Mediated Physicality: Inducing Illusory Physicality of Virtual Humans via Their Interactions with Physical Objects

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Myungho Lee
University of Central Florida

MEDIATED PHYSICALITY:
INDUCING ILLUSORY PHYSICALITY OF VIRTUAL HUMANS VIA THEIR INTERACTIONS WITH PHYSICAL OBJECTS

by

MYUNGHO LEE
B.S. Ajou University, 2007
M.S. Korea University, 2009
M.S. University of Central Florida, 2016

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ABSTRACT

The term virtual human (VH) generally refers to a human-like entity comprised of computer graphics and/or physical body. In the associated research literature, a VH can be further classified as an avatar—a human-controlled VH, or an agent—a computer-controlled VH. Because of the resemblance with humans, people naturally distinguish them from non-human objects, and often treat them in ways similar to real humans. Sometimes people develop a sense of co-presence or social presence with the VH—a phenomenon that is often exploited for training simulations where the VH assumes the role of a human.

Prior research associated with VHs has primarily focused on the realism of various visual traits, e.g., appearance, shape, and gestures. However, our sense of the presence of other humans is also affected by other physical sensations conveyed through nearby space or physical objects. For example, we humans can perceive the presence of other individuals via the sound or tactile sensation of approaching footsteps, or by the presence of complementary or opposing forces when carrying a physical box with another person.

In my research, I exploit the fact that these sensations, when correlated with events in the shared space, affect one's feeling of social/co-presence with another person. In this dissertation, I introduce novel methods for utilizing direct and indirect physical-virtual interactions with VHs to increase the sense of social/co-presence with the VHs—an approach I refer to as mediated physicality. I present results from controlled user studies, in various virtual environment settings, that support the idea that mediated physicality can increase a user's sense of social/co-presence with the VH, and/or induced realistic social behavior. I discuss relationships to prior research, possible explanations for my findings, and areas for future research.

To my family.

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CHAPTER 1: INTRODUCTION

Virtual Reality (VR) often refers to a field of study that aims to create a system that provides users a synthetic experience. The system usually consists of tracking systems to detect users' actions and various types of displays to deliver *computer-generated stimuli* based on *actions of the users*. Although displays for all five human senses are ideal, often VR systems in practice include only visual, auditory, and haptic/tactile displays. As the sensory stimulation to users is simulated and generated by the system, the experience is labeled as "synthetic," "illusionary," or "virtual" [76].

In 1965, Ivan Sutherland described the "Ultimate Display" concept that became a core goal for virtual reality experiences today [133]:

> "The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked." – Ivan Sutherland

Three key concepts for virtual reality experiences outlined in his essay are: (1) users see a virtual world through a head-mounted display (HMD) and hear augmented 3D sounds and feel realistic haptic/tactile sensations. (2) the computer system creates and maintains the virtual world in real time. (3) users can *"interact with objects"* in the virtual world realistically.

While many virtual experiences have been developed for various reasons, such as reducing cost and risk of training [95], treating post-traumatic stress [30], or for entertainment [1], virtual reality experiences are often designed with the goal to elicit the perceptual illusion of *presence* [126]

[1] http://www.theclimbgame.com/

in users. A high sense of presence is characterized by users responding realistically in a virtual environment as if they were in a comparable situation in the real world, which can be seen as an operational definition of presence [116].

Particularly, when virtual experiences are designed to train users to practice skills with *virtual human (VH)* role-players, as in medical, military, or teacher training, in general, a greater sense of presence has the potential to make training more effective [34]. In such virtual experiences involving VHs, researchers often use the terms *co-presence* and *social presence* to describe users' sense of "being together" and "being socially connected" with the virtual humans.

An overarching goal of this research is to improve the user experience when interacting with VHs, which would be assessed by but not limited to *co-presence* and *social presence*. To this end, the proposed approaches exploit virtually synthesized stimuli that are seemingly tied to VHs' actions on—or interactions with—an object in a user's space.

1.1 Motivation

Previous research has shown that VHs can provide users with a sense of "being together" and facilitate social interaction with the VHs similar to the behavior people would exhibit with real humans (RHs) in the real world [10, 12, 48]. When VHs are used to train skills that will be eventually employed for RHs, such perception and realistic behavior to VHs are often required. Historically, work related to social/co-presence has primarily focused on VH appearance, intelligence, and verbal and nonverbal behaviors [49, 52, 131]. These efforts are aimed at making VHs similar enough to RHs that, in turn, RHs respond to them in a socially plausible (perhaps "realistic") way—similar to how they would respond to a RH.

However, in the real world, social interaction not only involves RHs, it also involves the surroundings where the social interaction takes place. For example, people might hold a door open for others who are approaching, knock on a table to catch one's attention, or stomp their feet on the floor to express their anger. Furthermore, people often engage in and perceive others' existence from *indirect interactions*—interactions that are *mediated* through a common/shared object. For example, when one person hands off an object to another person, there is a short period of time when both humans are grasping the object and can feel the subtle forces exerted by each other.

Despite the frequency of such mediated/indirect perception of the other person's presence in everyday interactions, few have examined its effects on human-virtual human interaction.

1.2 Proposed Approach: Mediated Physicality

The concept of *Mediated Physicality* aims to induce an illusion from users to regard a VH as being able to affect them *physically*, therefore causing more realistic behaviors, but without direct physical contact with the VH. For that, I propose to make use of the surrounding environment where the primary social interaction and the interaction between the surrounding environment with the VH takes place. In other words, instead of directly perceiving the VH's physicality, users will perceive "outcomes of the VH's actions on the physical environment," i.e., the outcomes are *mediated* via objects in the environment.

In Slater's concept of presence, *place illusion* occurs when actions caused by the user lead to sensations dependent on the synchronous correlations between the user's actions and computer-generated sensory feedback [126]. If the actions are carried out through a virtual body, the congruent visual-motor synchrony leads to a feeling of owning the virtual body, which reinforces one's sense of being in the virtual environment [128].

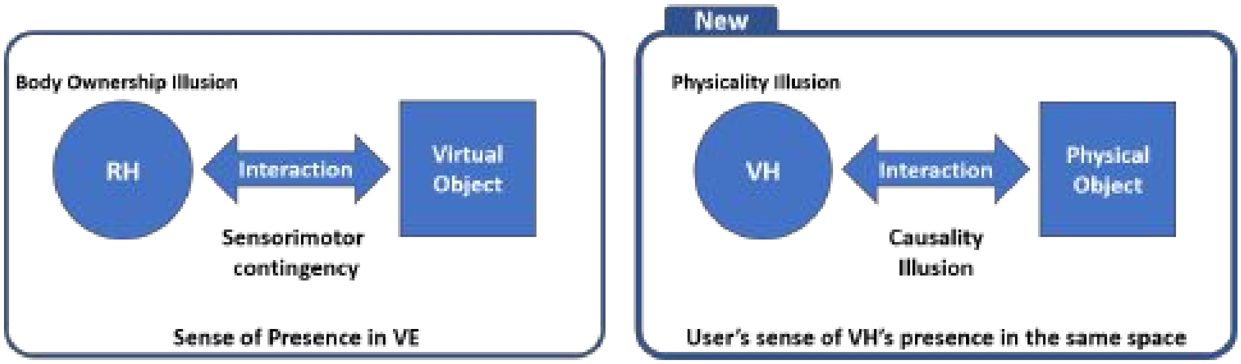


Figure 1.1: The similarity between the existing concepts in the sense of presence in virtual environments (left) and the proposed concepts in the sense of the other person's presence in the user's space (right).

Figure 1.2: Illustration of the process of mediated physicality with a simple example.

Similarly (see Figure 1.1), when people perceive the mediated outcomes synchronized with a VH's actions—i.e., apparent correlation between the actions and perceived sensory cues—then they would naturally attribute perceived outcomes to the VH's actions by forming an *illusion of causality* [2] between the actions and outcomes, similar to how sensorimotor integration could induce the illusion of body ownership [75].

And finally *physicality* of the perceived outcomes would be transferred to the VH (see Figure 1.2).

[2]I also call this *virtual-physical causality* or simply *causality illusion*.

Furthermore, the correlation between the VH's actions and perceived outcomes would remain unless counterevidence is observed.

Jeon and Choi [69] extended the *Reality-Virtual continuum* to a two-dimensional continuum of vision and haptics. Similarly, I consider *Physicality* to be a multi-dimensional concept; each dimension (relating to each sense) would be to some degree correlated, forming expectancy in other dimensions in connection with prior knowledge. In an immersive virtual environment, the surrounding environment and objects are all *virtual* in visual perception; therefore, the mediated outcomes should be perceived in other senses, e.g., auditory or haptic, as the only reliable *physical* reference is the user himself/herself. However, in a mixed/augmented environment, the mediator object can be a real object and people would consider it as *physical* as they are—from visual perception and prior knowledge, i.e., the reliable physical references could be extended to the surrounding space (see Figure 1.3).

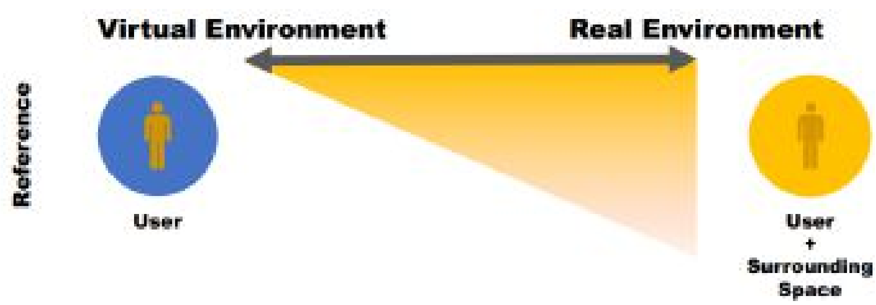


Figure 1.3: The reference for physicality is extended from a user's own body in virtual reality to the surrounding space in augmented/mixed reality.

1.3 Thesis Statement

Here, I present the Thesis Statements (TS) based on the results from several user studies exploring the concept of mediated physicality.

- **TS1 (Causality):** Naturally correlated cues associated with a virtual human's actions and physical outcomes can create a perception of virtual-physical causality;
- **TS2 (Physicality):** such perception of virtual-physical causality can create a further perception of physicality of the virtual human;
- **TS3 (Presence):** such perception of physicality can increase feelings of social/co-presence with a virtual human and induce realistic social behavior;
- **TS4 (Persistence):** such feelings and behavior can be maintained despite the temporary absence of some of the originally present correlated cues.

Table 1.1: Relevant thesis statements for each chapter. Each chapter contains one or two user studies to support relevant thesis statements.

	TS1 (Causality)	TS2 (Physicality)	TS3 (Presence)	TS4 (Persistence)
Chapter 3			$\surd$	
Chapter 4	$\surd$		$\surd$	
Chapter 5		$\surd$	$\surd$	$\surd$
Chapter 6	$\surd$	$\surd$	$\surd$	$\surd$

1.4 Contributions

I have carried out several controlled user studies to demonstrate the thesis statements under different mediated physicality scenarios, e.g., vibrotactile feedback through a floor and subtle movements of a real-virtual table, an actuated surface. Each user study addresses one or more thesis statements in different types of virtual reality experiences, including a projector-based mixed environment, immersive virtual environment, and optical see-through augmented reality (see Table 1.1).

The main contributions of this research can be summarized as follows:

1. I introduced the novel concept of *Mediated Physicality* that can assist researchers and practitioners in designing improved virtual reality and augmented/mixed reality experiences involving VHs. The concept of *Mediated Physicality* coherently explains findings from user studies present in this dissertation as well as other research that involves VHs affecting a user's space. Unlike the sense of presence, this concept applies to both virtual reality and augmented/mixed reality.

2. I identified the perceptual issue of unaugmented periphery in current state-of-the-art optical see-through augmented reality (AR) glasses when used in close proximity of virtual humans and demonstrated the potential of the multimodal aspect of *Mediated Physicality* as a means to improve overall user experiences with VHs under the limitations of current optical see-through AR.

3. I designed and presented novel physical-virtual interactive systems that could easily be added to other human-VH interaction systems, and provided guidelines that benefit others who like to adopt such methods.

1.5 Outline

The rest of the dissertation is organized as follows:

- **Chapter 2** introduces overall background of the thesis, including virtual reality, virtual humans, and social behavior with virtual humans. Also, I summarize concepts, such as presence, social/co-presence, physical-virtual interactivity.
- **Chapter 3** presents an experiment examining the effects of subtle movements of a real-virtual table on social/co-presence in a mixed reality setting. In this experiment, participants carried out a conversational task with a virtual human while sharing a wobbly table that spanned the physical-virtual space.
- **Chapter 4** presents an experiment investigating the effects of auditory and/or vibrotactile feedback of a virtual human's footsteps on social/co-presence as well as gaze/proxemic behavior in an immersive virtual environment.
- **Chapter 5** discusses issues related to current state-of-the-art optical see-through AR glasses, and presents an experiment investigating the effects of the unaugmented periphery and virtual human's footstep vibrations on social/co-presence, perceived physicality, and locomotion behavior.
- **Chapter 6** presents the effects of visually observed physical influence of a virtual human in the context of face-to-face interaction in a mixed reality environment. Also I discuss effects of latency in a physical-virtual interaction.
- **Chapter 7** provides a summary of overall results and future work needed to develop the concept of mediated physicality further.

CHAPTER 2: LITERATURE REVIEW

In Chapter 1, I introduced the concept of mediated physicality, along with the importance of interacting with objects for the sense of presence in a virtual environment as well as for the feeling of a VH's presence—that is related to social/co-presence—in a shared environment. In this chapter, I give a detailed account of the concepts of presence in a virtual environment and social/co-presence with VHs. I continue with social behaviors used in VH research that are later employed in the user studies presented to support this research on mediated physicality. Finally, I present work relevant to the physical influence of VHs, starting from a discussion of VHs in mixed reality and research focused on bridging physical and virtual worlds.

2.1 Presence in Virtual Environments

Virtual experiences often refer to user experiences in which some of the human perceptual stimuli are synthesized through a VR system. In order to mimic the way we experience our world, i.e., actions and consequent perceptual stimuli in the real world, the VR system usually includes technologies for detecting users' actions and various types of sensory displays for computer-generated stimuli based on the actions of the users.

For virtual experiences, developers often create a computer model, also known as a virtual environment (VE), that consists of a scene graph for 3D graphics (for visual display) as well as methods for generating other sensory display outputs; likewise, single objects in the VE are often called virtual objects. Because it is a computer-generated world, people can experience scenarios that are difficult, dangerous, or even impossible in real life, such as operating a spaceship for docking or being a bird and flying over a city. If a VE is designed to simulate a specific real-world experience closely, for instance, an assembly line of a factory, one can practice the job without having physical machinery. Moreover, because each component (or object) in the VE can be precisely controlled, the virtual experiences can be applied to controlled experiments as well [21, 45].

During virtual experiences, users often feel that they are somewhere other than their actual physical location, often described as "the feeling of being in a VE," due to the immersive sensory stimuli generated by the VR system [57]. VR researchers call such a feeling *presence.*

The term *presence* was initially defined for the experience of one's physical environment. Gibson defined *presence* as "[...] not surroundings as they exist in the physical world, but [the] perception of those surroundings as mediated by both automatic and controlled mental processes" [50]. Later, the term *telepresence* was introduced to describe the presence users have in computer-mediated environments, but in common practice researchers simply call the sensation *presence* [132]. Following Gibson's view on *presence* as a subjective feeling, researchers proposed various definitions of *presence* for VEs.

Skarbez grouped these various definitions into two overarching categories: *being there* and *non-mediation* [124]. the *being there* group considers presence as the feeling of being in a mediated environment. Definitions in this group generally focus on interactions in the environment. Schloerb [119] in his definition of *presence* emphasized one's ability to complete a specified task in an environment. Similarly, Flach and Holden [43] pointed out that the essential characteristics of the world are behavioral, i.e., interactions with the world, rather than aesthetic. In line with these, Zahorik and Jenison [142] considered *presence* as "tantamount to successfully supported action in the environment." Focusing on users' actions and consequent perceptual stimuli, Slater [125] defined presence as a "response" to "appropriate conjunction of the human perceptual and motor system and immersion." Similarly, Carassa et al. [26] stated that "presence depends on the proper integration of aspects relevant to an agent's movement and perception."

On the other hand, the *non-mediation* group considers *presence* as a lack of attention to the mediating technology. Slater and Usoh [129] proposed *presence* in a mediated environment as "belief that [one] is in a world other than where [one's] body is located," while Lombard and Ditton [96] defined *presence* as "the perceptual illusion of non-mediation," which means that one perceives presence via a technological medium if totally oblivious to the existence of the medium. The International Society for Presence Research in 2000 officially defined *presence* as follows [1]:

> Presence (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at **some level** and to **some degree**, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a person's observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience.

This definition again emphasizes the illusion of non-mediation in the interactions with the environment.

Based on decades of research, Slater [126] further characterizes *presence* with two concepts: *place illusion* and *plausibility illusion. Place illusion* is defined as the feeling of being in the virtual place despite the sure knowledge that one is not there. In contrast, the *plausibility illusion* is defined as the feeling that what is happening is real despite the knowledge that it is not. An essential component of *place illusion* is that events caused by the user lead to sensations dependent on the synchronous correlations between body movements and computer-generated sensory feedback. In contrast, an important aspect of *plausibility illusion* is that external events not caused by the user lead to both exteroceptive and interoceptive sensations, i.e., external stimuli and those produced within the organism, respectively. While many different views on presence exist (see [124]), this research and the proposed concept of mediated physicality generally follows the recently proposed definition of *presence* by Slater.

Slater also reported that virtual limbs and bodies could come to feel like real limbs and bodies, i.e., users can be given the illusion of ownership of the virtual body in a VE, that could reinforce one's feeling of being in the VE [128]. This phenomenon originated from a rubber hand illusion experiment in which synchronized tactile stimulation on both a visible fake hand and the user's hidden real hand induced the perceptual illusion of owning the fake hand as if it were his or her own body part [22]. Similarly, continuous visual-motor synchrony—the synchronous movement of the person's (hidden) real body and a virtual body—can induce the *virtual body ownership illusion*. It should be noted that the mechanism for inducing such an illusion is closely related to that of *place illusion*, in which users actions—internally perceived by proprioception—are correlated with synthesized stimuli (movements of the virtual body). Researchers in VR further examined combinations of different sensory cues, e.g., synchronized tactile sensations with relevant touch events on a virtual arm, as well as the fidelity of each cue, e.g., size/shape of the virtual body, and the mismatch between cues for inducing such perceptual illusion in VEs [75, 121, 128].

2.2 Social/Co-presence with Virtual Humans

The term *virtual humans* in general refers to human-like computer graphics manifestations. Traditionally, virtual humans are called *avatars* or *agents* depending on the entity controlling them; while avatars are controlled by humans (also referred to as inhabiters), agents are instead controlled by computer programs [12, 44]. As such, this research uses the term *virtual human* to avoid having to explicitly differentiate between avatars and agents, thereby allowing hybrid versions of control—a virtual human might be an avatar at one instant, an agent in the next, or a blend of both [106].

VHs can sometimes assume the roles of humans for purposes such as medical, military, or teacher training [28, 35, 36, 61, 135]. They can appear in a virtual environment or can share physical space during training [95]. Because of the resemblance of VHs' appearance and shape with humans, people naturally distinguish them from non-human objects and often treat them in a similar way as real humans [4, 10, 94]. This phenomenon is often leveraged in training simulations, where VHs assume the roles of instructors or training partners that may not always be available. The more realistic the interactions with VHs, the more likely simulated training experiences will translate to improvements in corresponding real-world experiences. In general, a greater sense of presence with VHs has the potential to make training more effective, leading to the formation of teams that perform better in a real environment [34].

Researchers often use the terms *social presence* and *co-presence* to describe the phenomenon. They are generalizable factors among many other simulation-dependent factors in assessing the effectiveness of training simulations that employ VHs. While many interpretations of the terms social presence and co-presence have been proposed (see [25]), Goffman et al. [51] indicated that co-presence exists when people feel that they are able to perceive others and that others are able to perceive them. Informally, just as one might think of presence in a virtual environment as a sense of "being there," one might think of co-presence with others as a sense of "being together." Blascovich et al. [19, 20] defined *social presence* both as a "psychological state in which the individual perceives himself or herself as existing within an interpersonal environment" and "the degree to which one believes that he or she is in the presence of, and dynamically interacting with, other veritable human beings." Harm and Biocca [55] defined social presence as "one's sense of being socially connected with the other" and co-presence as "one's sense of the other person's presence." They considered co-presence as one of several dimensions that make up social presence. A similar view on co-presence as a subfactor affecting social presence was also proposed by Skarbez et al. [123]. While there is no universal agreement on the definitions of these terms, this research adopts the Harms and Biocca perspective: *social presence* is considered to be one's sense of being socially connected with the other, and *co-presence* to be one's sense of the other person's presence.

2.3 Behavioral Responses to Virtual Humans

Slater postulated that people would respond realistically to a VE when both *place illusion* and *plausibility* occur [126], and research has demonstrated that VHs in immersive virtual environments (IVEs) could possibly induce a social behavior to the VHs from people [4, 10, 11] or even alter their behavior in the real world after the IVE experience [141]. Bailenson et al. [8] further suggested the use of nonverbal social behavior as a more sensitive measure of social/co-presence and general influence of VHs than self-reported measures.

One of the widely used social behaviors in interactions with VHs is proxemics behavior. Proxemics, also known as interpersonal distance, refers to concepts related to how people perceive and act in space between themselves and others. One may think of proxemics as involving a "bubble" of social space centered on and moving with a person. One can actually think of multiple layers to the bubble, each with different social allowances. People tend to keep a comfortable distance with others, which varies depending on one's relationship with the other, the behavior of the other, cultural background, and situation [54]. Various studies have been performed in VEs, where participants physically walked in a space while seeing one or multiple VHs. For instance, Bailenson et al. reported that participants maintained a larger space around a VH than they did for a similarly sized cylinder [10]. In a different study, they found that participants kept a larger distance from a VH when they walked towards the VH facing them with their front compared to their back [11].

A typical behavior involving proxemics is the avoidance of human or non-human obstacles. To avoid a collision while walking, one must observe the surroundings and obstacles, predict the possibility of a collision, and adjust the locomotion behavior accordingly [33]. In most cases, walking direction and speed are the parameters people change, but they can vary the types of adjustment based on the optimal strategy in each situation [40]. For a non-moving obstacle, people tend to favor adjusting their walking direction while keeping their walking speed unchanged [102]. However, in a smaller space, in crowded environments [103] with a higher uncertainty of the obstacle's behavior or surrounding environment [15], or in the presence of spatiotemporal constraints such as a revolving door [29], people tend to adjust their walking speed. Walking speed adjustments were also reported as an effect of a restricted field of view [68]. Regarding moving obstacles, the direction and angle of the obstacle's movement can influence one's strategy to avoid the collision. Basili et al. [15] found for a human obstacle approaching along the 90-degree path from one's progressing direction that participants tended to change their walking speed. Huber et al. [64] reported that the speed adjustment was favored only for acute angles while walking direction was always adjusted.

Finally, there has been some work comparing obstacle avoidance behavior in real and virtual environments. Fink et al. [41] conducted a study comparing obstacle avoidance behavior with a real or virtual stationary obstacle during real walking in VR, and found a larger clearance distance and slower walking speed with the virtual obstacle compared to the real counterpart. Argelaguet et al. [4] further investigated obstacle avoidance behavior including human obstacles, and confirmed similar effects of a virtual human compared to a real counterpart. They also reported a difference between a human and a non-human obstacle and that the orientation of the obstacle showed a significant influence on the locomotion behavior.

In addition to the proxemics behavior, gaze behavior and physiological responses have also been used in virtual human research. Mühlberger et al. [105] demonstrated that participants tended to look more at a VH with a happy face than a VH with an angry face, and social anxiety was correlated with avoidance gaze behavior associated with the angry VH. Similarly, Bailenson et al. [10] found that participants also gave more personal space to VHs when the VHs exhibited mutual gaze behavior. Their previous experiment that showed the association between VHs' approaching direction and the interpersonal distance participants kept could also be in part related to the VHs' gaze [11]. In relation to gaze as a social cue, Vertegaal et al. [138] applied gaze behavior as a predictor of conversational attention in a multi-agent conversational system. Bailenson et al. [9] further demonstrated that VH gaze behavior facilitated efficient task performance. With regards to physiological responses, electrodermal activity and heart rate are often used. Garau et al. [48] demonstrated that the electrodermal activity and heart rate of participants increased when they faced VHs in a library room compared to a training room with no VHs in an IVE. They found the Social Avoidance and Distress scores correlated with participants' intent not to disturb VHs in the library room. Llobera et al. [94] showed that physiological arousal extracted from electrodermal activity was increased when VHs approached the participants.

Experiments performed in this dissertation research actively used proxemics, gaze, and physiological responses in conjunction with subjective questionnaires.

2.4 Virtual Humans in Mixed Reality

Milgram et al. [100] classified virtual experiences using a continuous scale—also known as the Reality-Virtuality continuum—ranging between the entirely virtual, or *virtuality*, and the completely real, or *reality*, and called the area between the two extremes *mixed reality (MR)* (see Figure 2.1). Based on how much of the displayed scene is real, MR is further divided into augmented reality and augmented virtuality. In AR, computer-rendered virtual objects (or simply text or images) are registered and overlaid onto the user's real view, whereas in augmented virtuality, a small portion of the real world is displayed in the virtual environment. While VR aims to totally replace the real environment with a computer-generated virtual environment, MR aims to "mix" the virtual environment into the real environment, and vice versa [69, 100].

The process of "mixing" or "augmenting" the real and virtual world is called registration, and usually the accuracy of registration is important for coherent experiences in the mixed environment [6]. To provide a persistent illusion of being in the mixed environment, both spatial and temporal registration are required [143]. Spatial registration corresponds to the accuracy of geometric relations of virtual objects in real scene, i.e., proper location and occlusion of virtual objects; and temporal registration corresponds to the synchronized motion between virtual objects and real scene, i.e., relating to latency.

