Measuring the Components of Personal Space Cognition in Simulated Immersive Virtual Environments

Lauren E. Buck

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Approved:

Bobby Bodenheimer, Ph.D.

Catie Chang, Ph.D.

Sohee Park, Ph.D.

Alan Peters, Ph.D.

Jeanine Stefanucci, Ph.D.

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IEEE Copyright Statement

1 Introduction

This dissertation focuses on the interaction of virtual reality users with their immediate space. We commonly conceptualize the immediate space around the body as personal space, or the zone that separates our bodies from external stimuli. The maintenance of this space is an essential cognitive function that constantly shapes the way we interact with objects and people. We think about personal space in this dissertation in two categories: ***interpersonal*** and ***peripersonal space***. Social psychologists have provided evidence that interpersonal space, or the distance that is maintained between two individuals, is a foundational element of social interactions [Argyle and Dean, 1965; Hall, 1966; Kennedy et al., 2009; Sommer, 1959]. The interpersonal distance that one maintains between themself and others is correlated with the dimensions of the body, particularly height and arm length [Hall, 1966; Hayduk, 1983; Pazhoohi et al., 2019], and is linked to what neuroscientists have defined as peripersonal space [Coello and Cartaud, 2021]. Peripersonal space is defined as the perceived reaching and grasping distance around oneself [Berti and Frassinetti 2000; Delevoye et al. 2010; Farne et al. 2005; Iachini et al. 2014; Rizzolatti et al. 1997]. Both interpersonal and peripersonal space have been shown to change based on differing interactions [Iachini et al., 2014; Quesque et al., 2017; Teneggi et al., 2013].

Virtual reality facilitates interactions in ways that traditional technology does not – it offers a 3D interface that allows users to interact with objects and individuals similar to the real world and experience feelings of presence and embodiment [Kilteni et al., 2012a; Normand et al., 2011; Petkova and Ehrsson, 2008; Slater et al., 2010b]. Thus, how users treat the interpersonal and peripersonal space around their bodies becomes important to understand since we want to provide accurate perceptual feedback in virtual reality to create realistic experiences. There are a multitude of different applications for work in this area, such as medical applications that provide therapy and assistive care for those with disabilities [Alcorn et al., 2011; Boyd et al., 2018; Lange et al., 2010], defense training [Bhagat et al., 2016; Lele, 2013], and architectural and educational applications [Portman et al., 2015; Psotka, 1995], among many others [Fox et al., 2009]. In this work, we focus on understanding how interactions occur in these spaces. We show that: 1. interpersonal space is maintained in immersive virtual environments, but not always naturally [Buck et al., 2019]; 2. peripersonal space can be measured in immersive virtual environments and it is sensitive to the context of the interaction [Buck et al., 2020b] ; and 3. both interpersonal and peripersonal space change responsively in an immersive virtual environment, are dependent upon the level of embodiment a user experiences, and are not affected when the arm dimensions of users are manipulated. These findings inform the design decisions and problems that must be addressed to create quality virtual reality experiences.

In the past few years, virtual reality technology has become a commodity. HTC[1], Oculus[2], and Samsung[3], among many other companies, have released headsets and tracking systems that are easily accessible for home and research use alike. These systems provide new experiences for users that could otherwise not be easily accessed due to the constraints of everyday life, and they provide an opportunity for mediated social and non-social interaction in an environment that mimics – to a certain degree – what can be done in the real world. There are several benefits that can arise from this type of technology that even extend beyond the world of computing, but virtual reality is not fully developed and still has potential for growth. For example, there are no solutions for full body haptics, the solutions that exist for commodity level motion capture and tracking are not perfect (even though there are solutions, it is especially difficult to convey emotional expressions, mutual gaze, and accurate self-representations), and delivering high quality spatial sound is still a complicated problem. This dissertation examines the perceptual quality of immersive virtual environments, specifically through the lens of how peripersonal and interpersonal space are modulated.

A defining attribute of immersive virtual environments is space. Users of these environments have the ability to move around in 3D space and manipulate or interact with other objects and users as they would in the real world. From our perspective in the real world the space around us seems to extend outward from our bodies in an indefinite, continuous expanse. Under the hood, however, our brains segment this space into different categories that carry implications for and modify the way we interact with this space. Neuroscience literature has long recorded this segmentation of space [di Pellegrino and Ladavas 2015; Rizzolatti et al. 1997], which consists of near and far space, also known as peripersonal and extrapersonal space. The space that we

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[1] To date, HTC has released a line of head-mounted displays called the HTC Vive: https://www.vive.com/us/

[2] To date, Oculus has released several head-mounted displays including the Oculus Go, Oculus Rift, and the Oculus Rift S: https://www.oculus.com/compare/

[3] To date, Samsung has released a head-mounted display compatible with their mobile phones: https://www.samsung.com/global/galaxy/gear-vr/

focus on in this dissertation is peripersonal space, which is defined as the functional reaching and grasping distance around oneself. There are neurons in the frontal parietal and premotor cortices of the brain that expressly process multisensory stimuli within peripersonal space. Neurophysiological and neuropsychological studies along with fMRI data have demonstrated this (see di Pellegrino and Ladavas [2015] for a full review). Peripersonal space is sensitive to social context, different environmental factors and tool use, among many other things [Bailenson et al. 2001; Bergstrom et al. 2019; Coello et al. 2012; Hall 1963; Hayduk 1983], and it is considered to be an emotionally charged zone around the self that cannot be intruded upon without some level of discomfort [Hall 1963; Hayduk 1983; Iachini et al. 2014]. This zone is correlated with what is defined as our interpersonal space, or the distance that one maintains between one's self and others, which has been more of a focus in psychology literature. As with peripersonal space, the modulation of interpersonal space is contingent upon different situational circumstances [Bell et al. 1996; Hall 1963, 1966; Iachini et al. 2014; Kennedy et al. 2009]. There is plenty of literature that focuses on social and non-social interaction in immersive virtual environments, but in Chapter 2, we describe open problems that indicate there is still much to understand about peripersonal space and no direct quantitative metric has been employed to understand it in these environments.

Motivating this work is a need for an understanding of how this space is mediated in order to convey proper interaction scenarios in immersive virtual environments. Designers and developers of these environments for all purposes, from entertainment to research, currently lack a deep understanding of this interaction space. Previous work on peripersonal space shows analogous boundaries and modulations between real and virtual worlds [Bailenson et al. 2003; Iachini et al. 2014, 2015a] but work dedicated to the study of interpersonal space, or proxemics, sometimes indicates mismatches between its behavior in the real and virtual world [Buck et al. 2019; Buhler and Lamontagne 2018; Gerin-Lajoie et al. 2008; Olivier et al. 2010; Sanz et al. 2015]. However, the degrees of freedom allowed to designers of immersive virtual environments are far greater than reality allows for, and both the boundaries and allowable modulations of peripersonal space have not been established for immersive virtual environments. To our knowledge, prior work only discusses the general effect of different social perceptions on peripersonal space. Our work seeks to firmly establish peripersonal space boundaries and cement the reliability of a previously defined method [Serino et al. 2017] by which we can begin to understand the design space of interaction for immersive virtual environments. We will include assessments of a variety of factors that may play a key role in understanding peripersonal space in terms of the self representation that is provided to users of these environments. Additionally, we will provide further understanding of how interpersonal space is correlated with the modulation of peripersonal space in immersive virtual environments.

A better understanding of these boundaries and interactions can support and improve the design and development of applications employing virtual environments, such as those used in assistive therapy for children and adults with autism [Alcorn et al. 2011; Boyd et al. 2018], those used to enhance and improve the lives of those who are aging with and into disabilities [Lange et al. 2010], and those supporting an array of training and simulation applications for medical, military and educational purposes [Fox et al. 2009]. On a broader scale, this work can also aid researchers and game designers in developing immersive virtual environments that evoke intended reactions from users in order to improve user experience and increase ecological validity. Understanding how users react to different objects and agents under different conditions can allow developers to make conscious decisions about the effects of their products on users.

1.1 Contributions

This dissertation makes several contributions towards understanding personal space in immersive virtual environments. These include an initial insight into how personal space – in terms of interpersonal space – is treated in a multi-user immersive virtual environment, a confirmation of reliable measurements of peripersonal space boundaries in immersive virtual environments using a newly defined methodology [Serino et al., 2017], and further understanding of how both interpersonal and peripersonal space boundaries change in immersive virtual environments when characteristics of the self-body representation in these environments change. These contributions are discussed in detail subsequently:

- Contribution I: The first contribution that this work makes is a **determination of baseline proxemic behaviors in a multi-user immersive virtual environment**. There is little work on multi-user interaction in distributed immersive virtual environments, and Chapter 3 describes two experiments that help determine that interpersonal space is treated differently than it would be in the real world. Using the general affordance task of passing through an aperture, we find in one experiment that gender dynamics are at play when different pairings are asked to pass through together in the real world. In another experiment, we find no indication of an influence of gender dynamics on aperture passage, but we do find that participants need wider aperture widths than they do in the real world to perceive them as passable.

- Contribution II: The second contribution that this work makes is a **quantitative measurement of peripersonal space boundaries and how they respond to objects and agents in an immersive virtual environment**. Chapter 4 discusses two experiments in which we deploy a previously defined methodology [Serino et al. 2017] to determine an exact measurement of peripersonal space boundaries in an immersive virtual environment. We seek to determine whether or not these boundaries are affected by the characteristics of agents and objects that can be interacted with. We find that peripersonal space boundaries are sensitive to whether or not the interaction is with an agent or an object, and that certain characteristics of agents and objects cause users to modulate their peripersonal space boundaries differently. We ultimately find that peripersonal space can now be delimited and thus this opens a door for a further understanding of this interaction space in immersive virtual environments.
- Contribution III: The third contribution that this work makes is an **understanding of how interpersonal and peripersonal space both are affected by the level of embodiment a user experiences in an immersive virtual environment**. Chapter 5 reports an experiment in which we manipulate the level of embodiment a user experiences in a virtual environment and measure both the interpersonal and peripersonal space of the user. In this experiment we found that higher sensations of embodiment cause users to expand the interpersonal space that they maintain between themselves and another individual and contract the perceived peripersonal space around their bodies. The findings from this work imply that a high level of embodiment is required for users of immersive virtual environments to interact with the space around their bodies in a naturalistic manner.
- Contribution IV: The fourth contribution this work makes is that **both interpersonal and peripersonal space are not equally sensitive to the manipulation of a self-avatar's arm dimensions**. Chapter 5 presents a second experiment in which we manipulate the arm dimensions of a user to be both shorter and longer than their natural arm dimensions. We found that the interpersonal distance that users maintained between themselves and other avatars behaved unevenly when given different arm dimensions, and

that peripersonal space boundaries remained the same regardless of the dimension manipulation. These results further bolster the idea that experiencing embodiment is important for the maintenance of interpersonal space and give us insight into the separation between peripersonal space and the active reaching and grasping space that users perceive around their bodies in immersive virtual environments.

1.2 Significance

The main contribution of this work to the field of computer science is the provision of a new quantitative understanding of peripersonal and interpersonal space that aids in the design and development of immersive virtual environments that mediate more realistic experiences. While realistic experiences are not necessarily as important for virtual reality used as entertainment, a further understanding of perceptual problems aids virtual reality applications used for instances of training and simulation that require realism, such as those employed by the medical, military and engineering communities. This dissertation provides a novel metric (which has only been introduced in the field of neuropsychological science [Serino et al. 2017]) for the delineation of peripersonal space and provides an understanding of what is required of virtual reality developers to evoke realistic behaviors from users. In addition, it intends to provide novel insights into whether embodiment affects peripersonal and interpersonal space and what level might be required to produce desired interactions, and how self-perception affects these spaces from the size of a given virtual avatar to the viewpoint given to the user. All of these findings provide groundwork for further research in this area.

The work in this dissertation is highly interdisciplinary, and pulls from the fields of computer science, neuroscience, and psychology. While this dissertation makes its main contribution in the field of computer science, both neuroscience and psychology lend themselves to the design and assessment of this work in order to understand the fidelity of the technology. Computer science is a highly interdisciplinary field, but generally uses algorithms to manipulate data to convey information through software systems. This dissertation is particularly focused in the area of computer graphics and visualization, which involves the manipulation of image data. We use the medium of virtual reality for all research in this work. Insights from neuroscience inform our research and influence the development of our testing environments. The core biological mechanisms for understanding how the brain processes peripersonal and interpersonal space are key in understanding how to test how these spaces are modulated naturally and how to measure the modulation in an immersive virtual environment from the results we gather. Additionally, psychological concepts are important in informing our research as well as influencing the development of our testing environments. There are particular concepts, such as perception and affordances [Gibson, 1979], that are directly relevant in understanding peripersonal and interpersonal space which inform us on how users interact with these environments. Thus, leveraging both neuroscience and psychology are key to validating mediated immersive virtual environments in this work.

The environments built and used in this work facilitate the measurement of peripersonal and interpersonal space both in social and non-social contexts using different methodologies. Foremost, we design and build a program that supports a distributed virtual reality application within which users are given self-avatars and can interact with one another [Buck et al. 2019]. Using the psychological concept of an affordance, users are asked to perform the simple task of walking through an aperture and work together to determine whether they can simultaneously pass through openings of varied widths. The gender of virtual self-avatars do not always necessarily match the underlying gender of users in this experiment since virtual reality provides one the freedom of selecting any virtual appearance. Prior to performing the experiment in virtual reality, we conduct the analog of this task in the real world and determine baseline results. This particular experiment gives us insight into how social interaction is conducted and how interpersonal space is maintained in an immersive virtual environment. We ultimately find that, in the real world, pairs of individuals passing through an aperture together tend to adjust their behavior based on the gender composition of the dyad. Males are less likely to concede space to one another, whereas the pairing of a female and a male are more likely to give one another more interpersonal space while passing together through an aperture. In the virtual world, this does not appear to be the case in our particular experiment. Users do not follow the natural notion of gender dynamics, but they do need more space overall to believe that they can pass through a virtual aperture. This causes us to hypothesize that interpersonal space functions on a different level in an immersive virtual environment. The qualities of immersive virtual environments that support this interaction behavior are unknown and current knowledge can only lend us insight to make speculation about the reasoning behind these behaviors.

Our first work led us to ask the question of how we can understand close interaction space in an immersive virtual environment and what quantitative metric can we use to validate how this interaction space is treated.

Using a new methodology [Serino et al. 2017], which was previously untested in a fully immersive virtual environment, we built an environment that contained multisensory stimuli and could be used to measure the bounds of one's peripersonal space. We gave users of this immersive environment both an object and agent to interact with to measure both social and non-social interaction behavior. While an object or an agent approached the user, they were asked to respond to a tactile stimulus that would occur whenever the object or agent had reached a certain distance. This methodology is based in neuroscience, and is grounded by the finding that neurons in both the parietal and premotor cortices are responsive to both visual and tactile stimuli that are within the bounds of peripersonal space [di Pellegrino and Ladavas [2015]], and they are not responsive when these stimuli are outside of these bounds [Serino et al. 2017]. In the experiments conducted in this environment, we find that peripersonal space is sensitive to the interaction type, particularly in that users give more peripersonal space to agents, and that it is sensitive to the characteristics of both objects and agents. We also find this methodology to be a reliable measurement of peripersonal space boundaries in immersive virtual environments.

The findings from both of these works lay the groundwork for a greater understanding of interpersonal and peripersonal space in immersive virtual environments. The first work shows us that in some instances, interpersonal space is exaggerated in immersive virtual environments and users require a larger zone around themselves to feel comfortable completing a task. Our second work shows us that we can now measure this space with a reliable metric in order to understand how peripersonal and interpersonal space are modulated in these environments. These findings bring us to our last thrust of work, in which we seek to understand how interpersonal and peripersonal space change in relation to the characteristics of a self-avatar. We built another environment similar to that in our second work in which users experienced multisensory stimuli and both interpersonal and peripersonal space were measured. In two different experiments, we assessed how the sense of embodiment and differing arm dimensions affected the way users treated the space around their bodies. Users experienced low, medium, and high levels of embodiment and arm dimensions that were either their own, shorter, or longer than their own. We found that a higher level of embodiment led users to exhibit more naturalistic interpersonal and peripersonal space and that manipulated arm dimensions did not have a clear affect on interpersonal space and did not affect peripersonal space. These findings shed light on the elements required for successful interaction between users and the immersive environment around them, and open further questions into how other components of these environments might affect personal space.

There is a decent body of literature within the virtual reality community that addresses similar problems as this work and focuses more on how the user experiences the technology [Bailenson et al. 2001, 2003; Bonsch et al. 2018; Llobera et al. 2010; Olivier et al. 2010; Wilcox et al. 2006]. Thus, this work continues in making a contribution towards improving the fidelity of user experiences and uses both neuroscience and psychology concepts to do so. In utilizing these fields of study, this work also makes a contribution to those fields. Overall, this work demonstrates how users define the immediate space around them in immersive virtual environments and how they perceive social and non-social interactions in this space. There is much groundwork in the fields of neuroscience and psychology to understand interactions with this space (see Chapter 2 and the references therein). This work presents a tool with which those from these fields can perhaps implement to further understand this space and gives scientists and understanding of how this space is treated in immersive virtual environments.

1.3 Overview

The remainder of this proposal is organized as follows. The following chapter, Chapter 2, provides background information on work that is directly related to our own here that we build off of and expound upon. Chapter 3 includes our work on how interpersonal space is treated in an immersive virtual environment providing an experiment that assesses a basic affordance task. Chapter 4 introduces a quantitative metric for measuring peripersonal space and its malleability based on object and agent interaction in an immersive virtual environment. Chapter 5 extends the works in both Chapters 3 and 4 to delve deeper into understanding both interpersonal and peripersonal in the context where a user's bodily self-representation, or self-avatar, is manipulated. The implications of these works and the future directions are discussed finally in Chapter 6.

2 Background

Here we provide a thorough literature review of the current body of work in relation to this dissertation. There are several topics into which we take a deep dive, including personal space (Section 2.1), presence and interaction (Section 2.2), and affordances (Section 2.3). The purpose of this literature review is to provide the reader with a broad understanding of what has been done and directions that this dissertation intends to extend current knowledge in the field. Each section assumes no prior knowledge of these fields and works to provide the reader with a thorough understanding of the concepts addressed before discussing the preliminary data we have gathered.

2.1 Personal Space

We have broken our discussion of personal space down into two sections: Physiological Evidence for the Division of Space (Section 2.1.1) and Behavioral Evidence for the Division of Space, Including Virtual Reality Evidence (Section 2.1.2). Neuroscience first gives insight into the understanding of the biological processes that drive peripersonal space. Then, cognitive science gives insight into the understanding of both interpersonal and peripersonal space and how they respond to different environmental factors and correlate with one another.

2.1.1 Physiological Evidence for the Division of Space

Everyday we interact with the space around us without putting forth a significant amount of mental energy; space exists for us as a seamless, uncomplicated expanse in which our interactions are fluid. However, the brain is hard at work continuously processing this space and segmenting it into functionally distinct representations [di Pellegrino and Ladavas, 2015] without our conscious effort. A cognitive distinction appears between near and far space, or peripersonal and extrapersonal space [Brain, 1941], and there are several neuroscience studies that affirm the distinction between these spaces in the brain [Leinonen and Nyman, 1979; Mountcastle, 1976; Rizzolatti et al., 1981a,b]. In this dissertation, we are primarily concerned with the representation of peripersonal space. Peripersonal space is formally described as the immediate space around the body in which objects can be grasped or manipulated [di Pellegrino and Ladavas, 2015]. In this section we provide a review of neuroscience literature to provide an ample understanding of how our brains segment and process this space and why this space is essential to interaction.

Literature on peripersonal space finds its roots in neurophysiological studies done on animals (particularly macaque monkeys), in which the discrete processing of peripersonal space was first shown in the parietal and frontal premotor cortices of the brain [di Pellegrino and Ladavas 2015; Graziano et al. 1994; Rizzolatti et al. 1981a,b; Gentilucci et al. 1983]. Recent neuroimaging studies confirm and show activation in the intraparietal sulcus, lateral occipital complex, and the premotor cortex in response to objects entering peripersonal space [Makin et al. 2007]. A large portion of the neurons in the premotor cortex of the brain are multimodal, responding to visual, tactile and auditory stimuli [Graziano et al. 1997a,b], and there are several fMRI studies that demonstrate activation in these regions of the brain [Bremmer et al. 2001; Ehrsson et al. 2004; Gentile et al. 2010; Makin et al. 2007]. These neurons are particularly responsive to stimuli near the body within the peripersonal space [di Pellegrino and Ladavas 2015; Gentilucci et al. 1983; Graziano 1999; Rizzolatti et al. 1981a], and they code the location of objects with relation to certain body parts such as the face, hand, etc. [Andersen, 2011; Cohen and Andersen, 2002; Goldberg et al., 1990]. This body-centered representation allows for the direction of movements toward or away from visual stimuli within the peripersonal space.

There is evidence that peripersonal space is dynamic, meaning that the space changes dependent upon the sensorimotor input being delivered to the individual. Particularly, Fogassi et al. [1996] found that when signaling an approaching object, faster-moving objects had earlier responses than slower-moving ones; the visual receptive field [4], which provides fundamental spatial information to help the motor system compute the location of objects in relation to the body, expanded in response to the velocity of the object in anticipation of the execution of an action on that object. Peripersonal space has also been shown to be dynamic in tool use. Iriki et al. [1996] trained monkeys to use a rake to retrieve food that was further than the reach of the monkey. It was shown that when this tool was purposefully used, the visual receptive field extended upon the axis of the tool. Responses have also been recorded with relation to realistic representations of body parts (i.e., a fake arm) when physical body parts are hidden [Brozzoli et al., 2012; Farne et al., 2000; Graziano, 1999; Makin et al., 2007]. Additionally, there are neuropsychological studies that show active tool use to change the way individuals act with far space [Berti and Frassinetti 2000; Farne and Ladavas 2000; Holmes and Spence

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[4] The visual receptive field is the portion of sensory space that can elicit neuronal responses.

2006; Ishibashi et al. 2004; Ladavas 2002; Ladavas and Serino 2008; Maravita et al. 2002; Maravita and Iriki 2004].

Of even further interest is a recent study on the encoding of peripersonal space in relation to other individuals. Neurons have been shown to not only respond to visual stimuli placed near the body part of a monkey or an individual, but to visual stimuli placed near the same body part of another individual [Brozzoli et al. 2013; Ishida et al. 2010]. These findings suggest that the peripersonal space of other individuals beyond the self can be encoded based on a learned representation — that is, a representation that is similar to how mirror neurons encode the actions of others. Typically, studies of peripersonal space have been based on interaction with three-dimensional objects but there is work that assesses the social modulation of peripersonal space. Heed et al. [2010] have shown that there is a social modulation of visual-tactile integration when another person is placed within an individual's peripersonal space, suggesting that peripersonal space may shrink when others are close to us. Teneggi et al. [2013] demonstrated that peripersonal space shrinks when far space is occupied by another person, and that it behaves congruently with how the other person's behavior is perceived.

Neuroscience research lends insight into the way the brain processes peripersonal space with the support of physiological brain data. While this is not an exhaustive review, this literature helps us to understand the underpinnings of our work. As objects and other individuals enter our peripersonal space, neurons in the parietal and frontal premotor cortices of our brains become responsive to multisensory stimuli. This body of work provides a concrete foundation that we can build upon to understand how users of immersive virtual reality treat the near space around their bodies. In the next section, we discuss how cognitive scientists have studied both peripersonal and interpersonal space, sometimes making use of immersive virtual reality.

2.1.2 Behavioral Evidence for the Division of Space, Including Virtual Reality Evidence

While peripersonal space has dense roots in neuroscience, studies in psychological and computer science regarding both peripersonal and interpersonal space, which are closely linked [Coello and Cartaud, 2021], have also blossomed. Hall [1963] first introduced interpersonal space as the 'self-space' that one maintains around his or her body. There are layers to this self-space known as one's public, social, personal and intimate space at which different interactions – both social and non-social – take place [Hall 1963, 1966]. Social psychologists since have also determined that interpersonal space is the area around one's body that is considered to be emotionally charged [Iachini et al. 2014] and cannot be violated without some level of discomfort [Hall 1963; Hayduk 1983]. This space expands and contracts depended on different factors which include age, personality, race, gender, and cultural and subcultural differences [Hayduk 1983]. The study of peripersonal space has been considered hand-in-hand with the study of interpersonal space (known as proxemics), or the maintenance of the distance between oneself and other individuals. Personal spatial distance is coupled with one's actions and interactions with individuals [Iachini et al. 2014], and thus there are several works that investigate peripersonal space that encompass both it and interpersonal space [Bailenson et al. 2003; Llobera et al. 2010; Teneggi et al. 2013; Pellencin et al. 2018]. Thus, in this section we will discuss some foundational works on peripersonal space that guide our own work, including that which directly uses immersive technology to assess the behavior of peripersonal space.

There is work that addresses different factors affecting peripersonal space, such as how it is extended by tool use [Maravita et al. 2002; Serino et al. 2007; Bassolino et al. 2010; Canzoneri et al. 2013a,b] and what multisensory stimuli contribute to the modulation of this space. Some of this literature makes use of immersive technology and the unique environment it provides to assess peripersonal space. Bassolino et al. [2010] took the widely observed paradigm that tool use (i.e., the use of a rake [Farne and Ladavas, 2000; Holmes and Spence, 2006; Iriki et al., 1996]) extends peripersonal space, and applied it to a study in which participants who had prolonged experience with a computer mouse responded to auditory and tactile stimuli near their hand and a computer screen. It was found that, when participants were holding a mouse, peripersonal space was extended to the computer screen. Another study by Maister et al. [2015] interestingly observed the remapping of peripersonal space of individuals after they had shared sensory experiences with another individual. Results from the audio-tactile integration task employed in this study showed that peripersonal space does not extend to another person but is remapped to include the peripersonal space of the other individual after a social interaction. Peripersonal space has also been shown to be dynamic and to be remapped as an individual is walking [Noel et al. 2015] as different vestibular information is provided to the individual [Pfeiffer et al. 2018]. Other studies suggest sound to be a key multisensory element in determining the peripersonal space. For example, sounds within the peripersonal space, regardless of whether they appear to be approaching or receding, have been found to affect corticospinal excitability [Finisguerra et al. 2015]. Approaching sounds with emotional valence have been found to affect peripersonal space as well, with peripersonal space boundaries extending when the emotional valence is negative [Ferri et al. 2015]. In addition, the deprivation of audio-visual sensory stimuli has shown to degrade visuo-tactile peripersonal space [Noel et al. 2018]. Of particular interest to the work here in this dissertation is that of Serino et al. [2017], in which a method for delimiting peripersonal space in mixed, virtual, and augmented reality was developed and tested. Visual and tactile information presented in a mixed reality environment was enough to delimit exact peripersonal space boundaries; in a mixed reality environment a ball was thrown at an individual while a tactile stimulus was delivered when the ball reached certain distances from the user and quickened responses to these stimuli demarcated peripersonal space boundaries. This work was extended and validated in another mixed reality environment in which social perception was proven to modulate peripersonal space boundaries [Pellencin et al. 2018]. Confederates in this study were presented as either moral or immoral individuals, and peripersonal space retracted and expanded when confederates were viewed as immoral and moral respectively.

