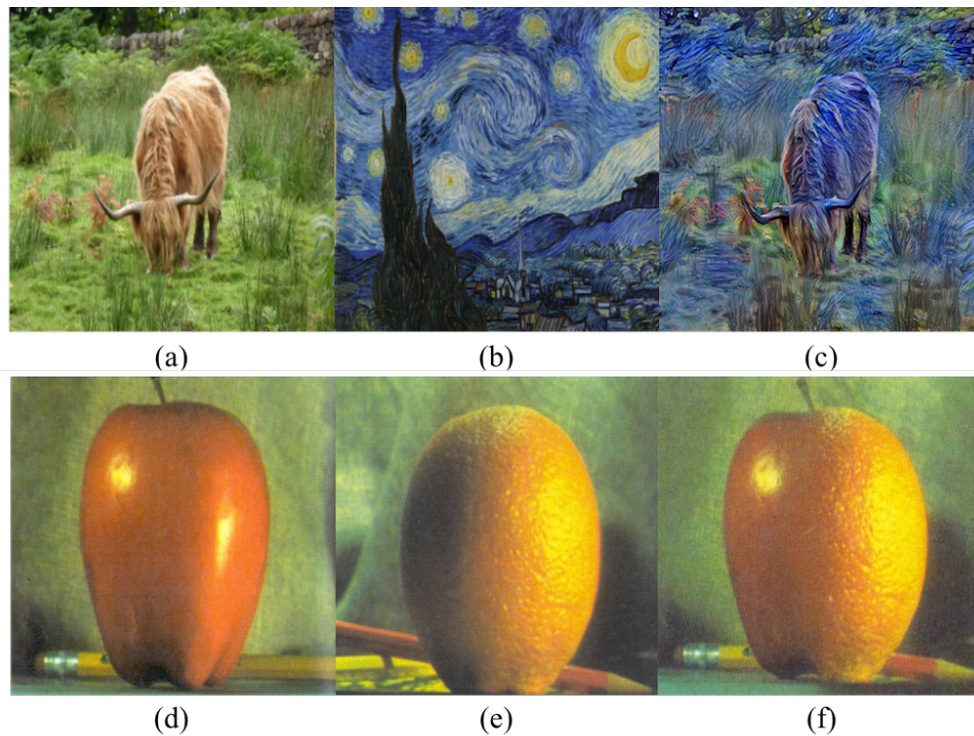


Figure 8.8: Examples of image composition using machine learning method(a-c) Thoma (2016), and traditional blending technique(d-f) Burt and Adelson (1983).

Here we described four key ideas regarding the proposed design.

- We use the Leap Motion or equivalent at the user's side so we can easily acquire joint points for the hand and fingers.
- We take photos of the palm and back of the hand using an orthogonal direction from the camera.
- We detect feature points on the contours near the joint points and mark anatomical regions based on data provided by the Leap Motion and those of the photos.
- We detect artificial features on the hand with visual salience and recognize them using machine learning.

#### 8.2.4 *Proposed Additional Research*

Building on the results presented in Chapters 3 through 7, we introduced an algorithm to produce a personalized virtual hand as a practical implementation in a virtual reality environment with a detailed explanation in Chapter 4. Because the proposed algorithm needs to quickly render the personalized virtual hand, we adopted a traditional texture warping based method that is suitable for VR applications. The goal is to complete this implementation and investigate whether and to what degree its use of each individual's hand image, including personal body features, could enhance the dominant illusions such as virtual body ownership illusion and spatial presence.

#### 8.2.5 *Proposed Future Research*

As future work, we plan to develop a system for blending a personalized virtual hand with a pre-defined virtual hand that does not have a human's anatomical hand structure. The blend will retain the structure of the game avatar, but also have personalized features from the human inhabiting that character. For example, a non-human soldier (perhaps a "Planet of the Apes" character) could have a hand and arm with species-specific features such as long hair, while also having a tattoo or partial glove like a human soldier. If we just replace the ape hand with a personalized human hand, it would break the illusions because the personalized virtual hand is not appropriate for the context of the VR application. To support the illusion of being this character, we will adopt computer vision technology to detect saliences from the captured human hand image, using a Deep Convolutional Neural Network (DCNN), while retaining the application-specific features of the base ape hand model in the final blended hand.

Also, using such generic rather than personalized accessory models could conflict with one's personality in VR. Since we detect the salience areas of such accessories from the hand image, we



will render its specific shape with texture using a combined technique for DCNN and computer vision.

As additional future work, we will go beyond first-person dominated illusions to conduct an experiment regarding the impact of personalized virtual hands from a social presence perspective. That is, we will study how personalized aspects influence the social behaviors of co-present players.

## **APPENDIX A: IRB APPROVAL OF HUMAN RESEARCH 1**



University of Central Florida Institutional Review Board  
Office of Research & Commercialization  
12201 Research Parkway, Suite 501  
Orlando, Florida 32826-3246  
Telephone: 407-823-2901 or 407-882-2276  
[www.research.ucf.edu/compliance/irb.html](http://www.research.ucf.edu/compliance/irb.html)

## Approval of Human Research

From: **UCF Institutional Review Board #1**  
**FWA00000351, IRB00001138**

To: **Sungchul Jung**

Date: **May 25, 2016**

Dear Researcher:

On 05/25/2016, the IRB approved the following human participant research until 05/24/2017 inclusive:

Type of Review: UCF Initial Review Submission Form  
Project Title: The Effects of Mirror Reflected Real Body Cues to Virtual Body  
Ownership and Presence in a Virtual Reality Environment.  
Investigator: Sungchul Jung  
IRB Number: SBE-16-12291  
Funding Agency:  
Grant Title:  
Research ID: N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at <https://iris.research.ucf.edu>.

If continuing review approval is not granted before the expiration date of 05/24/2017, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the [Investigator Manual](#).

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

A handwritten signature in black ink, reading "Joanne Muratori". The signature is written in a cursive style with a large initial "J" and a distinct "M".

Signature applied by Joanne Muratori on 05/25/2016 09:59:48 AM EDT

IRB Manager

## **APPENDIX B: IRB APPROVAL OF HUMAN RESEARCH 2**



University of Central Florida Institutional Review Board  
Office of Research & Commercialization  
12201 Research Parkway, Suite 501  
Orlando, Florida 32826-3246  
Telephone: 407-823-2901 or 407-882-2276  
[www.research.ucf.edu/compliance/irb.html](http://www.research.ucf.edu/compliance/irb.html)

## Approval of Human Research

From: **UCF Institutional Review Board #1**  
**FWA00000351, IRB00001138**

To: **Sungchul Jung**  
Date: **May 17, 2017**

Dear Researcher:

On 05/17/2017 the IRB approved the following human participant research until 05/16/2018 inclusive:

Type of Review:	IRB Continuing Review Application Form
Project Title:	The Effects of Mirror Reflected Real Body Cues to Virtual Body Ownership and Presence in a Virtual Reality Environment.
Investigator:	Sungchul Jung
IRB Number:	SBE-16-12291
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at <https://iris.research.ucf.edu>.

If continuing review approval is not granted before the expiration date of 05/16/2018, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the [Investigator Manual](#).

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

A handwritten signature in dark ink, reading "Renea Carver". The signature is written in a cursive style with a large, looped capital "R" and a trailing flourish.

Signature applied by Renea C Carver on 05/17/2017 10:03:23 AM EDT

IRB Coordinator

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