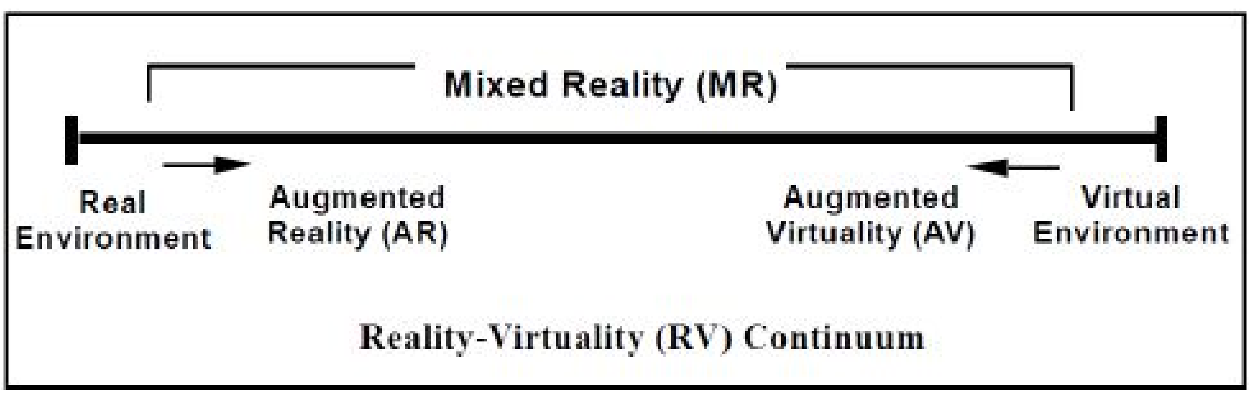


Figure 2.1: The Reality-Virtuality continuum [100].

Despite the popularity of AR/MR, however, a relatively small amount of research has attempted to bring realistic three-dimensional VHs to a users' physical environment in AR/MR, compared to the majority of research performed in VR. The increasing convergence of AR and robotics in different areas, such as using AR as a social interface for a robot [37], robot path planning [7], or implementing a VH's autonomous behavior such as eye and head motion [74] through the advances of the same topic in the field of robotics [24, 98, 118], can provide a turning point in AR research. Meanwhile, efforts to make a social robot, e.g., for a human companion, have been steadily made in the robotics community [23], but they faced Uncanny Valley related challenges due to the complexity of representing realistic human facial expression as well as subtle body gestures [117]. In this regard, the realistic 3D graphics of AR and the physical presence of robots might be mutually beneficial for both VHs in AR and for social robots [60].

When VHs are brought into a user's real space, two main approaches exist: (i) they can be partially or entirely projected onto physical objects that look like a human body, or (ii) they can be overlaid onto a user's view using AR technology. For example, Kotranza et al. [82] proposed a mannequin-based embodied agent, a virtual patient, that supports touch interaction with medical trainees. Similarly, Lincoln et al. [93] prototyped a robot-based embodied virtual human. They projected a human face onto an actuated robotic head which could convey nonverbal social behavior, such as gaze direction, as well as verbal communication. Obaid et al. [108] used video see-through AR glasses to augment the VH in a user's view in their study evaluating the relationship between the users' physiological responses and VHs' cultural behaviors.

However, there are perceptual issues one should consider when using AR glasses to overlay VHs in the users' view (see [85]). For instance, Kim et al. [78] indicated that VHs' conflicting physical behavior with real objects, e.g., passing through them, could reduce users' sense of co-presence with the VH. Also, the small augmented field of view of the current-state optical see-through AR glasses can affect users' behavior in the presence of VHs. Multiple studies have shown that when peripheral vision is restricted, one's situational awareness is limited [2], resulting in behavioral changes, such as turning the head more to compensate for the reduced field of view [5, 47]. A large number of studies have reported the underestimation of distances on HMDs (see [97, 114] for a review of the literature). Jones et al. [70] suspected the limited field of view in current-state

HMDs might be a factor contributing to this effect. Moreover, a restricted field of view was found to decrease target detection performance in VR [112] as well as in AR [113].

2.5 Physical-Virtual Interactivity and Physical Influence of Virtual Humans

Bridging the gap between the physical world and virtual worlds has been of increasing interest in recent years. For instance, Sra et al. [130] introduced a method to create a walkable area in a virtual environment that is based on the space in the real world. Similarly, Simeone et al. [122] proposed a *substitutional reality* where the physical world is substituted with virtual counterparts, and showed a relation between the level of mismatch and the user experience in such an environment. Regarding the opposite direction, from virtual to real, researchers have proposed methods utilizing mobile robots and actuators. He et al. [56] demonstrated three different mapping mechanisms between physical and virtual objects in such scenarios. Kasahara et al. [72] proposed "exTouch", a touchscreen-based interaction method, to allow users to manipulate actuated physical object through AR. Joshua et al. [92] used networked actuators to bring virtual events into the physical world in their *cross reality* implementation.

Unlike VR, however, in AR/MR, virtual content is overlaid onto or mixed with the real world, creating a unified world. In such cases, the means by which virtual entities interact with the physical environment can affect users' perception. For example, Kim et al. [78] demonstrated that users rated the sense of social presence higher with a VH that exhibited awareness of the physical space compared to one that did not in AR. This finding is comparable to the results of Bailenson et al. [10], in which a VH that exhibited awareness of the user in an immersive virtual environment received higher social presence and induced more realistic participant gaze and proxemic behavior.

We are entering an era where VHs can be given more and more control over physical objects at our homes and in public spaces. With the Internet of Things (IoT), common devices in our daily lives are connected to computer systems that enable them to be accessed by voice-controlled agents, such as Amazon Alexa, providing an intuitive and natural interface to interact with them [110]. For instance, Kim et al. [77] investigated IoT devices as a VH's physical influence channel and compared the effects of embodied voice-controlled agents and their behavior on the user experience as well as social presence. They found that exhibiting plausible behavior, e.g., walking over to an IoT lamp and pretending to touch a light switch to turn it on, similar to what real humans would do, induced significantly higher social presence with the agent than voice-only interaction.

However, when it comes to VHs' physical influence, most of the prior research has focused on the use of haptic/tactile feedback as a means to facilitate interpersonal touch with VHs through a physical embodiment.

Interpersonal touch refers to direct physical contact between people. Interpersonal touch has been found to elicit relevant positive responses [46]. For example, the "Midas touch" refers to the phenomenon where casual touch, such as a tapping on one's shoulder, promotes altruistic behaviors and willingness to comply with the one who touched [53]. Crusco and Wetzel [32] found that a waitress who tapped lightly on customers' shoulders received larger tips than a waitress who did not. Similar effects related to touch have been found in other studies, e.g., [38]. The effects of interpersonal touch, furthermore, are not limited to behavioral changes. Fisher et al. [42] found that incidental physical contact on the palm when returning a library card made students assess the librarian more favorably. Erceau and Guéguen [39] found a similar effect with car salespeople.

A large number of studies have shown similar positive effects of interpersonal touch in social interaction with a VH or a remote person. Basdogan et al. [14] found that haptic sensations of the partner, such as when pulling or pushing through a co-manipulating virtual object by two remote persons, increased the sense of being together (i.e., *co-presence*) as well as task performance.

Similarly, Sallnäs [115] reported that haptic feedback perceived through a shared virtual object increased presence, social presence, and the perceived performance when persons in two remote places passed a virtual object in a shared virtual environment. Blanke et al. [18] found the sensorimotor conflict in connection with spatial incompatibility of self-touch induced the feeling of the other person's presence. In these studies, a visual representation of the respective other person was not provided.

Researchers have also examined the effects of touch interaction with social agents—physically embodied and purely virtual. Rahman and El Saddik [99] developed a neck piece converting VHs kiss behavior to a tactile vibration on a user's neck. Similarly, Hossain et al. [62] developed a haptic jacket to enhance interaction with VHs in Second Life [1]. Huisman et al. [65, 66] further attempted to simulate interpersonal touch with a simpler vibrotactile mechanism in an AR setup, and showed its effects on affective adjectives. Bailenson et al. [13] found that people used less force with a VH than when they touched a non-human object, and that they touched the VH's face with less force than the VH's torso. They also found people used less force for female VHs than male VHs. Kotranza et al. developed a virtual patient that both responds using speech and gestures to participant touch [83] and touches the participant back [84] in an MR medical simulation. They found that people treated the virtual patient more like a real human and rated the overall quality of communication as higher with touch feedback compared to without. Bickmore et al. [17] found that squeezing behavior, conveyed by an air bladder, of a mannequin-based virtual agent was associated with the perception of affect arousal or valence. Nakagawa et al. [107] found that a robot with active touch encouraged motivation for a monotonous task compared to robots with a passive or no touch. Although the manner by which haptic/tactile feedback induced such effects is uncertain, the sensorimotor conflict might account for the increased feeling of the other person's presence [18] similarly to how sensorimotor integration could induce the illusion of body ownership [75].

[1] https://secondlife.com/

CHAPTER 3: SYNCHRONIZED MOVEMENT OF A SHARED REAL-VIRTUAL TABLE

Previous research has shown that direct physical contacts, i.e., interpersonal touch, with VHs elicit relevant positive responses (see Chapter 2). In this chapter, I further look into the question of whether indirect physical influence of VHs, i.e., mediated via a shared object, can induce similar effects found from direct physical influence.

With regards to the thesis statements, the relevant claim supported by this chapter is as follows:

- Naturally correlated cues associated with a virtual human's actions and physical outcomes can increase feelings of social/co-presence the virtual human.

This chapter substantially replicates a peer-reviewed paper, "The Wobbly Table: Increased Social Presence via Subtle Incidental Movement of a Real-Virtual Table," published in the proceedings of IEEE Virtual Reality 2016, co-authored with Kangsoo Kim, Salam Daher, Andrew Raij, Ryan Schubert, Jeremy Bailenson, and Gregory F. Welch [90]. Throughout this chapter, when I say "we," I am referring to these colleagues.

3.1 Overview

We ran an experiment to assess how presence and social presence are affected when a person experiences subtle, incidental movement through a shared real-virtual object. We constructed a real-virtual room with a table that spanned the boundary between the real and virtual environments. The participant was seated on the real side of the table, which visually extended into the virtual world via a projection screen, and the VH was seated on the virtual side of the table. The two interacted by playing a game of "Twenty Questions," where one player asked the other a series of 20 yes/no questions to deduce what object the other player was thinking about. During the game, the "wobbly" group of subjects experienced subtle incidental movements of the real-virtual table: the entire real-virtual table tilted slightly away/toward the subject when the virtual/real human leaned on it. The control group also played the same game, except the table did not wobble. Results indicate that the wobbly group had higher presence and social presence with the virtual human in general, with statistically significant increases in presence, co-presence, and attentional allocation.

Figure 3.1: The physical and virtual setting of the experiment with the virtual human in view.

3.2 Experiment

The aim of the wobbly table experiment is to examine whether subtle incidental movement of a real-virtual wobbly table can increase presence and social presence. For that purpose, we built a wobbly table spanning a real-virtual environment. The table serves as a medium by which incidental interactions with the table can be conveyed in the form of subtle table movement felt by a real and virtual human in a dyadic interaction. The table slightly wobbles depending on the weight both a RH and a VH put on it, and the wobbly motion in real/virtual parts of the table is synchronized.

3.2.1 Experimental Setup

To examine effects of subtle incidental movement of a real-virtual object in human-virtual human interaction, a VH interaction that facilitates a constrained but plausible conversation with a real user was developed. We implemented a female VH, "Katie," who could speak with a RH and perform upper-torso gestures (e.g., hand and head gestures). The VH was projected onto a screen in an office-like room as shown in Figure 3.1. The physical part of the table was positioned in front of the screen, creating a visual impression of facing a seated VH across the table. The physical table has a virtual counterpart that visually extended from the physical table into the (virtual) environment of the VH. The motion of physical and virtual tables were electromechanically linked to achieve visual-motor synchrony for the subtle incidental movement of the wobbly table. The slope of the table changed subtly depending on how much weight both the virtual and real human put on the table (Figure 3.2). By default, the VH put both arms on the table (Figure 3.1), thus putting the table into a default state. The VH could apply additional weight by leaning on the table further, in turn tilting it further toward the virtual world. If the VH moved her hands off the table (Figure 3.3), then all forces on the table came from the participant (if any), and the table tilted accordingly.

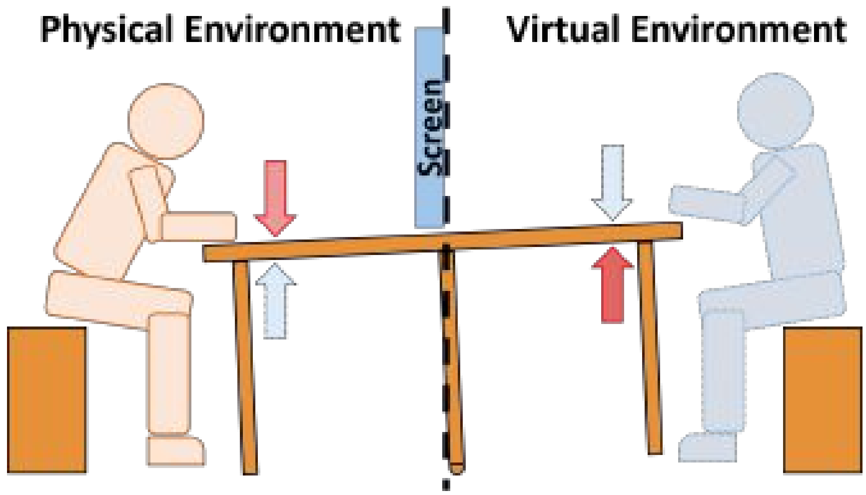


Figure 3.2: When a real human leans on the real side of the table, the virtual side of the table lifts up and vice versa.

We added office-like decorations to the physical experimental space, including a table and bookcases (Figure 3.1). The screen displaying the virtual world was placed on top of the table, between the bookcases. The edges of the virtual table were aligned with the physical table from the participant's viewpoint; thus, the virtual and physical parts of the table appeared to be a single table. To enable subtle wobbly movement of the table, the real side of the table was slightly lifted and anchored to pivot points on the bookcases. A handle to control pivoting was attached to the table behind the screen. Finally, a stopper was installed to enable a seesaw-like movement to the table (resulting in a maximum of 0.635 *mm* height difference at the edge of the real table). We attached a laser pointer to a leg of the table and adjusted the laser to point at a white panel on the floor about 1.5 *m* away. In this way, a change in the inclination of the real table in turn displaced the beam position on the white panel. We measured the displacement of the beam using a webcam and calculated the corresponding inclination. This calculated inclination was then applied to the virtual table, enabling synchronized movement between the real and virtual sides of the table.

Figure 3.3: Example gestures used by the virtual human. Our VH's basic posture was placing both arms on the table. During the Twenty Questions games, the VH used various gestures, e.g, raising both arms, leaning on the table and writing, and checking the table legs. Raising both arms gestures (left) and leaning on the table gesture (center) triggered wobbling of the table. Occasionally, the VH looked down at the table leg, ostensibly looking for the reason for the table's wobble (right).

3.2.2 Interaction Scenario

In this experiment, the participant and VH played a two-player parlor game commonly known as Twenty Questions. In Twenty Questions, one player thinks of an object but does not reveal the object to the other player (known as the guesser). The guesser then asks up to 20 yes/no questions to identify the object. If the guesser cannot identify the object after 20 questions, then he/she loses the game. The two players (virtual and real), played two games of Twenty Questions. In the first game, the participant was the guesser. These roles were swapped in the second game.

We chose the Twenty Questions game for several reasons. First, the game has been used in many studies examining social interaction, including those with virtual humans [9]. Second, with careful choices, speech in a Twenty Questions game can be constrained to reduce the chance the VH will respond awkwardly (or not at all) to the user.

We used a Wizard-of-Oz paradigm to control the VH, i.e. one of the experimenters controlled the VH using a button-GUI behind the scenes. Each button in the GUI triggered pre-recorded audio speech along with the VH's gestures corresponding to the speech. A wide range of audio/gestural responses to yes/no questions were pre-recorded. For the first round of Twenty Questions, the participant was the guesser and the object the VH was "thinking of" was a shoe. In the second round, the VH took the role of the guesser. To ensure the VH could ask plausible questions, the participant's object was pre-determined before the experiment, which was unknown to the participant. The participant chose the object by drawing lots, but the participant was not aware that all lots had the same word on them, "Smartphone." Thus, our VH could ask plausible pre-recorded questions about the object and always guessed the object correctly at the twentieth question.

3.2.3 Methods

Manipulations

A between-subjects design was used for this experiment. Participants were randomly assigned to either the "Wobbly" or "Control" groups described below.

- **Wobbly**: For the wobbly group, the table wobbled. The VH exhibited awareness of the table movement occasionally (two times per game) by briefly looking under the table. The VH did not verbally acknowledge awareness of the table movement.
- **Control**: For the control group, the table was fixed (did not wobble), and the VH did not exhibit any reactions to the table.

In both groups, participants played the two games of Twenty Questions with the VH until completion. Note that the participant could guess the object fairly early in the first round. Thus, the interaction duration was not predefined.

Measures

We measured presence and social presence primarily with a combination of post-experiment subjective surveys. We used the presence questionnaire by Witmer and Singer [140] and the social presence questionnaire by Harms and Biocca [55]. Both of these surveys are widely recognized as valid measures and have been used in many experiments. Since the study setup had both real and virtual components (mixed reality), questions specific to virtual-only interactions were removed from the Witmer and Singer questionnaire. We also measured social presence indirectly through questionnaires that assessed two possible correlates of high social presence, affective attraction (or liking) [59] and anxiety [139]. We also included questions related to how they correlate the perceived sounds and vibrations with VH's footsteps. Lastly, participants provided informal comments on the interaction verbally and on paper.

Hypotheses

We formulated the following two general hypotheses:

- **[Presence]** Participants in the wobbly group will report higher presence in the mixed environment than participants in the control group.
- **[Social Presence]** Participants in the wobbly group will report higher social presence with the VH than participants in the control group.

Procedure

When participants arrived, we guided them to the questionnaire area. They were asked to read and sign the informed consent and fill out a demographics questionnaire. We explained that they would play a couple of Twenty Questions games with a VH. We briefly described the rules of the game, and the participants were asked to pick a card from a card deck, which had the object name written on the other side (all cards said “Smartphone”). Before entering the experimental space, we asked them to write the answers for the 4th, 8th, 12th, and 16th questions during each game on a piece of paper taped to the wobbly table. This ensured participants would put weight on the table and experience subtle incidental movement. The participants were also informed that they would be the guesser for the first game, and then the VH would be the guesser in the second game. After video/audio recording started, participants entered the experimental space and played Twenty Questions with the VH. Once the participants completed both games, we guided them out of the room, and asked them to fill out post-questionnaires. After the questionnaires, the experiment ended.

3.2.4 Participants

We recruited participants within our university community including students, staff, and faculty. Twenty undergraduate and graduate students participated in the experiment (9 females, 11 males, mean age: 22.9, age $SD = 3.45$, age range: 18–33 years). All participants received fifteen dollars for their participation (duration: 30–60 min).

3.3 Results

We decided to use parametric statistical tests to analyze the questionnaire responses in line with the ongoing discussion in the field of psychology indicating that parametric statistics can be a valid and often more expressive method for the analysis of ordinal data measured by the experimental questionnaires [81, 86]. In agreement with this approach, the data did not fail the Shapiro-Wilk test at the 5% level for normally distributed data.

3.3.1 Presence

We used a seven-point Likert-scale for the presence questionnaire by Witmer and Singer [140]. These questions were originally designed and tested for use in purely virtual environments. Since our wobbly table setup was not a purely virtual environment, we excluded certain inappropriate questions (e.g., questions about navigation). The aggregate presence score was calculated by averaging all responses in the questionnaire. An independent-samples t-test was conducted to compare the presence scores in the control and wobbly groups, and there was a significant difference in the scores for the control ($M = 4.52$, $SD = 0.39$) and the wobbly ($M = 4.95$, $SD = 0.42$) groups; $t(18) = -2.396$, $p = 0.028$. (See Figure 3.4, Table 3.1 and 3.2 for detailed results).

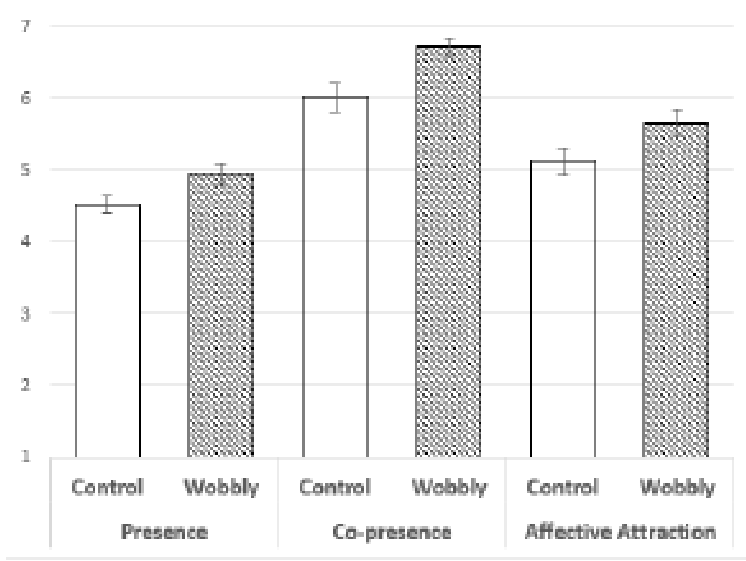


Figure 3.4: Means of Presence, Co-presence, and Affective Attraction scores for each group. Presence and Co-presence scores were significantly larger in the wobbly group. (Error bars represents standard error). These scores are aggregates, calculated by averaging.

Table 3.1: Independent-samples t-test on presence and sub-factors

	t	df	p	Cohen's d
Presence	-2.396	18	0.028	-1.072
Control Factor	-2.366	18	0.029	-1.058
Sensory Factor	-2.871	18	0.01	-1.284
Distraction Factor	0.596	18	0.559	0.267
Realism Factor	-1.552	18	0.138	-0.694

Table 3.2: Presence and sub-factors descriptives

	Group	N	Mean	SE
Presence	Control	10	4.52	0.123
	Wobbly	10	4.953	0.133
Control Factor	Control	10	4.114	0.189
	Wobbly	10	4.757	0.195
Sensory Factor	Control	10	4.975	0.222
	Wobbly	10	5.775	0.169
Distraction Factor	Control	10	4.167	0.273
	Wobbly	10	3.933	0.28
Realism Factor	Control	10	5.1	0.272
	Wobbly	10	5.65	0.227

3.3.2 Social Presence

We used the social presence questionnaire by Harms and Biocca, in which social presence was conceptualized as six sub-dimensions: co-presence, attentional allocation, perceived message understanding, perceived affective understanding, perceived affective interdependence, and perceived behavioral interdependence [55]. Each question in the questionnaire was on a seven-point Likert-scale, and we averaged participant responses to construct each sub-dimension score. We conducted independent-samples t-tests to compare the six sub-dimensions across the control and wobbly groups, and found statistically significant differences in the co-presence sub-dimension

($M = 6.02$, $SD = 0.66$ for control group; $M = 6.72$, $SD = 0.39$ for wobbly group) and the attentional allocation sub-dimension ($M = 5.32$, $SD = 0.85$ for control group; $M = 6.03$, $SD = 0.18$ for wobbly group) (See Figure 3.4, Table 3.3 and 3.4 for detailed results).

Table 3.3: Independent-samples t-tests on social presence sub-dimensions

	t	**df**	**p**	**Cohen's d**
Co-presence	-2.868	18	0.010	-1.283
Attentional Allocation	-2.224	18	0.039	-0.995
Message Understanding	-0.608	18	0.551	-0.272
Affective Understanding	-0.099	18	0.922	-0.044
Emotion Interdependency	0.186	18	0.855	0.083
Behavior Interdependency	-1.552	18	0.138	-0.731

Table 3.4: Social presence sub-dimensions descriptives

	Group	**N**	**Mean**	**SE**
Co-presence	Control	10	6.017	0.21
	Wobbly	10	6.717	0.124
Attentional Allocation	Control	10	5.317	0.268
	Wobbly	10	6.033	0.179
Message Understanding	Control	10	5.8	0.155
	Wobbly	10	5.933	0.156
Affective Understanding	Control	10	4.033	0.386
	Wobbly	10	4.083	0.323
Emotion Interdependency	Control	10	3.5	0.304
	Wobbly	10	3.4	0.445
Behavior Interdependency	Control	10	4.317	0.23
	Wobbly	10	5	0.35

3.3.3 Affective Attraction and Anxiety

We used the affective attraction items from [59] to measure the participants' attraction to the VH. The five sub-items were rated on a seven-point Likert-scale. We averaged all items to construct an aggregate affective attraction score. We conducted independent-samples t-tests on the both the aggregate and individual scores. Although there were no significant differences between groups, there appears to be a trend on the affective attraction score ($t(18) = -2.04$ and $p = 0.057$); that is, participants in the wobbly group felt more attraction for the VH than participants in the control group (See Figure 3.4, Table 3.5 and 3.6 for detailed results).

The anxiety questionnaire [139] was a single question "How did your interaction with the other player (Katie) make you feel?", followed by a list of anxiety subdimensions participants rated on a scale of 0 to 10, where 0 was "Not at all" and 10 was "Extremely Strong". We conducted independent-samples t-tests on each question in the control and wobbly groups. Participants in the wobbly group felt less "In control", however they all rated their desire to leave as zero. (See Table 3.7 and 3.8 for detailed results).

Table 3.5: Independent-samples t-test on affective attraction

	t	**df**	**p**	**Cohen's d**
Affective Attraction	-2.035	18	0.057	-0.91
Unpleasant-pleasant	-1.686	18	0.109	-0.754
Cold-warm	-1.709	18	0.105	-0.764
Negative-positive	-0.277	18	0.785	-0.124
Unfriendly-friendly	-1.555	18	0.137	-0.695
Distant-close	-1.8	18	0.089	-0.805

Table 3.6: Affective attraction descriptives

	Group	N	Mean	SE
Affective Attraction	Control	10	5.12	0.191
	Wobbly	10	5.66	0.184
Unpleasant-pleasant	Control	10	5.5	0.269
	Wobbly	10	6.1	0.233
Cold-warm	Control	10	5.2	0.2
	Wobbly	10	5.7	0.213
Negative-positive	Control	10	5.7	0.213
	Wobbly	10	5.8	0.291
Unfriendly-friendly	Control	10	5.5	0.269
	Wobbly	10	6.1	0.277
Distant-close	Control	10	3.7	0.396
	Wobbly	10	4.6	0.306

Table 3.7: Independent samples t-test on anxiety questionnaire

	Assumption	t	df	p	Cohen's d
Anxious	equal var.	-1.833	18	0.083*	-0.82
	not assumed	-1.833	13.515	0.089	-0.82
Excited	equal var.	-1.658	18	0.115	-0.742
	not assumed	-1.658	14.638	0.118	-0.742
Tense	equal var.	-0.461	18	0.65	-0.206
	not assumed	-0.461	17.465	0.65	-0.206
Alert	equal var.	-0.82	18	0.423	-0.367
	not assumed	-0.82	17.856	0.423	-0.367
In Control	equal var.	2.882	18	0.01*	1.289
	not assumed	2.882	12.74	0.013	1.289
Desire to Leave	equal var.	3.597	18	0.002*	1.609
	not assumed	3.597	9	0.006	1.609

*Levene's test is significant ($p < .05$), suggesting a violation of the equal variance assumption

Table 3.8: Anxiety questionnaire descriptives

	Group	N	Mean	SE
Anxious	Control	10	1.6	0.452
	Wobbly	10	3.4	0.872
Excited	Control	10	6.1	0.674
	Wobbly	10	7.4	0.4
Tense	Control	10	2.3	0.831
	Wobbly	10	2.8	0.696
Alert	Control	10	4.9	0.9
	Wobbly	10	5.9	0.823
In Control	Control	10	7.3	0.367
	Wobbly	10	4.8	0.786
Desire to Leave	Control	10	1.7	0.473
	Wobbly	10	0	0

3.4 Discussion

Here we discuss the experimental results in the context of presence and social presence, and speculate about potential causes and implications, in view of some relevant related work.