Of further interest is the work of Tina Iachini and colleagues [Cartaud et al. 2018; Coello et al. 2012; Iachini et al. 2014, 2015b,a, 2016, 2017; Ruggiero et al. 2017, 2019b,a]. This body of work has sought to understand several factors that might affect the modulation of peripersonal space and has done so in real and immersive virtual environments. These factors include the perceived moral quality of the interaction partner, personality factors, facial expressions, appearance and even perceived temperature. Coello et al. [2012] delved into understanding the plasticity of peripersonal space by conducting a real world study in which dangerous and non-dangerous objects were presented in different orientations to study participants. Participants were asked to report their perceived reachability distance, which was observed as a measure of peripersonal space. This study revealed that when dangerous objects were oriented in such a way that the threatening part of the object faced participants, peripersonal space was reduced, but not when the threatening part of the object was oriented away. In the subsequent work following this paper [Iachini et al. 2014, 2015b,a, 2016, 2017], Iachini and colleagues study the modulation of peripersonal space in social and non-social contexts with the focused theme of understanding the shared components between peripersonal and interpersonal space.

Iachini and colleagues set out to understand this correlation by measuring both reachability and comfort distance, which were meant to measure peripersonal and interpersonal space respectively. Foremost, Iachini et al. [2014] asked users of an immersive virtual environment to report both reachability and comfort distance in relation to objects and humanlike agents respectively. Participants responded to stimuli while passively standing still and actively walking towards the stimuli. This work found that peripersonal and interpersonal space behaved similarly when participants were active and that both spaces were socially modulated. Iachini et al. [2015b] then sought to understand the relation of personality dimensions and anxiety levels to reachability and comfort distance. Data showed that both peripersonal and interpersonal space were positively correlated with anxiety in that the more anxiety participants felt, the larger the reachability and comfort distance reported. Iachini et al. [2015b] also found that when participants were not active, comfort distance was associated with emotional components of the personality, whereas reachability distance was more associated with the cognitive component of the personality. Iachini et al. [2015a] looked into the affect the perception of morality would have on reachability and comfort distance when users were asked to interact passively and actively with humanlike virtual agents that were described by moral, immoral, and neutral sentences. Results from this study showed that both distances expanded when virtual agents were described as immoral and contracted when they were described as moral. Furthermore, Iachini et al. [2016] explored the similarities between peripersonal space and interpersonal distance in relation to age and gender. This work found that both distances were moderated by gender and age when participants actively approached virtual agents. There was a reduction in both reachability and comfort distance when participants approached females and children and an expansion when they approached males and adults. In this particular study, the validity of using immersive virtual environments for measuring reachability and comfort distances was explored and a comparison of the results from both immersive and real environments proved immersive virtual environments to be reliable in these measurements. Additional work has shown peripersonal space to be affected by temporal information [Iachini et al. 2017], perceived temperatures [Ruggiero et al. 2019a] and the appearance of individuals that share characteristics of their interaction partners [Ruggiero et al. 2019b].

Iachini and colleagues have also taken a detailed look into understanding how facial expressions and the emotional valence that they convey affects the modulation of peripersonal and interpersonal space. In Ruggiero et al. [2017], users of an immersive virtual environment were asked to report reachability and comfort distances from virtual agents that exhibited happy, angry and neutral facial expressions while either being approached by or approaching the agents. This work found an increase in comfort and reachability distance in the when users were interacting with agents that held angry facial expressions. Ultimately the authors concluded that peripersonal and interpersonal space are similarly sensitive to emotional valence. In a follow-up study measuring the electrodermal activity of participants, human-like point light displays bearing angry, happy and neutral facial expressions were presented in peripersonal and extrapersonal space to individuals [Cartaud et al. 2018]. The same results from the prior study were reproduced, and emotional valence similarly affected both peripersonal and interpersonal space.

Bailenson and colleagues have assessed social interaction in immersive virtual environments to a large degree, and have focused on how body language, or nonverbal communication, and physical characteristics affect interpersonal interaction in these environments. Most of this work deals with the levels of embodiment and copresence users experience, but there are a few papers that deal with the modulation of interpersonal space in immersive virtual environments. Bailenson et al. [2001] tested Argyle and Dean's [1965] equilibrium theory [5] in an immersive virtual environment. In this experiment, participants interacted with embodied agents who maintained various levels of mutual gaze. Participants maintained more personal space between themselves and agents that were human-like agents than objects and females maintained more personal space between themselves and agents that engaged them in eye contact while males did not. Bailenson et al. [2003] extended this work by having study participants approach and be approached by virtual humans that maintained different levels of mutual gaze behavior. The sentience of these virtual humans also varied – they were either perceived as controlled by another human (i.e., were perceived as an avatar) or by a computer (i.e., were perceived as an agent). This work found that participants maintained greater interpersonal distance when approaching the front of agents and avatars than they did when approaching from behind. In addition, participants gave more interpersonal distance when they were engaged in mutual gaze, and participants moved furthest away when they were approached by virtual agents. In other work, Bailenson and colleagues have also found interpersonal space to be maintained even in online environments where users control avatars via means of a desktop computer. Studying Second Life, an online community, Yee et al. [2007] found users comprised of male-male dyads to

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[5] The equilibrium theory presents a model in which proxemic and mutual gaze behavior are inversely related. Mutual gaze is viewed as an act that promotes intimacy between individuals, and when it is unwanted, the personal space between two individuals increases.

maintain more interpersonal distance between one another than female-female dyads, and that users that engaged in less mutual gaze maintained smaller interpersonal distances between one another than those who engaged in more. Bailenson et al. [2008] additionally showed that users of immersive environments are more prone to engage in more intimate behaviors, one of them being maintaining less interpersonal space, with virtual agents that look like themselves rather than those that do not have a similar appearance.

In addition to the literature discussed, other work in immersive technology and interpersonal space exists. Using a stereoscopic 3D display, Wilcox et al. [2006] presented images of objects and humans that were placed at different locations in a room to study participants and found that users experienced discomfort when human images violated their personal space. In an immersive virtual environment, Llobera et al. [2010] had both female agents and objects approach users while measuring physiological response. Results showed that when approached by either an agent or an object, the physiological response increased as the distance between visual stimuli and the user decreased. Additionally, Zibrek et al. [2017] asked users to approach different virtual agents that were all presented using different rendering styles and found that, regardless of the rendering style, there was no difference in the interpersonal distance that was maintained.

The behavioral evidence for how both interpersonal and peripersonal space are represented in the real world indicates that it would be affected by a multitude of environmental factors. The multisensory feedback available to the individual, presence or absence of other individuals, and emotional valence of the interaction are just a few examples of what might affect these representations. Due to the sheer quantity of interaction possibilities, there is still a large gap in the understanding of how differing factors of immersive virtual environments affect the representation of personal space. However, virtual reality lends itself as a tool for understanding these representations based on the control and precision virtual environments provide. Evidence from prior studies using immersive virtual reality shows that interpersonal and peripersonal space are maintained and are responsive to differing contextual factors of interaction in these environments. However, there are still significant open questions about the factors affecting the representation of space. For example, the realism of the environment can be controlled by the developer. The art style of the environment can range from cartoonish to realistic, verbal communication can be mediated through a microphone or not at all, and precise physical movements are only facilitated by high-end motion capture equipment that the commodity-level user does not have access to. There are other elements of virtual environments to consider, such as embodiment and presence, which we discuss in the next section.

2.2 Embodiment, Presence and Interaction

Since the advent of systems targeted toward home use, virtual reality has become accessible to a wide range of users. This introduction has piqued interest in social applications and thus has provided further kindling for researchers in fueling the understanding of social presence and interaction in immersive virtual environments. These environments boast high levels of social presence in comparison to other technological mediums of communication [Oh et al. 2018], and there are those who believe that it will radically change social interaction in our daily lives [Biocca and Levy 2013]. In this section, we will first discuss a key element of social interaction – embodiment and presence (Sections 2.2.1 and 2.2.2) – and then discuss interaction itself in immersive virtual environments (Section 2.2.3).

2.2.1 Embodiment and Presence in Immersive Virtual Environments

In the context of virtual reality technology, the sense of embodiment refers to the experience of sensations such as being inside of and controlling a body in an immersive environment that are similar to natural, biological sensations [Kilteni et al. 2012a]. Embodiment is a highly complex field of study, and has been suggested to affect physical presence, social and self presence [Biocca 1997; Slater et al. 2010a]. Kilteni et al. [2012a] argue that there are three different components that contribute to embodiment: the sense of self-location, agency, and body ownership. Gonzalez-Franco and Peck [2018] introduce external appearance as another component. These are important factors that contribute to interaction behaviors in immersive virtual environments, and thus we will discuss them in some detail below.

Self-location is a “determinate volume in space where one feels to be located," [Kilteni et al. 2012a] and includes body space since one typically feels self-located inside of their own bodily representation [Lenggenhager et al. 2009]. In essence, self-location is concerned with the sense of the self and body. The sense of self-location has been shown to be affected by the origin of visuospatial information [Blanke and Metzinger 2009; Ehrsson 2007] and Lee [2004] argued that first person perspective is important for self-location in highly immersive virtual environments. Further study has proven this correct [Maselli and Slater 2013, 2014]. For example, some studies find a greater physiological response to threats when the users of immersive environments are given a first person perspective rather than a third person perspective [Petkova et al. 2011; Slater et al. 2010b]. Additionally, vestibular signals have proven important to the sense of self-location [Blanke and Metzinger 2009; Lopez et al. 2008], along with tactile information. Tactile information is important here, as the boundary between our bodies and the environment is our skin and in direct relation is how the brain processes and encodes information in the space near the body [Kilteni et al. 2012a]. Peripersonal space is seen as an important key to understanding self-localization in immersive environments [Lenggenhager et al. 2009], since this space has been shown to expand during tool use [Giummarra et al. 2008] and vary when users are given self-avatars of different volume [Normand et al. 2011].

Perspective taking is also an important cognitive science concept to understand in the context of our work before addressing other components of embodiment. Perspective taking refers to one's access to spatial information as perceived from another viewpoint [Creem-Regehr et al. 2013] and suggests that one has the ability to predict the behavior from that viewpoint based on this information. Users of immersive virtual environments within close proximity have been shown to demonstrate generally accurate assessments of what other users can perceive [Kelly et al. 2004]. However, studies have shown that the ability of participants to detect where objects are located in relation to another viewpoint is not robust, and that cognitive processing becomes slower when one considers another viewpoint than their own [May 2004; Presson and Montello 1994; Rieser 1989]. More recent work discussing event segmentation, or the division of experiences into events [DuBrow and Davachi 2013; Kurby and Zacks 2008], has also determined that segmentation of events does not differ between first and third person perspectives [Swallow et al. 2018]. This literature suggests that we have the ability to categorize and understand different tasks and events from different perspectives, but that cognitive processing may be different when the visual perspective is not one's own.

Blanke and Metzinger [2009] describe the sense of agency as a sense of having "global motor control, intention, motor selection and the conscious experience of will." This sense has been hypothesized to result when one feels that they are an agent of actions when the predicted consequences of some actions match the actual consequences of those actions [Kilteni et al. 2012a]. Thus, in immersive virtual environments this sense is highly dependent upon the synchronicity of actual movement and visuomotor feedback in the environment, and providing this synchronocity has been correlated with positive notions of agency [Gonzalez-Franco et al. 2010; Kokkinara and Slater 2014]. There are additional studies that have shown that when visuomotor feedback is mismatched, the level of agency and embodiment that is felt is negatively affected [Blakemore et al. 2002; Sato and Yasuda 2005].

Body ownership, or the sense that a body is one's own, is the next component of embodiment. There are multiple influences on body ownership, such as the sensory information processed from tactile, visual, and proprioceptive inputs and the cognitive processes that modulate the processing from these stimuli [Tsakiris and Haggard 2005; Tsakiris 2010]. The rubber hand illusion, in which an individual experiences ownership of a fake rubber hand, is a popular methodology that cements the notion that body ownership is plastic and can be experienced even when one's bodily representation is not physically their own [Botvinick and Cohen 1998; Tsakiris and Haggard 2005]. This illusion has been replicated in an immersive virtual environment [Yuan and Steed 2010] and further research suggests that ownership of an entire virtual body can be experienced [Normand et al. 2011; Sanchez-Vives et al. 2010; Slater et al. 2009]. The evocation of body ownership hinges on the morphological similarity of the body or body part(s) [Armel and Ramachandran 2003; Ehrsson et al. 2004; Tsakiris and Haggard 2005; Tsakiris 2010].

The last element of embodiment we will discuss is external appearance, or the appearance of a virtual self-avatar. Gonzalez-Franco and Peck [2018] noted that the appearance of a self-avatar may enhance or diminsh embodiment felt by users of immersive virtual environments. While embodiment is increased when users are given gender and race matched self-avatars, it can be experienced when self-avatars not matched to these external qualities of users [Kilteni et al. 2013; Peck et al. 2013]. Additionally, embodiment can be felt when the dimensions [Kilteni et al. 2012b; Normand et al. 2011; Yee et al. 2009; Won et al. 2015], or bodily shape, and the age [Banakou et al. 2013] of a self-avatar do not match the physical dimensions of the user. This work has also found attitudinal changes to occur when users experience embodiment of self-avatars of these different qualities. For example, Peck et al. [2013] found racial bias to decrease in white participants who embodied black self-avatars. Yee and Bailenson [2007] and Yee et al. [2009] found that users who embodied taller self-avatars carried themselves more confidently in negotiation tasks. Kilteni et al. [2013] found that providing self-avatars that were professionally dressed decreased the musicality of users asked to play the bongos. This research demonstrates that the level of embodiment along with the social implications of the appearance of self-avatars affects the way users of immersive virtual environments behave. This is important to understand the interaction taking place in these environments.

Ultimately, it is important to understand the level of embodiment felt by users of immersive virtual environments and to apply prior findings to complete this dissertation. The level of embodiment felt by a user changes the way he or she interacts with that environment and how he or she may conduct his or herself in mediated social interactions. In the next section, we will delve deeper into how social interactions are treated in immersive virtual environments.

2.2.2 Social Presence in Immersive Virtual Environments

Social presence, or the subjective feeling of "being there" with another person in an immersive virtual environment and having access to their thoughts and emotions [Biocca 1997], is a key component of multi-user virtual reality. In contrast to other forms of computer mediated communication, virtual reality systems have the potential to offer various social cues through visual, audio, and haptic information [Oh et al. 2018]. Thus, social presence has been heavily studied and there is a large amount of literature assessing how to achieve social presence in immersive environments. Social presence is complex and there are many factors (such as contextual and individual factors) that influence the degree of presence and the interaction quality [Kang and Gratch 2014; Oh et al. 2018; Siriaraya and Siang Ang 2012; Verhagen et al. 2014]. Social presence has been linked to a positive communication outcomes, such as those related to persuasion, attraction, trust and enjoyment [Fogg and Tseng 1999; Hassanein and Head 2007; Lee et al. 2006]. If social presence is not elicited, Lee et al. [2006] noted, the interaction partner(s) is merely experienced as an artificial entity and not a social being. Social presence is a key element to eliciting the correct modulation of peripersonal space as one makes determinations about this space based on the different traits and emotions one conveys naturally in social situations.

Social presence was first defined by Short et al. [1976] as the importance of the interpersonal relationship of interactants during mediated conversation, and the two core components were intimacy[6] and immediacy[7]. Gunawardena [1995] later noted that intimacy and immediacy are affected by both verbal and nonverbal cues, such as facial expressions, vocal cues, gestures, and the physical appearance of the interaction partner(s). However, most early work on social presence has focused on how different modalities with different degrees of immersion afforded social presence. Much of this work is focused on the comparison between modalities that facilitate face-to-face communication and computer mediated communication. This body of work predominantly finds that face-to-face communication facilitates higher levels of social presence during interaction [Alge et al. 2003; Appel et al. 2012; Bente et al. 2007; Biocca et al. 2001; Cortese and Seo 2012; Zhan and Mei 2013]. There is further work that focuses on a deeper level understanding of social presence in immersive, e.g., head-mounted display and CAVE, and non-immersive, e.g., desktop, platforms, and this literature shows that immersive environments elicit a greater level of telepresence[8] [Cummings and Bailenson 2016], but not social presence [Oh et al. 2018]. The findings noted from this literature bring forth the sentiment that a higher degree of immersion does not always automatically facilitate greater social presence.

Another factor that affects social presence in immersive environments is the visual representation of the interaction partner(s). Most studies in this arena have focused on the presence or absence of and realism (i.e., photographic, anthropomorphic, and behavioral realism) of the visual representation. Studies find that social presence increases when there is a visual representation present [Feng et al. 2016; Kim et al. 2013a]. Additionally, the presence of behavioral realism is significantly linked with higher levels of social presence, and the positive effects of behavioral realism are mostly found when the interaction partner appears to be aware of the other's presence (e.g., when there is mutual gaze behavior, nodding in response at appropriate times, blushing) [Bente et al. 2008; Pan et al. 2008; Von der Putten et al. 2010]. However, studies focused on photographic and anthropomorphic realism present mixed results. There are studies concluding increasing photographic or anthropomorphic realism to have a positive effect [Kang and Watt 2013], no effect [Bailenson et al. 2001; Bente et al. 2008], and even a negative effect [Nowak and Biocca 2003] on social presence. Blascovich

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[6] Intimacy here refers to the feeling of connectedness between individuals during an interaction.

[7] Immediacy here refers to the psychological distance between the communicators

[8] Telepresence is the extent to which a user feels present in a mediated environment [Steuer 1992].

et al. [2002] and Nass et al. [1994] argue that this may just be a result of visual appearance being less important than behavioral realism in its contribution to social presence, while work by Bailenson et al. [2005b] and Garau et al. [2003] suggest it is perhaps correlated with the consistency of the appearance and behavioral realism.

Additionally, there are studies conducted on the effects of interactivity, haptic feedback, depth cues, and audio quality on social presence. The ability of an individual to interact with a computerized agent [Fortin and Dholakia 2005; Skalski and Tamborini 2007], increasing levels of haptic feedback [Kim et al. 2004], the inclusion of depth cues [Ahn et al. 2014; Kim et al. 2012; Takatalo et al. 2011], and higher fidelity audio quality [Skalski and Whitbred 2010] are all positively correlated with the social presence felt in an immersive environment.

Shifting gears, there are a variety of contextual factors that contribute to social presence: the personality and traits of virtual humans, agency, physical proximity, and social and identity cues. Many components of interpersonal dynamics contribute to the feeling of social presence such as how well an individual identifies with their interaction partner [Qiu and Benbasat 2010], how much personal information an interaction partner is willing to reveal [Kang and Gratch 2014], and how physically similar interaction partners appear [Jin 2012]. Agency in immersive virtual environments refers to whether a virtual human is being controlled by a computer algorithm (i.e., an agent) or a human (i.e., an avatar). Studies that observe the effects of agency on social presence find mixed results, with some studies finding higher levels of perceived social presence occurring when users interact with either avatars as opposed to agents [Appel et al. 2012; Blascovich et al. 2002; Fox et al. 2015; Lim and Reeves 2010] and some finding equal levels of perceived social presence for both agents and avatars [Dalzel-Job 2015; Felnhofer et al. 2018; Nowak and Biocca 2003; Von der Putten et al. 2010]. Physical proximity, or the physical collocation of users, has been found to positively correlate with higher levels of social presence, but with some caveats [Croes et al. 2016; Gajadhar et al. 2008; Hatta and Ken-ichi 2008; Jarvela et al. 2016]. In the context of current literature, users that were not physically collocated were visibly anonymous. Further study on the presence of social cues, or in this case simply the presence of multiple avatars or agents that are aware of the virtual environment and interact with it, have also found a positive correlation between social cues and social presence [Choi and Kwak 2017; Daher et al. 2016; Kim 2016; Lee and Nass 2004]. Finally, identity cues (i.e., name, picture of visual appearance) have also been shown to positively correlate with social presence [Choi and Kwak 2017; Feng et al. 2016; Li et al. 2015; Schumann et al. 2017].

Finally, there are some studies that assess how individual differences affect social presence. These studies focus in on how demographic characteristics, such as gender and age, and psychological traits affect the perception of social presence in immersive virtual environments. Studies that have focused on gender have found that females typically exhibit higher levels of social presence than males [Giannopoulos et al. 2008; Johnson 2011]. For the most part, studies have found no correlation with age and level of social presence [Cho et al. 2015; Hauber et al. 2005; Kim et al. 2004; Lim and Richardson 2016; Richardson and Swan 2003], but there are a small number of studies that have found older participants to experience lower levels of social presence [Felnhofer et al. 2014; Siriaraya and Siang Ang 2012]. These findings have not been thoroughly explored, and could suggest that familiarity with certain technologies or openness to experience might influence social presence [Oh et al. 2018]. Additional work assessing different psychological traits have found that people who have stronger immersive tendencies are more likely to feel high levels of social presence [Kim et al. 2013b], and that individuals who value and enjoy social interactions have higher levels of social presence [Cortese and Seo 2012; Jin 2010].

Social presence is a key component of interaction in a social virtual environment — one must feel that another is there with them, exhibiting visual, auditory, and tactile information — and it can be considered important to the representations of interpersonal and peripersonal space. Current literature demonstrates that there are elements of virtual environments that improve social presence like a visual representation of one's body [Feng et al., 2016; Kim et al., 2013b], mutual gaze behavior [Bente et al., 2007], and behavioral realism Blascovich et al. [2002]; Nass et al. [1994]; Von der Putten et al. [2010], and these elements are important to consider in the design of virtual environments. This section mainly serves to bolster our claim that the differing degrees of visual, auditory, and tactile feedback that one receives in a virtual environment can affect how the environment is experienced and thus affect the way the space is represented around the body. The subsequent section addresses current knowledge about interaction itself in immersive virtual environments.

2.2.3 Interaction in Immersive Virtual Environments

Interaction, whether it be social or non-social, has undergone a considerable amount of study in the context of virtual reality. There is a more recent understanding that in non-social situations, high fidelity interactions promote more positive user experiences [Rogers et al. 2019], and that socio-psychological effects play some role in how users behave in immersive virtual environments [Emmerich and Masuch 2018]. However, the fidelity of social interaction in immersive virtual environments has been hard to nail down, as some social interactions occur in parallel [Bailenson et al. 2003; Iachini et al. 2014] and some in opposition [Buck et al. 2019; Gerin-Lajoie et al. 2008; Olivier et al. 2010; Podkosova and Kaufmann 2018b; Rogers et al. 2019] to natural social interaction.

One method for assessing non-social interactions in immersive virtual environments is that of object manipulation. Object manipulation has been studied both in an individual [Mine 1995; Rogers et al. 2019] and in collaborative contexts [Fleury et al. 2012; Garcˇa et al. 2008; Margery et al. 1999; Noma and Miyasato 1997; Pinho et al. 2002], as the facilitation of object manipulation is key in interacting with immersive virtual environments. It has been shown that high degrees of interaction fidelity positively correlate with user experience when manipulating objects [Rogers et al. 2019]. In addition, object manipulation fidelity can be affected when some method of redirected walking is applied to the immersive virtual environment [Wilson et al. 2018]. Users of immersive virtual environments are able to experience tool extension [Sengul et al. 2012], in that the tool's reaching space is considered part of one's own reaching space, and given a self-avatar, users also experience high degrees of tool extension [Bergstrom et al. 2019]. Collaborative manipulation of objects is also essential to increasing the ease of some tasks performed in immersive virtual environments [Pinho et al. 2002], and it is important to understand the way users interact with the perceived reaching space around themselves in immersive virtual environments.

There is a large body of work that focuses more generally on interaction in shared immersive virtual environments. However, most of it is focused on desktop environments [Bainbridge 2007; Beck et al. 2013; Yee et al. 2007], which for the purpose of this work does not seem relevant. Thus, we will focus on that which is directly related to immersive virtual environments. There is significant foundational work on the benefits that shared immersive virtual environments can provide, particularly due to the strong sense of co-presence that these environments have the ability to evoke [Heldal et al. 2005, 2006; Hoppe et al. 2018; Steed and Schroeder 2015]. Pan and Steed [2017] have studied the effect of virtual avatars on collaborative tasks in shared immersive environments, and found that providing users with a full body avatar decreased task completion time and increased partner trust in comparison to a condition where no avatar was given to users. These results indicate the ability of these environments to mirror real world task completion behaviors. There is also other work that endorses the positive correlation of avatars on presence and interaction in shared immersive virtual environments [Herder et al. 2019; Wu et al. 2019]. In addition, our own work has shown that users of collaborative environments are able to successfully complete objectives such as walking through apertures together and, while not perfect, maintain basic naturalistic interaction behavior patterns [Buck et al. 2019]. There are some studies that observe the behavior of users in virtual crowds, and this literature is particularly promising in that levels of presence that evoke naturalistic interaction are present [Kyriakou et al. 2017; Nelson et al. 2019]. In these studies, crowd density, speed, the facilitation of collision avoidance, gaze behavior, and verbal salutations from agents have been shown to all positively correlate with the level of presence experienced.

Social interaction in immersive virtual environments has often been considered in the context of collision avoidance. Collision avoidance literature has demonstrated that users preserve personal space even in immersive virtual environments, and has been shown to be correlated with the environmental factors and levels of certainty that users experience during a task [Gerin-Lajoie et al. 2005]. However, the personal space that is preserved in virtual environments during these tasks seems to be larger than it is for the same type of task in the real world [Gerin-Lajoie et al. 2008; Podkosova and Kaufmann 2018b]. Other work has found that while users of virtual environments are able to predict and yield to objects they think they may collide with, they are not able to accurately predict if a collision will actually occur [Olivier et al. 2010]. Users are also more cautious during these tasks, slowing their walking speed and increasing clearing distance between themselves and agents and avatars [Buhler and Lamontagne 2018; Sanz et al. 2015]. This clearing distance is also affected by the orientation of objects in reference to the user. Podkosova and Kaufmann [2018a,b] have particularly explored the effects of distributed immersive environments (i.e., immersive environments in which users are not physically collocated) on collision avoidance. In both works physical collocation coincides with more cautious behaviors and ample provision of interpersonal space, while in distributed environments users disregard personal space and do not typically avoid collisions. Females were also shown to provide more interpersonal distance and exercise more caution in these instances than males [Podkosova and Kaufmann 2018a].

2.3 Affordances

2.3.1 An Introduction to Affordance Theory

Gibson [Gibson, 1979] initially introduced the concept of affordances, arguing that surfaces divide the environment into substances and the medium in which all organisms abide. These substances determine what the environment *affords* an organism. He meant that by perceiving the environment, an organism can make judgments about what actions it has the ability to perform, and he called this the *Theory of Affordances*. Gibson [Gibson, 1979; Gibson et al., 1982] argues that there are several properties of the world that we perceive and detect: spatial, spatio-temporal and the visual detection of the self. All of the things that we perceive and detect *relative to us* give way to what the environment *affords* us. "Roughly," he stated, "the affordances of things are what they furnish, for good or ill, that is, what they afford the observer." Gibsonian theory introduced a gamut of behavioral science questions that have been and are still being answered today. In this section, we describe affordances studied in the context of psychology and how they apply to immersive virtual environments. In doing so we hope to clarify the relation between the behavioral science of affordances in these contexts and the importance of the role that human behavior plays in increasing the sophistication of virtual reality technology.