Presence: The wobbly group participants' perceived level of presence was (statistically) significantly higher than the control group's in our mixed reality wobbly table setup. In particular, the mean scores for two sub-factors of presence, the "Control Factor (related to one's ability to control the surrounding environment)" and the "Sensory Factor (related to movement perception and sensory modalities to perceive the environment)," were higher for the wobbly group. The increase in the "Control Factor" could be a consequence of the wobbly participant's ability to exert control, however subtle, over the virtual side of the table. We note that the movement of the wobbly table was recurring during the interaction; so, the wobbly group's sense of the link between real and virtual spaces could be reinforced each time the table wobbled, and perhaps by extension, their sense of control over the virtual space could be maintained/enhanced without collapse. The higher "Sensory Factor" could result from the positive effect of the additional haptic feedback experienced by participants in the wobbly group, especially combined with the visual-motor synchrony when the table moved. The visually synchronized real-virtual table movement with subtle haptic feedback could induce an illusion of the object (self) extension, and this illusion might play a role in increasing presence in the wobbly group—similar to how virtual body-ownership can enhance one's sense of presence in a virtual environment. Although there was latency between the movement of the real and the virtual table, the latency (200 *ms* in our wobbly table setup) was ignorable to achieve one's illusion of visual-motor synchrony and object extension based on the findings from other previous literature, e.g., a rubber hand illusion occurred when the delay between visual and tactile sensations was less than 300 *ms* [121], and Mueller et al. reported 250 *ms* delay was tolerable in a physical-virtual airhockey game [104].

Social Presence: With respect to social presence, we hypothesized that the wobbly group's perceived social presence with the VH would be higher than the control group's (see Section 3.2.3). The results showed that there were significant differences in co-presence and attentional allocation between the groups. The reasons for the significant differences might be the increased mutual awareness and the tightly shared interpersonal space via the wobbly table and the VH's reactive behaviors (looking under the table) despite of the wobble table's subtle and incidental movement. This interpretation is along with our expectation—one's perceived mutual awareness and the shared interpersonal environment could be the factors to increase the level of social presence. The increased sense of presence previously discussed might also encourage the wobbly group's awareness of the shared space, and it could establish the mutual awareness in association with the VH's awareness of the shared space. While interpreting the results, we realized that our wobbly table setting might be more beneficial to encourage three particular sub-dimensions of social presence: co-presence, attentional allocation, and behavior interdependency, rather than the other sub-dimensions because the manipulations in the study were more related to visual/behavioral changes (i.e., visually synchronized wobbly table and the VH's reactive behaviors to the wobbly movement), which we think possibly affected the above three sub-dimensions. The other sub-dimensions: message/affective understanding and emotional interdependency seemed more associated with verbal communication or detailed facial expressions, which we did not adjust in our setting. Although the behavior interdependency sub-dimension did not show a significant difference, we could observe noticeably higher responses for the wobbly group than the control group similar to the responses in co-presence and attentional allocation, so might be able to see a significant difference if the sample size was large enough.

With regard to affective attraction, which we used as indirect measures for social presence, we did not see any significant differences between groups, but participants for the wobbly group rated the VH more positively in all affective attraction questions (e.g., pleasant, warm, and friendly). There could be various reasons for this result, but we speculate that the interpersonal touch—the subtle and incidental haptic sensation via the wobbly table—could be one of the reasons considering the previous observations, e.g., interpersonal touch altered one's assessment of the other person or a virtual agent more positively [17, 39, 42]. This subtle interpersonal touch via the wobbly table might also result in the lower desire to end the social interaction (playing Twenty Questions) with the VH in the anxiety questionnaire, as a robot with active touch encouraged motivation for a monotonous task in [107].

3.5 Summary

We examined the effects of subtle incidental movement of a real-virtual table on social presence during a conversational task. Specifically, we developed a scenario where a RH and a VH carried out a conversational task while seated at a table that spanned the physical-virtual space—i.e. the table included a physical half and a virtual half. We configured the physical (half) table so that it could tilt slightly toward/away from the subject, and tracked the tilting to ensure the virtual half (rendered) would move in synchrony with the physical half. We conducted a user study where the primary task involved participants interacting with the VH via a game of "Twenty Questions." We used a Wizard of Oz paradigm to control the VH, with pre-recorded audio and corresponding gestures triggered by a GUI. For one group of participants, the table wobbled and the VH showed awareness of the wobbles, while in the control group the table was fixed and the VH did not show any awareness of the wobbles. We employed pre- and post-questionnaires to assess the effects. Participants sharing a wobbly table with the VH exhibited a general increase in presence and social presence, with statistically significant increases in presence, co-presence, and attentional allocation. In addition, participants in the wobbly group showed more affective attraction for the VH.

In short, the results revealed that the indirect physical interaction mediated via a shared real-virtual object elicits similar effects on social/co-presence found from direct physical influence of VHs. The method for mediated physicality used in this chapter includes both visually synchronized movements of the real-virtual table and haptic feedback from the movements of the table. The following chapters further isolate factors that might have affected the observed results and look into the latent perceptual illusions related to mediated physicality.

CHAPTER 4: FOOTSTEP VIBRATIONS THROUGH A VIRTUAL FLOOR

In the wobbly table system in Chapter 3, both a virtual human and a user could affect each other's space through a shared real-virtual table. Also, the VH responded to wobbles caused by the user by exhibiting awareness behavior. Both bidirectional influences on each other's space and the VH's awareness of the wobbles might have in part affected the increased sense of social/co-presence.

In this chapter, I control such confounding factors. Instead, I focus on a combination of auditory and vibrotactile feedback of a VH's actions.

With regards to the thesis statements, the relevant claims supported by this study are as follows:

- Naturally correlated cues associated with a virtual human's actions and physical outcomes can create a perception of virtual-physical causality.
- Naturally correlated cues associated with a virtual human's actions and physical outcomes can increase feelings of social/co-presence with the virtual human and induce realistic social behavior.

This chapter substantially replicates a peer-reviewed paper, "Exploring the Effect of Vibrotactile Feedback through the Floor on Social Presence in an Immersive Virtual Environment," published in the proceedings of IEEE Virtual Reality 2017, co-authored with Gerd Bruder and Gregory F. Welch [89]. Throughout this chapter, when I say "we," I am referring to these colleagues.

4.1 Overview

We investigate the effect of vibrotactile feedback delivered to one's feet in an immersive virtual environment. In this study, participants observed a virtual environment where a VH walked toward the participants and paced back and forth within their social space. We compared three conditions as follows: participants in the "Sound" condition heard the footsteps of the VH; participants in the "Vibration" condition experienced the vibration of the footsteps along with the sounds; while participants in the "Mute" condition were not exposed to sound nor vibrotactile feedback. We found that the participants in the "Vibration" condition felt a higher social presence with the VH compared to those who did not feel the vibration. The participants in the "Vibration" condition also exhibited greater avoidance behavior while facing the VH and when the VH invaded their personal space.

4.2 Experiment

To investigate the effects of vibrotactile feedback through the floor, i.e. perceived at the soles of one's feet, on social presence, we built an immersive virtual simulator with a platform that can generate vibrotactile feedback. Participants were standing on the platform while observing the virtual environment. In this section, we describe details of the experiment.

4.2.1 Hypotheses

As outlined in Chapter 2, prior work has shown that haptic/tactile feedback affects one's perception of the interaction partner whether it is a real human or an agent (e.g., a robot or a VH). However, these findings were mostly in situations where the interaction partner directly touched the participant's body, which rarely happens in everyday interactions. Instead, we often perceive kinetic forces exerted by the other person through an object we are both touching. For example, if a person is walking on a rope bridge, one can become aware of a person behind of him/her via vibrations transmitted through the shared bridge. We therefore believe that interpersonal haptic/tactile feedback that is propagated through a shared object, such as the floor, could be more practical.

Based on the related work, we thus formulated the following two hypotheses:

- **H1:** Participants feel higher social presence with a VH when they experience vibrotactile feedback of the VH's footsteps through a shared floor in an IVE.
- **H2:** Participants exhibit more realistic social behavior with a VH when they experience vibrotactile feedback of the VH's footsteps through a shared floor in an IVE.

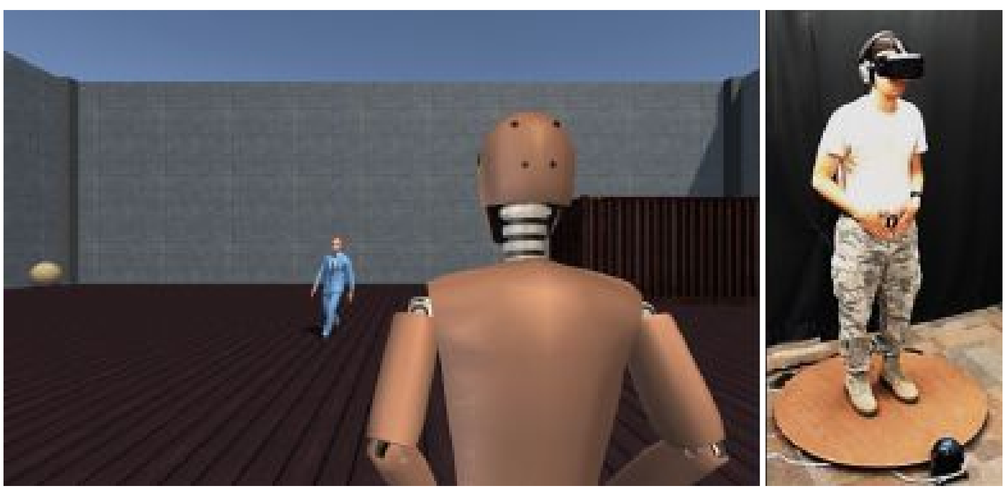


Figure 4.1: Each participant inhabited the virtual dummy shown in the left image, and observed the virtual environment from the dummy's perspective. The participant's head position/orientation were tracked and applied to the dummy's body posture to induce a virtual body-ownership illusion. Participants were asked to put both hands on their waist during the experiment, to avoid breaks in presence (shown in the right image).

4.2.2 Experimental Setup

Virtual Environment

Our virtual environment for this experiment comprised of a square space with a wooden floor surrounded by cement brick walls. Participants inhabited the virtual dummy shown in Figure 4.1, and observed the virtual space from its perspective. The participants wore an Oculus Rift DK2 HMD tracked by the Oculus tracking camera, and motion was applied to the dummy's head. The body—mainly its neck, spine, thighs, knees—was controlled based on the head motion using inverse kinematics. We placed a directional light that cast a shadow of the body in the front direction such that the participant could see their body motion from the shadow. The virtual space included a ball, a shipping container, a ladder on the right wall, and a VH. The ball and the VH were the only virtual entities that moved over the floor during the simulation. The shipping container hid the ball and the VH from the participants' view at the beginning of the experiment. The VH did not make any conversation with participants. Instead, the VH exhibited "walking", "pacing back and forth", and "looking vacantly in a direction" behaviors (see Figure 4.2). Prerecorded footstep sounds—footstep sounds on a wooden floor as seen on the HMD—were played when the VH's sole touched the floor. In addition to the internal 3D sound setting of the Unity engine, we used the footfall distance of each gait to control the volume of the footstep sound such that the volume matched the VH's pacing behavior.

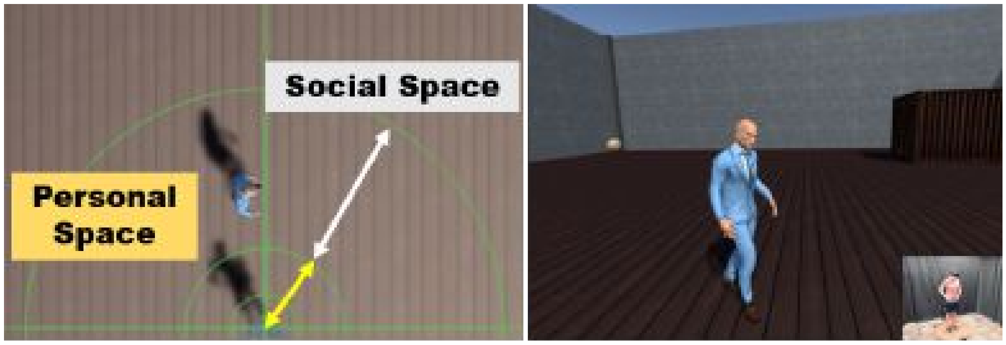


Figure 4.2: The virtual human was pacing back and forth in the social space (left). While pacing, the virtual human invaded the participant's personal space multiple times [54]. The right image shows a participant's view when the virtual human is pacing in the social space.

Footstep Platform

We designed and built a wooden platform to stimulate the soles of the participants' feet with vibrational feedback that can be observed when standing on a wooden floor. The platform comprises a round wooded board around one meter in diameter. Three equally-spaced floor plates support the wood at the curved boundary. Each plate has four rubber legs for vibration isolation, and one thin rubber pad to reduce vibration noise. The thin rubber pad covered roughly half of the top surface. The wood is mounted on top of the thin rubber pads (see Figure 4.3). We added a rubber support bumper between each plate for added stability. We used the ButtKicker LFE transducer [1]. The transducer was firmly mounted on the front floor plate (see Figure 4.4) as the VH approached from the front. An amplifier included in the Buttkicker LFE kit was used to amplify the sound source. We configured the amp such that participants could feel the footsteps gently when the VH paced in the social space. The amp configuration was the same for all participants.

[1] http://www.thebuttkicker.com/

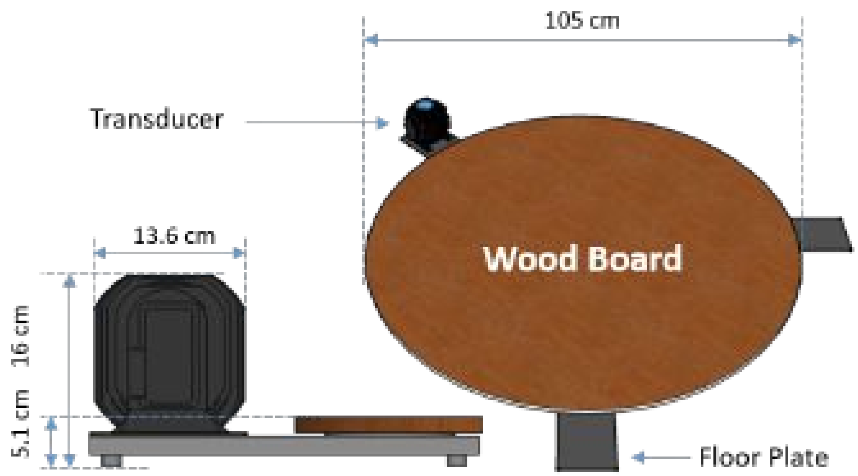


Figure 4.3: Footstep platform: We placed a round wooden board on top of three floor plates. For added stability we added rubber support bumpers between each plate at the boundary. A low frequency audio transducer was mounted at one of the floor plates. Participants stood in the center of the platform during the experiment.

Setup

This experiment was conducted in a laboratory room prepared as shown in Figure 4.4. We placed a wooden platform near an edge of the experimental space. On the other side of the space, the Oculus Rift DK2 tracking camera was slightly tilted down and placed about 1.7 m above the floor using a tripod. We attached the ButtKicker low frequency audio transducer to the front side of the platform. We used the Alesis MultiMix4USB[2] audio mixer to split the audio source from the graphics workstation on which the Unity engine was running. One branch of the audio source was amplified and fed to the transducer while the other branch of the audio source was fed to a Bose QuietComfort 15 acoustic noise canceling headphone[3] that was worn by the participants in the experiment in order to block out noises from the real world. The experimenter was able to

[2]http://www.alesis.com/

[3]http://www.bose.com/

selectively turn on/off each branch of the audio source depending on the experimental condition.

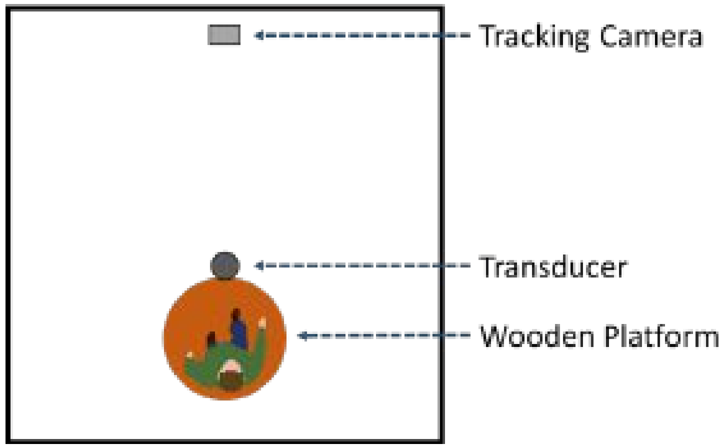


Figure 4.4: We used a 3.25 m (width) $\times$ 3.43 m (length) space surrounded by black curtains. The footstep platform was 105 cm in diameter. The distance between the center of the platform and the tracking camera was 2.46 m. The tracking camera was placed at 1.7 m above the floor. The transducer was attached to the front side of the platform. Participants were guided to stand in the center of the platform (see Figure 4.1).

4.2.3 Method

Study Design

We used a between-subjects design for this experiment. Participants were randomly assigned to one of the three conditions described below.

- **Mute**: The footstep sounds were not played in this condition, and vibrotactile feedback was not supplied.
- **Sound**: The footstep sounds were played, but the vibrotactile feedback was not supplied (we turned off the transducer).

- **Vibration**: The footstep sounds were played, and the vibrotactile feedback associated with the footsteps were generated.

In all conditions, the noise canceling functionality of the headphone was active.

Scenario

At the beginning of the experiment, the ball and the VH were placed near the right side wall behind the shipping container and were thus hidden from the participant's view. As the simulation started, the ball started rolling toward the left wall slowly. Once the ball hit the left wall and stopped, the VH started walking toward the participant, making a gently curved path. When the VH entered the participant's social space (3.6 m distance from the participant [54]), the VH started pacing back and forth for about a minute (see Figure 4.2). At the beginning of the pacing phase, the VH slightly invaded the participant's personal space (1.2 m distance from the participant [54]) five times. After the pacing phase, the VH stopped and looked at the left wall vacantly (from the participant's viewpoint) for about twenty seconds. Then, the VH returned to the container from where it started (see Figure 4.5).

Measures

Subjective Measures

We measured presence and social presence primarily with a combination of post-experiment subjective surveys. We used the social presence questionnaire by Bailenson et al. [11] and the presence questionnaire by Witmer and Singer [140]. Participants responded in seven-point Likert scales for each question. Since our experiment did not involve 3D navigation, object manipulation, questions

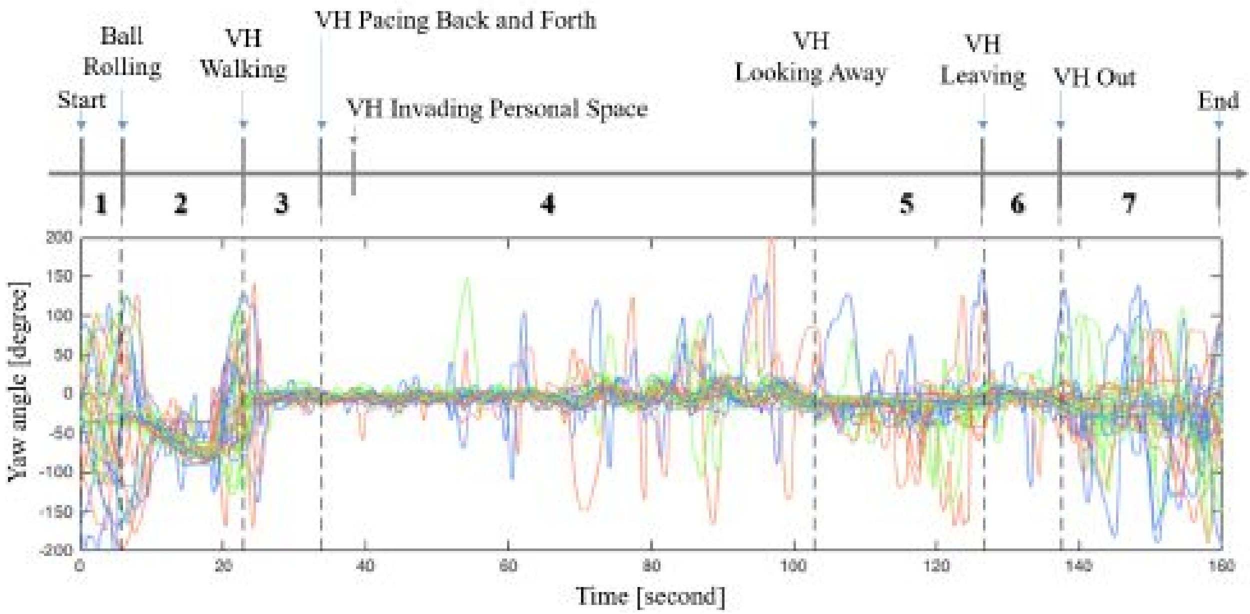


Figure 4.5: Simulation timeline (up): Starting times for major events were marked on the timeline. We divided the simulation into seven phases for behavior analysis. We named each phase for the sake of convenient reference as follows: 1 – Start, 2 – Ball rolling, 3 – VH face, 4 – VH pace, 5 – VH stop, 6 – VH back, 7 – End, from 3 to 6 – VH visible; Participants' head gaze behavior (down). Yaw angle difference between the head gaze direction and the VH's head position (0°: VH's head position, negative: left, positive: right) were plotted (Mute: blue, Sound: green, Vibration: orange).

specific to those aspects were removed from the Witmer and Singer presence questionnaire. We measured social presence indirectly through questionnaires that assessed two possible correlates of high social presence, affective attraction (or liking) [59] and anxiety [139]. We also performed a manipulation check, a measure often used in a social science study to determine whether an independent variable varies in ways researchers expect; Participants answered yes/no to questions asking whether they heard repeated sounds and perceived vibrotactile feedback associated with the footsteps during the simulation in the survey; we did not use any sentences that imply the association in the survey, and they were further asked to depict the sources of the sounds and the vibrations. Lastly, participants provided informal comments on the interaction verbally and on paper.

Behavioral Measures

During the experiment, the participant's head was tracked with the Oculus Rift DK2 tracking system. From the head position and orientation we derived the following behavioral measures.

Kinetic Energy: We calculated the kinetic energy of the participants' head motion by assuming the head as a solid sphere having average human head mass ($5kg$) and size ($56cm$) for all participants.

Dwell Time on VH/Ball: We converted head gaze—a proxy to eye gaze—into yaw and pitch angles from the VH's head and the Ball positions respectively. Then, we calculated the duration where both yaw/pitch angles were below a threshold angle ($10°$) per each phase (see Figure 4.5) [67].

Avoidance Magnitude: As described above, the VH invaded the participant's personal space during the "VH pace" phase. We calculated a backing away head distance—a proxy to making a step backward in the real world—for the first personal space invasion. We measured the distance within a two seconds time range—one second before/after the invasion moment.

Skin Conductance Response: We used the Empatica E4[4] (a wrist-worn physiological monitoring device) to measure the participants' skin conductance response (SCR). We used the Ledalab[5] Matlab-based software to decompose the SCR into continuous signals of tonic and phasic activities [16]. We calculated a summed phasic activity for the first personal space invasions (sum of phasic activity from the moment the VH invaded to four seconds after).

[4]http://www.empatica.com/

[5]http://www.ledalab.de/

Procedure

When participants arrived we asked them to read and sign the informed consent, and fill out a demographics questionnaire. Then, we guided them to the experimental space and explained that their task was to stand in the center of the platform and observe the virtual space. We instructed them to place both hands on their waist, and not to move their feet during the experiment. After the instruction, participants donned the physiological sensor (a wrist band) and the HMD. An experimenter helped them to don the noise canceling headphones over the HMD. The participants were asked not to look around until the experimenter told them to start. The experimenter told them to start through the headphones, and the participants experienced the simulation as described above. When the simulation was done, the experimenter helped them doff the devices, guided them to the questionnaire area, had them complete a post-questionnaire, and gave them the compensation.

4.2.4 Participants

We recruited 41 undergraduate and graduate students within our university community (15 female, 26 male, mean age: 24.2, age range: 19–34 years). All participants received $15 as a compensation for their participation. The average duration of the experiment was about forty minutes.

4.3 Results

We performed Kruskal-Wallis H tests on each measure with Dunn's tests with Bonferroni correction for the post-hoc pairwise comparisons. We removed participants who did not pass the manipulation check (seven participants) and who did not complete the survey (two participants). We analyzed data from 32 participants (mute: 11, sound: 11, vibration: 10).

4.3.1 Subjective Measures

Social Presence

The results of Bailenson's social presence questionnaire are shown in Figure 4.6 (left). We analyzed the questionnaire by averaging the five responses—scores for question 3 and 5 were inverted (see [11]). A higher value indicates that the participants estimated the VH as conscious, aware, and alive. We conducted a Kruskal-Wallis H test on the averaged scores at the 5% significance level. We found a significant main effect of the conditions on social presence, $\chi^2(2) = 6.09, p < 0.05$. Post-hoc comparisons indicated that the social presence score in the vibration condition was significantly higher than in the sound condition ($p < 0.05$).

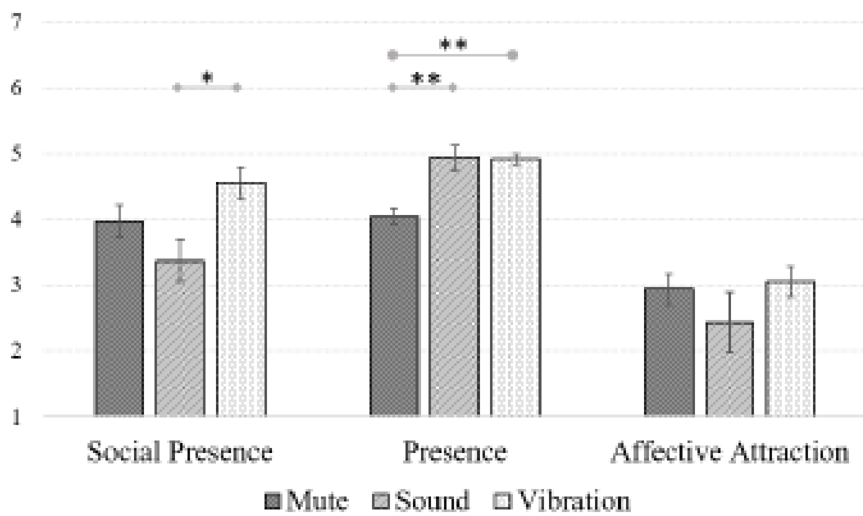


Figure 4.6: Means of social presence, presence, and affective attraction scores for each condition. Error bars represent the standard error, * ($p < 0.05$) and ** ($p < 0.01$) indicate statistically significant differences.

Presence

The results of the presence questionnaire are shown in Figure 4.6(center). As described in the measurements section, we used a subset of questions from the Witmer-Singer questionnaire [140]. We averaged the scores, computing an aggregated presence score. We used a Kruskal-Wallis H test on the aggregated scores at the 5% significance level. We found a significant main effect of the conditions on presence, $\chi^2(2) = 15.2, p < 0.001$. Post-hoc comparisons indicated that the mean score in the mute condition was significantly lower than in the sound condition ($p < 0.01$) as well as in the vibration condition ($p < 0.01$).

Affective Attraction and Anxiety

The participants' attraction to the VH in terms of the affective attraction items from [59] are shown in Figure 4.6 (right). The five sub-items were rated on seven-point Likert-scales. We averaged all items to construct an aggregate affective attraction score. We conducted Kruskal-Wallis H tests on the aggregated affective attraction scores as well as on the aggregated anxiety score at the 5% significance level. We found no significant main effect of the conditions on affective attraction, $\chi^2(2) = 3.73, p = 0.16$. However, note that in all conditions the mean values were below four, which means that the participants rated the VH with strong negative affect in general. Also, we found no significant main effect of the conditions on aggregated anxiety scores, $\chi^2(2) = 0.85, p = 0.65$.

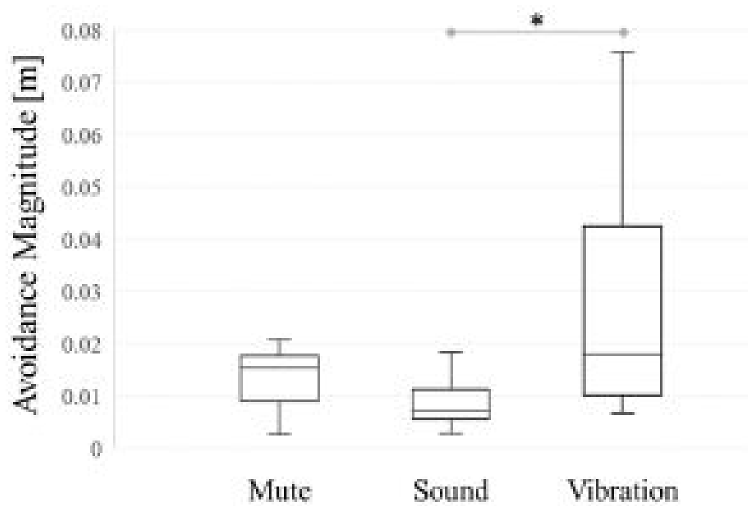


Figure 4.7: Avoidance magnitude for the personal space invasion for each condition. * ($p < 0.05$) indicates statistically significant difference.

4.3.2 *Objective Measures*

Avoidance Magnitude

Figure 4.7 shows the calculated backward head translation for the VH's first invasion of the participant's personal space. The backward head motion was calculated in a time range between one second before/after the invasion moment. A Kruskal-Wallis H test was conducted on the back-away distance. We found a significant main effect of the conditions on the back-away distance, $\chi^2(2) = 8.04, p < 0.05$. Post hoc comparisons indicated that the mean distance for the vibration condition ($M = 2.7cm, SD = 2.3cm$) was significantly different from the sound ($M = 0.9cm, SD = 0.5cm$) conditions ($p = 0.016$).

Gaze Behavior

Figure 4.5 shows all participants' head motion in yaw angle during the simulation. We computed a Kruskal-Wallis H for each variable, e.g. the dwell time on the VH during the VH pacing. We found no significant main effect of the conditions on the dwell times and the kinetic energies for all time periods.

However, when we analyzed the head gaze behavior (yaw and pitch angles—see Figure 4.8) we found a difference in participants' pitch behavior for the time periods "VH visible" and "VH stop". Two outliers were omitted. We used the common rule of 1.5 interquartile ranges to detect the outliers [101]. For the pitch variance during "VH visible", we computed a Kruskal-Wallis H which showed a significant main effect, $\chi^2(2) = 7.02, p < 0.05$ and post hoc comparisons showed a significant difference in pitch variance between the sound condition and the vibration condition ($p = 0.031$). For the "VH stop" period, a Kruskal-Wallis H and post hoc comparisons showed a significant main effect, $\chi^2(2) = 7.68, p < 0.05$, and a significant difference between the sound and vibration conditions ($p = 0.017$).

Skin Conductance Response

Similar to the avoidance magnitude, we generated a phasic SCR sum for the first social space invasion (see Section 4.2.3). The time window used for the SCR sum was from the invasion moment to four seconds after as there was a delay between a SCR and stimulus [16]. We computed a Kruskal-Wallis H on the phasic SCR sum. The result showed no significant main effect of the conditions on skin conductance, $\chi^2(2) = 0.94, p = 0.63$.

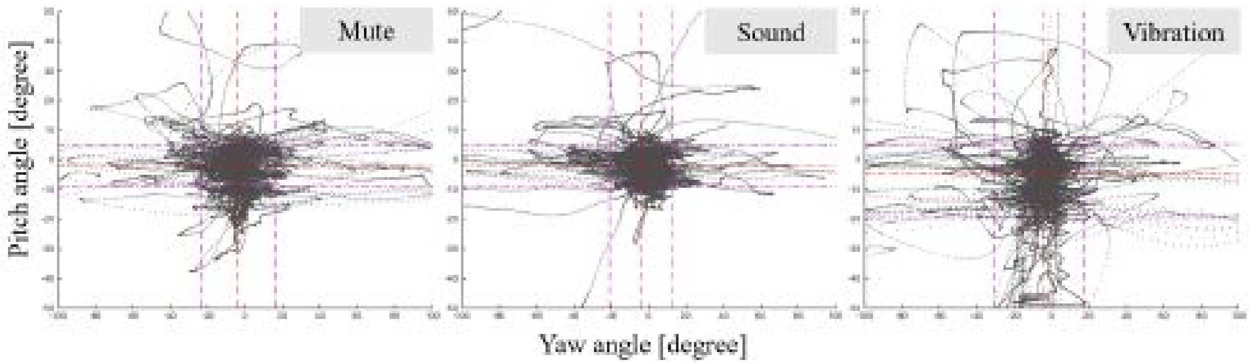


Figure 4.8: Participants' head movement trajectories relative to the VH during the "VH visible" phase of the interaction, i.e. phases 3–6 in Figure 4.5. The polar origin (0,0) of each plot corresponds to the direction from the participant's head to the VH; the pitch (up-down) and yaw (left-right) motion represent head excursions away from the VH. The standard deviations (purple lines) and medians (red lines) are indicated.

4.4 Discussion

Overall, the results show strong support for our hypotheses, which underline the importance of vibrational haptic feedback in VEs.

Bailenson's questionnaire showed a significant increase in social presence in the "vibration" condition compared to the "sound" condition, which supports H1, although we did not find a significant difference between the "vibration" and the "mute" condition. Regarding the surprisingly low social presence score in the "sound" condition, we speculate that this might be related to a violation of sensorimotor contingency (between sound and vibration), i.e., a situational implausibility that sound could be heard but not felt in this environment [126].

Regarding the behavioral responses, we found a significant difference in participants' gaze behavior in terms of head pitch movements between the conditions. Participants in the "vibration" condition exhibited more pitch motion than the other conditions when looking at the VH. We speculate that the negative affective attraction to the VH and the increased social presence might have led participants to avoid looking at the VH's face directly, resulting in greater pitch head motion, which is similar to results found in [105] when participants avoided looking at a VH with an angry face. We also analyzed participants' avoidance behavior when the VH invaded their personal space [11]. Participants in the "vibration" condition exhibited stronger avoidance behavior compared to the other conditions. We consider these two findings as support for H2.

We believe the increased social presence and realistic behavioral responses to the VH would not have been possible if participants did not correlate the provided footstep sounds and vibrations to the VH's walking behavior. Indeed, 92% of participants chose VH's footsteps as the cause of the repeated sounds they heard during the simulation, and 75% of participants also correctly correlated the vibrations with the VH's footsteps. The remaining 25% of participants depicted the floor as the source of vibrations, which seems to relate with their awareness of the mediating technology. We also received comments from our participants that implied the correlation between the vibrations and VH's footsteps, such as, *"It was amazing feeling the footsteps of him walking around. [...] I felt like I could almost touch him."*

Regarding skin conductance, we did not see any significant differences between the conditions. This could be explained by the results from [94]. In their experiment, they found that the skin conductance was increased in both a VH approaching condition and a human-sized inanimate object approaching condition, despite of the profound difference in qualitative response. Therefore, we consider the skin conductance response might not be an appropriate measure for the socially realistic behavior in this experiment.

We had considered including an additional "vibration only" condition in the experiment to examine the interaction effect between sound and vibration. However, vibrational platforms as the one developed for this experiment tend to generate a solid-borne noise due to the transducer and the vibrating wooden board such that a “vibration only” condition would have been confounded due to the low noise. By applying a low pass filter, the noise from the transducer could be reduced for the experiment, but the solid-borne sound from the wooden board could not. With regard to the ball, it was originally introduced to see the difference in participants’ behavioral toward a VH and an inanimate object. However, due to the short animated period of the ball compared to the VH, we did not perform any comparison. Most participants kept track of the ball once they found it moving.

While debriefing the participants we noticed that some of them stated that they did not notice the vibrations. It seemed to happen when they wore shoes with thick soles. We had considered this before running the experiment, but we had not wanted to produce an artificial situation by having them stand barefoot on the wooden platform. Even though the strength of the vibrations might have been reduced due to the shoes, the results still indicate a strong benefit of this condition over the others. We believe that by adjusting the strength of the vibrations based on the user’s shoes might further strengthen this effect.

Overall, based on our observations and findings in this experiment, we suggest the following implications and guidelines for future foot-related vibrotactile setups:

- A transducer such as the ButtKicker can produce mechanical noise that can penetrate noise canceling headphones. Superior headphones or masking sounds should be used.
- Each individual has a different sensitivity to the floor vibration, but the sensitivity is also affected by the user’s shoes, which can be compensated for.

4.5 Summary

In this chapter, we presented the first study that examined the effects of vibrotactile feedback through a shared floor on social presence in an IVE. For that, we built a vibrotactile feedback platform, the footstep platform, which can be easily adopted in other IVEs that exploit social interaction with VHs.

Our experiment revealed that the vibrotactile feedback of a VH's footsteps, when it was accompanied by appropriate sounds, can increase social presence of a VH in both subjective feelings and behavioral responses, compared to sounds only. We found that participants who experienced both the footstep sounds and vibrations exhibited a greater avoidance behavior to the unfavorable looking VH, e.g., avoided looking at the VH's face directly and moved their head backward more when the VH invaded their personal space.

Compared to the user study presented in Chapter 3, we further controlled factors that might affect the increased feelings of social/co-presence with VHs: namely, bidirectional influence through a shared object and the awareness of VH on the events mediated via the shared object. Therefore, the results are mainly attributed to the indirect physical influence of the VH. Although we did not have the vibration only condition in this study, the different patterns in presence and social presence scores between "Sound" and "Vibration" conditions imply that physicality illusion of the VH was only induced with vibrotactile feedback. In other words, as discussed in Chapter 1, the reference of physicality in an IVE is only a user himself or herself; therefore, one needs to perceive bodily sensations caused by a VH's actions to form an illusion of physicality of the VH. In the next chapter, the same mediated physicality method, i.e., footstep vibrations, is used in the real environment, but without footstep sounds. I discuss the limitations of AR HMDs in close proximity of VHs and investigate the effects of the footstep vibrations in two different AR view settings.

CHAPTER 5: FOOTSTEP VIBRATIONS THROUGH REAL FLOORS

From Chapter 3 and Chapter 4, I have demonstrated that users could associate the synthesized physical outcomes on a shared object with the actions of VHs. However, visually synchronized movements of the real-virtual table and the consistent visual quality of the VH and the virtual floor might have facilitated the association.

In this chapter, I apply the footstep vibrations to a VH in AR. Due to the limitations of the current state-of-the-art optical see-through AR glasses, the VH is visually distinct from the rest of the real world. Here, I examine whether users can make the association between the VH's actions and vibrations on real floors under such a condition.

With regards to the thesis statements, the relevant claims supported by this study are as follows:

- Naturally correlated cues associated with a virtual human's actions and physical outcomes can create a perception of physicality of the virtual human.
- Such perception of physicality can increase feelings of social/co-presence with the virtual human and induce realistic social behavior.
- Such feelings and behavior can be maintained despite the temporary absence of some of the originally present correlated cues.

This chapter substantially replicates a peer-reviewed paper, "Effects of Unaugmented Periphery and Vibrotactile Feedback on Proxemics with Virtual Humans in AR," published in the IEEE Transactions on Visualization and Computer Graphics (2018), co-authored with Gerd Bruder, Tobias Höllerer, and Gregory F. Welch [88]. Throughout this chapter, when I say "we," I am referring to these colleagues.

5.1 Overview

In this chapter, we discuss and evaluate two related factors affecting locomotion behavior and proxemics with a virtual human in AR, and compare them with behaviors in close proximity with a real human.

First, we examine the effects of the unaugmented periphery of the Microsoft HoloLens on human perception of a VH, and relevant changes in locomotion and proxemic behavior, by comparing two viewing conditions: an unrestricted but unaugmented periphery, and a physically restricted periphery. With an *unrestricted* periphery, the user is presented with a constant view of unaugmented peripheral imagery surrounding the augmented central region, and can thus be exposed to what we believe is an unnatural disappearance of part of a VH's body when the body crosses the boundary between the augmented central and unaugmented peripheral regions. With a *restricted* field of view, the user will *only* see the fully augmented central region, and because *all* imagery in the periphery will be blocked, we believe any "cropping" of VHs as they cross the boundary will appear more natural—it will be readily understood to be a consequence of the peripheral region being blocked. To test these ideas we examined how restricting the periphery affected a user's collision avoidance behavior for moving and non-moving VHs.

Second, we examine the possibility that a vibrotactile stimulus associated with physical movement of the VH (presented in synchrony with the visual stimulus) could compensate for the negative effects of the unaugmented periphery. We compared two corresponding experimental conditions: presentation of the VH visually, or presentation of the VH visually *together with* simulated VH's footsteps felt as vibrations through the floor, similar to the approach taken in Chapter 4. We examine whether the added vibrotactile feedback can indeed compensate for the restricted augmented visual field, and discuss the effects on perception and relevant locomotion behavior.

5.2 Issues with Optical See-through AR Glasses

Unlike immersive virtual reality, augmented reality allows users to see both real and virtual objects. In particular, optical see-through AR HMDs overlay virtual content on a users' natural view such that, with precise registration and tracking, the virtual content can appear seamlessly integrated into the real environment. When such AR technologies are applied to training simulations, trainees can practice their skills using a combination of real and virtual objects in the actual environments where the skills may be eventually used [58]. The behavior of the users in such circumstances are influenced by both real and virtual objects in that environment, therefore understanding how such real/virtual objects affect a users' behavior is of particular importance.

However there are limitations with state-of-the-art optical see-through AR HMDs that may affect a users' perception of real and virtual content [85]. First, the virtual content is semi-transparent, which can cause visibility issues in bright environments, and distort color perceptions due to the additive blending. Second, the augmented visual region is limited to a small central area, which can lead to a real-virtual information conflict between the central and peripheral vision, and produce unnaturally cropped virtual content. Finally, currently available AR HMDs are limited to visual and audio augmentation. All of these characteristics can affect one's perception of virtual content and therefore one's actions and reactions [126].

Significant prior research has examined the characteristics of AR/VR displays—e.g., screen size, field of view, resolution—and their effects on the user's perception and behavior. That research supports the ideas that such characteristics can influence immersion [63, 125], task performance [80, 113], and behavior with VHs [79, 111]. However, there has been relatively little exploration of the effects of the *unaugmented* real-world periphery in an optical-see-through AR HMD, and, to our knowledge, no prior work has investigated its effects on real-virtual human interaction. We believe that the constant presence of an unaugmented scene in the periphery (the absence of virtual information), could have unexpected consequences, especially when the *augmented* central area is relatively small. In particular, the progressive disappearance of the body of a VH passing in and out of the small augmented region, and the total absence of the body in the periphery, may reduce one's sense of co-presence with the VH. However we believe that these issues could be mitigated by other sensory information, e.g., vibrotactile feedback.

5.3 Experiment

In this section we present the experiment which we conducted to investigate the effects of the previously discussed related factors (real/virtual human obstacles, unaugmented visual field, floor-based vibrotactile feedback, and obstacle behavior) on locomotion behavior and proxemics in AR with a collision avoidance task.

5.3.1 Participants

We recruited 26 participants for our experiment, 14 male and 12 female (aged 20 to 50, $M = 25$). The participants were students or professionals from the local university community. All of the participants had correct or corrected vision; eight participants wore glasses during the experiment. None of the participants reported known visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. Fifteen participants reported that they had used AR head-mounted displays before, and two of them rated themselves as a frequent user. All participants reported that they were right-handed and twenty-three reported that they were right-footed, which we confirmed with the Lateral Preference Inventory questionnaire [31]. We measured the interpupillary distance (IPD) of each participant before the experiment and applied it to render the virtual content on the HoloLens ($M = 6.18\,\text{cm}$, $SD = .35\,\text{cm}$). Moreover, we measured the eye height of each participant ($M = 1.57$ m, $SD = .25$ m).

5.3.2 Material

As illustrated in Figure 5.2, we built a runway-like platform with a size of 6.4 m (length) $\times$ 2.13 m (width). On each end, at a distance of 0.4 m, we marked a start position and an end position with white and yellow tape, respectively. They were symmetrically aligned around the center position where a human obstacle (described below) was located closer to the edge of the platform. Because the platform is about 5 cm raised from the floor, we added safety lines around the platform (see Figure 5.1).

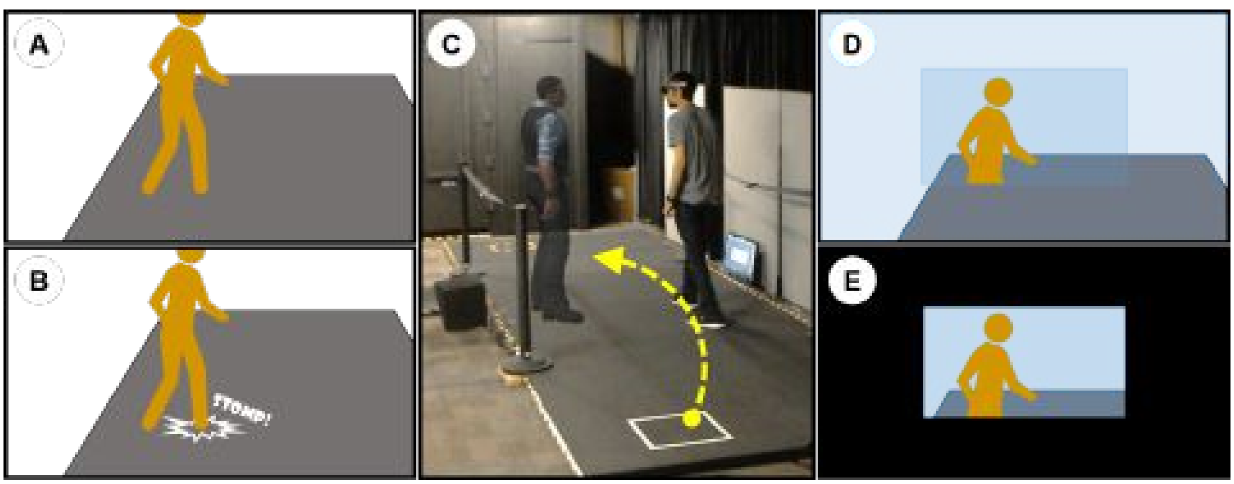


Figure 5.1: Participants in our study performed a locomotion task while avoiding collisions with a real or virtual human obstacle (C). In this setting, we manipulated the virtual human's floor-based vibrotactile feedback (A: footsteps did not make any vibration, B: footsteps vibrated the platform); the user's visual field (D: both augmented central area and unaugmented periphery were visible, E: field of view was restricted to the augmented central area); and the behaviors of the human obstacle (standing, jumping, walking).

Human Obstacles

Our participant's task was to walk from one end of the platform to the other while avoiding an obstacle in between. At the center of their path we placed an obstacle, which was either a RH or a VH. In a baseline condition, we asked participants to cross the platform without any obstacle. Both RH and VH exhibited three behaviors: (a) standing with idle behavior, (b) repeatedly jumping up and down, or (c) walking back and forth along the lateral axis of the platform, perpendicular to the participant's path (see Figure 5.3). For the VH, we choose a male 3D character model with a similar height ($1.75\,\mathrm{m}$) and body shape as the RH counterpart (a male actor). The VH and RH wore sunglasses to avoid any effect of eye contact on locomotion behavior during the study. The initial position of the human obstacle was at the center of the platform as shown in Figure 5.2. For the VH, we used predefined animations for the behavior, which were rendered using the Unity rendering engine. For the RH, a trained real human actor was mimicking the animations of the VH. In order to ensure a close match between the movements of the VH and RH, we provided the real human actor with two stage monitors that were located on the left and right side of the platform at the actor's position. On the monitors, we presented a real-time view of the platform and the movements that had to be matched. We trained the real human actor and confirmed the close match between the movements with an OptiTrack Duo optical motion tracking system before running the experiment.

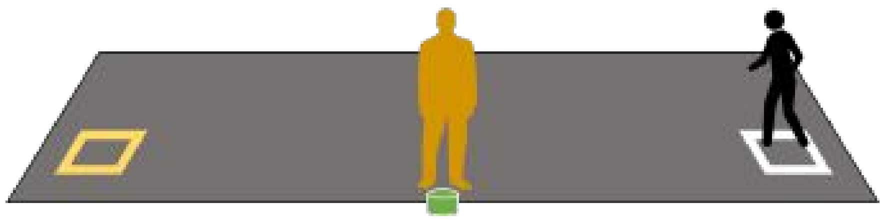


Figure 5.2: Layout of the experimental platform: The white and yellow boxes represent the participants' starting position and the turning position, respectively. The green cylinder represents the position of the transducer attached to the platform. The real human or virtual human obstacle are positioned as indicated by the orange colored human model.

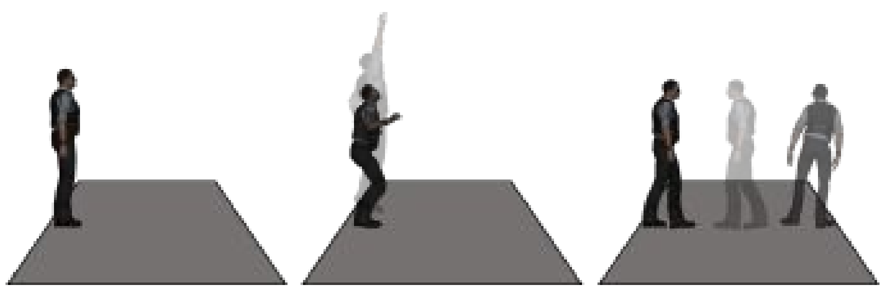


Figure 5.3: Obstacle behavior from left to right: (standing) the human stands and looks around idly, (jumping) the human jumps in place around 22 times/min, and (walking) the human walks back and forth along the shorter edge of the platform at .27 m/s.

Head-Mounted Display

We used a Microsoft HoloLens for the stimulus presentation in this experiment. As an optical see-through head-mounted display, the HoloLens provides a narrow (ca. 30 degrees horizontally by 17 degrees vertically) augmented field of view in the central region of the total human visual field (ca. 220 degrees horizontally by 120 degrees vertically) [109]. Therefore, a person wearing the HoloLens usually perceives a large unaugmented visual field in the periphery of the display. This means that if a virtual object is larger than the augmented central region, then the virtual object will progressively disappear as it passes into the unaugmented region. Such vanishing visual information does not naturally occur in normal viewing of healthy observers, and may negatively affect the overall AR experience. This is a particularly challenging issue when a virtual human is presented in close proximity of the observer, since at no point can the entire body of the VH be seen through the HoloLens, which can give rise to a visual conflict between the real and virtual world (see Figure 5.4 left column). In order to avoid such a conflict we devised a thin physical cover for the HoloLens that could block the unaugmented peripheral visual field, and we attached the cover to the inner side of the visor (see Figure 5.4 right column). Hence, the two considered viewing setups in this experiment were as follows.

- Unrestricted View: Participants can see both augmented central and unaugmented peripheral regions, allowing real-virtual visual disappearance/reappearance (Figure 5.4 left column).
- Restricted View: Participants can only see the augmented central region, eliminating the disappearance issues, but reducing the overall field of view (Figure 5.4 right column).

Figure 5.4: View conditions and captured photos for each condition: (left) unrestricted, (right) restricted. The augmented field of view is 30°x17°. The images here show only a small peripheral area because of photographing constraints. The peripheral FOV perceived through the HoloLens is much larger.

Footstep Vibration

To induce visually synchronized vibrations on the platform, we attached a transducer to the edge of the platform near the VH's position. We used the ButtKicker LFE Kit[1] covered with a black sound-proof box. To generate the vibrations, we used a client-server model. The client running on the HoloLens rendered the VH on the platform and sent a message to the server for all collisions between the VH's foot and the platform. The server played a pre-recorded low-frequency sound for the impacts, which was fed to the transducer through the ButtKicker amplifier. The communication between client and server was done through the Unity HLAPI, and both were connected to an

[1] `http://www.thebuttkicker.com`

ASUS RT-AC5300 high-speed router. Since the VH's animations were pre-recorded, collisions between the character's feet and the floor did not have to be computed in real time. The result was synchronous visual cues on the HoloLens and vibrotactile cues on the platform.

Tracking

During the experiment, we tracked the participant's head position and orientation as well as the real human actor. In particular, we logged the HoloLens' pose estimation in the tracking space. In order to ensure accurate pose estimations by the HoloLens, we made sure that sufficient feature points and light were available in the entire walking area. For the RH, we used an OptiTrack Duo mounted on the ceiling at the platform and had the RH actor wear an infrared marker on his head. All tracking data was logged on the server.