2.3.2 Joint Affordance and Action

Whether we are consciously aware of it or not, we perform assessments of our action capabilities within our environment a multitude of times each day. Often we are not alone and must perform actions with and in consideration of others. Take, for example, walking down a busy sidewalk or lifting a heavy box with the assistance of another person. We can think of the perception of joint action capabilities as *joint affordances*, and the actual execution of these actions as *joint actions*. Sebanz et al. [2006] gave us a succinct working definition of joint action - it "can be regarded as any form of social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment." The perception of joint affordances and execution of joint actions are complex, and we briefly discuss the science behind them here.

The process for perceiving and acting upon joint affordances thus builds upon Gibsonian theory. Knoblich and Sebanz [2006] suggest that we are able to perceive an action performed by another and produce a mental representation of that action. These mental representations, or action simulations, are formed by mentally encoding the procedures of actions we ourselves and others carry out during our lifetime. We use action simulations to predict the actions of others and to plan out our own actions in unison, as these action simulations can be shared. According to Knoblich and Sebanz, not only are our action simulations based on the visual input and motor response from performed actions, but are produced from the input we receive from proprioceptive and tactile signals. We build action simulations for ourselves and others based on our perceptual understanding of our own physical dimensions and those of our environment. But this is just a skim over the surface of what perceptual inputs we use to turn an affordance into an action and we must delve deeper into understanding how we perceive affordances according to our environment.

So how is it that we determine affordances and what causes us to actualize these affordances? Section 2.3.3 discusses in further detail the technicalities behind how our perception-action systems determine what certain environmental properties afford.

2.3.3 Operationalization of Affordances and Joint Affordances

Research based on Gibsonian theory began flourishing not long after his works, and William Warren linked the perception of an affordance to be an underlying component that controlled the action system. Warren [1984] built upon Gibson's underlying theories by performing stair climbing experiments to detect how singular individuals perceive and decide to act upon what they perceive. Warren noted that "intrinsic" measurements, or the bodily dimensions of oneself, affect action response decisions to an environment. He showed not only that the underlying dynamics of performance affected action, but that the perceived critical and optimal points - points at which action behavior changes occurred and points at which action exhibited the minimum energy expenditure and were therefore optimal - would be constants over scale changes between individuals. Results from his experiments demonstrated that perceptual behavior categories have a basis in critical points of dynamic systems and can be generalized to other affordance studies. These findings were extended in Warren and Whang [1987] in which the passability of an aperture also exhibited static critical points scaled in relation to bodily dimension.

Transitioning to joint affordances, Richardson et al. [2007] studied the fidelity of joint affordances as a means of further study in perception and action tasks. The experiments conducted in this paper observed behavior between participants who judged and performed a plank grasping task with one hand (1H), two hands

(2H), and a tool which extended their grip (TH) or another person (2P). Richardson et al. found that there were critical points at which grasping behaviors varied when the plank size reached a certain ratio in accordance to the arm and hand span of the subjects. It was demonstrated here that definitive measurements of action capabilities could be gathered from an extended affordance task. Higuchi et al. [2006] also observed participants in an aperture passability task that included external objects to increase the space required for passage with locomotor constraints. The authors determined shoulder rotation to be essential for quick, accurate execution of the task. Chang et al. [2009] asked adult and child subjects to judge and pass through an aperture together to determine the minimum aperture width that the dyad could pass through without shoulder rotation. Adult participants were able to make accurate perceptual judgments based on their own shoulder width and that of a large or small child, showing that these affordances are based on body-scaled units. Stefanucci and Geuss [2010] additionally tasked participants with ducking under a horizontal barrier naturally and with manipulated bodily dimensions. An increase in bodily dimensions (i.e., height) resulted in participants adjusting their behavior to fit the new scale of their body. The general message of psychological affordance literature denotes that affordances are perceived based on body dimensions, whether they be natural or scaled, and that there is a metric produced from affordance judgments that can be treated as a concrete quantitative measurement of task performance in a variety of different tasks (Mark [1987]; Kinsella-Shaw et al. [1992]; Fitzpatrick et al. [1994]).

2.3.4 Affordances in Immersive Virtual Environments

While many psychology studies have determined a baseline understanding of affordances and how they are determined in real life, computer scientists have utilized them to understand how users of immersive virtual environments perceive them. Stappers et al. [1999] concluded critical thresholds in affordance studies to be a key component to understanding presence in IVEs, and Gross et al. [2005] suggested that the realization of affordances is a key component to design of IVEs to enhance user experience by providing a more intuitive and natural environment. Here we will detail the literature encompassing affordances studied in VR and provide a basis for the experiments performed in this dissertation.

In an aperture passability task in a cave-like VE, Lepecq et al. [2009] asked participants to walk through a virtual doorway at different widths while critical thresholds were determined through the coding of behavioral transitions. The behavioral transitions were noted by the angle at which a participant's shoulders were rotated when crossing through the doorway. Results from this study strongly indicated that the angle of shoulder rotation displayed in the IVE was strongly aligned with that found in the real world and thus determined an objective indication of presence. Geuss et al. [2010] had participants make judgments on their perceived passability a real and virtual aperture to determine the geometric fidelity of IVEs. The study indicated that there was no difference in perceived passability between the real and virtual conditions and that affordances were a robust evaluation of the quality of presence in IVEs.

Regia-Corte et al. [2013] assessed the affordance of perceived upright stance in an IVE by having study participants view and judge different slanted surfaces. It was determined that the perceived affordance in VR was comparable to the same affordance in the real world since the critical threshold at which participants could no longer decide on the plausibility of an upright stance was determined as similar. The authors also found ground texture and participant position to effect the critical threshold; when presented with a ground surface textured with ice participants perceived their threshold for an upright stance to be lower, and when presented with a standing position at a more extreme height on that slanted surface participants also perceived their threshold for upright stance to be lower. This publication showed affordances to be pertinent to the development and design of IVEs.

Our own lab has contributed to literature on affordances in virtual environments, focusing on (1) determining the importance of the form of virtual self-avatars in the context of affordance tasks and (2) the validity of affordances in determining the fidelity of virtual environments. Wu et al. [2009] immersed subjects in a virtual environment consisting of a roundabout to study pedestrian street crossing decisions and found that subjects made gap affordance judgments relatively similar to those made in the real world. McManus et al. [2011] had subjects perform a distance estimation task, an object interaction task and a navigation task to assess how they were effected by animated avatars and self-avatars. Self-avatars were found to increase the accuracy at which all tasks were performed with the exception of the distance estimation task. There is a body of work that follows validating the findings from these experiments.

A series of papers were produced that demonstrated the importance of self-avatars in affordance judgment tasks such as stepping over or ducking under a pole, walking through or ducking under a doorway and stepping off of a ledge [Lin et al., 2012, 2013, 2015]. Interestingly, Lin et al. [2012] altered the size of a self-avatar and found that subjects would alter their perception of their body dimensions to those of a larger avatar. Lin et al. [2015] confirmed that affordance tasks were compelling in determining the accuracy of virtual environments in comparison with real environments. In that particular study, the analog of real world tasks (stepping over or ducking under a pole and stepping off of a ledge) were performed in virtual environments and demonstrated that a condition in which a subject was given an animated self-avatar reproduced the results found in the real world.

Bodenheimer and Fu [2015] went on to question whether the form of the self-avatar was important in affordance tasks, considering the accuracy that self-avatars provided. Subjects in that study performed the same task of judging whether or not stepping off of a ledge could be done gracefully with either no avatar, a full-body, gender-matched self-avatar, or a simple line avatar. Results showed that having a self-avatar was an important factor in performing more accurately, but however, the form of the avatar did not matter since there was no difference in the line avatar and full-body avatar conditions. Young et al. [2015] looked at the effect of the form of a self-avatar by having study participants perform a simple dyadic high-fiving task in a collaborative virtual environment either with no avatar, a full-body, gender-matched self-avatar or virtual hands. Greater accuracy was found in the two latter conditions, while greater presence was found when subjects possessed full-body, gender-matched self avatars.

Lastly, it is worth mentioning that some studies in IVEs have focused on pedestrian street crossing tasks and have validated gap affordance behaviors in IVEs to be consistent with natural gap affordance behaviors. Simpson et al. [2003] describe the ability to make a safe road crossing as a perceptual-motor skill involving the perception of oncoming traffic and the action of walking across the road. Appropriate gaps for crossing are selected by the size of the gap in terms of one's time to act. Research has found that young children make riskier road crossing decisions than adults in VR as they do naturally [Simpson et al., 2003; Plumert et al., 2004; Chihak et al., 2010], and after training sessions conducted in VR, young children make safer crossing decisions and retain training information [Thomson et al., 2005]. A general threshold at which crossing gaps move from safe to unsafe can also be found in VR [Wu et al., 2009]. The body of work here shows the importance of accurate affordance judgments in IVEs by demonstrating results and an application of VR software to improve child safety in pedestrian street crossing scenarios.

It is made clear by the work presented in this section that affordances are a staple in the toolbox for understanding how immersive virtual environments are perceived. Work on singular affordances shows that users performing certain tasks in immersive virtual environments perform them similarly to the way that they would in a real environment, and that spatial perception in these instances is accurate. However, there are some technical nuances about these environments that change affordances such as the visual representation of the body. There has not been much work, however, on joint affordances in immersive virtual environments. There is a need to understand how multi-user interaction takes place and what factors about these interactions change them. These factors can include the visual representation of the body, the nature of the distribution of the environment (i.e., whether users are collocated within the same tracking space), the type of interaction taking place (i.e., interaction taking place between an agent and an avatar or two avatars), and so on. In the next section, we lay the foundation for understanding joint affordances and action in immersive virtual environments.

3 Measuring Collaborative Affordance Judgments

One basic question research has continued to address is that of how everyday interactions are performed in virtual reality. Here we focus on collaborative interactions in a distributed, shared virtual environment (SVE). Specifically, the common task observed in this work is that of a dyad passing through an aperture together simultaneously. The aperture's width is varied from being too narrow to support passability to being so wide as to support the clear, simultaneous passage of both members of the dyad. First, baseline results are gathered by having all possible gender-based pairings perform that task in the real world before performing it in an SVE. Since virtual reality allows for the plasticity of human representation, all different combinations of gender-based pairings are tested. In this case, avatars are gender-matched or not gender-matched to users dependent on the condition. This work appeared in IEEE Transactions on Visualization and Computer Graphics [Buck et al. 2019].

The availability of commodity devices makes the possibility of distributed SVEs feasible (Guye-Vuilleme et al. [1999]; Young et al. [2015]; Pan and Steed [2017]), but the technology supporting high fidelity avatars is still limited. For example, commodity technology does not support eye gaze or facial expression tracking, which has been shown to be highly important in social interaction (Bailenson et al. [2005a]; Gallup et al. [2014]). However, interactions in SVEs in virtual reality still occur when users are given self-avatars to a significant degree without expensive solutions, and I focus on those interactions.

This work focuses on collaborative interaction through the lens of *affordances* and *proxemics*, which I have discussed in depth in Section 3.0.2. Affordances were introduced by the psychologist James J. Gibson (Gibson [1979]), and can be defined by the concept that the environment provides encoded meanings directly to the organism within it. The structures and features of the environment matter greatly in one's perception of the world. This concept has been applied to the study of the fidelity of IVEs (Geuss et al. [2010]; Lin et al. [2015]). Proxemics, or the interpersonal distance maintained between two or more persons or a person and one or more objects, were first introduced by Hall [1963]. The current literature on proxemics exhibited in IVEs focuses on the impact of avatars (Bailenson et al. [2003]; Llobera et al. [2010]; Wilcox et al. [2006]). The task of aperture passibility employed in this work focuses on the application of critical thresholds extracted from the affordance judgments made by subjects and the interaction occurring by subjects given a self-avatar to assess the fidelty of the current state-of-the art technology.

The classic study completed by Warren and Whang [1987] assessed the task of walking through an aperture when performed by a single person. We extend this task to two people and realize the behavioral changes this introduces. For example, subjects may choose to pass through an aperture side by side simultaneously when the aperture is wide or single file with one yielding to the other when the aperture becomes narrow enough. The social relation of the two people might also affect the passing behavior of the dyads. Men may choose to yield to women when passing through an aperture single file. A virtual environment adds complexity to these factors in that the driving person behind an avatar may not be the same gender as that avatar. We address this in some detail. The findings from this work contribute to knowledge on the fidelity SVEs and on affordances in proxemics in the real world. Additionally, the findings contribute to the knowledge of the embodiment of self-avatars based on characteristics of those avatars. This Chapter represents the first contribution of this dissertation and makes a determination of baseline proxemic behaviors in a multi-user immersive virtual environment.

3.1 Experiment 1: Affordance Judgments in the Real World

To be able to compare natural baseline passing behaviors to the virtual world, we first conducted an experiment in the real world. Consistent with previous literature (Lin et al. [2015]), we wanted to determine whether or not the actual passing behaviors differed from the judgments subjects made. Thus, we had within subjects conditions of *action* and *no action*. In the *action* condition, subjects were asked to walk through the aperture at the same time. In the *no action* condition, subjects were asked to simply judge whether or not they could pass through the poles together by giving a ‘yes’ or ‘no’ response. We asked subjects to perform the *no action* condition first so they would not receive feedback from the action of walking through the aperture together. Since it was found by Lin et al. that participants overestimated how they would perform in the *no action* condition, we predicted that our experiment would produce the same results. A pilot study to confirm experimental procedure was done before experimentation.

3.1.1 Pilot Study

Prior to performing the experiment, we ran a pilot study to determine the correct aperture widths to use in our trials. The goal of Experiment 1 was to determine the critical thresholds, or points at which behavioral changes occurred, and to characterize the behaviors that would occur and the widths of apertures that would be needed in order to better design the experiment. Initially we chose a maximum aperture width of 3m and a minimum aperture width of 0m since we knew that the majority of subjects could walk through the poles simultaneously at the widest width and would not be able to pass at the narrowest width, giving room for a full spectrum of passing behaviors. After several of our own tests, we observed the following passing behaviors which we believed could be visually coded and for which we could determine critical thresholds. These behaviors were: not being able to pass through the aperture; passing through the aperture single file with bodily adjustment, i.e., turning sideways, tucking arms into the body; passing single file without bodily adjustment; passing simultaneously with bodily adjustment; and passing simultaneously without bodily adjustment. We call and abbreviate these behaviors, respectively as: single file with adjustment (SFA), single file (SF), adjustment (ADJ), and clearing (CLR).

In total, we ran five pilot studies with two students from our lab and eight from our institution. All subjects provided written consent before participation. They had no prior knowledge of the study and were between the ages of 18-46. They were all compensated monetarily for their time. Participants were first given several trials in which they were asked to determine whether they believed they could pass through varying aperture widths together without performing the action. After performing the first set of trials, subjects were then asked to pass through the aperture at those same varied widths together. Warren and Whang [1987] explain that we use our shoulder width as a body metric to determine aperture passing affordances, therefore we chose to measure the shoulder width of each subject in each pair and combine their shoulder widths to determine the widths of the aperture that would be presented in the actual experiment. Behavioral changes were noted at these widths. Ultimately it was determined that subjects would perform the full range of passing behaviors within the range of 0.15-2.0 times their combined shoulder widths, so we chose thirteen ratios within this range (0.15, 0.25, 0.45, 0.5, 0.65, 0.75, 1, 1.25, 1.35, 1.5, 1.65, 1.85, 2) for our actual experiment.

3.1.2 Participants

Forty-eight subjects were recruited for this experiment: 24 males and 24 females. These subjects were grouped into 24 pairs: 8 male-male, 8 female-female, and 8 male-female. Participants were between the ages 18-53 and were gathered from our institution. All subjects provided written consent prior to participation. They had no knowledge of the experiment and were compensated monetarily for their time.

3.1.3 Materials and Methods

Figure 1: The real world environment used for Experiment 1. Poles are placed at max width of 3 meters. The blue tape marks the starting point at which subjects were instructed to stand before starting each trial. ©IEEE 2019

Two red PVC poles, approximately 1.98m high and 0.0254m in diameter, were used to form the aperture in this experiment. Since pilot testing confirmed that subjects could reach a natural walking speed when starting 3m away from the aperture, they were asked to start each trial 3m away at a central point between the poles. Figure 1 depicts this setup.

The distance between the poles was measured precisely and marked on the floor so that they could be placed accurately each trial. We generated the distance that the poles should be placed apart by measuring each subject's shoulder width and combining them. As determined in the pilot study, 39 trials for each condition (*action* and *no action*) were produced by multiplying the combined shoulder width (13 different ratios ranging from 0.15-2.0). This created 3 trials at each aperture width, and all trials were randomized to prevent learning. All of this was done through the implementation of a C# script, which generated and logged all trials. In total, 78 trials were performed by participants.

Additionally, we asked subjects to report their 'yes/no' judgments separately in the *no action* condition via a Xbox One controller since we did not want their answers to be influenced by one another. Participants pressed the 'A' button on the controller if they thought that the aperture was passable, and did not press anything

Behavior	Number of Pairs Exhibiting Behavior
Single File with Adjustment	M-F = 5, M-M = 8 F-F = 8
Single File	M-F = 8, M-M = 2 F-F = 5
Adjustment	M-F = 8, M-M = 8 F-F = 8
Cleared	M-F = 8, M-M = 8 F-F = 8

Table 1: The number of pairs exhibiting each behavior in Experiment 1. ©IEEE 2019

if they thought the aperture was not passable. All data was gathered from participants and logged. Additionally, passing behaviors were recorded on video and coded by hand into the behaviors described in Section 3.1.1.

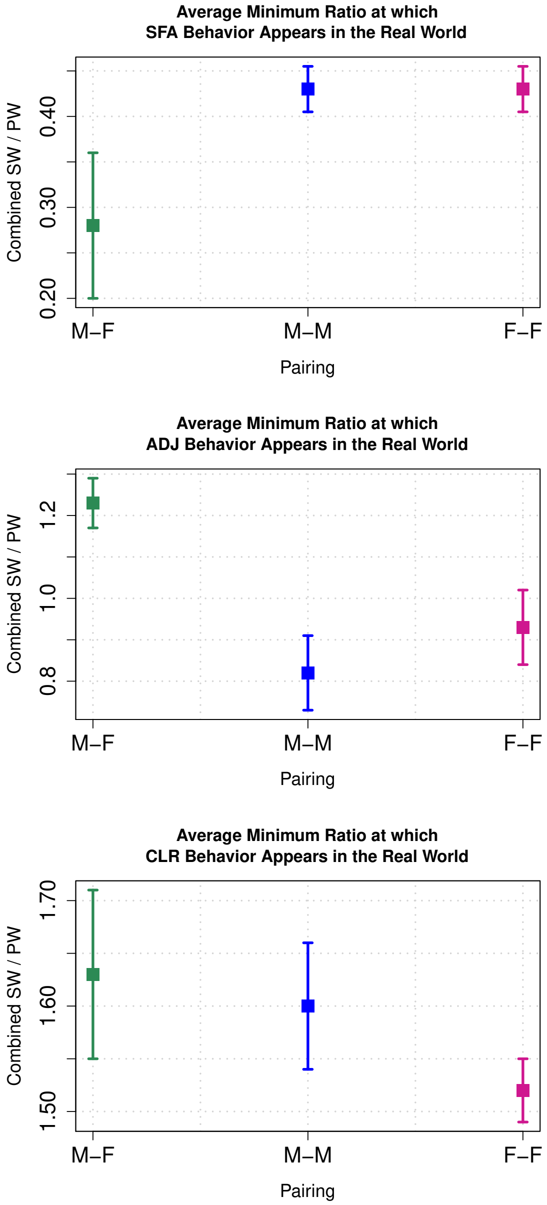
3.1.4 Results and Analysis

Before beginning the analysis, we checked the coded data to ensure that all passing behaviors were exhibited by subjects. This data is shown in Table 1. Some of the pairings did not exhibit all behaviors, and this is most apparent for the male-male pairings; male-male pairings did not typically go single file. They tended to adjust until the aperture width was so small that they were forced to pass through the poles single file with adjustment. Since this behavior was not reliably demonstrated by all sets of pairs, we remove it from the analysis of critical thresholds. Where some data is missing but we feel there is enough data, we impute it and describe that method below.

To analyze the critical thresholds, we first determined the minimum aperture width at which each of the exhibited behaviors were performed for each subject pairing. The minimum was calculated by determining the first occurrence during which the behavior was exhibited 2 of the 3 trials at a particular ratio of combined shoulder width to pole width. In the case of missing data, we imputed it conservatively based on the general progression of behavior from small to large aperture widths. In this case, a pair that did not perform single file with adjustment or single file behaviors were given a minimum critical threshold value of zero since the minimum critical thresholds for these were low. We did not need to impute any of the data for the adjustment and clearing behaviors in this experiment (see Table 1 for the values imputed).

Figure 2 depicts the average minimum critical ratios, along with the standard errors of the means (SEMs) for each of the pairings for each behavior. Male-female pairings exhibited SFA, SF, ADJ, and CLR behaviors respectively at 0.28, 0.63, 1.23, and 1.63 (SEM = 0.08, 0.07, 0.06, and 0.08 respectively) times their combined shoulder width. Male-male pairings exhibited SFA, ADJ, and CLR behaviors respectively at 0.43, 0.82, and 1.6 (SEM = 0.025, 0.09, and 0.06 respectively) times their combined shoulder width. Finally, female-female pairings exhibited SFA, SF, ADJ, and CLR behaviors respectively at 0.43, 0.41, 0.93, and 1.52 (SEM = 0.025, 0.12, 0.09, and 0.03 respectively) times their combined shoulder width.

We analyzed subjects' SFA, ADJ, and CLR behaviors with a one-way Analysis of Variance (ANOVA) with the three gender based pairs (male-female, male-male, and female female). The only significant difference found was that in the adjustment behavior, $F(2,21) = 7.15, p = 0.04$, and post-hoc tests showed that the male-female pairings were different from the male-male (Tukey's HSD = 0.41, $p = 0.04$) and female-female (Tukey's HSD = 0.30, $p = 0.037$) pairings.


Average Minimum Ratio at which
SFA Behavior Appears in the Real World

Average Minimum Ratio at which
ADJ Behavior Appears in the Real World

Average Minimum Ratio at which
CLR Behavior Appears in the Real World

Figure 2: Each graph represents the average minimum critical threshold along with the standard errors of the means at which pairings (m-f, m-m, and f-f) performed each behavior. From top to bottom: SFA, ADJ, and CLR. ©IEEE 2019

Finally, to analyze our *no action* data, we took all 'yes' responses to each aperture width and tallied them. Figure 3 depicts these responses. The data shows a linear response to aperture width, with a certainty of passage beginning at about 1.35 times the combined shoulder width. We chose not to perform any further analysis

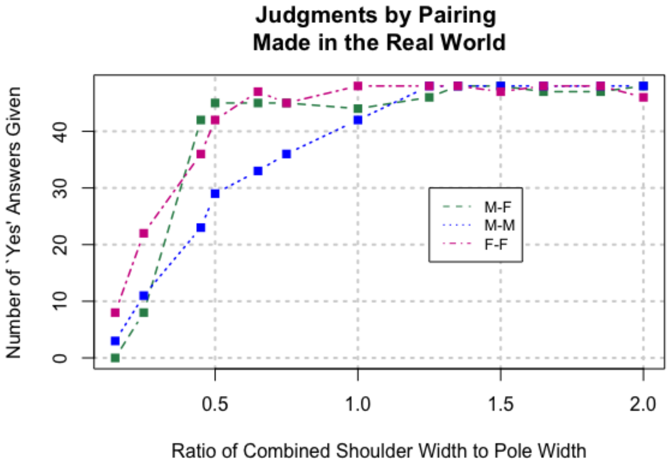


Figure 3: Graphical representation of the number of 'yes' responses at each ratio of combined shoulder width to pole width. ©IEEE 2019

here on this data, as it is more interesting to consider it along with the *no action* data we gathered in Experiment 2.

3.1.5 Discussion

We find evidence of different proxemic behaviors between gender pairings. Behavior breaks apart when the aperture width affords single file and adjustment behaviors. While we could not perform data analysis with the single file data, we argue that male-male pairings displayed behavior that was qualitatively different from both male-female and female-female pairings. Male-male pairings chose not to yield to one another, and this becomes apparent when we look at their adjustment behavior. Analysis of this behavior showed significant differences between male-female pairings and both the male-male and female-female pairings. The data indicates that the male-female pairings are more likely to perform adjustment behaviors even at high ratios (1.23), while male-male (0.82) and female-female (0.93) pairings do not. Male-female pairings preferred to give one another ample space when passing through an aperture, continuing to do so even as the aperture was perceived as wide enough for clear passage. Male-male pairings, on the other hand, continued to adjust until the aperture width was so small that it required they go single file with adjustment. We found no significant difference in the behavioral pattern of female-female pairings; their task performance was quite average.

While we chose to save analysis of the no action condition until data from Experiment 2 was introduced, it is interesting to note that all pairings reported, in a linear progression, that they could pass through the aperture with more certainty as it became wider. There was no gender pairing that did not exhibit this opinion. In addition, the critical ratio at which all pairings found that they could pass through together with absolute certainty was roughly 1.35 times their combined shoulder width. Warren and Whang [1987] found concrete evidence that, given a real aperture, subjects will pass through straight forward with no shoulder rotation at a ratio of 1.3 times shoulder width to aperture width. Our participants all agreed on passability at this ratio when making judgments based on the dimensions of the aperture width and the combined shoulder width of themselves and their partner. However, they did not perform this way most likely due to social proxemics since analysis demonstrated that pairing type made a difference in the minimum critical thresholds at which participants were choosing to make behavioral transitions.

3.2 Experiment 2: Affordance Judgments in an Immersive Virtual Environment

Since we established baseline results in the real world in Experiment 1, we extend the same task to a collaborative, distributed immersive virtual environment in this experiment. Participants are not collocated and do not see one another in the real world, therefore the gender of the avatar does not necessarily have to match that of the participant. Thus, there are more degrees of freedom made available in this experiment. There are three hypotheses that we wanted to test:

1. We believed that the same gender-based behaviors would be exhibited in the virtual environment, as in Experiment 1. Since participants never actually see their partner in the real world, we believed that they would treat the avatar realistically. We believed the fidelity of the commodity-level avatars could afford this behavior.

2. However, we also hypothesized that the underlying gender of the participant driving the avatar could generate behavioral effects that would allow differentiation across avatar gender based on the true gender of the participants. We did not believe that embodiment produced by our self-avatars would be perfect enough to remove these effects, even though there is some work that suggests that the embodiment may diminish them (Fox et al. [2013]).