5.3.3 Methods

We chose to use a within-subjects design in this experiment due to the expected interpersonal differences in locomotion behavior in such experiments [41]. The independent variables were

- *Obstacle type* (Real Human, Virtual Human, None),
- *Obstacle behavior* (Standing, Jumping, Walking),
- *View condition* (Restricted, Unrestricted), and
- *Vibrotactile feedback* (On, Off).

For the RH conditions, the vibrations were naturally accompanied by the RH's footsteps, i.e., we did not add additional vibrotactile feedback via the transducer. Due to the time overhead for changing the obstacle type and the cover between view conditions in the experiment, we chose to use a randomized block design with the obstacle type and view condition as blocking factors, i.e., we tested these conditions as a block, but we randomized the order of the blocks as well as the conditions that were tested within the block. For each combination, we performed two repetitions, resulting in 36 trials per participant. Additionally, at the beginning of the experiment, participants performed two trials without any obstacle per each view condition in order to gather baseline locomotion data. Table 5.1 summarizes the conditions.

Table 5.1: Overview of the study conditions. Each column refers to factors we controlled. The rows indicate the tested combinations. The three obstacle behaviors refer to Standing, Jumping, and Walking.

Obstacle	**View**	**Vibration**	**Behavior**
None	Unrestricted	-	-
	Restricted	-	-
Real Human	Unrestricted	-	S,J,W
	Restricted	-	S,J,W
Virtual Human	Unrestricted	On	S,J,W
		Off	S,J,W
	Restricted	On	S,J,W
		Off	S,J,W

Procedure

Prior to the experiment trials, participants gave their informed consent and filled out a demographic questionnaire, the Lateral Preference Inventory [31], and the Simulator Sickness Questionnaire [73]. After the participants completed the pre-questionnaires, they received written task instructions and the experimenter made sure that they understood the tasks in a walk-through of the experiment.

At the beginning of each trial, participants were instructed to stand still at the start position (inside the white box, c.f. Figure 5.2). Once they heard a bell sound from the HoloLens, they had to walk naturally at a comfortable pace to the turn position at the other end of the platform (yellow box). When they arrived at the turn position, they were asked to stop for three seconds, turn on the spot, and head back to the start position, again walking naturally at a comfortable speed. After arriving at this position, we again asked them to stop for three seconds before turning around. These three-second stops ensured that the start-stop walking segments were clearly distinguishable in the tracking data, and prevented participants from adopting a curved trajectory at each end.

We regarded walking from the start position to the turn position and coming back to the start position as one trial, consisting of two movement segments. Participants performed 40 trials in total consisting of trials with no obstacle (4 trials), RH obstacle (12 trials), and VH obstacle (24 trials). The experimenter helped them adjust the HoloLens correctly each time the view condition changed. For the VH conditions, we divided trials into four groups based on the view condition (2 levels) and vibrotactile feedback (2 levels). The order of the groups was randomized, and upon completion of each group participants took off the HoloLens and filled out post-group questionnaires. After completing all trials, participants filled out post-experiment questionnaires consisting of the Simulator Sickness Questionnaire and open questions, and received a monetary compensation.

Behavioral Measures

While performing the locomotion task, participants' head position and orientation were tracked by the HoloLens tracking system over time. As illustrated in Figure 5.5, the platform's longer edge is aligned with the x-axis and the shorter edge is aligned with the y-axis in a right-handed Cartesian coordinate system with the obstacle's initial position as the origin $(0, 0)$. The logged tracking data ranged from the start to the turn position on the x-axis, resulting in an overall range of $[-3\,\mathrm{m}, 3\,\mathrm{m}]$. The considered range along the y-axis was $[0\,\mathrm{m}, 2.13\mathrm{m}]$. However, in order to account for observed variability in acceleration/deceleration at the starting/turning positions, we limited our analysis of the considered range along the x-axis to the central range of $[-2\,\mathrm{m}, 2\mathrm{m}]$. As discussed in Section 5.3.3, each trial consisted of two movement segments (walking back and forth), which we analyzed separately. From the tracking data we extracted the following variables (see Figure 5.5).

- *Passing distance*: The distance on the y-axis between the participant and the obstacle at the moment when the participant passed the obstacle, i.e. the moment when the x-axis position of the participant and the obstacle were matched.
- *Walking speed*: The average walking speed per each path.
- *Trajectory length*: The path length of the trajectory that participants walked.
- *Head motion*: We calculated the head motion of the participant by calculating the length of the trajectory the participant's gaze traveled in a unit sphere that surrounds the head.
- *Observation ratio*: The ratio of time devoted to looking at the obstacle before they passed the obstacle.

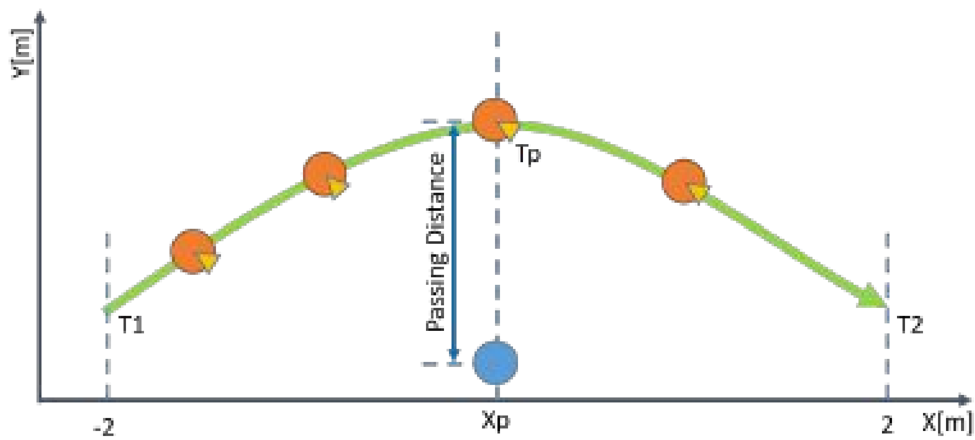


Figure 5.5: Illustration of the behavioral data analysis: The blue circle indicates the obstacle, and the orange circles the participant at different timestamps. The green line indicates the participant's walking trajectory (here from left to right). The yellow triangles indicate the participant's view direction. When participants passed the obstacle (at timestamp T_p), the x-axis positions of the obstacle and participant matched (at X_p). The *passing distance* is computed as the distance between the participant and the obstacle at time T_p. The *trajectory length* (L) is the length of the green line. The *walking speed* is computed as $L/(T_2 - T_1)$, with the timestamps T_2 and T_1 when entering and exiting the region of interest $[-2\,\mathrm{m}, 2\,\mathrm{m}]$ on the x-axis.

Subjective Measures

Results from previous studies considering VHs imply that one's perception of a VH regulates one's behavior to the VH (see Section 2.3). Hence, we included subjective measures assessing how the participants felt about the VH. We measured social presence (the likeness to an actual human being), co-presence (the sense of being together), perceived physicality (being able to physicality affect one), and perceived intelligence. Therefore, we used the social presence questionnaire (SPQ) by Bailenson et al. [11] and the co-presence questionnaire (CPQ) by Basdogan et al. [14]. In both SPQ and CPQ, we modified each question to refer to the VH as "Jack" instead of "the person" or "the other person"; for CPQ we also removed inappropriate questions related to the manipulation task that was used in their study; each question was rated on a 7-point Likert scale. Additionally, we designed four task-related questions to measure how much participants perceived the VH as being able to physicality affect them and being intelligent; each of these questions was rated on a 5-point Likert scale. All questions are listed in Table 5.2.

Table 5.2: Questionnaire used to assess the participants' perception of the VH obstacle (called *Jack*) with the dimensions social presence (SP1 to SP5), co-presence (CP1 to CP5), perceived physicality (PH1 to PH3), and perceived intelligence (PI). The social presence and co-presence questions were answered on 7-point Likert scales, and the perceived physicality and intelligence questions on 5-point Likert scales.

ID	Question
SP1	I perceive that I am in the presence of Jack in the room with me.
SP2	I feel that Jack is watching me and is aware of my presence.
SP3	The thought that Jack is not a real person crosses my mind often.
SP4	Jack appears to be sentient (conscious and alive) to me.
SP5	I perceive Jack as being only a computerized image, not as a real person.
CP1	To what extent, if at all, did you have a sense of being with Jack?
CP2	Do you remember this as more like just interacting with a computer or with another person?
CP3	To what extent did you forget about Jack, and concentrate only on doing the task as if you were the only one involved?
CP4	To what extent was your experience in passing by Jack like that other real experience?
CP5	Overall rate the degree to which you had a sense that there was another human being interacting with you, rather than just a machine?
PH1	I felt as if Jack could walk through me.
PH2	I felt as if Jack could touch me.
PH3	I felt cautious when Jack was close to me.
PI	I felt Jack had the intelligence to avoid collisions.

5.3.4 Hypotheses

Based on the related work, our study design, and data from a pilot evaluation, we formulated the following hypotheses for the behavioral measures:

H1 Participants will exhibit different (e.g., less natural, energy efficient, or slower) locomotion behavior with the VH obstacle compared to the RH obstacle.

H2 Participants will exhibit different (e.g., less stable, efficient) locomotion behavior with more head motion when the field of view is restricted compared to when it is unrestricted.

H3 Participants will exhibit locomotion behavior with the VH obstacle that is more similar to the RH conditions when the field of view is restricted (i.e., the real-virtual conflicts in the periphery of the display are removed) than when it is unrestricted.

H4 Participants will exhibit locomotion behavior with the VH obstacle that is more similar to the RH conditions when footstep vibrations are induced than when they are absent.

Moreover, we formulated the following hypotheses for the subjective measures:

H5 Participants will feel higher social presence and co-presence with the VH in the restricted view condition (i.e., without real-virtual conflicts) compared to the unrestricted condition.

H6 Participants will feel higher social presence and co-presence with the VH and feel higher perceived physicality of the VH when they experience vibrations seemingly caused by the VH's behavior.

5.4 Results

We first present the descriptive and inferential statistical analysis of the quantitative behavioral measures, followed by the subjective questionnaire responses.

5.4.1 Behavioral Measures

Figure 5.6 shows the averaged paths pooled over all participant trajectories in the different experimental conditions. Figure 5.7 shows the means and 95% confidence intervals for the three factors obstacle type, obstacle behavior, and view condition, for the five behavioral measures.

We found no significant differences between the paths when participants walked back or forth on the platform, as well as no lateral preference effects, so we pooled the responses. We analyzed the results with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We confirmed the normality with Shapiro-Wilk tests at the 5% level and QQ plots. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

Passing Distance

We found a significant main effect of each of the three factors obstacle type, obstacle behavior, and view condition, on passing distance (see Table 5.3). Pairwise comparisons revealed that participants kept a significantly larger distance from the obstacle when the view was restricted. Moreover, they revealed that participants kept a significantly larger distance from the VH than from the RH. This result in AR is in line with a similar effect found in an immersive virtual environment by Argelaguet et al. [4]. Regarding the effect of behavior, for both obstacle types, the distance was significantly monotonically increased in order of standing, jumping, and walking. However, the magnitude in the increase from standing to jumping was more drastic with the VH than with the RH (see Figure 5.7a and Figure 5.7b).

Table 5.3: Summary of the ANOVA results for the three factors obstacle type, obstacle behavior, and view condition for the behavioral measures.

Factor	*Passing Distance*			*Walking Speed*			*Trajectory Length*		
	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Obstacle	19.72	<**.001**	.441	9.58	**.005**	.277	7.66	**.010**	.234
Behavior	23.01	<**.001**	.480	35.18	<**.001**	.590	17.84	<**.001**	.420
View	8.18	**.008**	.247	26.64	<**.001**	.516	.062	.805	.002
Obstacle:Behavior	6.61	**.010**	.209	2.01	.162	.074	4.91	**.028**	.164
Obstacle:View	1.21	.280	.046	.39	.541	.015	7.20	**.013**	.224
Behavior:View	1.99	.148	.074	.03	.952	.001	7.66	**.010**	.234

Factor	*Head Motion*			*Observation Ratio*		
	F	p	η_p^2	F	p	η_p^2
Obstacle	11.97	**.002**	.277	5.91	**.023**	.191
Behavior	.26	.662	.590	132.15	<**.001**	.840
View	7.13	**.013**	.516	3.86	.061	.134
Obstacle:Behavior	1.65	.209	.074	4.59	**.027**	.155
Obstacle:View	.33	.572	.015	.002	.965	.000
Behavior:View	1.43	.249	.001	6.46	**.003**	.205

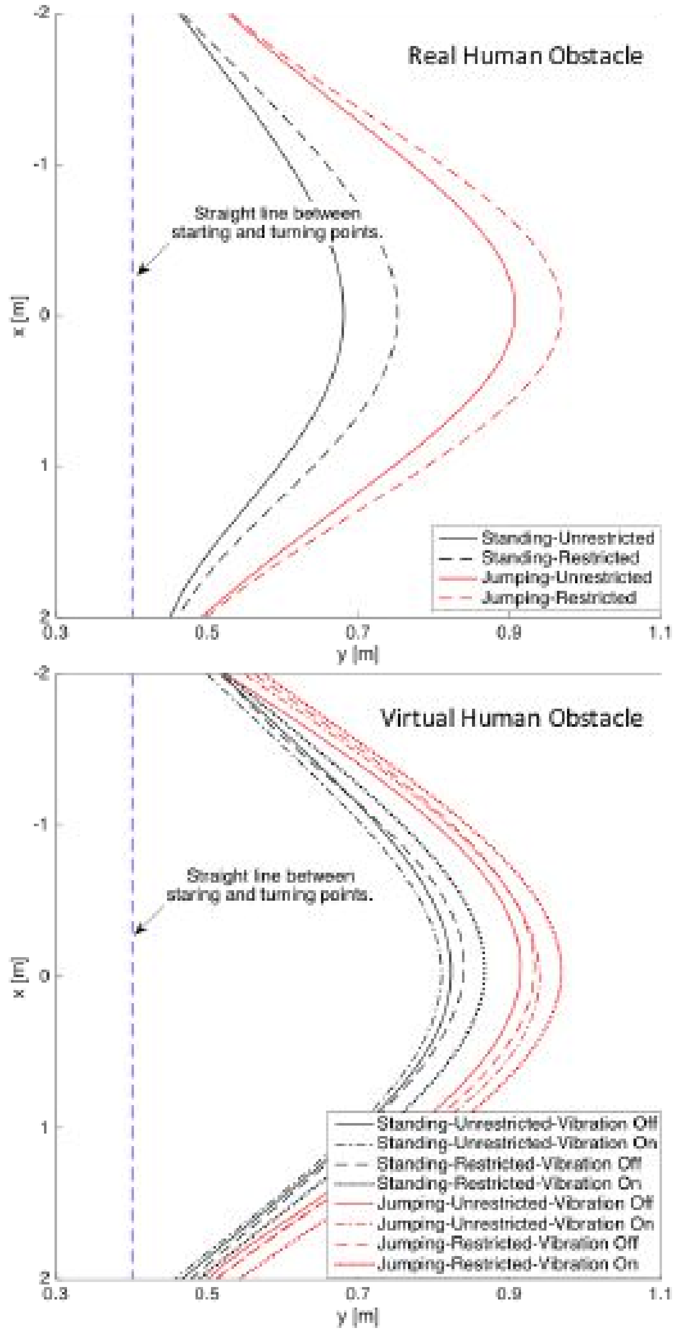


Figure 5.6: Plot of the averaged paths pooled over all participant trajectories in the different experimental conditions for real human obstacle (top) and virtual human obstacle (bottom). In both plots, the obstacle was located at position $(0, 0)$

Walking Speed

Again, we found a significant main effect of each of the three factors obstacle type, obstacle behavior, and view condition, on walking speed (see Table 5.3). Pairwise comparisons revealed that participants significantly decreased their walking speed in the restricted view condition, which is supported by results in [136, 137]. Also, participants walked significantly slower when passing the VH compared to the RH for all behaviors, which extends previous results found only for stationary obstacles in [4]. Regarding the obstacle behavior, participants did not change their walking speed for those obstacles that remained in a fixed position, i.e., in the standing and jumping conditions. However, they significantly slowed down for the moving obstacle, i.e., the walking condition, compared to the other behaviors. We have to point out that passing distance and trajectory length were also increased from standing to jumping. This favor of changing walking direction for non-moving obstacles and changing walking speed for moving obstacles may be explained by behavioral mechanisms as discussed in [102].

Trajectory Length

Here, we found a significant main effect of obstacle type and behavior on trajectory length (see Table 5.3). Moreover, we found significant two-way interaction effects between each two of three factors obstacle type, obstacle behavior, and view condition. Further tests performed for each obstacle type separately showed that the view condition still had a significant effect on trajectory length for RH, $F(1,25) = 8.35, p < .01, \eta_p^2 = .25$, but not for VH, $F(1,25) = 3.21, p > .05, \eta_p^2 = .11$; and multiple comparison with Bonferroni correction showed a significant increase from standing to jumping, and from standing to walking (see Figure 5.7d). However, in the ANOVAs performed for each combination of obstacle type and view condition, the difference between standing and walking was not significant (only) in the restricted view condition with the VH obstacle, implying that participants tried not to change their path. Note that the slowest walking speed was also found in this combination of restricted view with VH obstacle.

Head Motion

We found a significant main effect of obstacle type and view condition on head motion (see Table 5.3). Restricting the peripheral view on the HoloLens increased head motion, which is similar to the result reported for a helmet-mounted display in [47]. Participants moved their head significantly more in the presence of the VH compared to the RH. Further tests performed separately for each obstacle type revealed that the view condition did not have a significant effect on the participants' head motion for the VH, $F(1, 25) = .99, p > .05, \eta_p^2 = .04$, while it had a significant effect for the RH, $F(1, 25) = 9.87, p < .01, \eta_p^2 = .28$. Pairwise comparisons between behaviors revealed significant differences only in the combination of unrestricted view with the RH between all behaviors. Head motion was significantly increased in order of standing, jumping, and walking. We found no significant difference between behaviors in all other combinations of obstacle type and view condition (see Figure 5.7e).

Observation Ratio

We found a significant main effect of obstacle type and behavior on observation ratio (see Table 5.3). We also found significant interactions between obstacle type and behavior, and between view condition and behavior. Participants observed the VH more than the RH for all behaviors. However, the increase in walking was more striking compared to the other two behaviors (see Figure 5.7f). Regarding the view condition, there was a trend of participants observing the obstacle more when the view was restricted, but for the walking obstacle, the observation ratio was similar in both view conditions.

Effects of Vibration

Due to the partial factorial design, we analyzed the vibration factor separately from the three factors obstacle type, obstacle behavior, and view condition as it applies only to the VH conditions. To consider the effects of vibration on locomotion behavior, we performed repeated-measures ANOVAs for the vibration condition per each combination of factors obstacle behavior and view condition. For the standing behavior, we did not find any significant effect of vibration in the unrestricted view condition. However, in the restricted view condition, there was a trend that participants kept a larger distance when they felt the vibrations ($M = .831\,\text{m}$) compared to without vibrations ($M = .795\,\text{m}$), $F(1, 25) = 4.1, p = .054, \eta_p^2 = .14$ (see Figure 5.6). For the jumping behavior, in the unrestricted view condition, walking speed was significantly slower with vibrations ($M = .982\,\text{m/s}$) than without ($M = 1.0\,\text{m/s}$), $F(1, 25) = 4.31, p < .05, \eta_p^2 = .15$ (see Figure 5.8a). On the other hand, in the restricted view condition, we found a trend that participants kept a larger distance with the vibrations ($M = .94\,\text{m}$) compared to without ($M = .9\,\text{m}$), $F(1, 25) = 3.39, p = .077, \eta_p^2 = .12$ (see Figure 5.6). We observed a trend for the increase in observation ratio with vibrations ($M = .21$) compared to without ($M = .15$), $F(1, 25) = 3.46, p = .075, \eta_p^2 = .12$. For the walking behavior, there was a significant effect of vibration on walking speed ($F(1, 25) = 6.96, p < .05, \eta_p^2 = .22$) in the unrestricted view condition; participants walked significantly slower when they felt the vibration caused by the VH's footsteps ($M = .88\,\text{m/s}$) than when they did not ($M = .91\,\text{m/s}$).

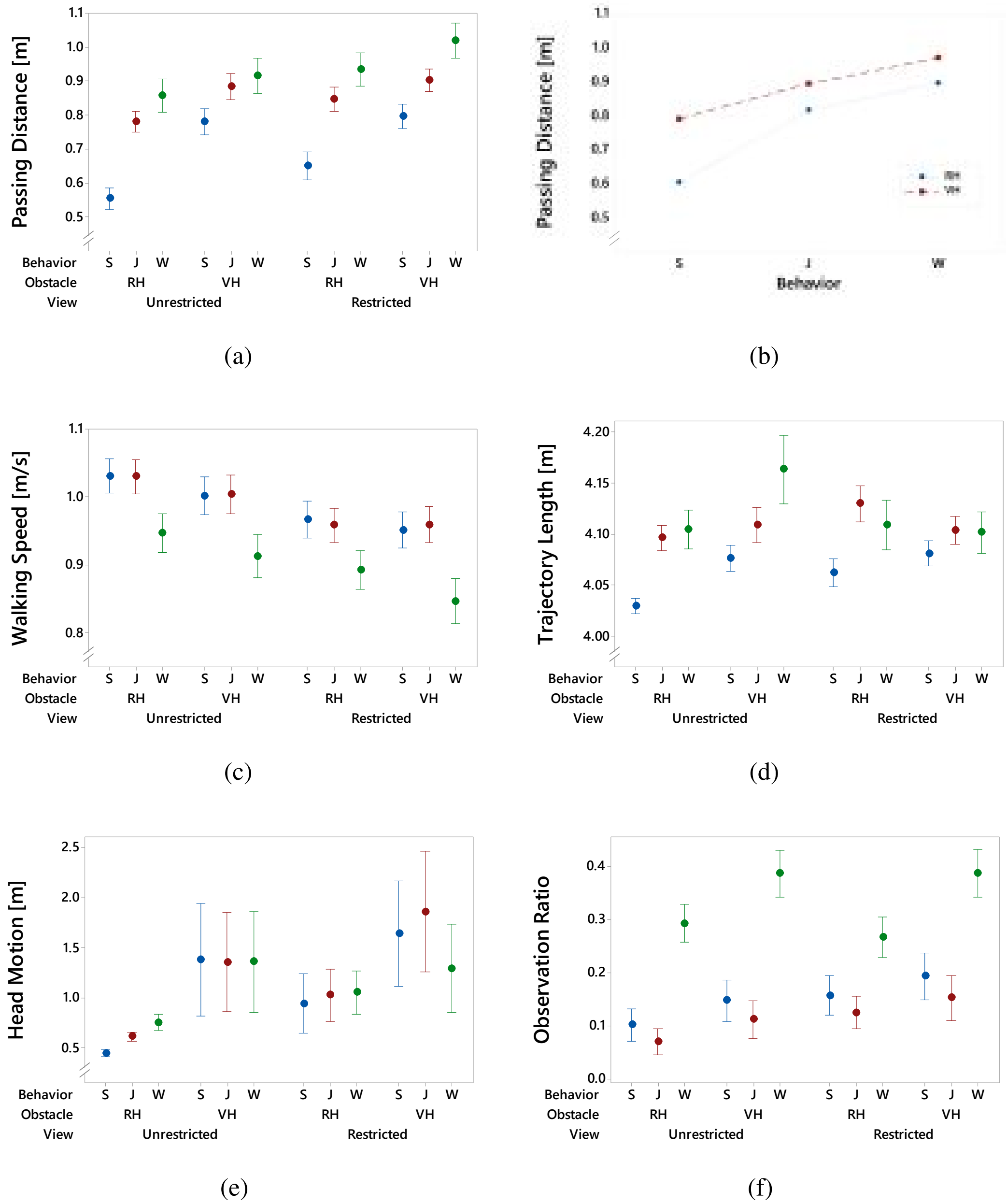


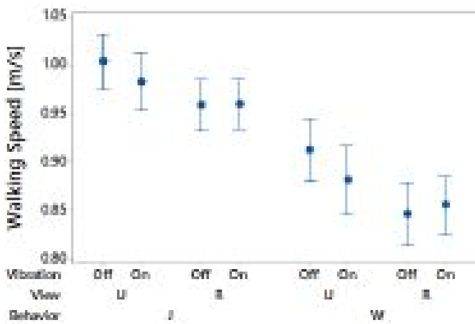
Figure 5.7: Results of the behavioral measures in the different conditions showing the means and 95% confidence intervals: (a) passing distance, (b) interaction between obstacle type and obstacle behavior for passing distance, (c) walking speed, (d) trajectory length, (e) head motion, and (f) observation ratio.

5.4.2 Subjective Measures

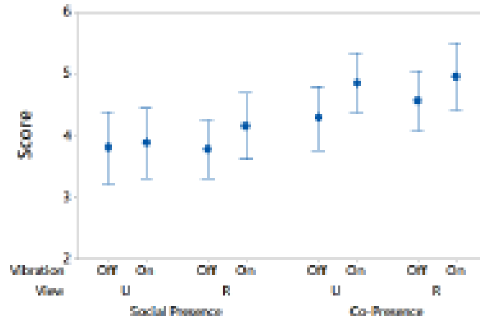
We analyzed the results with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

For social presence, we computed the mean for ratings from SP1 to SP5 (see Table 5.2) with inverted scores for SP3 and SP5 (Cronbach's $\alpha = .761$). A higher social presence score indicates that participants estimated the VH as more conscious and aware [11]. Our results showed no significant main effects of view condition, $F(1,25) = .52, p > .05, \eta_p^2 = .02$, or vibration, $F(1,25) = 2.65, p > .05, \eta_p^2 = .096$ (see Figure 5.8b).

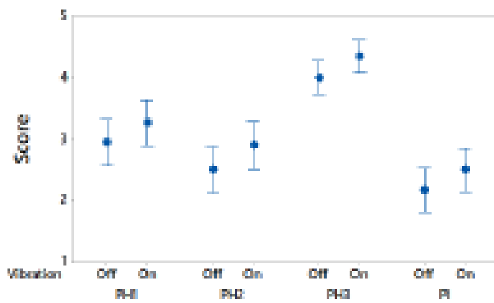
For co-presence, we also averaged ratings from CP1 to CP5 (Cronbach's $\alpha = .792$). A higher score means that participants reported a stronger sense of being together with the VH. The results indicate that there was a significant main effect of vibration on co-presence, $F(1,25) = 9.69, p < .01, \eta_p^2 = .28$. We found no significant main effect of view condition, $F(1,25) = 1.59, p > .05, \eta_p^2 = .06$, and interaction between view and vibration conditions, $F(1,25) = .35, p > .05, \eta_p^2 = .01$, on co-presence (see Figure 5.8b). Post-hoc tests indicated that participants rated higher scores in the vibration On ($M = 4.91$) than Off ($M = 4.42$) conditions, $p < .01$; and the unrestricted view with vibration Off ($M = 4.28$) was significantly lower rated than the other three combinations.