3. Finally, we hypothesized that the critical thresholds produced in the virtual world would be smaller than

Pairing Type	Avatar Type
Male-Male	Male-Male
Male-Male	Male-Female
Male-Male	Female-Female
Male-Female	Male-Female
Male-Female	Female-Male
Female-Female	Female-Female
Female-Female	Male-Male

Table 2: The seven distinct pair types used in Experiment 2. ©IEEE 2019

those found in Experiment 1. The self avatars used did not have collision detection – it is computationally expensive and we found the collision motions generated unconvincing and implausible. Together with the limited FOV of the HMDs compared to that of the real world, we also hypothesized that users would have a lower level of awareness of their partner's location at all times and would stray closer to the other avatar. Prior work (e.g., Bailenson et al. [2003]) has tended to show that interpersonal distance is preserved in immersive virtual environments as it is in the real world, but most of those studies are done with a forward-facing view where FOV may not matter.

3.2.1 Participants

One-hundred and twelve subjects participated in the second experiment. Eight pairings were male-male with male-male avatars, 8 were male-male with male-female avatars, 8 male-male with female-female avatars, 8 male-female with male-female avatars, 8 male-female with female-male gender swapped avatars, 8 female-female with female-female avatars, and 8 female-female with male-male avatars. Table 2 expresses this visually for ease of understanding.

In total, there were 56 dyads. Since female-female pairings did not exhibit behavior that was out of the ordinary in the first experiment, we did not choose to include a female-female pairings with male-female avatars in this experiment. Participants were between the ages of 18-53, were gathered from our institution and had no prior knowledge of the experiment. They were all compensated monetarily for their time and provided written consent before beginning the study. They all had normal or corrected-to-normal vision. A pre-test questionnaire was about VR usage was administered, and 64.6% of participants had used VR before, while 35.4% had never used it. The majority of participants that reported experience with VR noted that they had only tried demos, and only one person reported that they used it daily.

3.2.2 Materials and Methods

The second experiment utilized two HTC Vive systems (one for each participant). The HTC Vive has a resolution of 2160 x 1200 (1080 x 1200 per eye) and a nominal FOV of 110°. The refresh rate of the Vive is 90Hz, it weighs approximately 555g, and has an internal gyroscope, accelerometer, laser position sensor and a front-facing camera. It supports interpupillary distance (IPD) adjustment and comes with two “Lighthouse" base stations with photosensors that track the head-mounted display (HMD). Both controllers (one pair per system) were utilized, as well as four additional Vive trackers attached to two pairs of shoes to track positional data from the hands and feet respectively. Positional tracking data for the head was gathered from the HMD.


Figure 4: A first person perspective of the virtual lab (above) and partner (below) from a participant located at the task starting point. ©IEEE 2019

The virtual environment was built using Unity Game Engine and was modeled directly after our lab space. The virtual lab space is shown in Figure 4 Subjects were physically located in two separate rooms, so the IVE was scaled to the room with the smallest dimensions (8.5m x 6m x 5m) to prevent users from colliding with any walls or objects in that room. The male avatar that was used was taken from the Ikinema Orion beta and the female was taken from the Unity Asset Store. Both avatars are shown in Figure 5. All positional tracking data was given to the Final IK plugin for Unity, which solves avatar motion using inverse kinematics. Positional data for each of the avatars was networked between both rooms using a low-level UDP connection. Users were collocated in the same virtual space, which had the exact same dimensions (from room and aperture scaling to avatar bodily dimensions) in each instance. Each avatar’s height and arm length were scaled to match that of the participant. All aperture widths were randomized and scaled based on the combined shoulder width of the participants (we measured this prior to beginning the study) and were presented to each user at the same time during each trial.

Figure 5: The virtual male (right) and female (left) avatars used in the experiment. ©IEEE 2019

Participants were given the exact same instructions as Experiment 1. They were to judge the passability of the aperture by performing the no action condition first, and then were to pass through the aperture with their partner in the action condition. Instead of reporting answers with an Xbox controller during the no action condition, subjects reported their answers to the experimenter. Subjects were not collocated and had no verbal communication with one another throughout the entire study, so they could not hear the other's responses. All responses and passing behaviors were recorded by hand, and passing behaviors were also recorded on video. While verbal communication was not supported, subjects were allowed to communicate via gestures (motioning with hands, head nodding) in the action condition. There was a green panel that appeared on the far wall behind the aperture to let subjects know when a new aperture had been revealed and that they could walk through the aperture whenever they were ready.

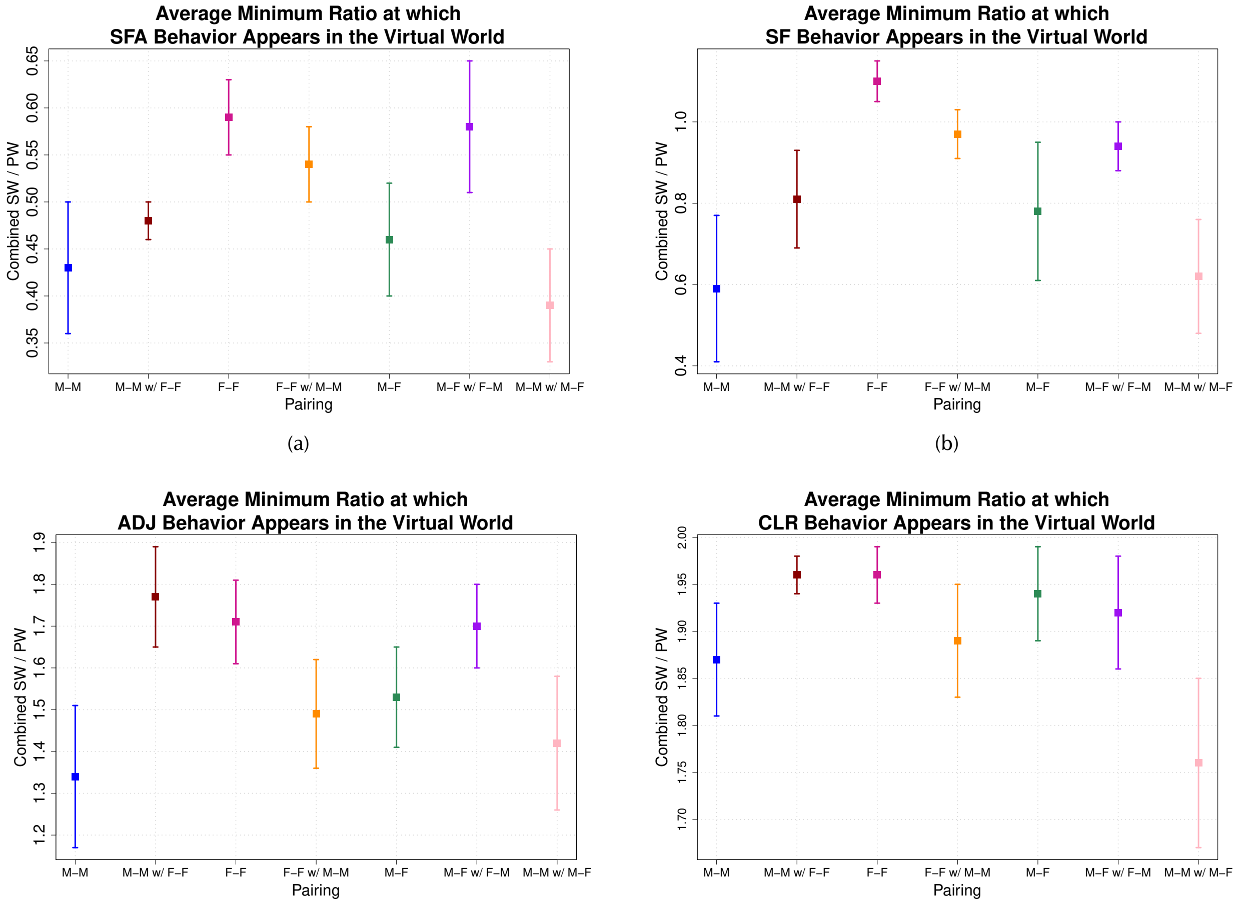
3.2.3 Results and Analysis

As we did with Experiment 1, we examined the data to ensure all passing behaviors had occurred in Experiment 2. While all behaviors were represented in this experiment, we do note that clearing behavior was underrepresented. This indicated to us that the aperture width in this experiment was simply not wide enough, and the clearing behavior would have occurred more if the aperture were presented at greater widths. It is clear here that perhaps our experiment did not produce results in line with our third hypothesis. Since we assumed that participants would clear the widest apertures presented to them in the experiment and adjust at higher widths, we imputed the data as follows: if a pair did not exhibit adjustment or clearing behaviors, a 2 was substituted for that pair's ratio. The rationale here is that critical ratios were typically high at these behaviors, and the largest width that participants were presented with was a critical ratio of 2. Single file with adjustment and single file behaviors

Behavior	Number of Pairs Exhibiting Behavior
Single File with Adjustment	M-F w/ M-F = 5 M-F w/ F-M = 8 M-M w/ M-M = 8 M-M = F-F = 8 M-M w/ M-F = 7 F-F w/ F-F = 8 F-F w/ M-M = 8
Single File	M-F w/ M-F = 6 M-F w/ F-M = 8 M-M w/ M-M = 5 M-M w/ F-F = 7 M-M w/ M-F = 6 F-F w/ F-F = 8 F-F w/ M-M = 8
Adjustment	M-F w/ M-F = 7 M-F w/ F-M = 7 M-M w/ M-M = 6 M-M w/ F-F = 4 M-M w/ M-F = 6 F-F w/ F-F = 6 F-F w/ M-M = 6
Cleared	M-F w/ M-F = 5 M-F w/ F-M = 5 M-M w/ M-M = 5 M-M w/ F-F = 3 M-M w/ M-F = 8 F-F w/ F-F = 4 F-F w/ M-M = 5

Table 3: The number of pairs exhibiting each behavior (SFA, SF, ADJ, CLR) in Experiment 2. ©IEEE 2019

were imputed as in Experiment 1. There were 56 pairs and 4 behavior transitions per pair, therefore there were 224 behavior transitions possible. Out of the total number of behavior transitions, 44 were imputed (with 21 in the clearing condition). Table 3 depicts this information. Averages of these data are depicted in Figure 6, along with the SEMs. Male-male pairings given male-male avatars performed single file with adjustment, single file, adjustment, and clearing behaviors at ratios of 0.43, 0.59, 1.34, and 1.87 (SEM = 0.07, 0.18, 0.17, and 0.06 respectively) respectively. Male-male pairings with female-female avatars performed the behaviors in the same order at ratios of 0.48, 0.81, 1.77, and 1.96 (SEM = 0.02, 0.12, 0.12, and 0.02 respectively) respectively. Female-female pairings with female-female avatars performed the behaviors at ratios of 0.59, 1.1, 1.71, and 1.96 (SEM = 0.04, 0.05, 0.1, and 0.03 respectively) respectively. Female-female pairings with male-male avatars performed these behaviors at ratios of 0.54, 0.97, 1.49, and 1.89 (SEM = 0.04, 0.06, 0.13, and 0.06 respectively) respectively. Male-female pairings with gender matched male-female avatars performed the behaviors at ratios of 0.46, 0.78, 1.53, and 1.94 (SEM = 0.06, 0.17, 0.12, and 0.05 respectively) respectively. Male-female pairings with gender swapped female-male avatars performed these behaviors at ratios of 0.58, 0.94, 1.7, and 1.92 (SEM = 0.07, 0.06, 0.1, and 0.06 respectively) respectively. And finally, male-male pairings with male-female avatars performed these behaviors at ratios of 0.39, 0.62, 1.42, and 1.76 (SEM = 0.06, 0.14, 0.16, and 0.09



(a)

(b)

(c)

(d)

Figure 6: Each of these graphs represents the average minimum critical threshold along with the standard errors of the means at which pairs (m-f w/ m-f, m-f w/f-m, m-m w/ m-m, m-m w/ f-f, m-m w/ m-f, f-f w/ f-f and f-f w/ m-m) performed each behavior (SFA (a), SF (b), ADJ (c) and CLR (d)). ©IEEE 2019

respectively) respectively.

A one-way ANOVA with the seven pairs in the virtual environment over the single file with adjustment, single file, adjustment and clearing behaviors revealed marginally significant differences in the single file with adjustment ($F(6,49) = 2.11$, $p = 0.69$)) and single file ($F(6,49) = 2.22$, $p = 0.56$) behaviors. There were no significant difference found in the other two behaviors.

To test the first hypothesis – that avatar gender would make a difference as it did in the real world – we ran pairwise comparisons of four behaviors using the pairs where the gender of the avatars matched the gender of the participant (male-male pairings with male-male avatars, female-female pairings with female-female avatars, and male-female pairings with male-female avatars). The only differences that emerged from the comparison were those between the male-male and female-female pairings in both the single file with adjustment ($t(df =$

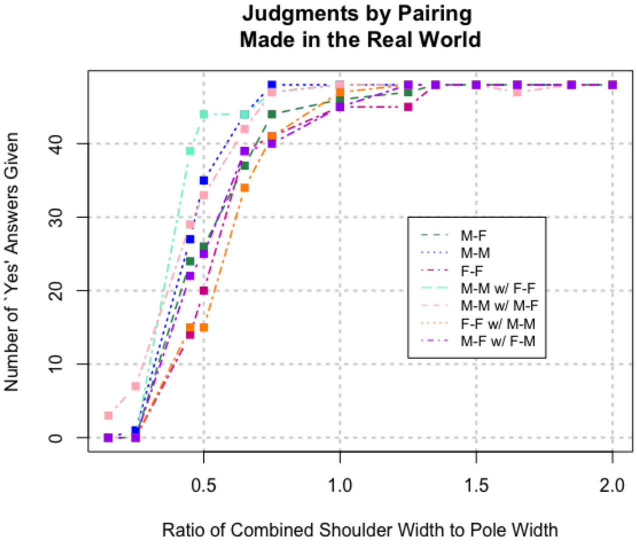


Figure 7: A graphical representation of the number of 'yes' responses at each ratio of combined shoulder width to pole width. ©IEEE 2019

14) = −2.21) and single file ($t(df = 14) = -2.74$, $p = .016$) behaviors.

To test the second hypothesis – that the underlying gender of the real world person would make a difference – we did pairwise comparisons where one pair had avatars with the same gender that corresponded to the participants and the other had avatars that did not correspond to the real world genders of the participants. For all of these combinations, only the adjustment behavior of male-male versus female-female avatars was found to be marginally significant ($t(df = 14) = -2.04$, $p = .06$). Thus, we cannot confirm the second hypothesis and must note that the underlying gender of the participants did not make a difference in the way participants behaved.

In addition, as we did in Experiment 1, to analyze the no action data we tallied all 'yes' responses to each aperture width. Figure 7 depicts these responses. As with the first experiment, the data exhibits a linear response to aperture width, with a certainty of passage for each pair beginning roughly at 1.35 times their combined shoulder width. We found reported answers to essentially be the same as those in Experiment 1, so we did not feel that these results should be analyzed further. In both the real and virtual world, participants believed they could pass through an aperture with their partner with certainty around the natural minimum critical threshold.

	SFA		SF		ADJ		CLR	
	RW	VE	RW	VE	RW	VE	RW	VE
FF (w FF av)	0.43*	0.59*	0.41*	1.1*	0.93*	1.71*	1.52*	1.96*
MM (w MM av)	0.43	0.43	-	-	0.82*	1.53*	1.6*	1.87*
MF (w MF av)	0.28	0.46	0.63	0.78	1.23*	1.53*	1.63*	1.94*

Table 4: The minimum critical thresholds for each behavior in both the real and virtual world. Significantly different thresholds between real and virtual environments are marked with an asterisk. ©IEEE 2019

3.2.4 Comparing Experiment 1 and 2

To test the third hypothesis – the critical ratios found in the virtual environment would be less than the critical ratios found in the real world – we must compare the results of Experiments 1 and 2. To compare the behavior between participants in these experiments, we used a Multivariate Analysis of Variance (MANOVA) with independent variables of participant pairs and the environment (real or virtual) in which they were tested. The MANOVA found an overall main effect of pairing ($F(1,280) = 1.98$, $p = .005$) and environment ($F(1,67) = 14.45$, $p < .001$), but there were no interactions.

Based on these results, we did planned comparisons consistent with our third hypothesis. We compared similar pairings in the real and virtual world where the gender of the participant and avatar's gender matched (i.e., male-male participants with male-male avatars). For male-male pairings in the real and virtual worlds, a oneway ANOVA found significant differences in the adjustment ($F(1,14) = 7.60$, $p = .015$) and clearing ($F(1,14) = 9.10$, $p = .009$) behaviors. For male-female pairings in the real and virtual worlds, a oneway ANOVA also found significant differences in the adjustment ($F(1,14) = 4.80$, $p = .046$) and clearing ($F(1,14) = 11.54$, $p = .004$) behaviors. Finally, for female-female pairings in both the real and virtual worlds, a oneway ANOVA found significant differences for all behaviors; single file with adjustment ($F(1,14) = 13.05$, $p = .003$), single file ($F(1,14) = 29.11$, $p < .001$) adjustment ($F(1,14) = 31.53$, $p < .001$), and clearing ($F(1,14) = 112.02$, $p < .001$) all showed significant results. The critical thresholds for all of these cases are shown in Table 4. In each case, the critical threshold for the pairs in the virtual environment were greater than the critical threshold for those in the real world. The differences for the female-female pairings were particularly large.

In line with this, the effect of environment (real versus virtual) on all behaviors was significant. Single file with adjustment ($F(1,70) = 7.79, p = .007$); adjustment ($F(1,70) = 30.24, p < .001$); and clearing ($F(1,70) = 52.40, p < .001$). Critical thresholds were larger in the virtual environment in all conditions. Real world critical thresholds were 0.38, 0.99 and 1.58 for single file with adjustment, adjustment and clearing behaviors respectively. Virtual world critical thresholds were 0.49, 1.53, and 1.92 for the same behaviors. Thus, when given virtual avatars, participants kept further apart and changed their behavior in order to keep further apart than they did in the real world. The findings here for pairs and environments are directly opposite of the predictions we made in the third hypothesis.

3.3 Discussion and Conclusions

In summation, these experiments examined human interaction in both real and virtual environments in a task requiring some collaboration between two individuals. This task provided an assessment of how users of commodity level equipment, including commodity level full body avatars, that made up a distributed, collaborative virtual environment performed in comparison to baseline real world behavior. It also provided a mechanism to potentially examine how avatar embodiment may affect such a task.

We had three hypotheses related to the outcomes of the second experiment. The first was that there would be differences among the gendered pairings in the virtual world as there were in the real world. We found gender-based differences in the virtual environment, however, they were not the same differences. The differences involve contrasting dyads (male-male with male-male avatars vs female-female with female-female avatars in the virtual world; male-male versus male-female and female-female versus male-female in the real world) and occur in different behaviors (single file and single file with adjustment in the virtual world; clearing in the real world). A single file behavior manifested for male-male pairings in the virtual world, while it was notably absent in the real world. As observed by Bailenson et al. Bailenson et al. [2003], the lack of physical collisions in the virtual environment may have caused this, since males may not be as predisposed to fear harm from physical aggression in a virtual environment. However it may be, while there are differences in both environments, the fact that they are not the same differences likely implies that the fidelity of the avatar and virtual environment scenarios could be improved.

Our second hypothesis posed that there would be measurable differences in embodiment among the avatars driven by the underlying gender of the user. We were not able to confirm this hypothesis. While there was a marginally significant effect in one passing behavior for male-male pairings, the effect is weak and more experimental power would be needed in order to deliver concrete evidence.

Our last hypothesis was that the critical threshold in the virtual environment would be smaller than that in the real world. This was based on the assumption that participants would not have a good sense of the location of their self-avatar, especially in relation to their partners, and would drift together as they sought to perform the task. In fact, the opposite is true. It seems likely that people feel alienated by the other self-avatar (and want to keep away from it), or that they realize that they don't have a good sense of where they are and are therefore conservative in their spacing. We note that the findings of our study replicate findings of Bailenson and colleagues Bailenson et al. [2001, 2003], who found that women maintained more space (in our experiment, higher critical thresholds indicated this) than men.

One important difference between the experimental conditions was that the participants in the real world were not forbidden to speak to one another, whereas in the virtual world there was no mechanism by which they could speak to one another. Other differences involve the fidelity of the collaborative virtual environment and the avatar used in it. The avatars themselves, as mentioned earlier, lacked facial expression, hand articulation, eye movement and a method of realistically colliding with one another. How important any of these are to the results is an area of open research. Presumably, as the fidelity of virtual avatars increases, the critical thresholds in a virtual environment would converge to the ones found in the real world. All of these issues are areas of active investigation.

Ultimately, shared virtual environments should be usable and tasks should be able to be performed as they are in the real world. We have shown how close one such environment is to the real world using an affordance measure. Our work shows that commodity level avatars, despite recent progression, could be improved to provide experiences that can better simulate the real world. This leaves ample opportunity for exploration and work for virtual reality researchers. Again, this chapter represents the first contribution of this dissertation and has given us the baseline determination of how users treat the space around their bodies when interacting with other users in an immersive virtual environment. We have shown that the affordance of walking through an aperture does not occur in virtual reality the same way as it does in the real world; personal space changes in these environments.

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4 Measuring Peripersonal Space

In this chapter, we create a foundation for the study and understanding of peripersonal space in immersive virtual environments. Work here is based on a developed and tested methodology for augmented, mixed and virtual reality [Serino et al. 2017] and presents a more concrete understanding of how users of immersive environments treat the reaching and grasping space around themselves. We completed two studies with visual and tactile stimuli to determine absolute peripersonal space boundaries. These studies investigated whether peripersonal space boundaries in an immersive virtual environment are consistent with those in the real world and whether they could be altered by object and agent interactions. We found peripersonal space boundaries that were consistent with real world findings and that they were responsive to the interaction type. The findings of this initial work have implications for the design and development of immersive virtual environments. This work appeared in the IEEE Conference on Virtual Reality and 3D User Interfaces proceedings [Buck et al. 2020b]. This chapter correlates to the second contribution of this dissertation in that we find we can reliably generate a quantitative measurement of peripersonal space boundaries in immersive virtual environments.

4.1 Research Motivation

In these two experiments, we use an immersive virtual environment to create conditions in which we attempt to modulate peripersonal space. Our research questions are:

- Can we modulate peripersonal space boundaries with objects in virtual reality?
- Can we modulate peripersonal space with agents in virtual reality?

Our first experiment sought to replicate the basic findings of Serino et al. [2017] and prove that this paradigm can be used to measure peripersonal space boundaries and determine how they are modulated using commodity level virtual reality software and hardware. We thought it worthwhile to do so since the mediated environment used in Serino et al.'s work was replicated to closely resemble the environment surrounding the experimental participant and was not similar to a more general, fully mediated environment. We also sought to examine the modulation of peripersonal space in the presence of different kinds of virtual objects that evoked different levels of emotional valence.

The second experiment sought to further understand how peripersonal space is modulated when users interact with agents in immersive virtual environments. It is well known in neuroscience and psychology literature that peripersonal space is modulated dependent on the social context of the situation [Iachini et al. 2014; Pellencin et al. 2018], and we believe that we can manipulate this perception through the appearance of a virtual agent. While the appearance of the agent is the only thing controlled in this experiment, there is ample scope for future investigation regarding other agent attributes.

4.2 Experiment 1: Peripersonal Space Boundaries Modulated by Objects

4.2.1 Power and Experimental Participants

Before conducting our study, we chose a sample size of forty participants. This was based on prior work which indicated that this was the minimum number of participants required to obtain a medium effect size [Hong et al. 2019]. Thus, forty participants (22 female, 18 male) between the ages of 18-40 took part in this experiment. Participants were recruited through our institution's sign up system for psychology studies and through flyers that were placed around campus. All participants had no prior knowledge of the study and had normal or corrected-to-normal vision. The protocol was approved by our institution's IRB. Participants gave informed, written consent and were paid. A survey was given to participants prior to beginning the study about their virtual reality use. 65% of participants reported that they had used virtual reality before, but the majority (62.5%) stated that they had only used it before when trying a demo.

4.2.2 Apparatus

To conduct this experiment we used the HTC Vive Pro head-mounted display and its lighthouse base stations, handheld controllers, and three Vive trackers that were each attached to a pair of shoes and a belt. We built the immersive virtual environment using Unity Game Engine (version 2017.2.0f3). All scripts were written in C#. The experiment was conducted in a virtual lab space (Figure 9) that was designed to resemble our physical lab space with dimensions of 7.3 m x 8.5 m x 3.7 m. The virtual ball launcher, normal and spiked balls that we used in this experiment were all modelled in Unity, and the androgynous virtual avatar was from Adobe Mixamo. The avatar executed idle and throwing animations that were from Adobe Mixamo as well. Users were given gender-matched self-avatars that were provided by Ikinema Orion, which is the software that we used to implement our motion capture. Ikinema Orion takes tracking information from the Vive Trackers on the lower back and feet of the user, the Vive handheld controllers and the head mounted display and uses inverse kinematics to calculate the motions of the user. The tracker positioning and full set up of equipment users wore is depicted in Figure 8. All data was recorded immediately into a text file as users participated in the experiment, and was extracted into a SPSS-ready CSV file by a Python script afterwards.

4.2.3 Experimental Design

Figure 8: The equipment participants used in both Experiments 1 and 2. Along with the head-mounted display and handheld controllers, Vive trackers were attached to both feet and the middle of the lower back via shoes and a belt. ©IEEE 2020

Before beginning the study, participants first answered a brief survey about their virtual reality usage and were instructed on how to adjust the head-mounted display. Participants were allowed to adjust the fit of the head-mounted display as well as the IPD as needed. They donned the tracking shoes, belt, and were given instructions on how to respond to each trial. Their self-avatar was calibrated using Ikinema Orion and then the experiment began. The experiment took place in a virtual lab (Figure 9) in which users were asked only to respond to a tactile stimulus (which was a vibration delivered by one of the handheld controllers) by pulling the trigger on one of the controllers each time a virtual visual stimulus (in this experiment, one of the two different balls) that was thrown or launched by an animated agent or ball launcher (Figure 10) in their direction. The virtual ball was presented in two forms: normal and spiked (Figure 10). We chose to add spikes to the ball to evoke a sense of an impending threat to the user. Each time the ball was thrown or launched, it travelled toward the user's head at a steady speed of 75 cm/s until making contact with the user's face. There were a total of 25 randomized trials in which a tactile stimulus was delivered either when the ball was 0.3 m, 0.6 m, 1.0 m, 1.3 m, or 1.6 m away from the user. Tactile stimuli were delivered five times at each distance.