(a)



(b)



(c)

Figure 5.8: Results of the behavioral measures for the vibration in jumping and walking behavior with (a) interval plot of the walking speed andresults of the subjective measures for the vibration and view conditions with (b) interval plot of social presence and co-presence, and (c) interval plot of the remaining questions PH1, PH2, PH3, and PI. The plots show the means and 95% confidence intervals.

For the remaining questions, we performed the statistics per each measure. For PH1, ratings were inverted for consistency with the rest of the questions. For the perceived physicality of the VH (i.e., PH1, PH2, PH3) we found a significant main effect of vibration; F statistics for each question were as follows: $F(1,25) = 4.8, \eta_p^2 = .16$, $F(1,25) = 4.33, \eta_p^2 = .15$, $F(1,25) = 5.82, \eta_p^2 = .19$, with $p < .05$ for all. We found no significant main effect of view condition and interaction between view and vibration for all questions. Post-hoc tests indicated that for PH1, participants felt the VH as being more physical (as opposed to phantasmal) when they felt vibrations synced with the VH's behavior ($M = 3.27$) compared to the non-vibration condition ($M = 2.94$). For PH2, participants rated the VH's ability to physically affect them higher in the vibration On condition ($M = 2.9$) compared to the vibration Off condition ($M = 2.5$). For PH3, participants felt more cautious for vibration On ($M = 4.35$) than for vibration Off ($M = 4$). We also found a main effect of vibration, $F(1, 25) = 4.8, p < .05, \eta_p^2 = .16$, on the perceived intelligence level of the VH. Interestingly, post-hoc tests indicated that participants who felt the vibration rated the VH's intelligence level as higher ($M = 2.5$) than those who did not feel the vibration ($M = 2.17$) (see Figure 5.8c).

5.5 Discussion

In this section, we discuss the behavioral and subjective results of the experiment, potential explanations, and implications. In general, the locomotion behavior participants exhibited in our study is affected by proxemics, obstacle avoidance, and motor behavior, as it involved interpersonal space, awareness of the surroundings, and motion planning. In proxemics, one's invisible boundaries can expand or contract depending on one's characteristics and physical activity [54]. Therefore, participants may have planned their motion—route and speed—in consideration of the expanded or contracted obstacle's boundary and surroundings. Whether real or virtual human, in this regard, would primarily affect the initial size of the boundary. A more active behavior of the obstacle would thus result in an expansion. On the other hand, the view conditions with restricted or unrestricted periphery would primarily have effects on the participants' awareness of the surroundings and the position or motion of the obstacle. In the following sections, we discuss each factor in the experiment in detail.

5.5.1 Effects of Obstacle Type

Our results showed that participants stayed significantly farther away and walked a longer path at a slower speed around the VH than the RH, while looking more often towards the VH than the RH. Overall, our results provide strong support for Hypothesis H1. One possible explanation for this effect is that the VH did not appear to be a social entity that obeys social norms to the same level as the RH could be expected to. The moderate social presence and perceived intelligence scores suggest that participants had lower social expectations for the VH. These lower expectations of social behavior may thus result in the expectation that the VH may behave in unpredictable ways, such that participants increased their clearance distance, showed increased observation time, and decreased their walking speed. We received multiple comments by our participants that seem to support this interpretation. For instance, one participant stated, *"I was more focused on the virtual human [..] because I don't interact with a virtual human as much,"* and another participant said, *"[..] he would not change the course of direction in order to not run into me."* Interestingly, these differences between the VH and RH were less prominent in the more active behavior of the human obstacles, i.e., when they were jumping or walking, which may have made it easier for participants to predict their future behavior.

5.5.2 Effects of Obstacle Behavior

Regarding the effects of the real or virtual human obstacle's behavior, understanding what was changed between the behaviors is important. From standing to jumping, the obstacle's invisible boundary would have been increased due to the increased activity, but behavioral uncertainty would have been reduced as the obstacle repeated its jumping behavior in a loop. The observed increase in passing distance and the decrease in observation ratio supports this interpretation. In both of these behaviors, the location of the obstacle has not changed. Therefore, participants could focus less on tracking the obstacle and avoid the collision by simply changing their route with a greater clearance distance. Changing the walking speed would not have been necessary for this case as there was no additional uncertainty of the obstacle's behavior, as discussed in [102]. However, if the obstacle is actively walking, participants have to divide their attention to track the obstacle, maintain spatial awareness, and predict a safe route based on the current movement of oneself and the obstacle to avoid a collision while reaching the goal position. Due to this increased mental load, one may reduce the walking speed and look more towards the obstacle. Our results clearly show the decrease in walking speed and the increase in observation ratio, and these changes were the same regardless of the obstacle type. For the walking obstacle, participants would have needed to dynamically adjust their motion—direction and speed—to avoid collision, resulting in a more irregular path trajectory. The increased variances in walking speed and trajectory length support this assumption. Regarding the obstacle behavior, we logged comments in this scope such as, *"Jumping made me walk around more, and walking made me pause and wait,"* as well as, *"Jumping [was] least alarming because it was predictable; standing could become walking at any moment."*

5.5.3 Effects of View Condition

With respect to our Hypothesis H2, we expected that participants would need to look around more in the restricted view condition to have a confident level of spatial awareness, and would walk slower as the uncertainty of the surroundings increased. Our results support this hypothesis and showed these significant changes in head motion and walking speed regardless of obstacle type. However, when it comes to the awareness of obstacle position, which is an important factor for collision avoidance behavior, the view condition affects the locomotion behavior with more complicated interactions with the other factors. For the unrestricted view condition, participants could have kept both awareness of the RH obstacle and the surroundings with less head motion as the RH was still visible when they looked around (see the low variation for RH-U in Figure 5.7e, while for the VH, participants should have kept turning back to the probable location of the VH to reduce uncertainty, and this process—mental demand and behavioral restriction—of obstacle tracking in the VH condition might reduce one's spatial awareness due to the limited cognitive capacity and behavioral constraint. Hence, differences in locomotion behavior between the RH and VH obstacles in the unrestricted view condition would be mostly due to the limited augmented area. On the other hand, in the restricted view condition, head motion to gain spatial awareness would have affected obstacle position tracking in the same way (increasing uncertainty of the obstacle position) for both the RH and VH. Our results for passing distance, trajectory length, head motion, and observation ratio support this interpretation and Hypothesis H3.

Regarding the subjective responses, we expected that the view condition would have an effect on the participants' perception of the VH, which may explain some of the effects on the locomotion behavior. In particular, we initially expected that social presence and co-presence would increase for the restricted compared to the unrestricted view condition. The rationale behind this expectation was that the progressive disappearance in the unaugmented area when looking at the VH would reinforce one's belief that this obstacle is not real. Therefore, by removing this reinforcement, we would see the increase (as less decreased) in the related subjective measures. However, our subjective responses did not show significant effects in support of this Hypothesis H5, although we received multiple comments to this effect. For instance, participants commented, *"I felt Jack is more real with restricted view,"* and, *"Restricted view did make the experience slightly more realistic and harder,"* but also, *"I preferred the unrestricted view because it was easier for me to see where I was going."*

5.5.4 Effects of Vibrotactile Feedback

We expected that vibrotactile feedback would have an effect on the participants' perception of the VH and, therefore, would have indirect effects on the locomotion behavior. In particular, we assumed that social presence and co-presence would increase when vibrotactile footstep feedback was provided for the VH. We assumed that this effect would be related to expectancy violations. That is, participants knew that the obstacle was virtual, and they would not expect such vibrations caused by the VH. Therefore, when they felt the vibration, their expectation would be violated in favor of a higher regard for the VH. Indeed, we found that footstep vibrations synced with the VH's behavior significantly increased co-presence and perceived physicality of the VH, thus supporting H6. We also received multiple informal comments by our participants to this respect, such as, *"The floor vibration made both the jumping and walking virtual human seem more real, and made me especially nervous when the virtual human was walking towards me,"* and, *"Vibration made more impact on believing it's real."* In addition, vibrations also affected participants' locomotion behavior. However, we only found significant effects for unrestricted view condition, for which vibrations decreased walking speed in jumping and walking behavior. It is interesting that the benefits of vibrotactile footstep feedback thus mainly lie in subjective estimates rather than in objective locomotion behavior.

5.6 Summary

In this chapter, we presented, to the best of our knowledge, the first study investigating factors and issues related to human locomotion behavior and proxemics in the presence of a virtual human in AR. First, we discussed a unique issue faced in current-state optical see-through HMDs, namely the mismatch between a small augmented visual field and a large unaugmented periphery, and its potential impact on locomotion behavior in close proximity of a virtual human. We discussed a potential simple solution based on restricting the field of view to the central region, and we presented the results of a controlled user study, which revealed objective benefits of this approach with behaviors that more closely matched those when seeing a real human, but also drawbacks in subjective responses and overall limited acceptance of restricting the field of view. Second, we discussed the limited multimodal feedback provided by virtual humans in AR, presented a potential improvement based on vibrotactile feedback induced via the floor, and found in a controlled user study that benefits of such vibrations are less visible in objective locomotion behavior than in subjective estimates of co-presence. Third, we investigated and documented significant differences in the effects that real and virtual humans have on locomotion behavior in AR with respect to clearance distances, walking speed, and head motions. We discussed potential explanations for these effects related to social expectations, and analyzed effects of different types of behaviors including idle standing, jumping, and walking that such real or virtual humans may exhibit in the presence of an observer. We believe that investigating behavioral and perceptual differences induced by these technological and social factors in AR is important for practitioners and researchers aiming to further bridge the gap between real and virtual humans in shared spaces.

Throughout Chapter 3 to this chapter, I applied mediated physicality to different shared environments: mixed, virtual, and AR environments. Depending on the shared environment, the physical influence of VH actions was mediated through the real-virtual table, virtual floor, and real floor. Results from this chapter, in line with previous chapters, strongly supported that participants could correlate synthesized physical outcomes on shared objects to VH actions, even under the limitations of AR HMDs. This chapter further provided the evidence of changes in physicality perception of VHs when participants perceived the tangible physical outcomes. The following chapter further focuses on potential physical outcomes with regard to the extended reference for physicality in AR (see Figure 1.3).

CHAPTER 6: SYNCHRONIZED MOTIONS OF REAL AND VIRTUAL OBJECTS

In the experiments presented in previous chapters, the actions of VHs resulted in physical outcomes on the shared objects. Here, "shared" means both VHs and participants contacted the objects. Therefore, participants knew that the shared objects physically existed because they touched them.

In this chapter, I investigate the effects of the solely visually observed physical influence of a VH in the context of face-to-face interaction in a mixed reality environment. The VH in this study moves a real object, and participants do not have physical contact with the object. Therefore, if any physicality illusion of the VH were induced, it would be from the extended physicality reference discussed in Chapter 1 (see Figure 1.3).

With regards to the thesis statements, the relevant claims supported by this study are as follows:

- Naturally correlated cues associated with a virtual human's actions and physical outcomes can create a perception of virtual-physical causality;
- Such perception of virtual-physical causality can create a further perception of physicality of the virtual human;
- Such perception of physicality can increase feelings of social/co-presence with the virtual human and induce realistic social behavior;
- Such feelings and behavior can be maintained despite the temporary absence of some of the originally present correlated cues.

This chapter substantially replicates a peer-reviewed paper, “The Physical-Virtual Table: Exploring the Effects of a Virtual Humans Physical Influence on Social Interaction,” published in the proceedings of ACM Symposium on Virtual Reality Software and Technology 2018, co-authored with Nahal Norouzi, Gerd Bruder, Pamela J. Wisniewski, and Gregory F. Welch [91]. Throughout this chapter, when I say “we,” I am referring to these colleagues.

6.1 Overview

We present a technical approach to realize physical-virtual interactivity in AR in the scope of a tabletop environment, and we present an example application and user studies designed around a tabletop gaming experience between a real and a virtual human. In Experiment 1, participants played a tabletop game with a VH, in which each player takes a turn and moves their own token along the designated spots on the shared table. We compared two conditions as follows: the VH in the *virtual* condition moves a virtual token that can only be seen through AR glasses, while the VH in the *physical* condition moves a physical token as the participants do; therefore the VH's token can be seen even in the periphery of the AR glasses. For the *physical* condition, we designed an actuator system underneath the table. The actuator moves a magnet under the table which then moves the VH's physical token over the surface of the table. Our results indicate that participants felt higher co-presence with the VH in the *physical* condition, and participants assessed the VH as a more physical entity compared to the VH in the *virtual* condition. We further observed transference effects when participants attributed the VH's ability to move physical objects to other elements in the real world. Also, the VH's physical influence improved participants' overall experience with the VH. In Experiment 2, we further looked into the question how the physical-virtual latency in movements affected the perceived plausibility of the VH's interaction with the real world. Our results indicate that a slight temporal difference between the physical token reacting to the virtual hand's movement increased the perceived realism and causality of the mixed reality interaction. We discuss potential explanations for the findings and implications for future shared mixed reality tabletop setups.

6.2 Apparatus

This section describes the tabletop setup with the magnetic actuator system underneath the surface that we developed for use with a virtual human presented in AR (see Figure 6.1).

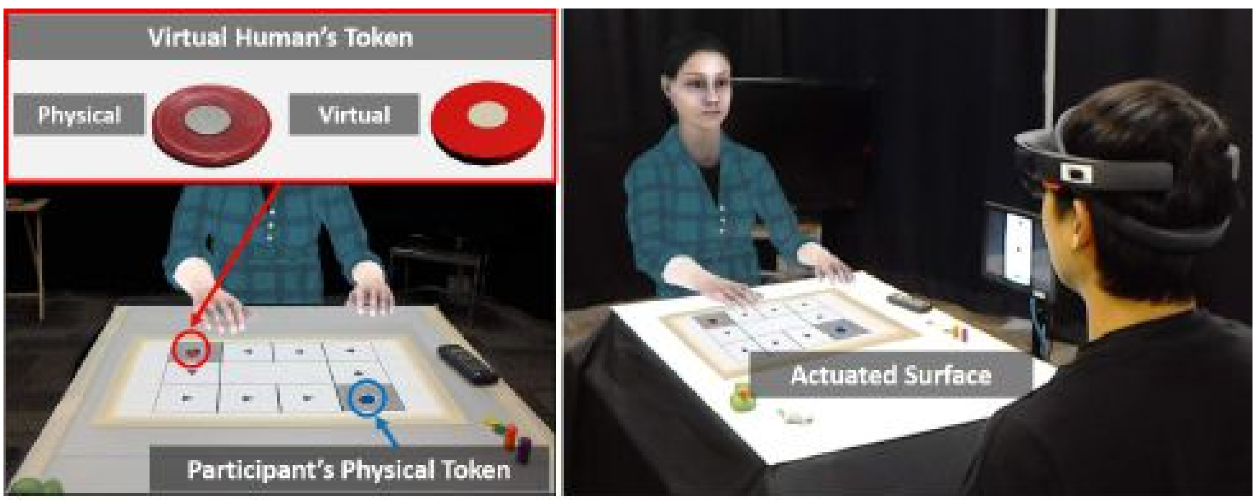


Figure 6.1: Illustration of the augmented reality game mechanics with virtual or physical game tokens on the left. The image on the right side shows the tabletop gaming surface with the magnetic actuator system underneath, which gives the illusion of the virtual human being able to touch and move physical objects over the surface.

6.2.1 Magnetic Actuator Surface

We designed an apparatus that can extend the ability of VHs in AR to move physical objects on a surface (see Figure 6.2).

The apparatus comprises the four main components:

- A magnet that can attract magnet- or metal-patched physical objects on the surface of the table.
- A two-axis motorized *translation stage* that can move the magnet parallel to the surface of the tabletop.
- A tracking system that tracks the positions of physical objects on the table and sends the data to AR glasses to register virtual content accordingly.
- A tabletop that covers the translation stage and hides it from the user's view.

We used an EleksDraw Computer Numerical Control (CNC) machine for the two-axis motorized translation stage and mounted a magnet to the mobile part of the CNC machine at the tip where usually a drill or laser is attached. The working range of the translation stage is $280\,\text{mm} \times 200\,\text{mm}$, and the maximum speed is $83\,\text{mm/s}$. We used an ease in/out velocity curve for a natural movement of the token; the average speed of the token was $50\,\text{mm/s}$. We compared different electromagnets and permanent magnets, and we decided to use a robust permanent magnet (a neodymium magnet) for the study presented in this paper due to trade-offs between its magnetic force, the weight of the physical object on the surface, and the thickness of the surface.

We used an OptiTrack Duo optical tracking system to track the position of the physical objects on the surface. We mounted the cameras on the ceiling of the experimental space, looking down at the tabletop surface. As the OptiTrack system requires retroreflective infrared markers to track the position of objects, we attached small markers to the corners of the tabletop and to the game tokens.

We decided to use a Microsoft HoloLens, an optical see-through HMD, and the Unity 2017.2.1f1 graphics engine for rendering virtual content and presenting it to the user.

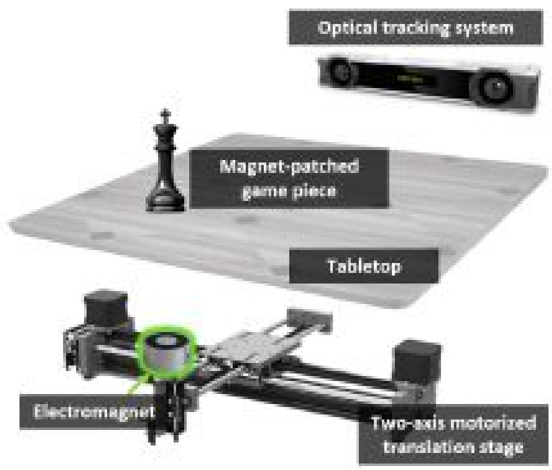


Figure 6.2: Apparatus: Tracked magnetically actuated game pieces on a tabletop surface realized through a motorized translation stage hidden from view underneath the surface.

6.2.2 Tabletop Gaming Setup

Our AR setup is inspired by a two-player tabletop gaming setup, in which a real human and a virtual human sit on opposite sides of a table and take turns to move their tokens over the tabletop surface with the intention to win a rudimentary board game.

We mounted the magnetic actuator system on a 70 cm $\times$ 114 cm table surface in our experimental space (see Figure 6.1). On the actuated surface, we placed a board game map (24 cm $\times$ 32 cm) that contained ten designated fields for game tokens to be placed. The fields were arranged in a rectangle around the board. The size of each field was 8 cm $\times$ 8 cm. Each player started on a different field. We marked the starting positions for the VH and participant as well as the direction to move the tokens on the map. The starting positions of the tokens were located on the rightmost side of the row near each player, on opposite ends of the board. The tokens had to be moved in counterclockwise direction around the board. The player who completed a round and reached the starting position with their token first was declared the winner of the round.

A small monitor was placed next to the table to indicate whose turn it is (i.e., either the participant's or VH's) and the number of fields to move the token. We decided not to use physical dice for the tabletop game in our setup for the purpose of the experiment due to the fact that this would introduce an element of randomness to the study. Instead, we decided to use a computer-controlled virtual number wheel (similar to that of a slot machine), which was rendered in Unity and presented on the monitor. The numbers presented by the number wheel appeared random to the participants but they were predetermined and counterbalanced in our study.

For the VH to move a physical token on the tabletop surface, we attached a thin magnet (diameter: 20 mm) to the bottom of the token (diameter: 22 mm) and an unobtrusive flat IR-reflective marker on top (see markers shown in Figure 6.1). The tracked marker positions were streamed to the HoloLens. When it was the VH's turn, the VH first placed her right hand on the tracked position of the token, then the motorized translation stage underneath the table moved the magnet from the current position to the target position, which resulted in the token moving over the tabletop surface. Due to the smooth surface of the board game, the token slided over the table without any noticeable friction. The VH's right-hand position was updated in real time based on the tracked marker position, and inverse kinematics was applied for the upper body posture while the token was moving. Latency between the physical and virtual movements was in the range of 125 ms.

For the virtual human player, we used an ethnically ambiguous female character that could perform predetermined gestures and had multiple dialogue options for the game scenario. The character was modeled and rigged in Autodesk Maya and animated in the Unity graphics engine. For the VH's speech we hired a female actor to record audio for the dialogues. The gestures and dialogues were linked to the stage of the game. Since the progression of the game was predetermined, the actions could be advanced automatically without noticeable delays with minimal help by a human controller using a GUI-based desktop application. For example, while the number wheel was rotating on the small monitor, the VH moved her head and eyes to look at the wheel and responded appropriately to the result such as by saying, "Oh! I got a three." or "Yes! I am almost done."

6.3 Experiment 1

In this section we describe the experiment that we conducted to investigate differences between purely *virtual* and *physical-virtual* interactions between a VH and other objects.

6.3.1 Participants

34 participants (11 female, 23 male, age 18–36, average 23.6) volunteered for this paid study through an advertisement posted at the local university. 11 participants had normal vision and 23 participants had corrected-to-normal vision, either using contact lenses (8 participants) or glasses (15 participants). Participants used a 7-point scale (1=no expertise to 7=expert) to rate their level of familiarity with VR (average 4.5), AR (average 3.79), VHs (average 2.5), and tabletop games (average 5.9). 27 participants ranked their level of computer expertise as proficient or expert.

6.3.2 Material

In this experiment, we used the physical setup, virtual human, and Unity rendering environment described in Section 6.2. Verbal interaction between the participant and the VH is performed while wearing headphones of type Sony MDR-ZX110NC. Ambient noise (a sound recorded from a café) was played via the headphones to render the humming background noise of about 40–46 dB caused by the current realization of the apparatus imperceptible, assuming that it could have an effect on the results.

6.3.3 Method

We used a within-subjects design. Participants experienced both conditions in randomized order.

The two conditions were:

$\mathbf{C}_V$ The VH moved a *virtual* token.

$\mathbf{C}_P$ The VH moved a *physical* token.

Participants moved their physical token by themselves in both conditions.

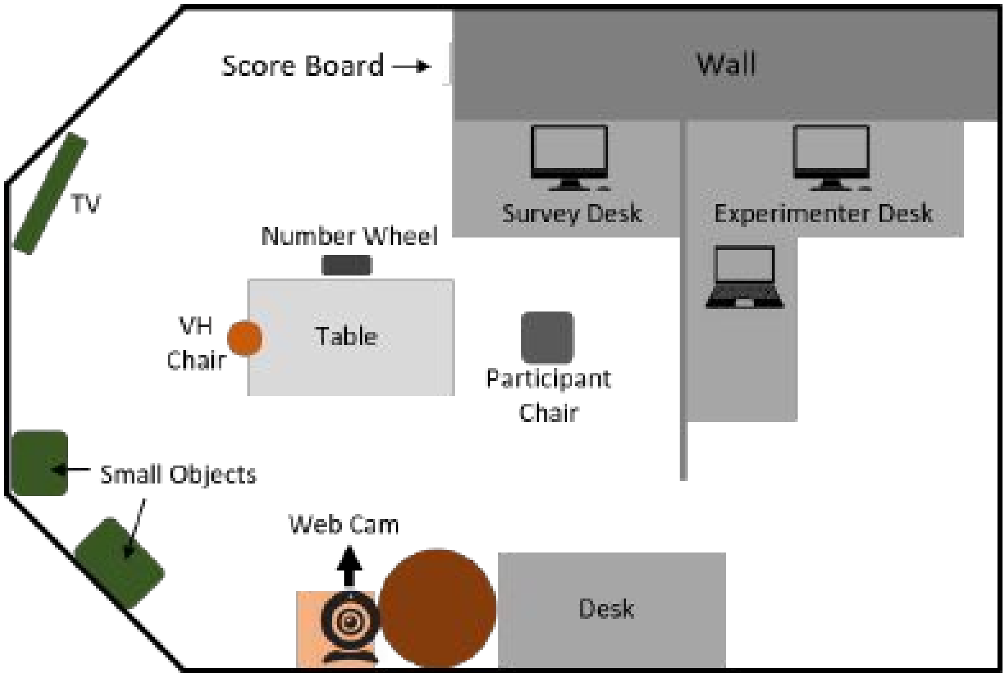
Procedure

Before the experiment, the experimenter asked participants to read an informed consent form and briefed them on the study and protocol. Once participants gave the informed consent, they donned the HoloLens and went through the procedure of the HoloLens' IPD calibration app. The experimenter helped participants to correctly adjust the Hololens on their head. Participants filled out a pre-questionnaire that contained demographics questions as well as questions about their prior experience with AR, VR, VHs, and tabletop gaming.

The experimenter then left the experimental room, and the participants started their first game. We used the tabletop gaming scenario described in Section 6.2.2. Participants played the game with the VH once for each of the two conditions in randomized order. We designed two sequences, A(1-3-3-2-2-2-3-2-2) and B(3-2-1-2-2-3-3-2-1). Depending on the sequence chosen for each game, the numbers in that sequence were displayed sequentially on the small monitor next to the table. The VH started the game both times and according to the number, players and the VH took their turns one after another. Each turn, they advanced their token by the number of steps displayed each time on the screen. In order to be comparable between both conditions, we decided that the VH should win both games.

When the game ended, participants were asked to mark the winner on a score board on a wall behind the VH, which required them to pass by the VH (see Figure 6.3). We included this part of the study to investigate effects of the physical-virtual interaction on the participants' locomotion behavior and passing distance when walking past the VH. Once participants made their way back to their seat, the experimenter re-entered the room and helped them take off the HoloLens and asked them to fill out a post-questionnaire. Participants then repeated the same procedure for the second condition.

Upon completion of both games, participants were asked to fill out a comparative questionnaire with also contained open questions. Participants then received a monetary compensation for their participation.



(a)

(b)

Figure 6.3: Experimental setup: (a) Illustration of the experimental space with the tabletop setup and other furniture and equipment, and (b) photo of the room with the tabletop gaming setup.

Subjective Measures

We measured the following items at the end of each game.

- **Co-Presence:** We used Basdogan's co-presence questionnaire (CPQ) [14] to measure the level of "togetherness," being present together, experienced by the participants while playing the game with the VH.