Figure 9: The virtual lab space used in Experiment 1 (left) and Experiment 2 (right). ©IEEE 2020

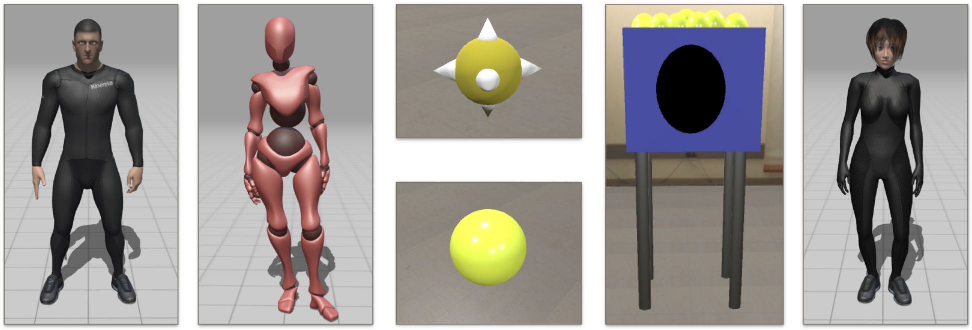

Figure 10: Male self-avatar (far left), animated agent (left), spiked ball (middle top), normal ball (middle bottom), ball launcher (right), and female self-avatar (far right) used in Experiment 1. Self-avatars were additionally used in Experiment 2. ©IEEE 2020

Each set of these 25 trials occurred for each ball type and launcher type. Thus, a single subject experienced 100 trials total. All response times to all trials were logged in a text file as they were completed.

4.2.4 Object Likeability Ratings

In addition to conducting the study, we asked a separate pool of subjects from our institution to complete a likeability survey [Bartneck et al. 2009] to determine the attitudes users would have when interacting with the objects used in this experiment. We recorded 38 (28 female, 10 male) responses from participants between the ages of 18-74. We again chose this sample size since it would provide us with a medium effect size. The survey asked participants to rate both the spiked and normal balls (Figure 10) on five different descriptive scales: dislike-like, unfriendly-friendly, unkind-kind, unpleasant-pleasant and awful-nice. These scales were presented as Likert scales between 1-5 with each descriptor on each opposite end of the scale. Mann-Whitney U Tests were performed on the data for each question and the results follow.

Ball Type	**Likeable**	**Friendly**	**Kind**	**Pleasant**	**Nice**
Normal Ball	58%	49%	38%	59%	53%
Spiked Ball	22%	3%	3%	6%	8%

Table 5: Depicted in this table are the positive ratings (meaning ratings of a 4 or 5 on the Likert scale) for each question in the likeability survey for the normal and spiked balls. ©IEEE 2020

The dislike-like responses showed a significance between ball type $Z = 3.625$, $p < 0.01$, the unfriendly-friendly responses also showed a significance between ball type $Z = 5.611$, $p < 0.01$, the unkind-kind responses showed a significance between ball type $Z = 4.662$, $p < 0.01$, the unpleasant-pleasant responses showed a significance between ball type $Z = 5.313$, $p < 0.01$ and finally results from the awful-nice scale found a significant difference between ball type $Z = 4.803$, $p < 0.01$. Table 5 depicts how respondents felt each ball type to be likeable, friendly, kind, pleasant and nice. Overall, responses trended more positively toward the normal ball and negatively toward the spiked ball. Thus, we could expect that with our experiment users would perceive the spiked ball as more dangerous as intended.

4.2.5 Results

Our data consists of reaction times measured from different distances where the tactile stimulus was given for different ball types and launched by either the ball launcher or thrown by the animated avatar. We perform two primary analyses. First, we determine how individual reaction times were influenced by the conditions of the study, and second we determine the peripersonal space boundaries for the (group) conditions of the study. We first noted that the data contained outliers, such as, for example, trials where a participant forgot to pull the trigger in response to the tactile stimulus. We systematically removed such instances using Tukey's method of fences. We calculated the upper fence for each reaction time at each distance and condition and removed any reaction time that was greater than the upper fence. The upper fence was the boundary at which a data point would be three standard deviations from the mean. We chose not to calculate the lower fence since this would produce a negative reaction time to compare against, which there were none of. This process removed less than 1% of the data; as noted above, the outliers removed were typically instances where the subject did not respond.

Using IBM SPSS Statistics, we submitted the cleaned data to a repeated measures anaylsis of variance (RM-ANOVA) with factors of distance, social condition (whether the ball was thrown by the animated avatar or launched by the ball launcher) and ball type (spiked or normal). Assumptions were checked and corrected for by SPSS. The RM-ANOVA found main effects of distance $F(4, 152) = 521.132$, $p < 0.001$, social condition $F(1, 38) = 18.984$, $p < 0.001$, and ball type $F(1, 38) = 13.170$, $p < 0.01$. There were interactions between social condition and ball type $F(1, 38) = 8.456$, $p < 0.01$, social condition and distance $F(4, 152) = 3.421$, $p < 0.05$, and a three-way interaction between social condition, ball type and distance $F(4, 152) = 8.459$, $p < 0.001$.

Bonferroni corrected paired samples t-tests revealed that all reaction times at each distance were significantly different from one another $p < 0.001$, that reaction times were significantly different for social and non-social conditions $p < 0.001$ (except at 1.6m), and that reaction times were significantly different between ball types $p < 0.001$ (except at 1m). Figure 11 offers a visual supplement to these findings.

The exact peripersonal space boundaries are not determined from the raw data depicted in Figure 11. Rather, to determine the peripersonal space boundaries, we employed the same method of fitting a sigmoid function to the data and extracting the boundary as used by Serino et al. [2017]. In that work (and others [Canzoneri et al. 2012; Kandula et al. 2017]) the fitting equation is as follows:

$$y(x) = \frac{y_{\min} + y_{\max} e^{(x-x_c)/b}}{1 + e^{(x-x_c)/b}} \tag{1}$$

where *x* is the *independent* variable, or the distance of the ball, *y* is the *dependent* variable, or the reaction time; $y_{\min}$ and $y_{\max}$ are the upper and lower saturation levels of the sigmoid; x_c is the value of the abscissa at the central point of the sigmoid; and *b* is the slope of the sigmoid at the central point. Both x_c and *b* vary and are estimated. The parameter x_c represents the midpoint of the region of greatest increase in reaction time to the visual stimulus, i.e., the boundary of peripersonal space. To determine it, all reaction times for each of the trials for each subject were averaged at each distance for both ball types, giving us a set of (x, y) data points to fit the sigmoid function to. The coefficient of determination (R^2) was extracted as a goodness-of-fit measures. For this experiment, we found the average peripersonal space boundary (x_c) over all conditions to be at 1.27 m. The exact boundaries for each condition are as follows: social at 1.27 m, non-social at 1.28 m, normal ball at 1.25 m and spiked ball at 1.29 m. Goodness of fit measures were greater than 0.9 for all conditions.

To determine if the conditions in this experiment modulated the peripersonal space boundaries found, we first ran Bonferroni corrected paired samples t-tests. These t-tests revealed that the peripersonal space boundaries for the normal and spiked balls were significantly different $t(39) = 0.003, p < 0.01$ while the social and non-social conditions were not. We next performed a Bayes factors analyses. Bayes factors provide support for the null hypothesis through an odds ratio[9]. We use the method described by Rouder et al. [2009],

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[9] An online calculator for Bayes factor analyses can be found at http://pcl.missouri.edu/bayesfactor.

which takes into account sample size and adjusts for power. Prior odds were set to 1, which favors neither the null nor the alternative. Comparing social and non-social conditions gives a Jeffrey-Zellner-Siow (JZS) Bayes factor of 8.11 indicating substantial evidence in favor of the null hypothesis. Comparing the spiked and normal ball conditions gives a Bayes factor in favor of the alternative, with a JZS Bayes factor of 10.43. These results strongly indicate that social condition does not modulate the peripersonal space boundaries in this study, but ball type does.

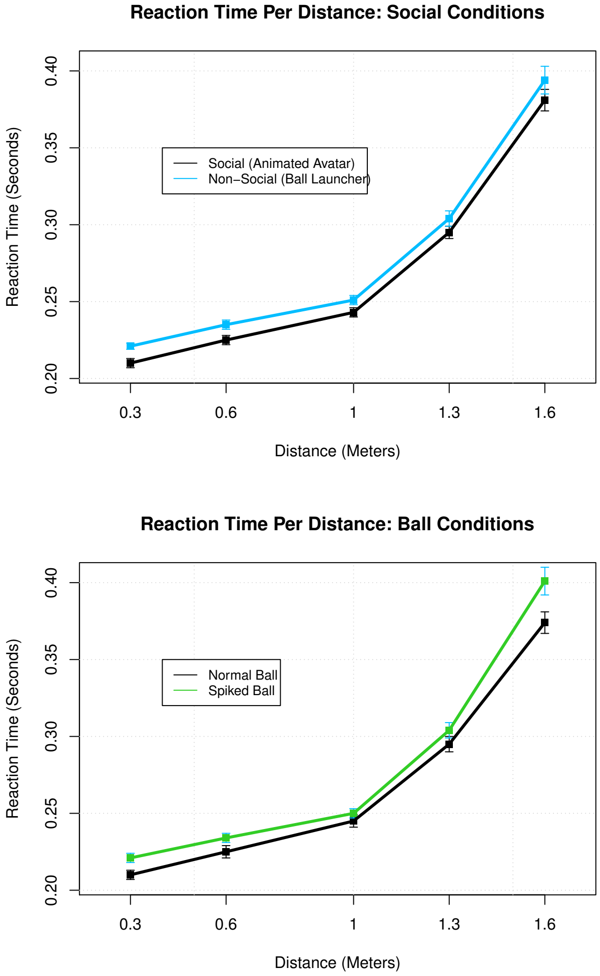

Figure 11: These graphs depict the average reaction time recorded at each perceived distance for both social and non-social (top) and normal and spiked ball (bottom) conditions. We extracted these by collapsing across the appropriate conditions. ©IEEE 2020

4.2.6 Discussion

Drawing from the results of this first study, we can confirm the validity of the method used by Serino et al. [2017] for delineating peripersonal space boundaries in immersive virtual environments. We were able to replicate the same exponential relationship between reaction time and distance of the visual stimulus, where reaction time significantly increased as the distance of the visual stimulus from the user increased. This relationship was robust throughout the study and was reflected no matter the condition. We successfully fitted our data to find a reasonable peripersonal space boundary at 1.27 m, which is similar to Serino et al.'s at 1.23 m and hinges on the established bound between personal and social space Hall [1963], within the immersive virtual environment. However, there are some different nuances to our findings that bring some complexity to the understanding of how peripersonal space boundaries behave in immersive virtual environments. Our statistical analysis showed that reaction times were significantly different for social and non-social conditions, where reaction times were faster in the social condition, and that reaction times were significantly different between the ball types, where reaction times were faster when the ball was normal rather than spiked. Results also indicated that the peripersonal space boundary itself was responsive to the ball type only, and contracted when the ball was non-threatening.

As in the real world, as people are more attentive to human rather than object interaction, the differences between social and non-social conditions seem natural. Users reacted more quickly to a ball being thrown at them by a social virtual agent than a ball launcher, and users of immersive virtual environments have been shown to be more responsive and careful of their personal space when perceived levels of sentience increase [Bailenson et al. 2001, 2003; Llobera et al. 2010; Wilcox et al. 2006]. However, it is interesting that users responded slower to the spiked ball than they did the normal ball and that peripersonal space boundaries retracted when the ball was non-threatening. These results are not in conjunction with behavior that suggests peripersonal space boundaries to retract in the context of danger [Coello et al. 2012; Ruggiero et al. 2017] and does not follow established work that shows users to be responsive and reactive to perceived danger in immersive virtual environments [Ma and Hommel 2013; Yuan and Steed 2010]. These results are not reinforced by the responses to the likeablity survey, which indicated that the normal ball was more likeable, kind, friendly, pleasant and nice than the spiked ball. It is possible that these results are due to an order effect in the experimental protocol.

Users always reacted to the normal ball at the beginning of the experiment for the first 25 trials, and could have become familiar enough with the task. It is also possible that they did not feel the danger convincing and plausible. If not reacted to, the ball would disappear through the user before another trial would begin, therefore users could have gained the sense that it was inconsequential to react to the ball. The plausibility illusion is directly correlated with the evocation of realistic behaviors in IVEs [Slater 2009] and a lack thereof could draw unrealistic reaction times from users. It could also be assumed that the anticipatory motion would cause users to respond differently to the social condition, but we note here that users were specifically asked only to respond to the tactile stimulus and thus the motion of the avatar throwing the ball was unimportant.

While some of our results raise questions for further study rather than answer those that we posed before implementing this study, we have results for measuring peripersonal space in immersive virtual environments. Thus, we chose to continue with a second study to measure peripersonal space in relation to social agents, or computer driven characters, with different social characteristics.

4.3 Experiment 2: Peripersonal space Boundaries Modulated by Agents

In this experiment, we sought to determine how the peripersonal space boundaries would modulate when an agent, potentially perceived as another individual, was the visual stimulus. In particular, five different agents of varying visual features approached each participant using the same method as in the first experiment.

4.3.1 Participants

Forty participants (25 female, 15 male) between the ages of 18 - 40 took part in this study. Participants were recruited through our institution's sign up system for psychology studies and flyers placed around campus. All participants had no prior knowledge of the study and had normal or corrected-to-normal vision. The protocol was approved by our institution's IRB. Participants gave informed, written consent and were paid. A survey was given to participants about their virtual reality use. 80.9% of participants reported that they had used virtual reality before, but the majority (61.7%) had only used it once when they tried a demo.

Figure 12: Agents used in Experiment 2. From left to right: average female, intimidating female, average male, intimidating male and monster. ©IEEE 2020

4.3.2 Apparatus

We also used the HTC Vive Pro and built the immersive virtual environment using Unity Game Engine (version 2018.2.17f1) for Study 2. All Scripts were written in C#. Agents were either modeled using Adobe Fuse or taken from the avatar collection provided on Adobe Mixamo, and imported into Unity. There were five agents (see Figure 12) that each user saw during the study: an average female and male, intimidating female and male and a monster. The dimensions of these agents were as follows: the height and shoulder width of the average female were 1.65 m and 0.34 m respectively, of the average male were 1.8 m and 0.4 m respectively, of the intimidating female were 1.65 m and 0.43 m respectively, of the intimidating male were 2.15 m and 0.65 m respectively, and of the monster were 1.7 m and 0.68 m respectively. These agents were all given the same walking animation that was also downloaded from Adobe Mixamo. Users were given their own self-avatars, which were the same used as in Study 1 (see Figure 10). The Vive tracker configuration was the same as well, and avatars were tracked by using Ikinema Orion. The immersive virtual environment was the same as used in Study 1 with one slight modification: we modelled a doorway and enclosed room from which the agents emerged and placed it 2.3 m away from where the user would stand (see Figure 9).

4.3.3 Experimental Design

Before beginning the study, subjects were asked to fill a virtual reality experience questionnaire. Once completing the questionnaire, subjects were asked to don the HMD as well as the tracking shoes and belt, and were given the hand controllers. They were asked to adjust the headset to their comfort, including the IPD. Ikinema Orion was started to track the movement of the subjects, and then they were placed in the virtual lab environment. Subjects were allowed to familiarize themselves with the environment before beginning the study by looking around and viewing their self-avatar's body. Once they were ready to begin, subjects stood behind a virtual piece of tape on the ground of the immersive environment that was approximately 2.3 m away from the doorway out of which the agents would emerge.

In a randomized order, one of the five different agents would emerge from the doorway and walk toward the participant at a speed of 75 cm/s. All agents followed the same walking animation. Subjects were instructed to watch as the agents approached, and to respond to the tactile stimulus (which was a vibration delivered to one of the controllers) by pulling one or both of the triggers on the controllers as soon as they felt the stimulus. The tactile stimulus occurred randomly at each distance of 0.7 m, 1 m, 1.2 m, 1.5 m and 2 m. These distances were chosen due to the size of the agents, but still with the bounds of natural peripersonal space in mind. If some agents approached users at distances closer than 0.7 m, the user could see the inside of the agent. There were a total of 125 trials; each subject responded to each of the five agents on five different occasions per each of the five perceived distances. Reaction times were logged into a text file and data was extracted by a python script in an SPSS-ready format. Once all trials were completed, the study was concluded.

4.3.4 Agent Likeability Ratings

The same likeability survey that was administered in the first study [Bartneck et al. 2009] included the same questions regarding the agents used in Study 2. Again we wanted to determine the attitudes users would display when interacting with the agents. The average female and male, intimidating female and male and monster were all rated against the same Likert scales: dislike-like, unfriendly-friendly, unkind-kind, unpleasant-pleasant and awful-nice. Again, Mann-Whitney U Tests were performed on the data for each question and were Bonferroni corrected. Almost all comparisons were significant, with p-values smaller than 0.05 and no larger than 0.008. However, for all questions, responses to the intimidating female and male were never significantly different. Additionally, responses to the average and intimidating males were not significantly different for questions 1 (dislike-like) and 4 (unpleasant-pleasant) and were not different between the average male and intimidating female for questions 1 (dislike-like), 3 (unkind-kind) and 4 (unpleasant-pleasant). A full list of significance values

Agent Type	Likeable	Friendly	Kind	Pleasant	Nice
Average Male	5%	18%	24%	13%	18%
Average Female	47%	45%	47%	47%	42%
Intimidating Male	18%	8%	13%	11%	18%
Intimidating Female	11%	2.6%	8%	11%	11%
Monster	18%	5%	8%	8%	5%

Table 6: Depicted in this table are the positive ratings (meaning ratings of 4 or a 5 on the Likert scale) for each question in the likeability survey for the agents used in Study 2. ©IEEE 2020

for each question and agent comparison can be found in the supplementary material included with this paper. Table 6 depicts how respondents felt each agent type to be likeable, friendly, kind, pleasant and nice. Overall, the female character is rated most positively amongst survey participants, while the monster is rated most negatively. We would expect participants of Study 2 to react differently to the agents according to the positive and negative perceptions recorded here.

4.3.5 Results

Our analysis follows the first experiment. We first chose to remove all outliers from our data. We did so by using Tukey's Method. We calculated the upper fence for each set of reaction times at each distance for each agent and rejected any reaction time greater than that fence. Again, we did not calculate the lower fence. This removed approximately 7% of the data, and the majority of the outliers removed were instances where the subject did not respond. Once outliers were removed, we then averaged all reaction times for each of the trials at each distance for each agent. For ease of understanding we chose to collapse the agents into three groups: "average" agents, "intimidating" agents, and the monster. The "average" agent group consisted of the average female and male, and the "intimidating" agent group consisted of the intimidating female and male.

Using IBM SPSS Statistics, we submitted this data to a repeated measures analysis of variance (RM-ANOVA) with factors of distance and agent. Assumptions were checked and corrected for by SPSS. The RM-ANOVA found main effects of distance $F(1, 33) = 8.314, p < .01$ and agent $F(1, 33) = 14.794, p < .01$, and no interactions. Bonferroni corrected paired samples t-tests revealed that all reaction times at each distance were significantly different $p < 0.001$, with the exception of reaction times at 1m and 1.2 m.

To delimit exact peripersonal space boundaries, we fitted the data to the same sigmoidal function as described in Study 1. We performed a fitting on the averaged data of each agent grouping. This sigmoidal fitting found the average peripersonal space boundary to be around 1.36 m (1.35 m for the "average" agents, 1.39 m for the “intimidating" agents, and 1.33 m for the monster). Again, the goodness of fit measure (R^2) was greater than 0.9 for all fits.

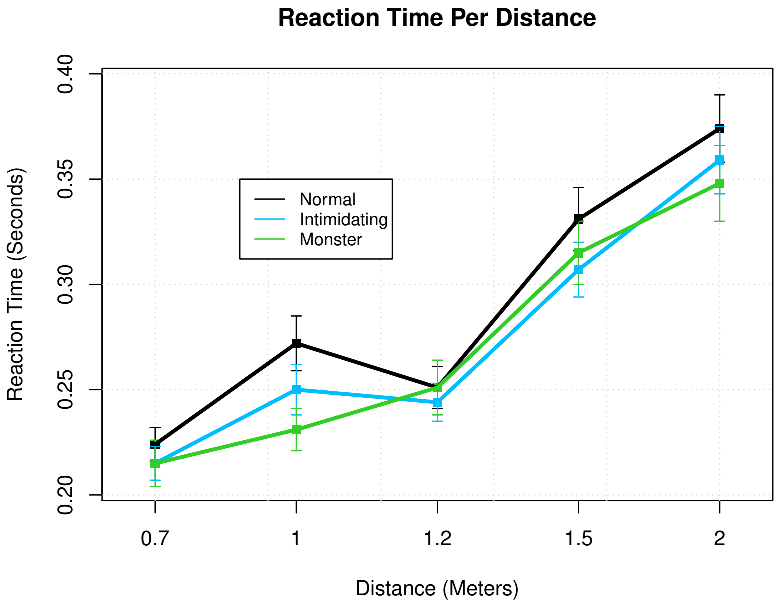

Figure 13: This graph depicts the average reaction time recorded at each perceived distance for average, intimidating and monster agents. Error bars represent the standard error of the mean. ©IEEE 2020

Additionally to determine if the peripersonal space boundaries were modulated by the agent type, we again performed Bonferroni corrected paired samples t-tests. These tests revealed a significant difference in the peripersonal space boundaries defined by the monster and the “intimidating" agents $p < 0.001$, but there were no other significant results. Thus we performed Bayes factor analyses to further shed light on these results. Comparing the “average" and “intimidating" agents generated a JZS Bayes factor of 3.11 substantially in favor of the null, comparing the “average" agents and the monster generated a JZS Bayes factor of 7.04 substantially in favor of the null, and comparing the “intimidating" agents and the monster a JZS Bayes factor of 6.57 substantially in favor of the alternative. These results indicated that the peripersonal space boundary was modulated by the most negatively perceived agent, or the monster.

4.3.6 Discussion

It is noteworthy that the agent had a significant effect on how users responded to the tactile stimulus. The results of the RM-ANOVA paired with the Mann-Whitney U Test results for the likeability survey are a clear representation of the significant difference we see in reaction times. Reaction times to the “average" agents (0.224s, 0.272s, 0.251s, 0.331s, and 0.374s at 0.7 m, 1 m, 1.2 m, 1.5 m, and 2 m respectively) were slower than those for both the “intimidating" agents (0.215s, 0.250s, 0.244s, 0.307s, and 0.359s) and the monster (0.215s, 0.230s, 0.251s, 0.315s, and 0.348s). The results from the likeability survey demonstrated that the average female was the most desirable of all of the agents, since she was always viewed the most positively by survey participants. There were mixed results for the average male in comparison to the average female, as the average male was sometimes not seen as different than the intimidating female, male or both, but this result is similar to conclusions drawn from other works that the comfort distance of users of immersive virtual environments from males is extended further than that for females and that males are viewed as a more intimidating presence [Bailenson et al. 2003; Iachini et al. 2016; Yee et al. 2007]. The intimidating agents were most always viewed in a more negative light than the average female and sometimes the average male and were never different from one another, and the monster was always considered in the most negative light. Upon reviewing Figure 13 we can see a visual representation of the significance between the reaction times to different types of agents as discussed just above.

It is also notable that there is a shift here in the peripersonal space boundary from the first experiment. The peripersonal space boundary has extended to 1.36 m here instead of the 1.27 m boundary found in the first experiment, showing that users of an IVE give more space between themselves and humanoid agents instead of objects. This result is also consistent with previous literature [Bailenson et al. 2003; Iachini et al. 2014; Llobera et al. 2010; Wilcox et al. 2006] that has found the same. It is worth mentioning that it may be assumed that the peripersonal space boundary may be modulated by the size of the agents since they are significantly larger than the balls used in the first experiment. However, prior literature has shown virtual reality users to modulate peripersonal space differently even when an object’s size is comparable to that of an agent [Bailenson et al. 2001; Sanz et al. 2015]. The peripersonal space boundary was modulated by the monster, but remained the same for all other agents when compared. While more work needs to be done to confirm and replicate the findings here, this gives the implication that there is some negative quality that is required in immersive virtual environments for peripersonal space boundaries to retract as has been shown in prior work [Coello et al. 2012; Pellencin et al. 2018; Ruggiero et al. 2017]. Body size, or the volume of the agents, may have contributed to the decreased peripersonal space boundary since it has been shown that larger perceptions of body size decrease personal space [Phillips 1979; Sanders 1976]. But our results do not show a clear correlation since the monster has a body size intermediate between the intimidating male and the rest of the avatars.

Figure 13 also shows us that once the peripersonal space boundary is crossed, reaction times trend slower for both the average and intimidating agents. The reaction times for both of these agent groupings appear to be non-monotonic. The implication here is that depending on the social characteristics that are conveyed, there may be an initial acceptance of an agent once the peripersonal space boundary has been crossed. This may be tied to the idea that when a person breaches another's peripersonal space, behavior is adjusted to respond appropriately to this new situation fast (i.e., a fight or flight situation). Under such circumstances, one's capacity is tied up to cope with the emergency situation of having another body directly in the space around his or her own body. Distress could lead to an increase in reaction time and thus a decrease in attention and concentration in cognitive tasks Kato et al. [2009]. This trend did not happen with the monster, as the reaction times to this agent monotonically increase. The latter two findings, to our knowledge, have not been reported previously.

4.4 General Discussion

In this work we delimited peripersonal space boundaries and showed the interaction that these boundaries possess with objects and agents in the environment. Study 1 demonstrated that the method of Serino et al. [2017] could delimit peripersonal space boundaries in a reliable manner in an immersive virtual environment as they do in the natural world. It also demonstrated that those boundaries were sensitive and responsive to the characteristics of an object, in our case either non-hostile or threatening. Study 2 showed that the peripersonal space boundaries were malleable, since they were different for agents from the object based boundaries. Study 2 also showed peripersonal space boundaries to be responsive to an agent that is perceived in a negative light. The peripersonal space boundaries for immersive virtual reality in the presence of these two types of stimuli are within established bounds for such space Hall [1963].

Interestingly, the reaction times to the stimuli varied within type outside the peripersonal space boundary. The threatening spiked ball evoked slower reaction times from users than the non-threatening normal ball, which seems at odds with the results from the likeability survey about these objects. Users responded significantly more slowly to the average agents than they did both the intimidating agents and the monster. Additionally, the monster, who was rated as the most "unlikeable" by participants of the likeability survey, was the only character that had reaction times that monotonically increased (meaning that the further away it was perceived, the slower the reaction time got). For both the average and intimidating characters, there was an increase in reaction time when the initial peripersonal space boundary was breached before it decreased again.

The type variations and reaction time results can give guidance to designers of virtual spaces who are interested in specific types of interactions. Direct interaction methods within virtual reality is difficult [Mine et al. 1997; Poupyrev et al. 2000; Kjeldskov 2001]. Collaborative interactions of avatars have been the subject of significant study but remain a difficult topic because the fidelity of the interaction is still low [Hrimech and Merienne 2010; Zibrek et al. 2017]. Our results can give some indication for the proper spatial requirements of virtual environments that lie within comfortable interaction distances for social and object interaction. Reaction times may serve as proxies for attention, with shorter reaction times indicating stronger reactions, and give guidance about the nature of what users will be tempted to attend to within such spaces.

4.4.1 Limitations and Future Work

This study has limitations due to the nature of commodity-level virtual reality equipment and avatars typically employed in virtual reality. Mutual gaze is a known moderator of peripersonal space [Argyle and Dean 1965; Bailenson et al. 2001, 2003; Yee et al. 2007], and eye tracking in virtual reality is only on the cusp of accessibility. The agents used in our study did not exhibit naturalistic gaze behavior, and this can change people's perception of them [Bailenson et al. 2003; Garau et al. 2003]. In particular, facial expressions are also a moderator of peripersonal space [Ruggiero et al. 2017], as well as preconceived notions of an interaction partner's personality traits [Iachini et al. 2015a; Pellencin et al. 2018] and the general nonverbal cues that body language conveys [Yee et al. 2007]. While it is possible to generate and give agents facial expressions and to convey some body language cues in immersive virtual environments, the process is arduous and inverse kinematics for commodity level equipment do not yet convey naturalistic movements. In addition, there are other social factors involving things such as the personality of the agent that we did not account for [Hayduk 1983]. Achieving lifelike virtual agents in both appearance and action is an open problem, of course.