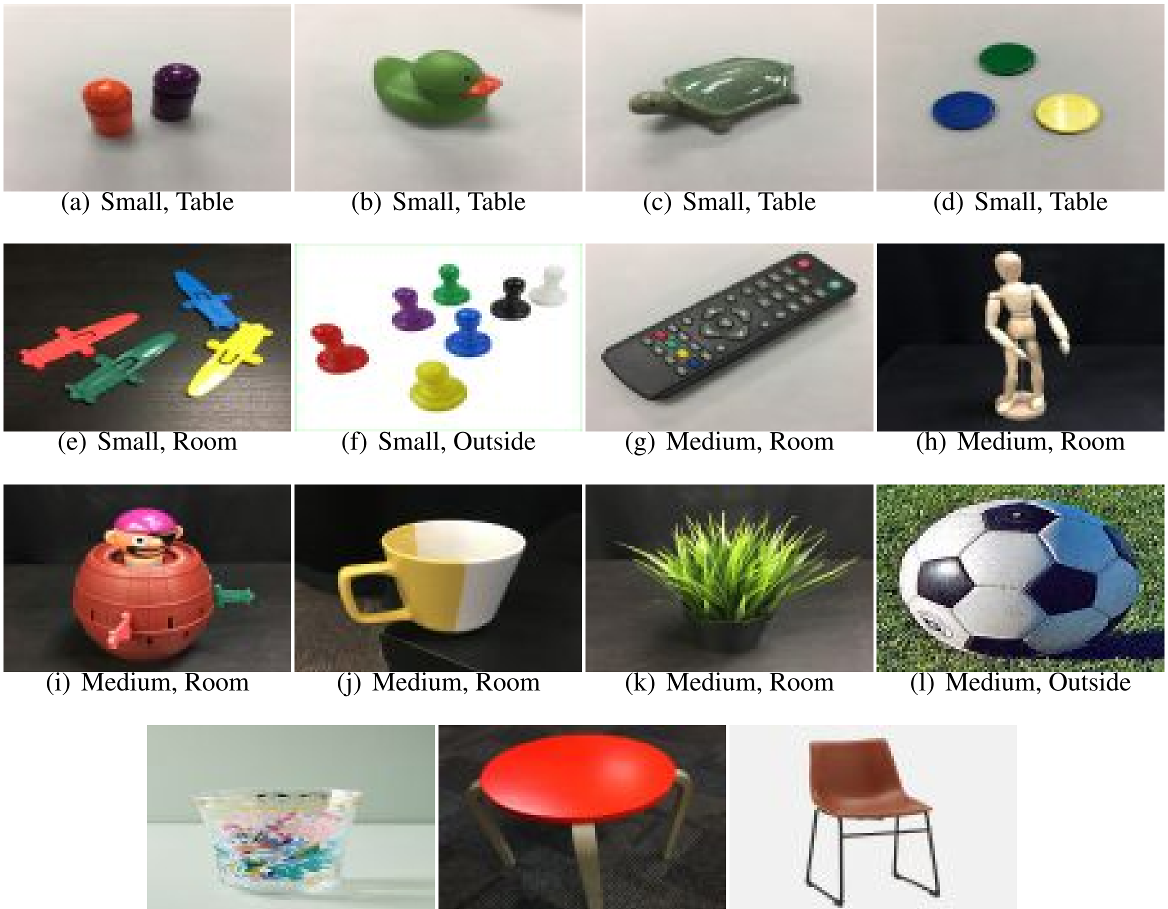
- **Perceived Physicality:** For this measure, participants were shown photos of objects (see Figure 6.4) that were located inside the experimental room (see Figure 6.3b) or not. Their task was to rate whether or not they believed that the VH is able to physically move these objects using a 7-point Likert scale (1=strongly disagree, 7=strongly agree).

  We grouped the object-related questions based on the following criteria:

  - Object's size: *small* (e.g., game tokens and miniature figurines), *medium* (e.g., TV controller, ceramic mugs), and *large* (e.g., chairs)
  - Object's location: objects that were placed on the table with the game board, objects that were place inside the experimental area, and objects that were not in the room.

- **User Experience:** We used the User Experience Questionnaire (UEQ) [120] to measure the quality of the participants' gaming experience in each condition.

- **AR Tabletop Gaming Questions:** We designed additional custom questions about different aspects of the VH and the experiment and asked participants to choose their preferred condition and explain their choice (see Table 6.1).



(a) Small, Table (b) Small, Table (c) Small, Table (d) Small, Table
(e) Small, Room (f) Small, Outside (g) Medium, Room (h) Medium, Room
(i) Medium, Room (j) Medium, Room (k) Medium, Room (l) Medium, Outside
(m) Medium, Outside (n) Large, Room (o) Large, Outside

Figure 6.4: Collection of physical objects presented in the questionnaire, tagged based on the size (small, medium, large) and location (on-table, in-room, outside) criteria. Participants were asked to rate their sense that the VH could physically move these objects.

Table 6.1: Augmented reality tabletop gaming related questions.

O1	In which condition did you feel that you were playing a tabletop game with another person?
O2	In which condition did you feel that the virtual human was able to handle physical game pieces?
O3	In which condition did you enjoy the game more?
O4	Would you like to have such a tabletop gaming system at home? Which one would you prefer?

Behavioral Measures

During the experiment, the participants' head position and orientation tracked by the HoloLens' internal tracking system were logged. From the tracking data, we extracted the following measures.

- **Head Motion:** We measured the amount of overall head motion of the participant by calculating the length of the trajectory the participant's gaze (forward vector) traveled on a unit sphere that surrounds the head (i.e., the origin of the forward vector) during the game, and divide it by the duration of the game.
- **Dwell Time Ratio on VH:** The ratio of time devoted to looking at the VH during the game. We computed this with an angle of ± 10 degrees from the forward direction obtained from the HoloLens.
- **Dwell Time Ratio on Token:** The ratio of time devoted to looking at the VH's token during the game. We computed this with an angle of ± 10 degrees from the forward direction obtained from the HoloLens.
- **Clearance Distance:** The minimum distance between the participant and the VH when the participant walked toward the scoreboard (see Figure 6.5).
- **Walking Speed:** The mean walking speed of the participants while walking toward the scoreboard.

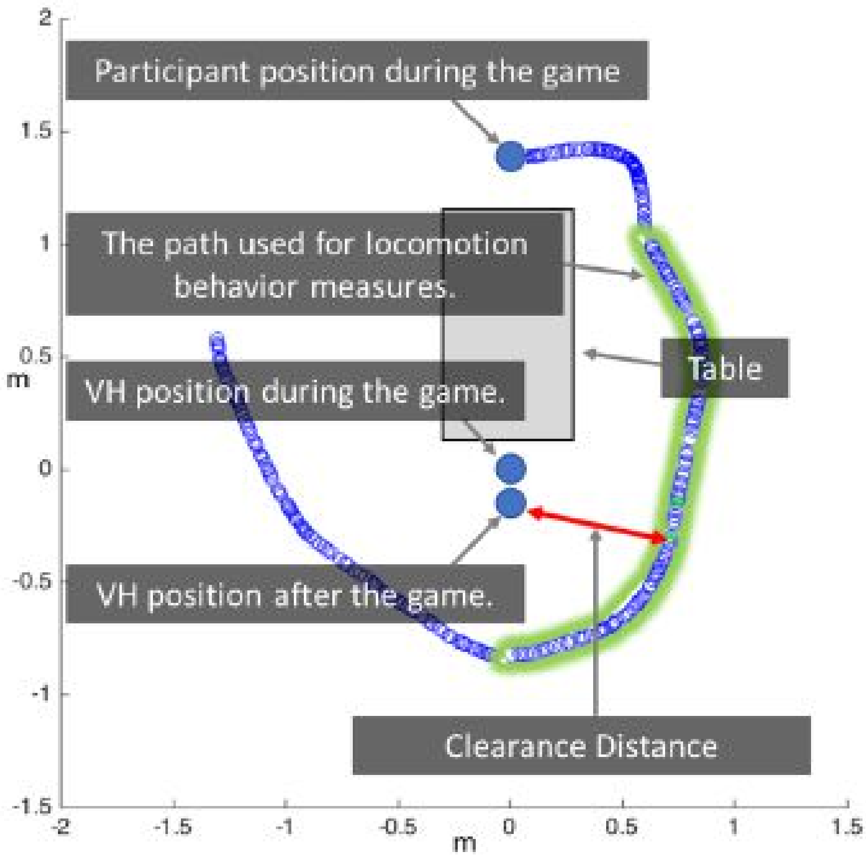


Figure 6.5: Example walking path of a participant. The walking speed and clearance distance were calculated from the path highlighted in green.

Hypotheses

Based on the related work and our study design, we formulated the following hypotheses:

H1 Participants indicate higher co-presence with the VH when they observe its ability to move a physical token ($C_P > C_V$).

H2 Participants indicate a more enjoyable gaming experience when the VH can move a physical game token ($C_P > C_V$).

H3 Participants transfer their experience of the VH being able to move a physical token on the table to other physical objects.

H4 Participants exhibit different (e.g., a greater passing distance, a slower walking speed) proxemic and gaze behavior in the C_P condition compared to the C_V condition.

6.3.4 Results

This section presents the results of the subjective and behavioral measures in the experiment.

Subjective Measures

The questionnaire responses were analyzed using Wilcoxon signed-rank tests at the 5% significance level. Pair-wise comparisons were conducted between the physical and virtual token conditions. We performed multiple comparisons with Bonferroni correction for the object categories in the perceived physicality questionnaire. Box plots in Figure 6.6 are in Tukey style with whiskers extended to cover the data points which are less than $1.5 \times$ interquartile range (IQR) distance from 1st/3rd quartile.

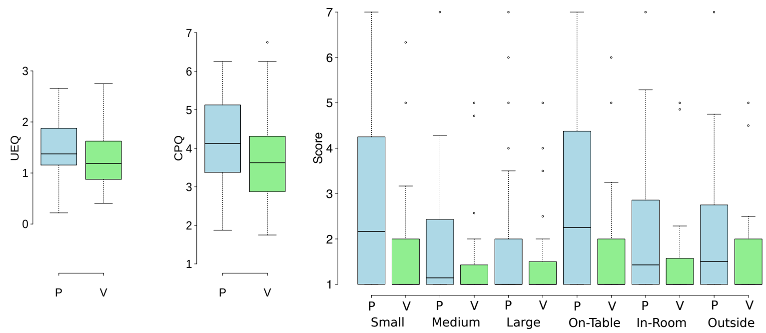
Co-Presence: The results for the CPQ questionnaire [14] are shown in Figure 6.6(b). As is common practice for this standard questionnaire, we computed the mean of all ratings from questions 1 to 8 with an inverted score for question 4 (Cronbach's α = .894). We found a significant difference between the two conditions (W = 325.5, Z = -2.9191, $\boldsymbol{p = 0.003}$, r = 5.38), indicating a higher sense of togetherness when the VH can move a physical token.

Perceived Physicality: The results for this measure are shown in Figure 6.6(c). We computed the sum of the ratings for each object and then the means for all the objects in each group. In this measure, higher scores indicate that participants rated the VH's ability to move physical objects in this condition higher. As expected, when comparing the physical and virtual token conditions we found significantly higher ratings in the condition with the physical token for the small objects (W = 203.5, $Z = -3.058$, ***p* = *0.002*** , $r = 4.58$), medium objects (W = 116, $Z = -2.482$, ***p* = *0.013***, $r = 0.62$), objects on the table (W = 200.5, $Z = -2.954$, ***p* = *0.003***, $r = 4.58$), objects in the experimental area (W = 141.5, $Z = -2.438$, ***p* = *0.014***, $r = 4.24$), and objects outside (W = 126.5, $Z = -2.366$, ***p* = *0.017***, $r = 4.12$). We found no significant effect but a trend for the large objects (W = 73.5, $Z = -1.956$, ***p* = *0.054***, r = 3.61).

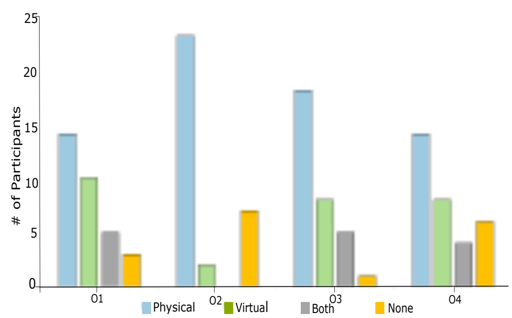
Looking at the physical token condition in more detail, we compared the effect that seeing the VH move a small physical token on the table had on the participants' sense that the VH could move other objects in the room (in the absence of direct evidence for or against this ability). We found a significantly higher probability for participants to judge that the VH could move an object on the table than anywhere else in the room (W = 120, $Z = -3.407$, ***p* = *0.002***, $r = 3.87$) or outside the room (W = 120, $Z = -3.407$, ***p* = *0.002***, $r = 3.87$). We further found a significantly higher probability for participants to judge that the VH is able to move a small object than a medium (W = 120, $Z = -3.407$, ***p* = *0.002***, $r = 3.87$) or large object (W = 91, $Z = -3.179$, ***p* = *0.004***, $r = 3.60$).

AR Tabletop Gaming Questions: At the the end of the experiment participants were asked the custom questions in Table 6.1. Based on their responses, we categorized them in four groups which were *physical*, *virtual*, *both*, and *none*. Figure 6.6(d) shows the number of participants in each group for each question.

User Experience: The results for the UEQ questionnaire [120] are shown in Figure 6.6(a). For this standard questionnaire, means and variances for all 26 questions are computed between -3 and 3, with scores higher than 0.8 indicating a more positive evaluation. We found a significant difference between the means in the two conditions (W = 255, Z = -3, ***p* = *0.002***, $r = 4.90$), indicating a higher user experience when the VH could move the physical token.



(a) UEQ (b) CPQ (c) Physicality



(d) Gaming Questions

Figure 6.6: Subjective results with *P* and *V* indicating the physical and virtual token conditions, respectively: (a) user experience questionnaire, (b) co-presence questionnaire, (c) perceived physicality questionnaire with higher scores indicating a higher perception of the VH's ability to move physical objects, and (d) numbers of participants indicating preferences grouped based on their answers to each AR tabletop gaming question.

Behavioral Measures

For the analysis of the behavioral data, we performed paired-samples t-tests at the 5% significance level for each measure. Results for all behavioral measures are shown in Figure 6.7.

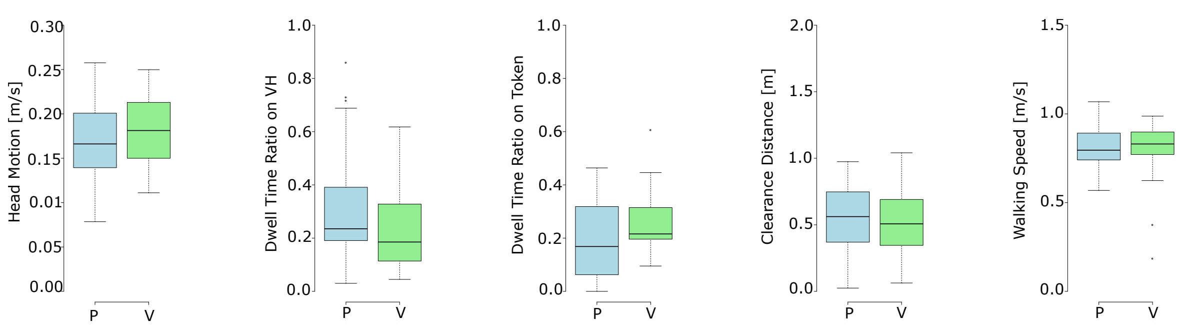
Head Motion: Participants moved their head significantly more in the C_V condition (M = 0.185 m/s, SD = 0.045) than in the C_P condition (M = 0.169 m/s, SD = 0.043); $t(31)$ = -2.341, ***p* = 0.026**.

Dwell Time Ratio on VH: We found a significant difference in the time participants dwelled on the VH between the C$_P$ condition (M = 0.316, SD = 0.204) and the C$_V$ condition (M = 0.239, SD = 0.153); $t(31)$ = 2.504, ***p = 0.018***. Participant spent more time looking at the VH in the physical token condition than with the virtual token while playing the game.

Dwell Time Ratio on Token: We found a significant effect of the conditions on the time participants dwelled on the physical (M = 0.191, SD = 0.144) or virtual (M = 0.260, SD = 0.108) token; $t(31)$ = -2.808, ***p = 0.009***. Participants looked down at the VH's token more in the C$_V$ condition than in the C$_P$ condition.

Clearance Distance: We found no significant difference in the clearance distance while walking past the VH for the C$_P$ condition (M = 0.542 m, SD = 0.254) and the C$_V$ condition (M = 0.499 m, SD = 0.260); $t(31)$ = 0.789, p = 0.436.

Walking Speed: We also found no significant difference in the means between the C$_P$ condition (M = 0.806 m/s, SD = 0.120) and the C$_V$ condition (M = 0.799 m/s, SD = 0.164); $t(31)$ = 0.198, p = 0.844.



(a) (b) (c) (d) (e)

Figure 6.7: Results of the behavioral measures with P and V indicating the physical and virtual token conditions, respectively: (a) head motion, (b) dwell time ratio on VH, (c) dwell time ratio on token, (d) clearance distance, and (e) walking speed. Whiskers in the box plots are extended to represent the data points less than 1.5 IQR distance from 1st and 3rd quartile.

Table 6.2: Summary of the hypothesis testing results.

	Hypothesis	Statistical test	Results
H1	Participants indicate higher co-presence with the VH when they observe its ability to move a physical token ($C_P < C_V$).	Wilcoxon signed-rank test	**Accepted** ($p < .01$)
H2	Participants indicate a more enjoyable gaming experience when the VH can move a physical game token ($C_P < C_V$).	Wilcoxon signed-rank test	**Accepted** ($p < .01$)
H3	Participants transfer their experience of the VH being able to move a physical token on the table to other physical objects.	Wilcoxon signed-rank test	**Accepted** Small objects ($p < .01$) Medium objects ($p < .05$) Large objects ($p > .05$)
H4	Participants exhibit different (e.g., a greater passing distance, a slower walking speed) proxemic and gaze behavior in the C_P condition compared to the C_V condition.	Paired-samples t-test	**Partially accepted** Head motion ($p < .05$) Dwell time ratio on VH ($p < .05$) Dwell time ratio on Token ($p < .01$) Clearance distance ($p > .05$) Walking speed ($p > .05$)

6.3.5 Discussion

Overall, the sense of co-presence with a VH as well as the perceived physicality of the VH and the user experience was greatly increased by observing the VH's ability to physically affect users' space. In contrast, participants' behavior seemed to be more affected by the limitations of the current state AR glasses, while their gaze behavior showed the potential of our physical-virtual table in mitigating the limitations. In the following, we discuss the results of the experiment in depth, provide potential explanations and implications.

VH's ability to affect the physical space increased co-presence.

Our results indicate that the sense of co-presence with the VH was significantly higher in the physical token condition where the VH exhibited its ability to affect the user's physical space compared to the virtual-only condition. The results support our Hypothesis H1.

Our findings are in line with a recent study by Kim et al. [77], in which participants reported a higher level of co-presence with a VH that walked towards a lamp (showing awareness of physical entities) and performed a plausible manipulating gesture to turn on the lamp (showing the ability to affect physical entities) compared to a VH that used a non-physical means to complete the task. The VH in both conditions in our experiment exhibited a similar level of awareness of the surrounding physical space, i.e., the VH moved her token to the designated spots on a physical game board, looked at the number wheel on the small monitor at the side of the table, and looked towards the participant when it was their turn. Hence, the increased sense of co-presence in the physical condition is likely mainly a result of the VH's ability to *affect* the physical space and less of the *awareness* of the physical space in our study.

Observed VH's physical ability on one object increased expectation of VH's ability on other objects in the physical space.

Regarding the perceived physicality, our results show a significant effect that participants were more likely to believe that the VH would be able to move other physical objects when they observed the VH move the physical token on the tabletop surface, thus supporting our Hypothesis H3. However, it is interesting that the participants were less likely to expect the VH to be able to move objects of larger size than the small physical token or when the distance of the object from the location of their observation of the VH's physical influence increased. When we asked participants about the criteria for their answers, we noticed that most of our participants applied criteria to the virtual human they would also apply to a real human. For example, one participant said "because she could move the real token, she also can move small objects," and another participant explained it with "the size of the object and how heavy it is." In other words, participants expected the VH to behave like a real human and have physical abilities in line with a real human. Along these lines, it is also interesting to note that one participant mentioned to have paid more attention to the VH's actions in the virtual token condition because the VH was perceived to be able to cheat more easily with the virtual token than with the physical token.

Physical-virtual table improved the user experience of AR game.

The UEQ questionnaire is designed to assess user experience in terms of attractiveness, perspicuity, efficiency, dependability, stimulation and novelty [120], which are important elements of an engaging game. The subjective responses for this UEQ questionnaire, the game-related questions listed in Table 6.1, as well as the informal feedback collected from our participants all are in support of our Hypothesis H2 that the physical token condition would result in a more enjoyable experience. Many of our participants described their interaction as fun, interesting, and exciting. It should be noted that it appears that the limited field of view of the HoloLens may have worked in advantage of the physical token condition, since it satisfied the efficiency and dependability aspects of the UEQ more than the virtual condition according to some of our participants.

The physical-virtual table mitigated the usability issue of small augmented FoV.

The results for the behavioral measures partially support our Hypothesis H4. We found significant differences between the two conditions in participants' head motion behavior (amount of head motions, dwell time on VH, dwell time on token) in favor of the physical token condition. These differences could be caused by the relatively small augmented field of view of the HoloLens used in this study. Similar to what was described in Chapter 5, participants in our study could not see both the VH's face and the virtual token at the same time during the game. Thus, they needed to keep moving their head up and down to see the progress of the game as well as maintain the social interaction with the VH. Whereas, for the physical condition, they could just look down with their eyes to check the position of the opponent's physical token while keeping their head up. Once participants observed the VH's hand touching and moving the physical token, they could mentally connect the VH's visible upper body behavior with the moving physical token seen in the unaugmented periphery of the HoloLens. The reduced dwell time on the token and increased dwell time on the VH in the physical condition seems to match this explanation. Considering the weight of current-state AR glasses, reducing the amount of required head motion to keep track of large virtual content in close proximity of the user could greatly improve the user experience. In this regards, participants' strong preference of the physical condition, as well as the highly rated user experience, might to some degree result from the reduced head motion.

Based on related work (e.g., [4, 78, 88]), we initially expected to see more realistic locomotion behavior for the physical condition, e.g., keeping a more considerable clearance distance as well as slower walking speed. However, we did not find significant differences between the conditions on locomotion behavior. Interestingly, most participants stated in open-ended questions that they were more cautious passing by the VH in the physical condition compared to the virtual condition, which suggested a possible decrease in walking speed and an increase in clearance distance. However, the effect was not shown in their actual behavior, rather we found that five participants even walked *through* the VH instead of around it. We found a possible reason for the observed locomotion behavior in the participants' comments. Some participants stated that they did not notice the VH standing in their way when they walked towards the scoreboard, which again resulted from the small augmented field of view. Similar results have been reported in Chapter 5, in which vibrotactile feedback of a VH's footsteps increased co-presence with the VH but did not affect users' locomotion behavior in AR, while the locomotion behavior heavily depended on the AR view condition.

Limitations and potential of the physical-virtual table

The apparatus presented in Section 6.2 showed a reasonable performance as indicated by the aforementioned high sense of physical-virtual interactivity judged by the participants in our experiment. During debriefing, when asked about the potential cause of the physical token's movement, 10 participants described it with terms such as *mechanical*, *external force*, or *motorized*, while 15 participants described it as *magnetic*. The fact that most participants came up with a potential computer-controlled cause of the physical movements might be related to the overall high level of computer expertise among our participant population. It would be interesting to compare our results in this experiment with children and participants with less computer experience in future work.

A limitation of the current realization of the prototype is the humming background noise by the motors of the translation stage. During the debriefing, when asked whether they heard sounds while playing the game, 25 participants stated that they did not perceive any noise related to the movement of the token, while the remaining 9 participants perceived some noise coming from the table and/or token. In our study, we used headphones to compensate for the background noise of the system, but for future realizations of such actuator systems for tabletop gaming and related experiences, we suggest integrating a noiseless translation stage.

Overall, 23 participants indicated that they enjoyed the condition with the actuated physical token more than the virtual condition, and 18 participants indicated that they would like to have such a tabletop gaming system with actuated physical game tokens at home. We believe that tabletop mechanical actuator systems as described in this paper have much potential for a wide range of tabletop gaming scenarios including serious games such as strategic or tactical wargaming scenarios, e.g., based on an AR Sand Table (ARES) [3] and related efforts.

6.4 Experiment 2

In this section, we further investigate the characteristics of the observed latency in the actuated surface and the effects of latency on users' perception of observing the virtual human moving a physical token, i.e., physical-virtual interaction.

6.4.1 Latency in Physical-Virtual Interaction

Two third of the participants in Experiment 1 reported that they observed a lag between the motion of the virtual hand and that of the physical token—eight of them judged the delay as moderate or higher. The observed lag in our actuated surface setup mainly results from the network delay when the optical tracking software transmits the tracked position of the physical token to the AR application running on the HoloLens and the smoothing technique we used to filter out the noise in the tracked position when updating the virtual hand position. As a result, the virtual hand motion was slightly delayed compared to the physical token.

This *physical-to-virtual* latency is specific to our implementation. However, in contrast to updating the virtual hand position to match the translation stage, one could update the position of the translation stage to match the virtual hand position, in which the direction of data transmission would be reversed compared to the implementation we used in Experiment 1. In such a case, the token's motion would be slightly delayed compared to the virtual hand, i.e., causing a *virtual-to-physical* latency. In the following, we consider physical-to-virtual latency as a latency with a negative sign compared to virtual-to-physical latency. For instance, when we talk of a latency of -200 ms we mean a physical-to-virtual latency of 200 ms, i.e., the virtual hand is 200 ms behind the physical token.

In this experiment, we analyze how participants perceive the magnitude and directionality of the latency in the mixed reality tabletop setup.

6.4.2 Participants

We recruited 13 participants (6 female, 7 male, age 19–56, average 29.8) from the local university community for this study. All of the participants had correct or corrected vision; 5 participants wore glasses and 2 participants wore contact lenses during the experiment. None of the participants reported known visual disorders. Participants used a 7-point scale (1=no expertise to 7=expert) to rate their level of familiarity with VR (average 5.2), AR (average 4.8), VHs (average 4.6), and tabletop games (average 5.2). 10 participants ranked their level of computer expertise as proficient or expert.

6.4.3 Material

We used the same physical-virtual table setup described in Section 6.2 but modified the mechanism of synchronizing the hand motion and token motion in order to study how the direction and magnitude of latency affect users' perception of the observed physical-virtual interaction, i.e., the virtual human moving the physical token.

We first simplified the token motion to travel the game board once with stopping only at the corners—four Grbl motion commands were sent at once through a serial communication, then the micro-controller of the translation stage executed the commands in order. For the hand motion, we recorded the entire sequence of the token motion and played it back instead of updating the hand position based on the physical token position in real-time. By doing so, we could initiate the hand motion and token motion separately at different points in time.