Giving participants surveys based on their attitudes toward a broad range of factors could give us a more refined model of how users treat and form peripersonal space. Such factors might include the mental health of the user (the level of anxiety they possess [Iachini et al. 2015b] or if they have any behavioral medical diagnosis [Alcorn et al. 2011; Delevoye-Turrell et al. 2011]) and the personality type of the user [Iachini et al. 2015b]. Thus, they might be fairly invasive, but understanding the complexities of human interaction through a psychological lens could lead to models that would help developers refine interaction distances in applications with more specificity and nuance than is currently possible. Such applications may include the assistive and rehabilitative ones mentioned in the Introduction.

It would be interesting to see how the dimensions of a self-avatar affect the modulation of peripersonal space and thus interactions, since the dimensions of self-avatars affect action possibilities in virtual environments [Lin et al. 2012; Kilteni et al. 2012b]. Determining how self-localization affects perception of action capabilities and the modulation of peripersonal space in multi-user environments considering seems fruitful given recent work [van der Veer et al. 2019] on errors in self-localization. It would also be interesting to see if and how peripersonal space boundaries change with embodiment and the factors influencing it [Gonzalez-Franco and Peck 2018]. And finally, it would be interesting to determine the required level of copresence to evoke naturalistic peripersonal space modulation considering the findings of Podkosova and Kaufmann [2018a] that show collocated users to modulate some level of peripersonal space while distributed users do not.

4.4.2 Conclusions

Again, this Chapter represents the second contribution of this dissertation. We have shown that peripersonal space boundaries in immersive virtual environments can be measured easily with commodity level virtual reality equipment. These boundaries can be modulated and reactions to these boundaries can be varied based on salient features of objects and agents in those environments. These results are promising and have implications for the design of immersive virtual environments using current technology to improve user experience and facilitate successful social interaction. As mentioned in the Introduction, these findings can have a positive impact on applications such as those related to assistive therapy for children and adults [Alcorn et al. 2011;

Boyd et al. 2018], training and simulation applications for medical, military and educational purposes [Fox et al. 2009]. While these findings are novel and have promise, future work should focus on the factors affecting peripersonal space boundaries in virtual reality. The future work that we intend to conduct to expand our understanding of peripersonal and interpersonal space is discussed in the following chapter.

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5 Measuring Personal Space with Relation to Bodily Manipulation

This chapter takes a closer look at how personal space is maintained in immersive virtual environments. We now know that peripersonal space can be measured and that its boundaries depend on the type of interaction occurring in virtual reality. In this chapter we want to understand how different characteristics of self-avatars affect the boundaries of interpersonal and peripersonal space. This chapter uses the same methodology as in the previous chapter, and presents a novel understanding of how both embodiment and manipulated arm dimensions affect both interpersonal and peripersonal space in an immersive virtual environment. Two experiments using visual and tactile stimuli to determine interpersonal and peripersonal space boundaries were employed. In the first experiment, users experience differing levels of embodiment, and both interpersonal and peripersonal spaces are affected. In the second experiment, users experience self-avatars with differing arm dimensions, and we found that interpersonal space was affected by the change in dimension while peripersonal space was not. These findings have important design implications for virtual reality developers and researchers to consider, and tease out interesting results that lead toward new research questions.

5.1 Research Motivation

We consider personal space here in two categories: interpersonal and peripersonal space. Interpersonal space is the distance that an individual maintains between themselves and another individual [Hall, 1963; Hayduk, 1983]. Peripersonal space is an individual's perceived reaching and grasping distance [Berti and Frassinetti, 2000; Delevoye et al., 2010; Farne et al., 2005; Rizzolatti et al., 1997]. We measure interpersonal space by asking virtual reality users to report their comfort distance, or the distance at which the user is no longer comfortable with an object or person being in their personal space. We measure peripersonal space through reaction times extrapolated by a multisensory task that requires users to react to objects and people within peripersonal space. Interpersonal and peripersonal space are intermingled, and the expansion and contraction of both spaces is contingent upon interaction context in a similar way [Iachini et al., 2014].

Embodiment is a sensation that can easily be induced in immersive virtual environments [Kilteni et al., 2012a; Slater et al., 2010b], and the level of embodiment can affect the way users feel about self-avatars [Waltemate et al., 2018]. The way space is mediated around the body can be directly affected by the sense of embodiment [Kilteni et al., 2012a; Lenggenhager et al., 2009]. Virtual reality affords developers the option to design environments that offer users different senses of embodiment. Therefore we seek to determine what degree of embodiment is required to evoke naturalistic peripersonal space boundary modulation in immersive virtual environments.

Physical characteristics of humanoid models are readily manipulated in immersive virtual environments; users can be given self-avatars that do not match their physical appearance whatsoever. Prior literature suggests users of immersive virtual environments adapt to the size of their given self-avatar and behave accordingly [Creem-Regehr et al., 2015; Jun et al., 2015; Lin et al., 2012; Stefanucci and Geuss, 2009, 2010]. Additionally, there is work showing that perception of immediate reaching and grasping space extends when tools are used that increase arm length [Berti and Frassinetti, 2000; Farne and Ladavas, 2000; Holmes and Spence, 2006; Iriki et al., 1996; Ladavas and Serino, 2008; Witt et al., 2005] and can vary when virtual reality users are given self-avatars of different volume [Normand et al., 2011].

Thus, these are the research questions this work seeks to answer:

- Q1: Does the level of embodiment a user experiences affect the interpersonal and peripersonal space of users in an immersive virtual environment?
- Q2: Do an avatar's physical characteristics, such as arm length, affect the interpersonal and peripersonal space of users in an immersive virtual environment?

5.2 Experiment 1: Personal Space Boundaries and Embodiment

In this first experiment we seek to understand how varying degrees of embodiment affect the perception of one's interpersonal and peripersonal space in an immersive virtual environment. We test this by having users report their comfort distance as well as perform the same task as in Buck et al. [2020b] while providing low, medium and high degrees of embodiment. In the low embodiment condition, users will experience a generalized humanoid self-avatar from a third person viewpoint that exhibits both latency and slow down. Latency refers to the delay between the input and visual response in a simulation caused by a network delay. Slow down refers to the slowed movements of a user's self-representation in a simulation that may occur when using a low performance graphics card. The low embodiment condition represents a distinctively poor virtual reality experience in which the user's sense of agency, self-location and appearance are all manipulated and mismatched from what is perceptually natural. In the medium embodiment condition, users will experience a generalized humanoid self-avatar from the first person viewpoint that exhibits latency. The medium embodiment condition represents a virtual reality experience where the sense of agency and appearance are manipulated and mismatched from what is perceptually natural, but to a lesser degree than in the low embodiment condition. Finally, in the high embodiment condition users will experience a gender and race-matched self-avatar from a first person viewpoint that exhibits minimal latency. The high embodiment condition represents the highest fidelity virtual reality experience in which the sense of agency, self-location and appearance all align most closely with one's natural perception. The particulars of these manipulations are explained in Section 5.2.3.

Our levels of embodiment are evoked through manipulations of appearance, self-location and agency, which are contributing factors to embodiment [Gonzalez-Franco and Peck, 2018; Kilteni et al., 2012b]. The external appearance of a self-avatar can enhance or inhibit levels of embodiment [Gonzalez-Franco and Peck, 2018; Kilteni et al., 2013; Yee et al., 2009; Normand et al., 2011; Won et al., 2015], but there is evidence that suggests that personalized avatars increase the sense of body ownership and presence [Waltemate et al., 2018] (although the avatars in this work were highly personalized). With respect to self-location, Kilteni et al. [2012a] found that the viewpoint of the avatar is important to self-localization. Visuospatial perspective is typically egocentric hence the origin of this perspective is important [Blanke and Metzinger, 2009; Ehrsson, 2007]. Physiological responses to perceived threat are stronger when one is given a self-representation in the first person perspective rather than the third [Petkova et al., 2011; Slater et al., 2010b]. The sense of agency is reduced when the visual feedback of an action and the actual movement are mismatched [Blakemore et al., 2002; Franck et al., 2001; Sato and Yasuda, 2005], and Franck et al. [2001] show that the sense of agency is reduced when virtual reality users experience latency greater than or equal to 150 ms.

The hypotheses that we developed about this experiment are as follows:

- H1: Given current knowledge about what affects embodiment, our conditions should be sufficient enough to evoke differing levels of embodiment.
- H2: Users experiencing the highest degree of embodiment will regulate both interpersonal and peripersonal space more naturally than users experiencing lower degrees of embodiment.

5.2.1 Power and Experimental Participants

Prior to conducting our study, we ran an a priori power analysis using G Power[10] to determine an appropriate sample size. We chose two effect sizes of $d = 0.25$ and 0.5, accounting for small and medium effect sizes, to compute an appropriate range for the sample size, as well as an alpha error probability $\alpha = 0.05$, and power $\beta = 0.8$. The number of measurements given to G Power was 100, since this experiment would consist of 100 trials, and the number of groups was dependent upon the within subjects factors which were in this case 3. Finally, the correlation among repeated measures was left as the default value of 0.5. The power analysis revealed that we would need 24 participants to obtain a medium effect size. We also considered the experiment conducted by Serino et al. [2017], which is similar to our own, which had a similar number of participants. Thus, 24 participants (13 female, 11 male) between the ages of 18-30 (20.7 ± 3.1) were recruited and took part in this experiment. Participants were recruited through our institution's sign up system for psychology studies as well as through flyers that were placed around campus. All participants had no prior knowledge of the study and had normal or corrected-to-normal vision. The protocol was approved by our institution's IRB and sanitation measures were taken to protect participants against COVID-19. Participants gave informed, written consent and were paid $10/hour.

5.2.2 Apparatus

We used an HTC Vive Pro head-mounted display with two HTC SteamVR base stations, version 2.0, in addition to handheld controllers and two Vive trackers attached to a pair of shoes. The computer driving the HTC Vive Pro contained a 4.0 GHz Intel i7 6700K Quad-Core CPU equipped with 32GB RAM and an Nvidia GeForce GTX 1080 Ti graphics card. We measured the end-to-end latency of this system for one tracker using the technique described by Feldstein and Ellis [2021] using an iPhone XS Max in Slo-Mo mode as our 240 frame per second camera. Over five tests the maximum latency was 12.5 ms, which is roughly consistent with the latency of the Vive system reported in Le Chenechal and Chatel-Goldman [2018], and we will assume that as our system latency.

We built the 3D immersive virtual environment using the Unity Game Engine (Version 2019.1.7f1), and

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[10] https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html

Low Embodiment	Medium Embodiment	High Embodiment
Avatar: Generic Humanoid	Avatar: Generic Humanoid	Avatar: Gender and Race Matched
Latency: 500 ms	Latency: 250 ms	Latency: System, < 9 ms
Slow Down: 350 ms	Slow Down: None	Slow Down: None
Viewpoint: Third	Viewpoint: First	Viewpoint: First

Table 7: This table shows the embodiment manipulations for each condition.

all scripts were written in C#. The experiment was conducted in three different virtual rooms (see Figure 14) that were designed differently so that participants would not become accustomed to landmark cues that could affect their performance. Room 1 was 8 m x 7.7 m x 3.5 m, Room 2 was 9 m x 9 m x 3.5 m, and Room 3 was 6 m x 6 m x 3.5 m. Each room contained a mirror, a marker on the floor where the user stood during the trials, five doors, some windows and various furniture items, pictures and plants. The items placed in the room were either modelled in Unity or taken from CGTrader.

The agent and avatar used in the low and medium embodiment conditions (pictured in Figure 15) was taken from Adobe Mixamo and the avatars used in the high embodiment condition (see Figure 15 as well), which were gender and race matched, were all made using Adobe Fuse (which has since been discontinued). The agent executed a walking animation that was also taken from Adobe Mixamo. The self-avatars that were used were all driven by Final IK, which uses inverse kinematics to compute the motions and positions of the self-avatar. Tracking data was used from the feet (Vive trackers), hands (Vive controllers), and head-mounted display to drive the self-avatar. The tracker positioning and full set up of equipment that users wore is depicted in Figure 16. All data was recorded immediately into a text file as users participated in the experiment, and was extracted into a csv file for analysis.

5.2.3 Experimental Design

Before beginning the study, participants were instructed on how to wear the virtual reality equipment and were allowed to adjust the head-mounted display and IPD to their comfort. They donned the head-mounted display, tracking shoes, and controllers and were given instructions on how to respond to each trial. We asked the participant their height to calibrate the self-avatar, and refined the dimensions as needed. Once the avatar was calibrated, the experiment began. The experiment was done in three different blocks for each condition (low, medium, and high embodiment). The details of the embodiment manipulations are as follows, and are listed in Table 7 for ease of understanding. To manipulate appearance, the standard self-avatar given in the low

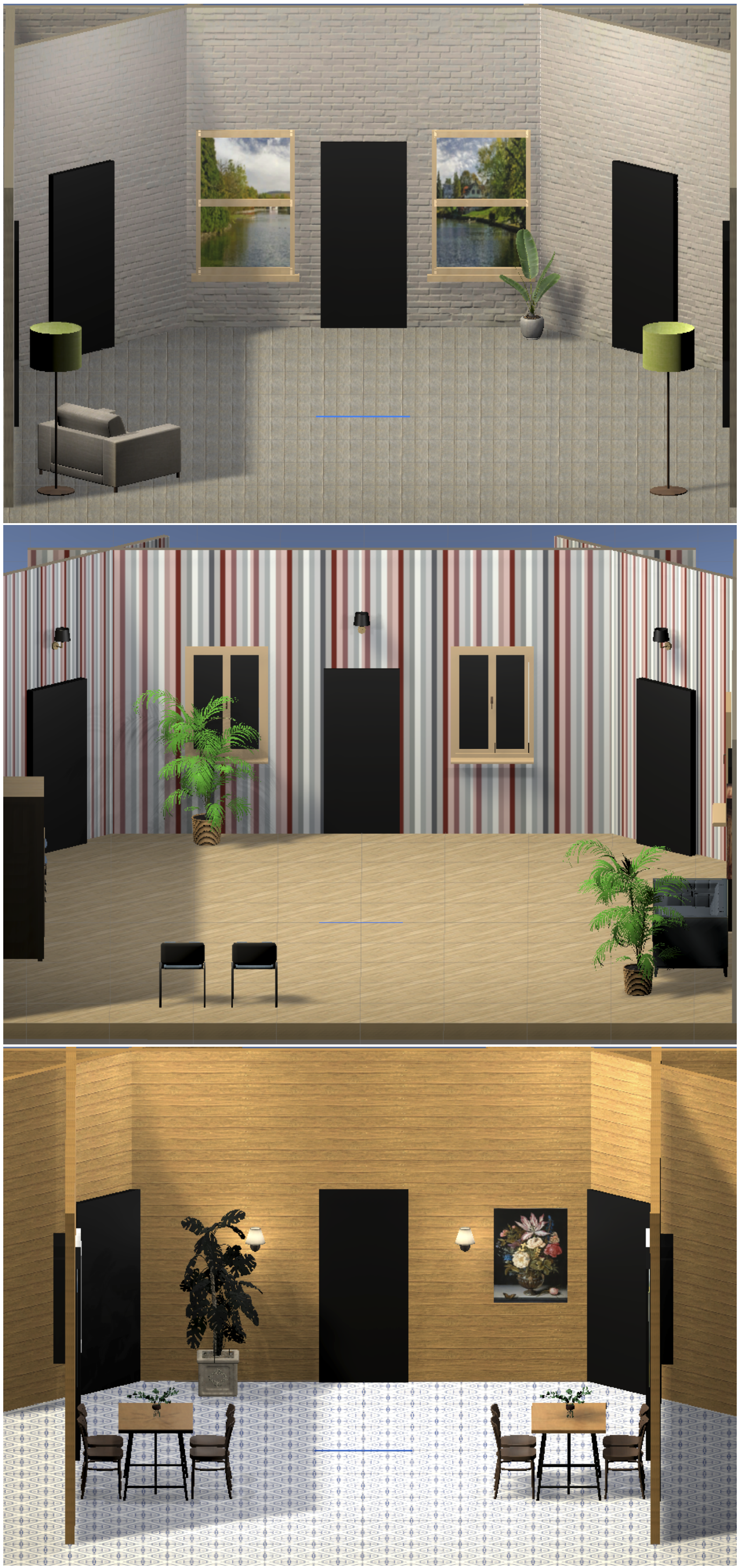

Figure 14: The virtual rooms used in both experiments. From top to bottom are Room 1, Room 2 and Room 3. The mirror, an occluding wall and ceiling were removed from each room to allow a clear view of the scene.

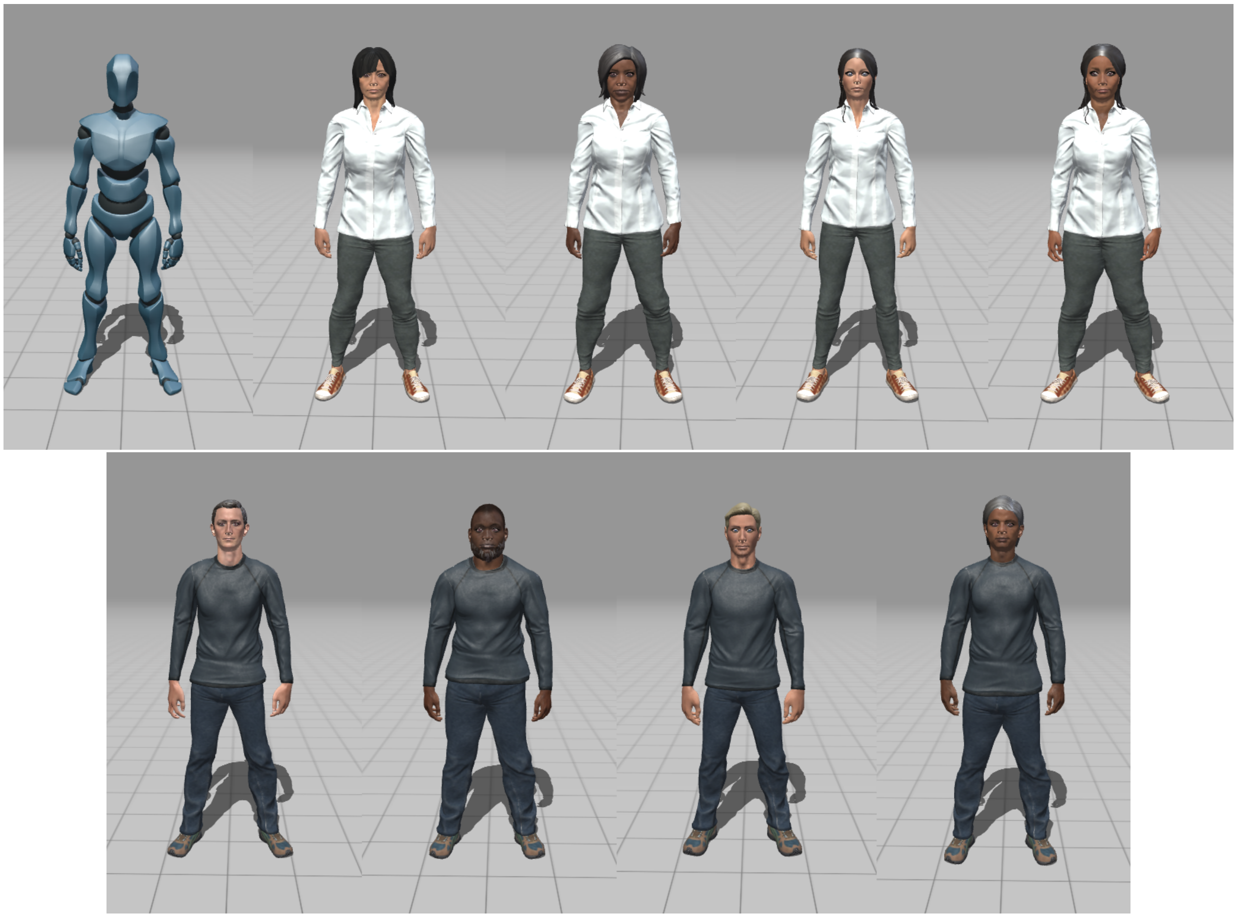

Figure 15: The avatars used in both experiments. Top, from left to right: humanoid, Asian female, Black female, Caucasian female and Indian female. Bottom, from left to right: Asian male, Black male, Caucasian male and Indian male.

Figure 16: The equipment used in both experiments. As seen, the Vive Pro HMD was worn, along with the handheld controllers and two Vive Trackers placed on the feet.

and medium embodiment conditions is a generic, androgynous self-avatar. In the high embodiment condition, the given self-avatar is a gender and race matched humanoid. To manipulate self-location, the avatar is seen from the third person viewpoint in the low embodiment condition and from the first person viewpoint in the medium and high embodiment conditions. Finally, to manipulate agency, latency of 500 ms and a slow down of 350 ms are applied to the self-avatar in the low embodiment condition. In the medium embodiment condition, latency of 250 ms is applied to the self-avatar and in the high embodiment condition no latency or slow down are applied. The degree of latency and slow down applied were chosen to be noticeable by the user and greater than the determined level of latency that affects embodiment [Franck et al., 2001; Kilteni et al., 2012a]. We tested these levels of latency and slow down ourselves when building the environment to determine what would be greatly noticeable in the low embodiment condition and less so but still noticeable in the medium embodiment condition. We felt that by generating a higher level of latency and including slow down in the low embodiment condition, users would experience little to no agency over the self-avatar, and that by generating some latency in the medium embodiment condition users would experience only disturbed agency. These are meant to mimic network latency and GPU overload that could occur during virtual reality useage.

The same experimental protocol was followed for each block, and each block was done in a different room (Figure 14) with a different degree of embodiment. First, users were asked to perform an egocentric pointing task in the mirror so they would acclimate to their virtual body, and they were then asked to move and interact with their body while looking at themselves in a mirror. This period lasted 2 minutes, as prior literature shows that users can be primed and acclimate to a virtual body during priming phases that last from 1-5 minutes [Adams et al., 2018; Mohler et al., 2010; Yee and Bailenson, 2007]. After this initial priming phase, users were asked to perform the same multisensory task as in Chapter 4 with a few differences to fit the experiment. Users were asked in one set of trials to report their comfort distance and another set to respond to a tactile stimulus. These sets of trials were counterbalanced to prevent an order effect. In the comfort distance trials, a virtual agent would approach the user from one of five doorways, which were placed at different angles around the user (0°, 45°, 90°, -45° and -90°). When the user became uncomfortable with the agent being in their personal space, they would pull the either of the triggers on the controllers and the agent would disappear. There were 25 total randomized comfort distance trials, where each user experienced the agent approaching from each doorway five times. In the trials were the user exclusively responded to the tactile stimulus, which was a vibration delivered by one of the handheld controllers, the user would pull one of the triggers on the controllers each time the visual stimulus (the agent) approached in their direction. The agent walked towards the user at a speed of 75 cm/s until making contact with the user. There were a total of 25 randomized trials in which the tactile stimulus was delivered either went the agent was 0.75 m, 1 m, 1.25 m, 1.45 m, or 1.85 m away from the user. The tactile stimulus was delivered five times at each distance and angle. Once the comfort distance and tactile response trials were complete, the user would answer an embodiment questionnaire to determine how embodied they felt during each condition [Gonzalez-Franco and Peck, 2018]. A single subject experienced a total of 150 trials and answered the embodiment questionnaire 3 times. All comfort distances and response times were logged as they were completed.

5.2.4 Results

Our data consists of comfort distances and reaction times measured as agents approached during the different conditions (low, medium, and high embodiment). We performed three primary analyses. First, we determine how both the comfort distance and reaction times were influenced by the conditions of the study, and then we determined the peripersonal space boundaries and how they were influenced by the conditions of the study. We first note that the data contained outliers, which was expected, as there were trials where participants would forget to react and pull the trigger in response to the visual stimulus when they were reporting their comfort distance or tactile stimulus when their response times were recorded. We systematically removed these instances using Tukey's method of fences. The upper fence for each reported comfort distance and reaction time were calculated and we removed any distance or reaction time that was greater than the upper fence. The upper fence was the boundary at which a data point would be three standard deviations from the mean. We chose not to calculate the lower fence in this instance since there are no negative distances at which someone could report their comfort distance, and there are also no negative reaction times. This process removed 2.8% of the data; as noted, the outliers removed were typically instances where the participant did not respond during the trials.

We first performed an analysis to determine if comfort distances were different based on the level of

Level of Embodiment		Mean Difference
Low (0.817 m)	Medium (0.857 m)	0.040
	High (0.986 m)	0.170*
Medium (0.857 m)	High (0.986 m)	0.129*

Table 8: Fisher LSD post-hoc comparisons of the comfort distances between the three levels of embodiment for Experiment 1. Mean comfort distance for each condition are denoted in parenthesis. *Denotes statistical significance.

embodiment. Using SPSS, we submitted the data to a repeated measures analysis of variance (RM-ANOVA) with a factor of condition (low, medium, and high embodiment). All assumptions were checked and corrected for by SPSS. The RM-ANOVA found a main effect of condition $F(2, 46) = 3.242$, $p = 0.048$, $\eta_p^2 = 0.12$. Post-hoc pairwise analysis used Fisher's LSD. This method controls for multiple comparisons among three groups and thus additional significance correction was not used [Meier, 2006]. The LSD test revealed statistically significant differences between the comfort distances in the high embodiment condition ($M = 0.986$ m, $SE = 0.019$) and both the low ($M = 0.817$ m, $SE = 0.018$) and medium ($M = 0.857$ m, $SE = 0.023$) embodiment conditions. There was no significance in the comfort distances between the low and medium embodiment conditions. Table 8 shows the post-hoc comparisons, and Figure 17 offers a visual of these results.

Next, we determined if the reaction times were different based on the level of embodiment as well as the distance that the tactile stimulus was delivered. We ran a 3 (embodiment: low, medium, high) x 5 (distance) RM-ANOVA and found a main effect of embodiment $F(2, 46) = 8.354$, $p = 0.001$, $\eta_p^2 = 0.27$, distance $F(4, 92) = 45.638$, $p < 0.001$, $\eta_p^2 = 0.67$, and an interaction between embodiment and distance $F(8, 184) = 3.189$, $p = 0.002$, $\eta_p^2 = 0.12$. Post-hoc analyses were run for each main effect using Fisher's LSD. For embodiment, a significant difference in the reaction times was found between the low ($M = 0.319$, $SE = 0.011$) and medium ($M = 0.368$, $SE = 0.023$) embodiment conditions and the medium and high ($M = 0.314$, $SE = 0.012$) embodiment conditions. Table 9 shows these post-hoc comparisons. For distance, there was a significant difference between all reaction times at each distance. The average reaction times for each distance are as follows: 0.267 s ($SE = 0.008$) at 0.75 m, 0.291 s ($SE = 0.010$) at 1 m, 0.325 s ($SE = 0.013$) at 1.25 m, 0.354 s ($SE = 0.018$) at 1.45 m, and 0.431 s ($SE = 0.026$) at 1.85 m. With regard to the interaction, the medium embodiment condition evoked slower reactions at each distance than both the low and the high embodiment conditions. The significance comparison can be seen in Table 10. Figure 18 provides a visual supplement to

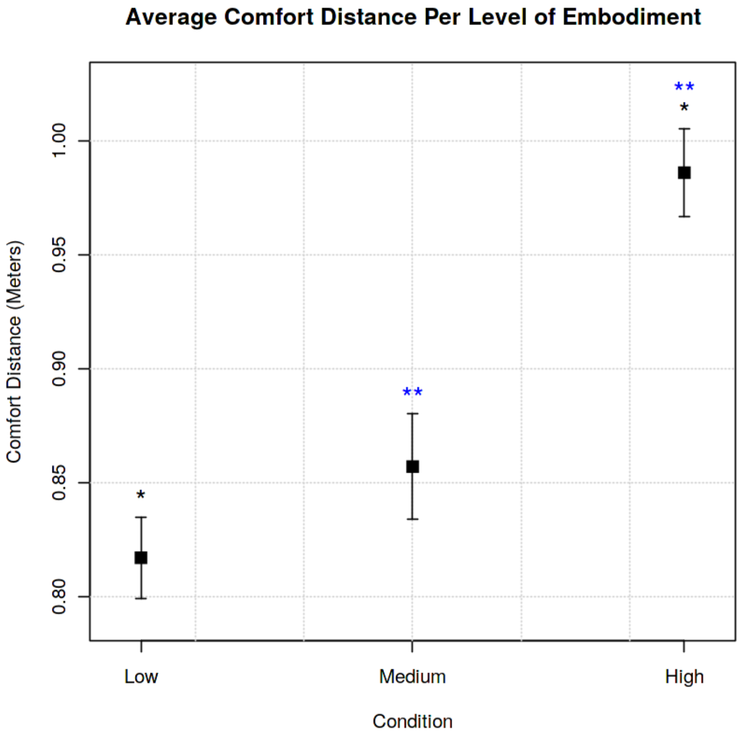

Figure 17: This figure depicts the average comfort distance at each level of embodiment - low (AVG = 0.817 m, SEM = 0.018), medium (AVG = 0.857 m, SEM = 0.023) and high (AVG = 0.986 m, SEM = 0.019). Significance is represented by asterisks. Asterisks of the same color and number represent a unique significance between two conditions. Error bars represent the standard error of the mean.

Level of Embodiment		Mean Difference
Low (0.319 s)	Medium (0.368 s)	0.049*
	High (0.314 s)	0.005
Medium (0.368 s)	High (0.314 s)	0.054*

Table 9: Fisher LSD post-hoc comparisons of the reaction times between the three levels of embodiment for Experiment 1. Mean reaction time in seconds for each level are in parenthesis. *Denotes statistical significance.

Distance		Mean Difference
0.75 m (0.267 s)	1 m (0.291 s)	0.024*
	1.25 m (0.325 s)	0.058*
	1.45 m (0.354 s)	0.087*
	1.85 m (0.431 s)	0.164*
1 m (0.291 s)	1.25 m (0.325 s)	0.033*
	1.45 m (0.354 s)	0.063*
	1.85 m (0.431 s)	0.140*
1.25 m (0.325 s)	1.45 m (0.354 s)	0.029*
	1.85 m (0.431 s)	0.106*
1.45 m (0.354 s)	1.85 m (0.431 s)	0.077*

Table 10: Fisher LSD post-hoc comparisons of the reaction times at each distance for Experiment 1. Mean reaction time in seconds for each distance are in parenthesis. *Denotes statistical significance.

these results.

Up to this point, the peripersonal space boundaries of the participants have not been determined. To determine the peripersonal space boundaries we employed a method that has been used in several previous works [Buck et al., 2020b; Canzoneri et al., 2012; Kandula et al., 2017; Serino et al., 2017]. This method involves fitting the data to a a sigmoid function to extract the boundaries. The fitting equation is as follows:

$$y(x) = \frac{y_{\min} + y_{\max} e^{(x-x_c)/b}}{1 + e^{(x-x_c)/b}} \tag{2}$$

where x is the *independent* variable, or the distance of the agent, y is the *dependent* variable, or the reaction time; $y_{\min}$ and $y_{\max}$ are the upper and lower saturation levels of the sigmoid, or the minimum and maximum reaction times recorded across trials; x_c is the value of the abscissa at the central point of the sigmoid; and b is the slope of the sigmoid at the central point. Both x_c and b vary dependent on the data and are estimated during the fitting. The parameter x_c represents the midpoint of the region of greatest increase in reaction time to the visual stimulus, i.e., the boundary of peripersonal space. To determine each peripersonal space boundary,

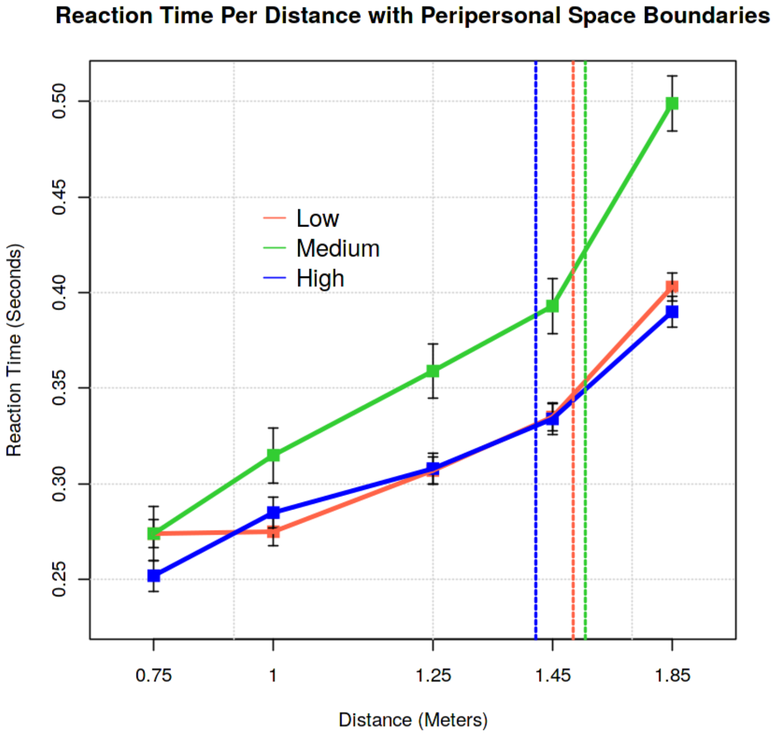

Figure 18: This figure depicts the average reaction time per distance for each condition at each distance. Low embodiment is represented by the red line, medium represented by the green line, and high represented by the blue line. Peripersonal space boundaries are represented by the dotted lines (AVG = 1.351 m, 1.383 m, and 1.259 m for low, medium and high embodiment respectively). Error bars represent the standard error of the mean.

Level of Embodiment		Mean Difference
Low (1.352 m)	Medium (1.383 m)	0.032
	High (1.259 m)	0.093*
Medium (1.383 m)	High (1.259 m)	0.125*

Table 11: Fisher LSD comparisons of the peripersonal space between the three levels of embodiment for Experiment 1. Mean peripersonal space boundaries for each level are in parenthesis. *Denotes statistical significance.

all reaction times for each trial were averaged at each distance per subject, providing a set of (x, y) data points to fit the sigmoid to. The coefficient of determination (R^2) was extracted as a goodness-of-fit measure. For this experiment, the average peripersonal space boundary was 1.33 m. The exact boundaries for each condition are as follows: low embodiment was 1.35 m, medium embodiment was 1.38 m, and high embodiment was 1.26 m. The average goodness-of-fit measure was 0.81.

We ran a RM-ANOVA with condition as the independent variable to determine if the peripersonal space boundaries changed based on level of embodiment. A main effect of condition was found $F(2, 46) = 4.206, p = 0.021, \eta_p^2 = 0.16$. We again used Fisher's LSD for post-hoc analyses. A significant difference in the peripersonal space boundaries were found between the low and high embodiment conditions as well as the medium and high embodiment conditions, while there were no other differences between the other conditions. The comparisons can be seen in Table 11. We next performed a Bayes factor analyses. Bayes factors provide support for the null hypothesis through an odds ratio[11]. The method that we used is described by Rouder et al. [2009], which takes into account the sample size and adjusts for power. Prior odds were set to 1, which favors neither the null nor the alternative hypothesis. Comparing the low and high conditions gives a Jeffrey-Zellner-Siow (JZS) Bayes factor of 2.01 in favor of the alternative, and comparing the medium and high conditions gives a JZS Bayes factor of 3.96 in favor of the alternative. Finally, comparing the low and medium conditions gives a JZS Bayes factor of 5.26 in favor of the null hypothesis.

Finally, we analyzed the results from the embodiment questionnaires to determine if users experienced differing levels of embodiment during each condition. Embodiment questionnaire scores ranged from -3 to 3 with -3 being the lowest level of embodiment and 3 being the highest. We performed a RM-ANOVA with condition as the independent variable and found a main effect, $F(2, 46) = 32.824$, $p < 0.001, \eta_p^2 = 0.61$. Post hoc

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[11] http://pcl.missouri.edu/bayesfactor

Level of Embodiment		Mean Difference
Low (-0.519)	Medium (0.523)	1.042*
	High (0.708)	1.227*
Medium (0.523)	High (0.708)	0.185

Table 12: Fisher LSD comparisons of the embodiment questionnaire scores between the three levels of embodiment for Experiment 1. Mean scores for each condition are in parenthesis. *Denotes statistical significance.

analyses run using Fisher's LSD showed a significant difference in the embodiment scores between the low ($M = -0.519$, $SE = 0.198$) and both the medium ($M = 0.523$, $SE = 0.156$) and high ($M = 0.708$, $SE = 0.137$) embodiment conditions, but no difference between the medium and high embodiment conditions. Table 12 shows the comparisons.

5.2.5 Discussion

In this experiment, the level of embodiment had an effect on both interpersonal and peripersonal space. We were able to confirm or partially confirm all hypotheses. Our conditions evoked differing levels of embodiment (H1), and users experiencing the highest degree of embodiment regulated interpersonal and peripersonal space differently than those experiencing lower degrees of embodiment (H3). There was a significant difference in the reported comfort distance between the high embodiment condition and both the low and medium embodiment conditions. Additionally, peripersonal space boundaries generated were similar to those generated in previous literature Buck et al. [2020b]; Serino et al. [2017], with a bound of 1.35 m for the low condition, 1.38 m for the medium condition, and 1.26 m for the high condition. Another thing to notice is that interpersonal and peripersonal space were inversely correlated; the interpersonal distance expanded as embodiment increased while the peripersonal space contracted as embodiment increased.

We were able to manipulate the sense of embodiment successfully. The sense of embodiment decreased as users experienced the lag and slowdown that we implemented to replicate problems that might arise such as network lag and GPU slowdown. Users that experienced the third person avatar often commented that they did not think of the avatar as themselves, and this is reflected in previous literature [Gorisse et al., 2017; Petkova and Ehrsson, 2008; Slater et al., 2010b]. Additionally, users seemed to respond positively to the avatars that were gender and race matched. One even commented that the hair and skin color of the avatar made it feel like the avatar was customized. There has been work that has shown avatar personalization to positively impact the sense of embodiment [Waltemate et al., 2018]. However, it is important we treat this result with caution, considering the fact that there are some instances in which avatar customization adversely affects embodiment [Lugrin et al., 2015] and has the potential to not affect it at all [Latoschik et al., 2017]. Any of the other factors, such as the omission of lag and slow down combined with the first person viewpoint, could be the key to the increased level of embodiment in the high embodiment condition.

Another interesting finding to note is the interaction of distance and embodiment on reaction time. Figure 18 shows that the reaction times are slower at all distances in the medium embodiment condition. This can be attributed to a few different factors. In the low embodiment condition, the third person perspective gave participants a wider field of view. This field of view allowed users to see, and thus react more quickly to the approaching avatars. In the medium embodiment condition, the first person perspective afforded users a more restricted field of view that required users to turn their heads to find the approaching avatars. This, coupled with the applied latency, slowed the reaction times of the users. Latency beyond the system latency was not present in the high embodiment condition to evoke slower reactions.

The results from this work are nicely in line with results from previous literature. Self-localization, a component of embodiment, is associated with one's peripersonal space [Kilteni et al., 2012a; Normand et al., 2011]. It could be expected then, and we have shown, that peripersonal space should change as one's sense of self-localization changes. The results from the embodiment questionnaire supported these findings, with significantly higher embodiment scores for the high versus low embodiment conditions. We also see that as embodiment increases, that the comfort distance that users report between themselves and the virtual agent increases. We know that physiological responses to threats increase as users experience a higher sense of self-localization as well [Petkova et al., 2011; Slater et al., 2010b], and would expect users to see the approaching avatar as more of a threat when experiencing increased levels of embodiment. Additionally, we know that embodiment mediates the level of fear experienced in virtual environments [Hofer et al., 2017], and would also expect a decrease in embodiment to temper the fight or flight response that occurs when one's personal space is infringed upon [Dosey and Meisels, 1969]. Comfort distance has also been shown to increase between virtual reality users and agents who are perceived to present a moral threat [Iachini et al., 2015a], and has been shown to increase when users interact with agents versus objects [Sanz et al., 2015].

It is also notable that the peripersonal space boundaries shrunk as embodiment increased. Previous literature regarding the plasticity of peripersonal space in the context of social interaction has shown peripersonal space to shrink when people interact in social situations [Teneggi et al., 2013]. This shrinking is perhaps due to the fact that as embodiment increases, the interaction became more realistic and presents the natural consequences of social interaction within personal space to the user. Buck et al. [2020b] did demonstrate that when a user interacted with a threatening agent, that peripersonal space boundaries contracted.

Ultimately, the findings from this experiment show that eliciting high levels of embodiment are important for realistic interactions in immersive virtual environments. These findings have important implications for the future development of 3D immersive applications, which will be discussed in Section 5.4.

5.3 Experiment 2: Personal Space Boundaries and Arm Manipulation

In this second experiment, we examined how personal space would change when the body dimensions of a self-avatar change. Prior work indicates that users immersed in virtual environments are able to adapt to body dimensions that do not match their own and perceive scale based on these dimensions [Creem-Regehr et al., 2015; Jun et al., 2015; Linkenauger et al., 2013]. Not only can the perception of scale change, but so can the perception of the self [Yee and Bailenson, 2007], and the feeling of embodiment [Gonzalez-Franco and Peck, 2018]. Interpersonal space is correlated with arm-reaching distance [Iachini et al., 2014], and these spatial representations changed based on interaction context. There are layers of cognitive complexity that changing the self-avatar of a user adds, and they change the way that one perceives themselves in an immersive virtual environment. This leads us to believe a few things about how interpersonal space might be affected by a manipulation of arm dimension. If the action capability of reaching is changed by an increase or the decrease in the arm dimension of a self-avatar, the interaction space around the body has changed and it would be expected that a user would adapt to this change in space. Thus we developed these hypotheses about comfort distance:

- H1: As arm dimensions decrease, comfort distance will decrease.
- H2: As arm dimensions increase, comfort distance will increase.

However, peripersonal space has a different narrative. Peripersonal space is the near space around our bodies, within which objects and people are reachable [di Pellegrino and Ladavas, 2015; Coello et al., 2008], and it shares some characteristics with arm-reaching space [Zanini et al., In Press]. The cognitive computations that occur for arm-reaching space and peripersonal space are complementary, but different [Lara et al., 2018], and are two distinct spatial representations that should not be confused [Zanini et al., In Press]. There is work around understanding peripersonal space (some in virtual reality) that has confused these two spaces [Coello et al., 2008; Iachini et al., 2014], and our work will provide further evidence to mitigate this confusion. If peripersonal space and arm-reaching space operate on different cognitive processes, the representation of peripersonal space should not change in the context of manipulated arm dimensions. Thus we developed this hypothesis about peripersonal space:

- H3: Lengthened or shortened arms will not change the representation of peripersonal space.

With these three hypotheses in mind, we then conducted our experiment.

5.3.1 Power and Experimental Participants

Prior to conducting the second experiment, we again ran an a priori power analysis using G Power to determine the appropriate sample size. It determined again that we would need 24 participants to obtain a medium effect size. Thus, 24 participants (13 females, 11 males) between the ages of 18-78 years (mean 31.8 ± 16.5) took part in this experiment. Participants were recruited via word of mouth and our institution's sign up system for psychology studies. All participants had no prior knowledge of the study and had normal or corrected-to-normal vision. The protocol was approved by our institution's IRB and sanitation measures were taken to protect participants against COVID-19. Participants gave informed, written consent and were paid $10/hour.

5.3.2 Apparatus

To conduct this experiment we again used the HTC Vive Pro head-mounted display and its lighthouse base stations, handheld controllers, and two Vive trackers that were attached to a pair of shoes. We built the 3D immersive virtual environment using Unity Game Engine (Version 2019.1.7f1), and all scripts were written in C#. The experiment was conducted in three different virtual rooms so that participants would not become accustomed to landmark cues that would affect their performance. These rooms were the same as the ones

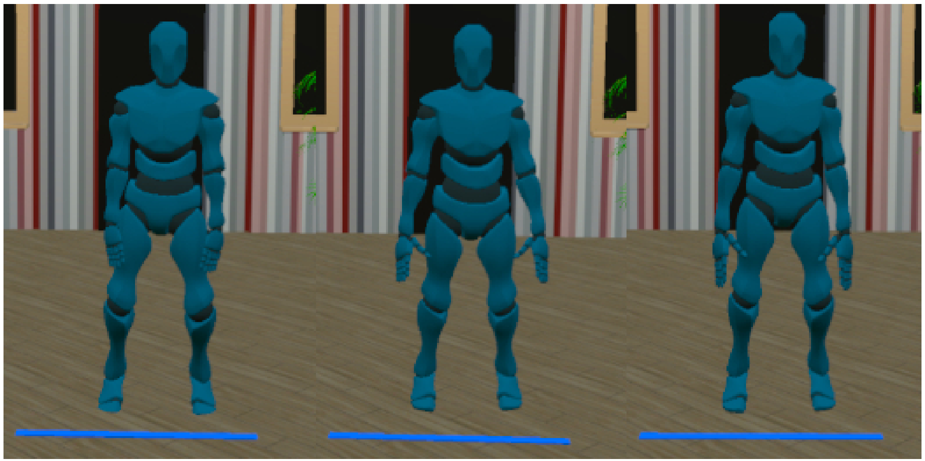

Figure 19: The self-avatar with each different arm manipulation. From left to right: shortened arms, normal arms, and longer arms.

used in Experiment 1 (see Figure 14). The self-avatar and the approaching avatar were the same humanoid avatar that was used in Experiment 1 (see Figure 15). The agent executed the same walking animation as in Experiment 1, taken from Adobe Mixamo. The self-avatars were again driven by Final IK. Tracking data was used from the head-mounted display, the Vive controllers, trackers, and the setup is pictured in Figure 16. All data was recorded immediately into a text file in real time.

5.3.3 Experimental Design

Before beginning the study, participants were instructed about how to wear the virtual reality equipment and were allowed to adjust the head-mounted display and IPD to their comfort. They donned the head-mounted display, tracking shoes, and controllers and were given instructions on how to respond to each trial. The trials were done in three blocks. In the first block, the dimensions of the avatar were always calibrated to those of the user. In the second and third block, which were counterbalanced, the dimensions of the self-avatar's arms were calibrated to either be 12.5% longer or shorter than the natural arm length of the user. The different arm lengths are pictured in Figure 19.

The same experimental protocol was followed for each block of trials. First, users were asked to perform an egocentric pointing task in the mirror so that they would acclimate to their virtual body, and they were then asked to move and interact with their body while looking at themselves in the mirror. This period lasted 2 minutes. After this initial priming phase, users were asked to complete a “block task" in which they would reach towards blocks that were placed in front of them at different heights so that they could acclimate to

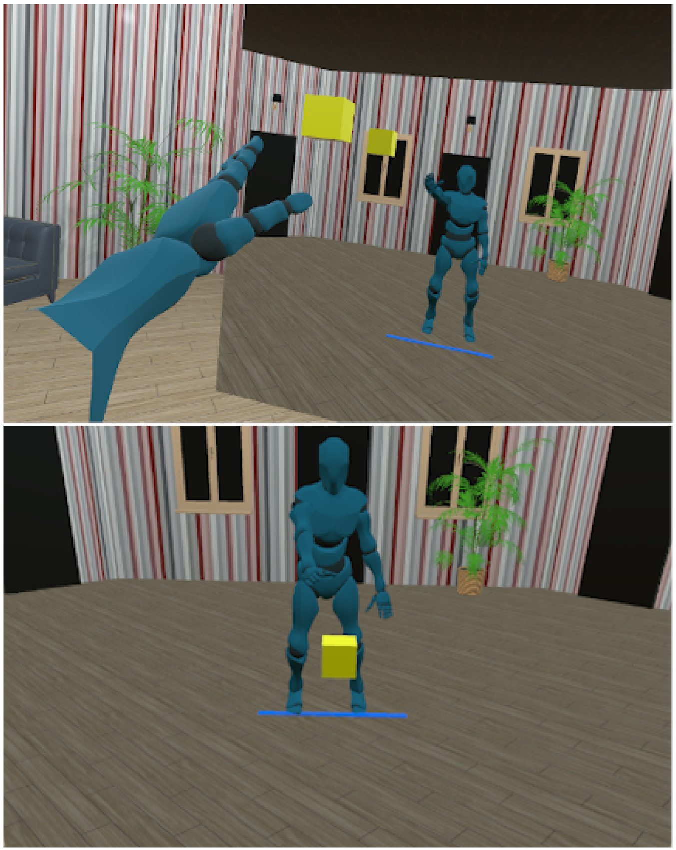

Figure 20: A user performing the pre-trial block task.

their given arm length. This task also lasted 2 minutes. A user can be seen performing this task in Figure 20. After this task, they were asked to either report their comfort distance or to respond to a tactile stimulus (as in Experiment 1, the same task used in Buck et al. [2020b]) as they were approached by an agent. The protocol of the experiment from here on out was the exact same that was used in Experiment 1 with one exception. Every 5 trials, a yellow cube that was 0.15 m x 0.15 m x 0.15m would appear 0.5 m away directly in front of the user at a height of 1.25 m, and the user would reach toward the cube to receive a quick reminder of their arm length. Once the user touched the cube, it would disappear and trials would resume. Again, each user experienced a total of 150 trials. Along with the embodiment questionnaire, users were asked about their arm length after each set of trials. They were asked if they noticed their arms to be longer or shorter than their actual arm length.

Dimension Manipulation		Mean Difference
Normal (1.269 m)	Short (1.269 m)	0.115*
	Long (1.161 m)	0.108*
Short (1.269 m)	Long(1.161 m)	0.007

Table 13: Fisher LSD comparisons of the comfort distance between the three arm dimension manipulations for Experiment 2. Mean comfort distance for each manipulation are in parenthesis. *Denotes statistical significance.

5.3.4 Results

The data for this experiment consists of comfort distances and reaction times measured as agents approached during the different conditions (normal, shorter, and longer arm dimensions). First we determined how comfort distance and reaction time were influenced by the different conditions and then we determined the peripersonal space boundaries and how they were influenced by the conditions. Following the method of analysis performed in the prior experiment (Section 5.2.4), we determined and removed the outliers. This process removed 2.8% of the data again.

We performed an analysis to determine if comfort distances were different based on the arm dimensions of the given self-avatar. Using SPSS, we ran a RM-ANOVA with condition as a factor (normal, shorter, and longer arm dimensions). All assumptions were checked and corrected for. The RM-ANOVA found a main effect of condition $F(2,46) = 4.596$, $p = 0.015$, $\eta_p^2 = 0.17$. Post-hoc analyses were run using Fisher's LSD. The results revealed that the comfort distance for the normal arm dimension manipulation ($M = 1.269$ m, $SE = 0.111$) was significantly different from both the short ($M = 1.154$ m, $SE = 0.095$) and long ($M = 1.161$ m, $SE = 0.094$) arm dimension manipulations. There was no significant difference in the comfort distance when the arm dimensions were longer versus shorter. Table 13 shows the post-hoc comparisons, and Figure 21 depicts these results.

Next, we determined if the reaction times were different based on the different arm dimensions as well as when the tactile stimulus was delivered at different distances. We submitted our data to another 3 (condition) x 5 (distance) RM-ANOVA and found a main effect of distance $F(4,92) = 80.268$, $p < 0.001$, $\eta_p^2 = 0.78$, but no effect of condition. We performed post-hoc analyses using Fisher's LSD. The results revealed a significant difference between all reaction times for each distance. The average reaction times for each distance are as follows: 0.250 s ($SE = 0.011$) at 0.75 m, 0.266 s ($SE = 0.010$) at 1 m, 0.290 s ($SE = 0.011$) at 1.25 m, 0.313

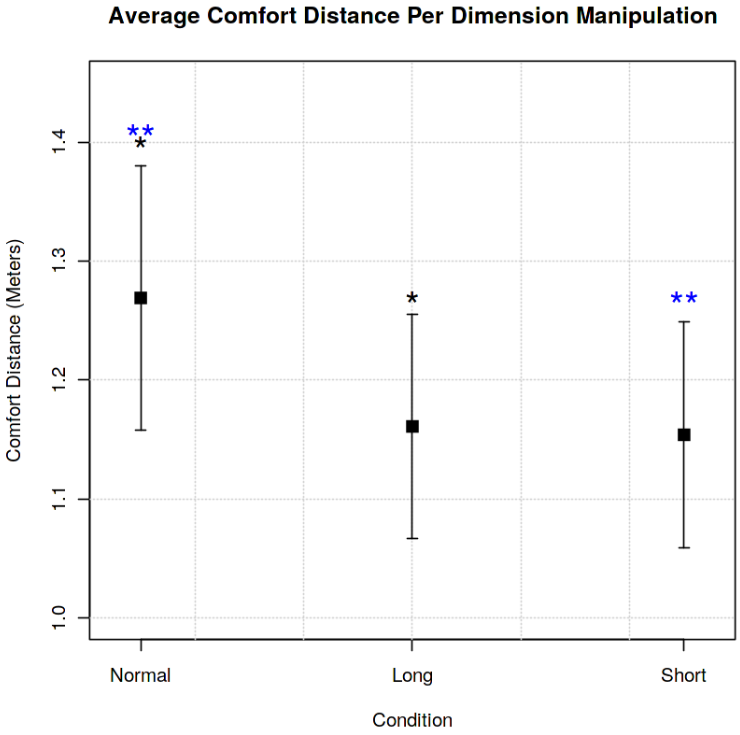

Figure 21: This figure depicts the average comfort distance at each arm dimension manipulation - normal (AVG = 1.269 m, SEM = 0.111), long (AVG = 1.161 m, SEM = 0.094) and short (AVG = 1.154 m, SEM = 0.095). Significance is represented by asterisks. Error bars represent the standard error of the mean.

s ($SE = 0.011$) at 1.45 m, and 0.367 s ($SE = 0.013$) at 1.85 m. The significance comparison can be seen in Table 14. Figure 22 provides a visual supplement to these results.