To compensate for the network delay, we triggered the hand motion first with a fixed delay (3 seconds) then triggered the token motion with an adjusted delay (3 seconds minus the measured network delay). Then, we varied the order of the initiations of the two motions as well as the waiting time between two initiations by adding or subtracting a target delay time. We prepared 15 latency conditions from -350 ms to 350 ms in steps of 50 ms.

However, it should be noted that there are a few factors that we do not have control over. The hidden internal process of the translation stage generates an arbitrary latency between the trigger and the actual start time of the motion. Also, Unity's Invoke method which we used to trigger the motion with a delay has a small varying offset. We measured the offset between the token motion from a reference motion recorded for the hand motion as well as the offset from the delayed trigger, and applied a post-hoc adjustment to correct the latency conditions shown to the participants.

6.4.4 Method

We used a within-subjects design. Each participant observed the virtual human moving the physical token around the game board 30 times in total. We prepared two sets of 15 latency conditions, from - 350 ms to + 350 ms in steps of 50 ms, and randomized the order between participants.

Procedure

Upon arrival, participants were given a study brief, protocol, and informed consent. Once they agreed to participate in the study, they donned the HoloLens and the headphones and went through the IPD calibration procedure with help from the experimenter and then were guided to stand in front of the table. Participants were asked not to move their head during the experiment and we provided them with a chin rest (see Figure 6.8). During the experiment, participants were asked to look at the VH's hand and the physical token when they were in motion; otherwise, they were asked to look at the VH. The VH looked at the participants by default, while she moved her gaze toward the token before and while moving the token. Once the VH completed moving the token, participants answered four questions we prepared using verbal responses. At the end of every six observations, participants had a short break and were asked to move one token from the left to the right side. For this, we placed 5 tokens on the participant's side of the table. Upon completion of 30 observations, they took off the HoloLens and headphones and took a survey containing demographics and open-ended questions.

Figure 6.8: Experimental setup for Experiment 2. Participants stood at a side of the table and kept their head position fixed during the experiment.

Measures

We prepared four representative questions. Each item intended to measure the overall perceived realism, causality, co-presence, and latency, respectively. Participants rated each question on a 7-point Likert scale. For realism and causality, we asked participants to rate how much they agree or disagree with the following statements (1=strongly disagree, 7=strongly agree): for realism, *“The virtual human’s movement of the token seemed realistic”*; for causality, *“The token was moved by the virtual human’s hand”*. For co-presence, participants answered the question, *“How much did it seem as if you and the virtual human you saw were together in the same place?”* (1=not at all, 7=very much). And for the perceived latency, participants were asked to choose the delay category they saw (1=the token movement was extremely delayed, 4=the token and hand moved together, 7=the hand movement was extremely delayed).

Data Preparation

Due to the random latency factors in our actuated surface setup (see Section 6.4.3), we recalculated the occurred latency for each observation using the measured offsets. Then, based on the adjusted latency values, we regrouped the data into six groups:

H-: -300 ms to -200 ms,

M-: -200 ms to -100 ms,

L-: -100 ms to 0 ms,

L+: 0 ms to +100 ms,

M+: +100 ms to +200 ms,

H+: +200 ms to +300 ms.

For the sake of convenience, we refer to the groups with indicators High (H), Moderate (M), and Low (L). A positive sign indicates a virtual-to-physical latency, i.e., the physical token was delayed behind the virtual hand. A negative sign indicates a physical-to-virtual latency, i.e., the token's motion preceded the virtual hand motion.

Hypotheses

The real-world counterpart of the event participants observed in this experiment has a strong causal relationship, i.e., a hand moves a token. Violating the temporal order of the cause and effect might break the illusion of co-presence with respect to the simulated event, if any was induced. For example, if the token moved before the virtual human approached it, users would hardly perceive this as a plausible interaction, though there also might be a tolerable delay. Based on this rationale and our study design, we formulated the following hypotheses:

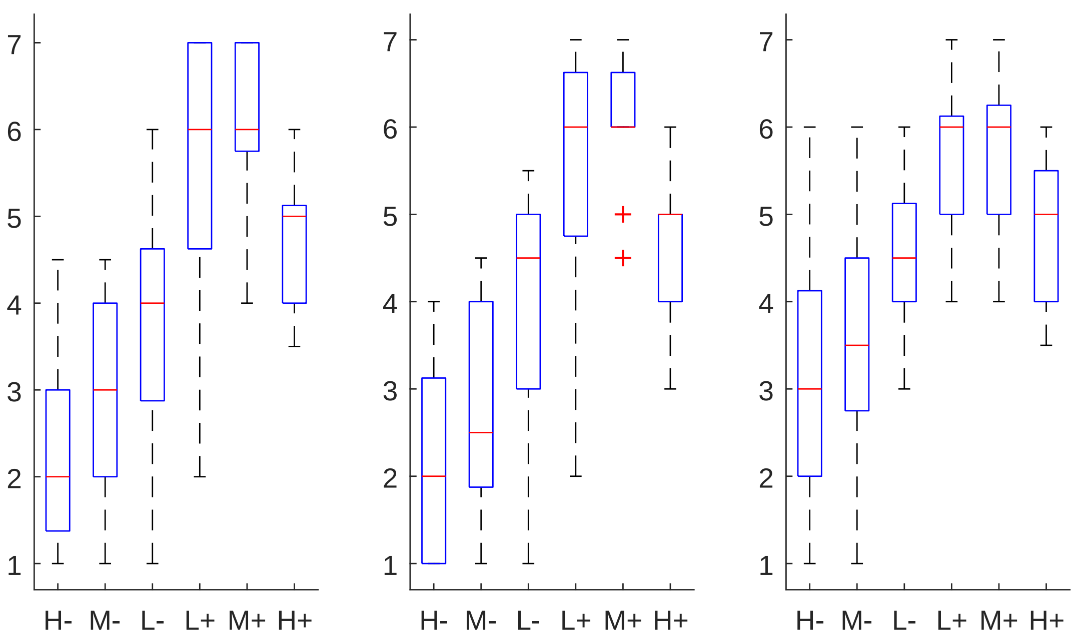
- **H1** Participants indicate lower causality, co-presence, and realism regardless of the sign of the latency when the magnitude of the latency is high.
- **H2** Participants indicate higher causality, co-presence, and realism when the physical token's motion is slightly delayed compared to the hand.

6.4.5 Results

This section presents the results of the subjective measures and the range of delay participants rated as "no delay".

The questionnaire ratings were pooled and analyzed using Friedman tests at the 5% significance level. Wilcoxon signed-rank tests with Bonferroni correction were performed for post-hoc comparisons of the groups. Results for each measure are shown in Figure 6.9. Significant main effects of latency were found on the perceived causality ($\chi^2 = 52.910$, $p < 0.001$), perceived realism ($\chi^2 = 58.055$, $p < 0.001$), and perceived co-presence ($\chi^2 = 49.584$, $p < 0.001$). Results of the post-hoc comparisons are shown in Table 6.3.

For the perceived latency ratings, we asked participants to choose the delay category they perceived per each observation during the experiment. We grouped the adjusted latencies by each category (see Figure 6.10).



(a) Causality (b) Realism (c) Co-presence

Figure 6.9: Subjective results for each group (see Section 6.4.4). Whiskers in the box plots are extended to represent the data points with less than 1.5 IQR distance from 1st and 3rd quartile.

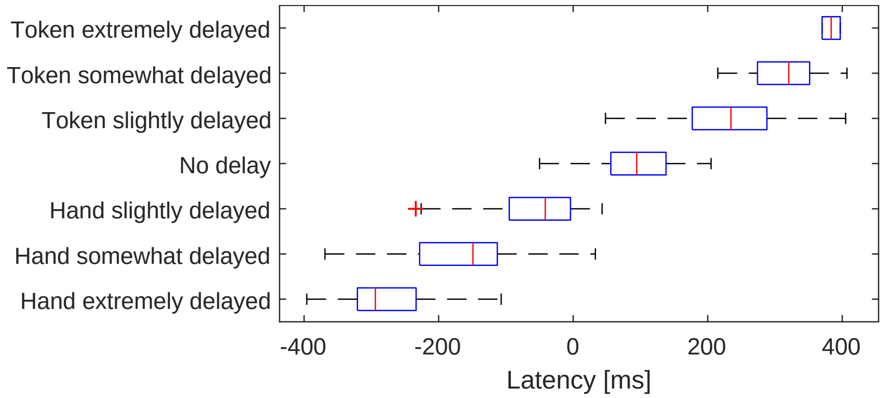


Figure 6.10: Ranges of latencies based on the perceived delay categories. Whiskers in the box plots are extended to represent the data points with less than 1.5 IQR distance from 1st and 3rd quartile.

Table 6.3: Summary of the pair-wise Wilcoxon signed-rank test results. Adjusted alpha level = .003 was used to determine significance (*).

Comparison	Causality		Realism		Co-presence	
	Z	p	Z	p	Z	p
H- vs. M-	-2.295	.022	-1.916	.055	-1.150	.250
H- vs. L-	-3.070	.002*	-3.078	.002*	-2.615	.009
H- vs. L+	-3.192	.001*	-3.186	.001*	-3.068	.002*
H- vs. M+	-3.194	.001*	-3.192	.001*	-3.069	.002*
H- vs. H+	-3.195	.001*	-3.194	.001*	-2.809	.005
M- vs. L-	-2.536	.011	-2.958	.003*	-2.384	.017
M- vs. L+	-3.202	.001*	-3.187	.001*	-3.072	.002*
M- vs. M+	-3.194	.001*	-3.188	.001*	-3.065	.002*
M- vs. H+	-2.982	.003*	-2.989	.003*	-2.623	.009
L- vs. L+	-3.197	.001*	-3.213	.001*	-2.969	.003*
L- vs. M+	-3.077	.002*	-3.192	.001*	-2.956	.003*
L- vs. H+	-2.148	.032	-1.845	.065	-1.406	.160
L+ vs. M+	-1.552	.121	-1.703	.088	-1.512	.131
L+ vs. H+	-1.558	.112	-1.671	.095	-2.714	.007
M+ vs. H+	-2.808	.005	-3.219	.001*	-2.840	.005

6.4.6 Discussion

Overall, our results show a strong effect of latency on the perceived causality of synchronized physical and virtual motions, overall realism of the observed physical-virtual interaction, as well as the sense of co-presence with a VH affecting physical space. The results are in line with our Hypothesis H1, suggesting negative effects of high latency on the perception of the physical-virtual interaction, independent of the sign of the latency.

Moreover, the results indicate an overall higher tolerance and even a preference for a slight amount of virtual-to-physical (positive) latency compared to the opposite direction, which is in line with our Hypothesis H2. Participants rated higher scores for all measures when the token's motion was slightly delayed compared to the virtual hand. We believe that this direction of latency is more tolerant in terms of preserving a natural causal relationship between a hand and an object that is moved by the hand, considering friction and similar effects that are known to play a role in similar situations in the real world. We received mixed comments on this effect from our participants. One participants commented, *"virtual hand being slightly ahead seems about as good as virtual being slightly behind,"* while one commented, *"Virtual hand moving ahead of the token seemed more realistic than the physical token moving ahead of the hand even if there was a slight delay present."* Meanwhile, our results for the tested range of latencies indicate that there is a perceptual bias in the perceived amount of latency based on which motion was delayed; participants rated latency group L+ more as "no latency" while L- was rated more as "slight delay."

Psychological studies suggest that people perceive the world not by an instantaneous moment-by-moment construction but by integrating information within a short temporal window, while also suggesting that our brain may fabricate the temporal order of stimuli to make sense, e.g., the causal context, during an integration [27]. Given this, it is interesting that our participants' prior knowledge of the causal relation may have shaped their perception of the physical-virtual interaction. Overall, we seem to be more tolerant toward the virtual-to-physical latency direction as we often observe such a delay between a cause and effect in the real world. The results of pair-wise comparisons for the moderate and high delay groups (M− vs. M+, H− vs. H+) are in line with this rationale, thus supporting H2.

However, although the overall patterns are similar, it seems that the sense of co-presence is less affected by the latency compared to the causality or realism. For instance, one participant commented: *"[..] the perspective rendering, proper occlusion, clipping (via field of view), etc. played a large role in establishing the answer to this question regardless of the delay."*

6.5 Summary

In this chapter, we investigated the effects of a VH's physical influence on participants' perception of the VH and its abilities. Unlike the mediated physicality methods presented in the previous chapters in this dissertation, the physical influence of the VH in this chapter was only visible, not tangible.

We described an apparatus based on a motorized translation stage capable of magnetically moving small physical objects over a tabletop surface, while the physical source of the movement is hidden from an observer's view. Instead, in this setup, users wear a HoloLens and see a VH reach out with its hand and move the physical object. Based on this setup, we designed a basic interaction scenario, a tabletop board game, and performed a user study where participants played the game twice, each time with the VH either moving a virtual or a physical token throughout the game. Our results show significant benefits of the VH being able to move a physical token with respect to a positive impact on participants' sense of co-presence, physicality, and the VH's abilities.

We further addressed the research question of how the latency between physical and virtual movements in this mixed reality setup affects the perceived plausibility of the interaction with the VH. We formalized the latency in two directions with the physical object's movement preceding the virtual hand's movement or vice versa. Our results show that a slight temporal delay of the physical token moving after the virtual hand lead to a significant increase in ratings of realism, co-presence, and perceived causality during the mixed reality interaction.

Future work may focus on extending the presented setup to the third dimension, i.e., moving physical objects not only on the tabletop surface but integrating an electromagnetic mechanism to levitate them in mid air (e.g., see [87]). This would enable situations where the VH could pick up an object from the tabletop and set it down again, such as when picking up and rolling dice.

CHAPTER 7: CONCLUSION AND FUTURE WORK

This dissertation research introduced a novel method for improving user experience in interactions with VHs. The method exploits the perceptual illusion of causality between plausibly correlated VH actions and outcomes associated with real physical objects. As a result, users regard VHs as being able to affect them physically—an effect previously achieved only by explicit physical and robotic body parts. This approach of making objects responsive to VH actions can potentially reduce the overall cost of building the human-virtual human interaction system compared to the previous approach. Furthermore, this novel approach can make use of existing IoT devices such as IoT lamps, as seen in [77]. I also demonstrated positive effects of this method with controlled user studies involving experiences with VHs, and have provided a theoretical framework, the concept of mediated physicality, that can assist researchers and practitioners in the MR community in designing improved MR experiences involving VHs. More broadly, improved social experiences with VHs can potentially benefit socially isolated individuals, e.g., patients confined to a hospital or home, or elderly persons with reduced mobility.

7.1 Summary

The following is a summary of the findings from this research in connection with the thesis statements:

- **TS1 (Causality):** In Chapter 4 and Chapter 6, I demonstrated that participants could form a causal relation between observed VH actions and perceived physical stimuli. As a result they recognized the stimuli as outcomes of observed actions, even though the appearance of the VHs was not photo-realistic. From the latency study performed in Chapter 6 and the literature review, I identified that the behavioral realism of VHs' actions and the natural temporal order between the actions and their outcomes are crucial factors for the virtual-physical causal illusion.

- **TS2 (Physicality):** In Chapter 5 and Chapter 6, I provided evidence that an illusory perception of VHs' physicality, i.e., physicality illusion, can be induced from such falsely formed causal relationships. Furthermore, the results from Chapter 6 showed the transference effects of physicality illusion, showing that even if the VH's physical ability was observed on only one specific object, people regarded the VH as being able to affect other objects in the real world.

- **TS3 (Presence):** Throughout Chapter 3 to Chapter 5, I showed that the sense of social/co-presence was increased by observing the VH's physical influence. Unlike previous studies exploring the effects of the physicality of VHs, our VHs had neither a physical body nor a part of the physical body to have such effects. Instead, participants' perceptual illusion of the physicality of VHs increased the sense of social/co-presence with the VHs. In the user studies detailed in Chapter 4 and Chapter 5, participants also exhibited realistic gaze and proxemic behavior to the VH when such illusion of physicality was induced.

- **TS3 (Persistence):** The analysis on participants' gaze behavior from Chapter 4 to Chapter 5 supported that once the causal illusion was formed between the VHs' actions and physical stimuli, it remained throughout the entire interaction, even if participants were often shown the outcome stimuli without an action being made by the VH. In other words, participants continually perceived the physical influence of VHs by attributing the stimuli to the VHs' invisible actions through the causal illusion formed at an early point in the interaction.

7.2 Limitations and Future Work

Throughout the controlled user studies presented in this dissertation research, I have provided support for each thesis statement as summarized above. In each user study, I intentionally varied the type of the virtual environment and the physical properties of the mediator objects in order to demonstrate the generalizability of the concept of mediated physicality.

Nevertheless, there are a few limitations to this research that need further investigation. First of all, the durations of the VH interactions in the user studies conducted in this dissertation were relatively short. Although the short interaction time would not invalidate the comparisons between conditions, it raises the question of the long-term effects of the mediated physicality on users' perception of VHs. Throughout the user studies, I had speculated that participants would have a low expectation on the VHs' ability to affect their space due to the low visual realism of the VHs, and this low expectation would have been re-adjusted after they observed or felt the physical influence of the VHs. The transference effects discussed in Chapter 4 support this line of thinking. However, whether the increased expectation can remain intact over time is unknown; thus, a longitudinal study should be conducted.

Second, the present experiments were conducted under the limitations of current VR/AR technologies. Specifically, both VR/AR HMDs had a low resolution, and the AR HMD had a small augmented FoV with a semi-transparent view, thus resulting in the low visual realism of VHs. Again this low realism would have resulted in the low physicality expectations of VHs, as similar to how it reduced the sense of presence in a VE and social/co-presence with VHs [71, 127]. One might naturally ask—because VR/AR HMDs are getting better—whether the results would be different if the experiments were conducted using better HMDs that have higher resolution and wide FoV with non-transparency. I think this question leads to the extreme case where VHs become so realistic that people cannot visually distinguish them from real humans. Even in such a case, I believe incorporating mediated physicality method would be beneficial, but the way it affects users' perception of VHs would be different. While mediated physical outcomes of VHs' actions increased users' expectation of physical ability of the VHs in the present experiments, missing mediated physical cues when interacting with visually realistic VHs could perhaps result in cognitive dissonance, similar to the uncanny valley reported in humanoid research. Therefore, systems with realistic VHs might need to provide all expected mediated physical outcomes associated with actions of the VHs, in order to avoid falling into the uncanny valley.

Lastly, the questionnaire used for measuring perceived physicality of VHs needs further validation. Since the physicality illusion is a novel concept proposed in this research, I had to develop new measurements for it. I compiled a set of questions from relevant research and modified some of the items to reflect experiment scenarios better. In Chapter 6, I further devised a photo-based method to measure the perceived physicality of VHs. Although each question seemed to ask aspects related to physical abilities of VHs clearly, the questions should be tested for reliability by statistical analysis, such as a Cronbach's alpha coefficient, with large sample size. Besides, in this dissertation, I measured the perceived physicality of VHs as an independent variable along with social/co-presence, although I considered the perceived physicality would be one of the factors that affect social/co-presence, more specifically co-presence. Therefore, along with the validation of the perceived physicality measures, further statistical analysis methods, such as structural equation modeling, should be applied to better understand the relationship between perceived physicality and social/co-presence.

Apart from the issues listed above, the limited number of user studies presented in this dissertation is insufficient to examine each element of the proposed concept thoroughly. Therefore, I end the dissertation research here, with suggestions for future work.

- **Mediated physicality of a virtual object:** Although I have discussed perceived physicality of VHs in the context of social interaction in this dissertation, physicality is a more general characteristic that every physical object has. The physicality of the object is determined by its interaction with other physical and virtual masses; therefore, people would likely regard a virtual object as more physical when the mediated physicality method is applied to the virtual object. This paradigm of focusing on interactivity between virtual and physical objects may help to design better measures for the sense of virtual objects' presence in non-immersive displays.

- **Second-order mediation:** The presented experiments examined the first-order mediation, i.e., VHs' actions affect an object, and then users perceive outcomes of the VHs' actions mediated through the object. I believe that the involvement of a second or third object in the chain of physicality transfer would be possible (see Figure 7.1); however, the transferred physicality might be restricted by the physicality of the mediator object, and the mediated physicality might be gradually decreased each time it is transferred to a new object.

- **AR visualization:** Kim et al. [77] showed the importance of behavioral realism when VHs are interacting with a physical object. Also Kim et al. [78] further demonstrated physical conflict, e.g., a VH occupying the same space as a physical object can decrease co-presence with VHs in augmented reality. However, sometimes this physical conflict is inevitable when a VH's realistic behavior involves a motion while a physical object does not have an actuator to move. I believe such presence-reducing issues can be alleviated with appropriate visual effects, such as substitutional reality [134] or a visual effect that represents the physical characteristics of the interaction.

Additional user studies and the exploration of the topics mentioned above will continue to expand on the ideas presented in this dissertation and will lead us closer to more realistic and believable interactions with VHs.

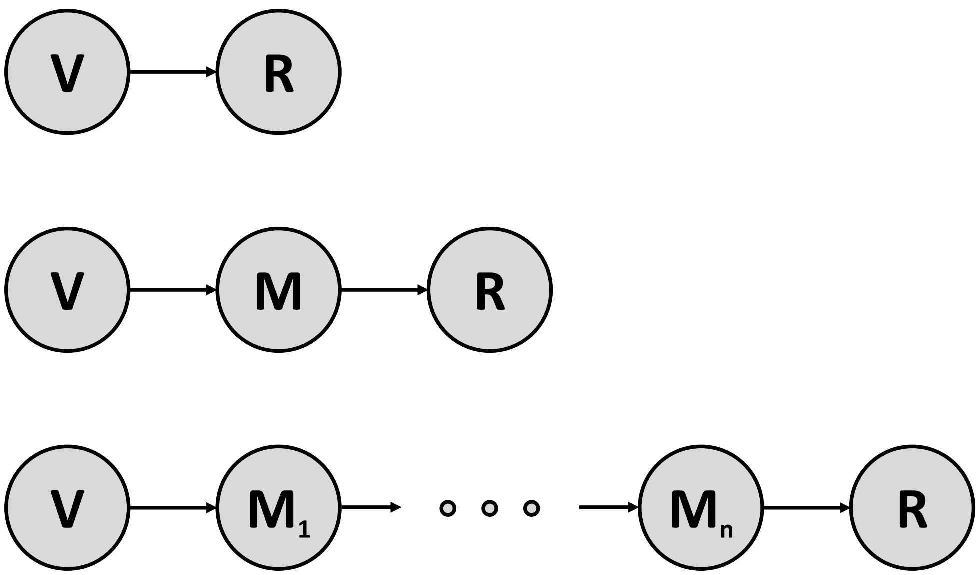


Figure 7.1: Concept diagram of *Mediated Physicality*. The first row represents direct physical influence; the second row represents 1st order mediation; the third row represents n-th order mediation. (V: virtual human, M: mediator object, R: real human)

APPENDIX A: IRB APPROVAL LETTERS

University of Central Florida Institutional Review Board
Office of Research & Commercialization
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Orlando, Florida 32826-3246
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Approval of Human Research

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

To: **Greg Welch** and Co-PIs: **Andrew Brian Raij, Charles E. Hughes**

Date: **July 13, 2015**

Dear Researcher:

On 07/13/2015, the IRB approved the following human participant research until 07/12/2016 inclusive:

Type of Review:	UCF Initial Review Submission Form Expedited Review Category #4, 6, and 7 This approval includes a Waiver of Written Documentation of Consent
Project Title:	The Effects of Realism Cues on Interactions with Human Surrogates
Investigator:	Greg Welch
IRB Number:	SBE-15-11405
Funding Agency:	Office of Naval Research
Grant Title:	Human-Surrogate Interaction
Research ID:	1056687

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

If continuing review approval is not granted before the expiration date of 07/12/2016, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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

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

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

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

Joanne Muratori

Signature applied by Joanne Muratori on 07/13/2015 12:53:09 PM EDT

IRB manager

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Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
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Approval of Human Research

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

To: **Greg Welch** and Co-PIs: **Andrew Brian Raij, Charles E. Hughes**

Date: **June 23, 2016**

Dear Researcher:

On 06/23/2016, the IRB approved the following human participant research until 06/22/2017 inclusive:

Type of Review:	IRB Continuing Review Application Form Expedited Review
Project Title:	The Effects of Realism Cues on Interactions with Human Surrogates
Investigator:	Greg Welch
IRB Number:	SBE-15-11405
Funding Agency:	Office of Naval Research
Grant Title:	
Research ID:	1056687

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

If continuing review approval is not granted before the expiration date of 06/22/2017, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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

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In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

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

Joanne Muratori

Signature applied by Joanne Muratori on 06/23/2016 04:19:14 PM EDT

IRB Manager

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Office of Research & Commercialization
12201 Research Parkway, Suite 501
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Approval of Human Research

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

To: **Greg Welch** and Co-PIs **Charles E Hughes 3104349 and Gerd Bruder**

Date: **May 15, 2017**

Dear Researcher:

On 05/15/2017 the IRB approved the following human participant research until 05/14/2018 inclusive:

Type of Review:	Submission Response for IRB Continuing Review Application Form Expedited Review Category 4, 6, and 7
Project Title:	The Effects of Realism Cues on Interactions with Human Surrogates
Investigator:	Greg Welch
IRB Number:	SBE-15-11405
Funding Agency:	Office of Naval Research
Grant Title:	
Research ID:	1056687

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

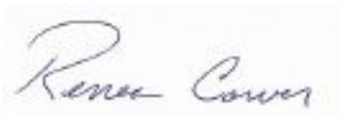
If continuing review approval is not granted before the expiration date of 05/14/2018, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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

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

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

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



Signature applied by Renea C Carver on 05/15/2017 01:05:11 PM EDT

IRB Coordinator

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Approval of Human Research

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

To: **Gregory Welch** and Co-PIs: **Charles E Hughes & Gerd Bruder**

Date: **April 16, 2018**

Dear Researcher:

On 04/16/2018 the IRB approved the following human participant research until 04/15/2019 inclusive:

Type of Review:	IRB Continuing Review Application Form Expedited Review Category # 4, 6, & 7
Project Title:	The Effects of Realism Cues on Interactions with Human Surrogates
Investigator:	Gregory Welch
IRB Number:	SBE-15-11405
Funding Agency:	National Science Foundation, Office of Naval Research
Grant Title:	Extended Augmented Reality: Autonomous Virtual Behaviors and Extrasensory Perceptions Integrated Into Ad Hoc Spaces
Research ID:	1062408

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

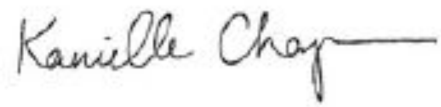
If continuing review approval is not granted before the expiration date of 04/15/2019, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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

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

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

This letter is signed by:



Signature applied by Kamille Chaparro on 04/16/2018 12:38:15 PM EDT

Designated Reviewer

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