As before, we next determined the peripersonal space boundaries. We did so by using the same fitting equation used in Section 5.2.4. For this experiment, the average peripersonal space boundary was at 1.39 m. The exact boundaries for each condition are as follows: normal arm dimensions at 1.429 m ($SE = 0.044$), longer arm dimensions at 1.404 m ($SE = 0.044$), and shorter arm dimensions at 1.350 m ($SE = 0.041$). The average goodness-of-fit measure was 0.87.

To determine if the peripersonal space boundaries changed based on the manipulation of arm dimensions in this experiment, we ran a RM-ANOVA with condition as the factor. There was no significant difference in the peripersonal space boundaries between each manipulation. To further confirm these results we again performed Bayes factor analyses. Comparing the peripersonal space boundaries of those with normal versus long arm dimensions gives a JZS Bayes factor of 5.54 in favor of the null, those with normal versus short arm dimensions gives a JZS Bayes factor of 6.28 in favor of the null, and those with short versus long arm dimensions gives a

Distance		Mean Difference
0.75 m (0.250 s)	1 m (0.266 s)	0.017*
	1.25 m (0.290 s)	0.040*
	1.45 m (0.313 s)	0.064*
	1.85 m (0.367 s)	0.117*
1 m (0.266 s)	1.25 m (0.290 s)	0.024*
	1.45 m (0.313 s)	0.047*
	1.85 m (0.367 s)	0.100*
1.25 m (0.290 s)	1.45 m (0.313 s)	0.023*
	1.85 m (0.367 s)	0.077*
1.45 m (0.313 s)	1.85 m (0.367 s)	0.054*

Table 14: Fisher LSD post-hoc comparisons of the reaction times at each distance for Experiment 2. Mean reaction time in seconds for each distance are in parenthesis. *Denotes statistical significance.

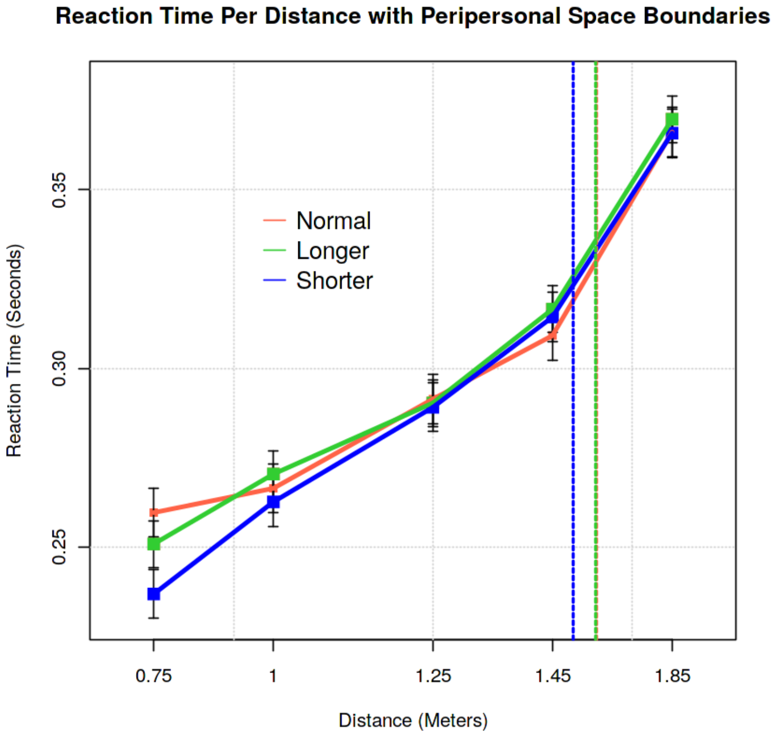

Figure 22: This figure depicts the average reaction time per distance for each condition at each distance. Normal arm dimensions are represented by the red line, longer arm dimensions are represented by the green line, and shorter arm dimensions are represented by the blue line. Peripersonal space boundaries are represented by the dotted lines (AVG = 1.411 m, 1.409 m, and 1.353 m for normal, longer and shorter arm dimensions respectively). Error bars represent the standard error of the mean.

Dimension Manipulation		Mean Difference
Normal (1.429 m)	Short (1.350 m)	0.079
	Long (1.404 m)	0.025
Short (1.350 m)	Long (1.404 m)	0.025

Table 15: Fisher LSD comparisons of the peripersonal space boundaries between the three arm dimension manipulations for Experiment 2. Mean peripersonal space boundaries for each manipulation are in parenthesis. *Denotes statistical significance.

Dimension Manipulation		Mean Difference
Normal (0.451)	Short (0.404)	0.047
	Long (0.250)	0.201
Short (0.404)	Long (0.250)	0.154*

Table 16: Fisher LSD comparisons of the embodiment questionnaire scores between the three arm dimension manipulations for Experiment 2. Mean questionnaire scores for each manipulation are in parenthesis. *Denotes statistical significance.

JZS Bayes factor of 6.06 in favor of the null. Thus we can see that there are strong odds in favor of the peripersonal space boundaries of the users being the same even when the arm dimensions of the self-avatar are manipulated.

Finally, we again analyzed the results from the embodiment questionnaires to determine whether manipulating the arm dimensions of the user would affect the level of embodiment experienced by the user. We ran a RM-ANOVA with condition as the factor and found a main effect of condition $F(2,46) = 3.262, p = 0.047, \eta_p^2 = 0.12$. Post-hoc analysis using Fisher's LSD revealed a significant difference between the embodiment scores in the short versus long arm dimension manipulations, but no other significant differences. The average embodiment scores for each arm dimension manipulation are as follows: 0.451 ($SE = 0.112$) for the normal condition, 0.404 ($SE = 0.109$) for the short condition, and 0.250 ($SE = 0.125$) for the long condition. Table 16 shows the comparisons.

5.3.5 Discussion

Our data analyses have presented some interesting, complex findings with regard to both interpersonal and peripersonal space. We confirmed H1, that when users experienced shorter arm dimensions the comfort distance would decrease. However, we did not confirm H2, that when users experienced longer arm dimensions the comfort distance would increase – the opposite occurred. The average comfort distance users reported between themselves and the agent in the normal condition was 1.269 m, in the longer arm dimension was 1.161 m and in the shorter arm dimension condition was 1.154 m. Our analysis revealed that there was a significant difference between the normal comfort distance and both the longer and shorter arm dimension conditions. Our analysis also found no difference between the embodiment scores for the short and normal arm dimension conditions. The decrease in embodiment in the long arm dimension condition could explain why users allocated a shorter comfort distance between themselves and the agent, since we have seen in Section 5.2 of this Chapter that as embodiment decreases, so does comfort distance. Overall, users also responded that they noticed more when their arm dimensions were longer (they noticed the longer arm dimension manipulation 10% more than they noticed the shorter arm dimension manipulation), and an examination of Figure 19 shows a more pronounced exaggeration of the arms when they are longer versus shorter. This could explain why users felt less embodiment in the longer arm dimension condition. Additionally, we manually set a clipping plane on the camera view so that users could not see the inside of their virtual avatar. This caused the view of the upper arm to be clipped when the user looked down at themselves and this clipping changed to reveal more or less of the arm as the user rotated their head (you can see this happening in Figure 20). The clipping of the upper arm could have affected the perceived length of arm dimension. We also have to take into account the fact that comfort distance could have shortened for both the short and long arm dimension manipulation simply because users always received feedback from the normal arm condition first before ever experiencing both the short and long arm dimension manipulations. Users could have been more comfortable with the experiment after completing the first round of trials and felt less risk associated with the approaching avatars. Regardless, our findings pertaining to H1 support previous literature that denotes that users of virtual reality adapt the way they interact with the space around them to the given dimensions of their self-avatar [Jun et al., 2015]. However, there is some caution that we have to take in making this statement due to the nature of our results here and further study is required to truly confirm this.

It is also noteworthy that reaction times were not responsive to condition – meaning that the manipulation of the arm length did not affect how quickly users responded to the tactile stimulus. This hints at further results that we will discuss in the next paragraph, meaning that the peripersonal space boundaries were not affected by the arm dimension manipulation. The reaction times, were however, significantly different for each condition as the agent approached closer to the user. This response is expected, as in the previous experiment and other previous literature [Buck et al., 2020b; Serino et al., 2017], as objects and agents approaching within the peripersonal space cause the reaction time of the user to the tactile stimulus to significantly increase. It would be worrisome if this exponential trend did not occur.

Finally, a really interesting result from this experiment is the fact that the peripersonal space boundaries did not change based on the manipulation of the arm dimensions. We were able to confirm H3. The peripersonal space boundaries for the normal, longer and shorter conditions were 1.411 m, 1.409 m, and 1.353 m respectively. The results here provide evidence for the distinction between peripersonal space and arm-reaching space [Lara et al. [2018]; Zanini et al., In Press]; they show that there is a distinction between the cognitive processes that segment and deal with these spaces. These results further demonstrate that users do perceive the peripersonal space around their bodies as they should and would in a natural environment to some degree, and that these boundaries are not sensitive to the manipulation of arm dimensions in immersive virtual environments. Our work provides further support for the idea that we can use immersive virtual environments to reliably understand peripersonal space.

5.4 General Discussion

In this work we measured two different components of personal space – interpersonal and peripersonal space. In Study 1, we showed that the sense of embodiment is essential in evoking a realistic mediation of personal space in immersive virtual environments. Both interpersonal and peripersonal space changed as embodiment changed. Users required more interpersonal distance between themselves and another agent when they felt embodied in their self-avatar, while they required less interpersonal distance when they felt less embodied. Conversely, peripersonal space contracted as users felt more embodied in their self-avatar and it expanded as users felt less embodied. In Study 2, we showed that interpersonal space is sensitive to the manipulation of a self-avatar's arm dimensions, while peripersonal space is not. When the arm dimensions of the self-avatar were not the natural arm dimensions of the user, users needed less interpersonal space between themselves and another agent. Peripersonal space boundaries did not change when the arm dimensions of the self-avatar were manipulated.

Comfort distance and reaction time were both measured reliably based on previous metrics [Dosey and Meisels, 1969; Hayduk, 1983; Serino et al., 2017; Buck et al., 2020b], and our results reflected realistic interpersonal and peripersonal space measurements. It is interesting to see that we were able to reliably manipulate the sensation of embodiment in Study 1, but particularly so with regard to the appearance of the self-avatar since there is conflicting literature about the effects of increasing avatar realism on embodiment [Gonzalez-Franco and Peck, 2018; Lugrin et al., 2015; Latoschik et al., 2017; Waltemate et al., 2018]. Our embodiment manipulation provides the insight that gender and race matched avatars can perhaps be deployed to enhance embodiment, but we caution that there is a fine line that could be crossed into the uncanny valley [Seyama and Nagayama, 2007] that might reverse this positive effect and there is still work to be done in this space with regard to embodiment in immersive virtual environments. In general, personal space behaved as expected in Study 1, and this gives credence to the importance of evoking embodiment in virtual reality users to support realistic interaction behaviors.

Study 2 also provided us with some interesting findings with regard to self-avatar manipulation. The change in interpersonal space when arm dimensions are manipulated show that, perhaps when users feel that some dimensions of self-avatars do not reflect their own, there is a decrease in the required interpersonal space around the body. No change in peripersonal space was experienced, and this result shows that peripersonal space can behave reliably in an immersive virtual environment. There is mounting evidence that peripersonal space requires separate cognitive processes from arm-reaching space [Lara et al. [2018], Zanini et al., In Press] and there is no reason for peripersonal space to change when one’s arm dimensions change.

Ultimately, the combined results from Studies 1 and 2 can give guidance to designers of immersive virtual environments who are interested in creating specific interactions. The fidelity of collaborative interactions that occur in immersive virtual environments is still low [Buck et al., 2019; Hrimech and Merienne, 2010; Zibrek et al., 2017] and this is a difficult area of study that must be addressed. Our results give some insight into the proper design decisions one needs to make in order to facilitate realistic, comfortable social and non-social interactions. Both measurements of comfort distance and reaction times to agents can give researchers and developers insight into how users interact within their personal space and what types of interactions users are particularly attentive to and comfortable with, and what needs to be changed and studied to increase the realism of these interactions.

5.4.1 Limitations and Future Work

Our work has limitations and need for further investigation. One limitation of our work stood out in our first experiment: we were only able to evoke two levels of embodiment instead of the intended three. Looking at the results, there is a distinction between the high embodiment condition and the other conditions, but no distinction between the medium and low conditions. We could have chosen to conduct a pilot study in which we were able to tease out what factors would have differentiated all conditions, but we did not based on the difficulties we faced recruiting subjects caused by the ongoing pandemic. Therefore we were not able to determine the gradient that may have occurred in distinct levels of embodiment.

Another area for further investigation regards why the results of the second experiment were not symmetric, i.e., why users are affected consistently by perturbations in arm length. An examination of Figure 19 shows a more pronounced exaggeration of the arms when they are longer versus shorter. This could explain why users felt less embodiment in the longer arm dimension condition. Additionally, we manually set a clipping plane on the camera view so that users could not see the inside of their virtual avatar. This caused the view of the upper arm to be clipped when the user looked down at themselves and this clipping changed to reveal more or less of the arm as the user rotated their head (this is illustrated somewhat in Figure 20). The clipping of the upper arm could have affected the perceived length of arm dimension. We also have to take into account the fact that comfort distance could have shortened for both the short and long arm dimension manipulation simply because users always received feedback from the normal arm condition first before ever experiencing both the short and long arm dimension manipulations. Users could have been more comfortable with the experiment after completing the first round of trials and felt less risk associated with the approaching avatars. A third possibility is that it is known that people typically overestimate how much they can reach, and thus seeing a longer arm in a self-avatar may look reasonable [Carello et al., 1989; Gagnon et al., 2021; Rochat and Wraga, 1997]. Regardless, our findings pertaining to H3 support previous literature that denotes that users of virtual reality adapt the way they interact with the space around them to the given dimensions of their self-avatar [Jun et al., 2015]. However, further study is needed in this area.

Other limitations are due to the nature of current commodity-level virtual reality systems that are readily available. Nonverbal cues (facial expressions, gaze behavior, precise tracking, etc.) can change the way people perceive personal space [Argyle and Dean, 1965; Bailenson et al., 2001, 2003; Ruggiero et al., 2017; Yee et al., 2007], and there are several nonverbal communication modes that commodity level systems simply cannot easily support. Additionally, there are personality factors that affect the mediation of personal space [Hayduk, 1983], but this extends beyond the scope of our study and this area is still largely untouched in the virtual reality literature. However, it is important in the future that we consider how differences in personality affect the way users treat and maintain the personal space around their bodies. For example, those afflicted with different mental disorders treat personal space differently [Alcorn et al., 2011; Iachini et al., 2015b; Lee et al., 2021], and personality type shapes personal space [Iachini et al., 2015b].

It would be particularly interesting to continue this line of work to shed light on how differing technical factors of virtual reality affect and support interpersonal interactions. For example, it would be fascinating to understand how distributed environments affect the mediation of personal space. Previous work has introduced differing results with regard to how people treat their interpersonal space in these scenarios, with some users exhibiting caution around others [Buck et al., 2019] and others carelessly colliding with the avatars of other users [Podkosova and Kaufmann, 2018a]. It would also be interesting to understand how differing degrees of sentience, or interactions with human-driven avatars and computer-driven agents, affect personal space since we know that eye gaze increases sentience and changes the way users mediate interpersonal space [Bailenson et al., 2003]. There are many different avenues for this work to take, and we continue this discussion in Chapter 6.

5.5 Conclusions

Ultimately, this work has shown that personal space - both interpersonal and peripersonal space - are responsive to the level of embodiment that a user experiences in an immersive virtual environment. Interpersonal comfort distance expands when one feels highly embodied, and contracts when one does not feel embodied. Peripersonal space contracts when one feels highly embodied, and expands when one does not feel embodied. These results continue to suggest the importance of embodied interaction to support high fidelity virtual reality experiences. Additionally, we have also shown that personal space can be responsive to a manipulation of the dimensions of a self-avatar. Comfort distance changes when the arm dimensions of a self-avatar are not natural, but peripersonal space does not change significantly. These results give a glimpse into how differing factors of immersive virtual environments might change the way users mediate personal space, and this is an important finding that enables designers and developers to create these environments to convey the type of interaction that is desired. High quality interaction is important for a diverse range of virtual reality applications, such as those meant for therapy and training in many differing venues such as medicine, defense, and education [Alcorn et al., 2011; Boyd et al., 2018; Fox et al., 2009]. The findings from our second experiment on peripersonal space are also incredibly important in the neuroscience community, where there has been debate about the link between peripersonal space and arm-reaching space [Zanini et al., In Press]. Our work provides evidence for the theory that peripersonal space and arm-reaching space are two distinct spaces processed differently in the brain. We have just touched the surface on how users interact with the personal space around their bodies in immersive virtual environments, however, and there is still much to be understood about this complex space in the context of virtual reality.

6 Conclusions and Future Directions

6.1 Conclusions

This dissertation presents the beginnings of an understanding of interpersonal dynamics and the measurement of personal space in immersive virtual environments. Virtual reality is an emerging communication medium through which a variety of applications can facilitate 3D interactions for different purposes and disciplines. With virtual reality becoming available at a commodity level, this technology is more accessible and there is increasing interest in its use. Virtual scenarios can transcend road blocks that are faced in analogous scenarios in the real world such as time, expense, and potential danger, and can make what was previously impossible possible. Additionally, the current COVID-19 pandemic has generated interest in its possibility to facilitate interaction where face-to-face interaction is not available (i.e., virtual conferences and concerts, etc.). Creating compelling interactions within virtual reality is already possible, but there is great room for improvement and growth on its path forward. Human social interaction that takes place in VR still faces many challenges.

To advance virtual reality experiences we must provide developers and designers with a framework that details how interactions can be created. Chapter 2 discusses the current landscape of how interactions are taking place in virtual reality and where they can be improved by taking a deeper look into the interdisciplinary science behind them. Cognitive science and neuroscience give us insight that there are cognitive processes that drive interaction based on environmental context, and computer science shows us that some cognitive processes shift to different paradigms in virtual environments. We chose to focus on how virtual reality users perceive the near space, or personal space, around their bodies since this is the space in which physical interaction occurs with the environment. The perception of action potential within this space is tantamount to understanding how to facilitate, for example, training scenarios in which medical professionals are learning to perform a complex surgical procedure or psychologists are creating a controlled experimental scenario.

We first established a basic understanding of interaction dynamics in a collaborative immersive virtual environment in Chapter 3. We measured interaction in the real world and in a 3D immersive virtual environment by utilizing the critical thresholds extracted from a passability affordance, and were able to compare interaction dynamics between both worlds. We were able to replicate real world findings for the passability of a dyad through an aperture [Davis et al., 2010], and uncovered the gender dynamics that would naturally occur. We found that, in 3D immersive virtual environments, dyads needed *more* interpersonal space than in the real world. We also uncovered that the gender dynamics that occurred in the real world did not translate to the virtual environment. These findings revealed that users do not treat interpersonal space the same way in the real and virtual world, and thus pinpointed the need for further study on personal space in virtual environments.

Chapter 4 then picks up to determine how we can measure the behavior of an individual's personal space in an immersive virtual environment. There are several modalities for measuring the personal space around the body (i.e., comfort distance, reaching distance and peripersonal space). We chose to measure peripersonal space, or the body-centered representation of near space that is coded by the unique response of neurons to multisensory stimuli. This space has not been extensively measured in immersive technology, but it provides a reliable metric of the space around the body that is not subjective [Serino et al., 2017] and is interrelated with interpersonal space [Coello and Cartaud, 2021]. We used the methodology created by Serino et al. [2017] to determine how peripersonal space expanded and contracted when a user experienced both social and non-social interaction in a virtual environment. We found that we could reliably measure peripersonal space using this methodology and that it was sensitive to the context of the interaction, just as it would be in the real world. Peripersonal space expanded in the presence of agents and contracted in the presence of objects.

Finally, we expanded our knowledge about personal space in immersive virtual environments in Chapter 5 by measuring both interpersonal and peripersonal space in the context of different self-representations. There is some literature that addresses peripersonal space and its relation to embodiment in immersive virtual environments [Kilteni et al., 2012a], which implies that embodying a self-avatar will cause realistic mediation of peripersonal space. Since there are an array of different self-representations that can be attributed to virtual reality users that evoke differing levels of embodiment, we wanted to understand if personal space would change with the degree of embodiment. Additionally, peripersonal space has often been confounded with reaching distance, and we wanted to see if changing the arm length of a self-avatar would affect the peripersonal space. In this chapter, we found that both interpersonal and peripersonal space changed when users experienced differing degrees of embodiment. Users were more comfortable with their personal space being invaded when they felt less embodied, and peripersonal space contracted. We additionally found that reaching distance and peripersonal space may not be interrelated – when we changed the arm length the peripersonal space did not change. These findings bolster the need for embodied self-avatars and have implications for understanding peripersonal space within the neuroscience community, as the debate on the relation between reaching and peripersonal space has been ongoing.

Our work in Chapters 3-5 has developed novel insights into the roots of personal space allocation within 3D immersive virtual environments. We have done so by creating algorithms and assessing them based on methodologies from both cognitive science and neuroscience. The techniques used to employ our experiments can be easily replicated and applied to any state-of-the-art virtual reality system. High quality interaction is a requirement for the success of virtual reality technology, and thus it is important to continue the development of algorithms to facilitate realistic interactions. Social interaction is still an open research problem for psychologists, and with the advent of immersive technology, the need for understanding it in mediated environments only increases the number of questions to be answered. Immersive technology can be deployed in a multitude of different disciplines and fields, including medicine, defense, entertainment, education, etc. The goal of this dissertation has been to create an understanding of how users interact with the near space around their bodies in immersive virtual environments to lay the groundwork for realistic, high quality virtual reality experiences. There are an abundance of different directions that this line of research can expand into, and we discuss this in the next section.

6.2 Future Work

The work completed in Chapters 3-5 opens the door for some interesting experimental considerations, and there is plenty of room to explore how personal space behaves in virtual reality. In the context of virtual reality, there is very little known about peripersonal space itself, and what we do know about interpersonal interaction in these environments is quite basic in comparison to the complex interaction possibilities that occur in reality (see Chapter 2). We have not yet scratched the surface of collaborative interactions either [Buck et al., 2020a; Fleury et al., 2012; Pan and Steed, 2017; Young et al., 2015], whether they be with two or more people, and we need to understand how the unique attributes of immersive virtual environments facilitate these interactions. Even though we do see an extension of realistic behavior in certain instances in immersive virtual environments

[Bailenson et al., 2003; Buck et al., 2019, 2020b; Iachini et al., 2014], social dynamics are still largely unknown in the virtual world. In particular, this dissertation has created a framework for understanding interaction in the context of how personal space behaves and what contributing factors affect it. This framework provides great potential for work in variety of different areas that have a broad impact.

Knowing what we have uncovered in this dissertation, the immediate questions that require answering are those directed at understanding how the unique factors of virtual reality technology affect the behavior of personal space in immersive virtual environments. It would be interesting to understand to what degree the perceived sentience of another user affects the maintenance of personal space in an immersive virtual environment, since we do know that adding mutual gaze behavior to an avatar impacts interpersonal space [Bailenson et al., 2003]. The avatars used in state of the art environments do not completely possess the human characteristics that are important to communicating information nonverbally, like facial expressions and precise gestures and movements, and it would be beneficial to understand how the introduction of these characteristics affect personal space. Another factor to consider would be the realism of both the environment and the avatar, as computer graphics are still developing to achieve higher levels of realism. It is also important to understand how the collocation of users impacts the maintenance of personal space; we need to understand the differences in personal space maintenance that arise from environmental distribution where one user is located in an entirely different space than another user. There is additionally room to understand how collisions and the potential advent of haptics technology affect the mediation of personal space. Finally, there is the question of how personal space is mapped in the brain and attributed to other users in these environments, since we know that this occurs in real environments [Brozzoli et al., 2013; Ishida et al., 2010].

Another branch of work arises from the concern of user privacy and user data privacy. We have shown in Chapters 4 and 5 that the space around one's body is reliably mediated in an immersive virtual environment, and that this space is sensitive to certain interactions. We know that as levels of embodiment rise, this sensitivity increases and that naturally, an invasion of this space poses a stress threat on our central nervous system [Quesque et al., 2017]. In a 3D environment meant to mimic reality, interactions have the potential to have positive and negative psychological effects in more profound ways than what might occur in a 2D virtual environment [Bailey and Bailenson, 2017; Keles et al., 2020]. This brings to mind the work of Mel Slater and colleagues [Neyret et al., 2020; Seinfeld et al., 2021], who have found virtual experiences to be emotionally compelling, provoke empathy, and to change the perspective of users. Knowing that we have the tools to understand how personal space (measurements of interpersonal distance, arm-reaching distance and peripersonal space) we aim to assess how different kinds of interactions taking place within personal space in immersive virtual environments affect users, and what interactions produce positive and negative psychological impacts. For example, it would be pertinent to know the threshold of when multisensory stimulation within the personal space begins to negatively affect users, what sorts of multisensory stimulation are regarded positively and negatively, and how to give users private personal space where appropriate.

Finally, would be interesting to understand how personal space changes in virtual reality with regard to the mental state of the user. We have already found that we can reliably understand how the brain segments peripersonal space in those afflicted with schizophrenia by using virtual reality technology [Hong et al., 2019; Lee et al., 2021]. It is well known that the mental state of the individual affects the perception of the self and the other [Symons, 2004]. For example, those afflicted with anorexia nervosa and schizophrenia have a distorted perception of the self [Bortolon et al., 2017; Esposito et al., 2018]. Personality also affects social perceptions and interactions between individuals [Back et al., 2011]. Chapter 2 and the subsequent chapters that follow (Chapters 3-5) already demonstrate how different perceptions of objects, individuals, and the self can change interactions in immersive virtual environments. Conducting this work to understand how individuals treat the space around their bodies will lend insight into individual differences that should be considered in the design and development of interaction scenarios within immersive virtual environments. There are additional implications of this work in field of psychology to bring the philosophical debate of what the “self" is and the concept intersubjectivity to an empirical domain. It can help to answer questions like how does one know where the self ends and others begin, as well as how we access the internal states of others.

The final directions proposed here create a diverse field of research with a wide range of impact. While this work aims at improving algorithms for realistic interaction within virtual reality applications and directly contributes to computer science, it also has potential to reach into the fields of privacy and security, psychology and neuroscience, and medical therapy and training. Understanding interaction is a highly important problem in the virtual reality community, and giving developers and designers the tools to implement realistic interaction is important. We plan to continue this research agenda to expand the understanding of how virtual reality users interact with 3D immersive virtual environments, and aid different disciplines in understanding complex problems that could not necessarily be facilitated without this line of work.

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