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The Effect of Anthropometric Properties of Self-Avatars on Action Capabilities in Virtual Reality

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Abstract

The field of Virtual Reality (VR) has seen a steady exponential uptake in the last decade and is being continuously incorporated into areas of popular interest like healthcare, training, recreation and gaming. This steady upward trend and prolonged popularity has resulted in numerous extravagant virtual environments, some that aim to mimic real-life experiences like combat training, while others intend to provide unique experiences that may otherwise be difficult to recreate like flying over ancient Egypt as a bird. These experiences often showcase highly realistic graphics, intuitive interactions and unique avatar embodiment scenarios with the help of various tracking sensors, high definition graphic displays, sound systems, etc. The literature suggests that estimates and affordance judgments in VR scenarios such as the ones described above are affected by the properties and the nature of the avatar embodied by the user. Therefore, to provide users with the finest experiences it is crucial to understand the interaction between the embodied self and the action capabilities afforded by it in the surrounding virtual environment.

In a series of studies aimed at exploring the effect of gender matched body-scaled self-avatars on the user's perception, we investigate the effect of self-avatars on the perception of size of objects in an immersive virtual environment (IVE) and how this perception affects the actions one can perform as compared to the real world. In the process, we make use of newer tracking technology and graphic displays to investigate the perceived differences between real world environments and their virtual counterparts to understand how the spatial properties of the environment and the embodied self-avatars affect affordances by means of passability judgments. We describe techniques for creation and mapping VR environments onto their real world counterparts and the creation of gender matched body-scaled self-avatars that provides real time full-body tracking.

The first two studies investigate how newer graphical displays and off-the-shelf tracking devices can be utilized to create salient gender matched body-scaled self-avatars and their effect

on the judgment of passability as a result of the embodied body schema. The study involves creating complex scripts that automate the process of mapping virtual worlds onto their real world counterparts within a 1cm margin of error and the creation of self-avatars that match height, limb proportions and shoulder width of the participant using tracking sensors. The experiment involves making judgments about the passability of an adjustable doorway in the real world and in a virtual to-scale replica of the real world environment. The results demonstrated that the perception of affordances in IVEs is comparable to the real world but the behavior leading to it differs in VR. Also, the body-scaled self-avatars generated provide salient information yielding performance similar to the real world. Several insights and guidelines related to creating veridical virtual environments and realistic self-avatars were achieved from this effort.

The third study investigates how the presence of body-scaled self-avatars affects the perception of size of virtual handheld objects and the influence of the person-plus-virtual-object system created by lifting the said virtual object on passability. This is crucial to understand as VR simulations now often utilize self-avatars that carry objects while maneuvering through the environment. How they interact with these handheld objects can influence what they do in critical scenarios where split second decisions can change the outcome like combat training, role-playing games, first person shooting, thrilling rides, physiotherapy, etc. It has also been reported that the avatar itself can influence the perception of size of virtual objects, in turn influencing action capabilities. There is ample research on different interaction techniques to manipulate objects in a virtual world but the question about how the objects affect our action capabilities upon interaction remains unanswered, especially when the haptic feedback associated with holding a real object is mismatched or missing. The study investigates this phenomenon by having participants interact with virtual objects of different sizes and making frontal and lateral passability judgments to an adjustable aperture similar to the first experiment. The results suggest that the presence of self-avatars significantly affects affordance judgments. Interestingly, frontal and lateral judgments in IVEs seem to similar unlike the real world.

Investigating the concept of embodied body schema and its influence on action-capabilities further, the fourth study looks at how embodying self-avatars that may vary slightly from your real world body affect performance and behavior in dynamic affordance scenarios. In this particular study, we change the eye height of the participants in the presence or absence of self-avatars that are either bigger, smaller or the same size as the participant. We then investigate how this change in eye

height and anthropometric properties of the self-avatar affects their judgments when crossing streets with oncoming traffic in virtual reality. We also evaluate any changes in the perceived walking speed as a result of embodying altered self-avatars. The findings suggest that the presence of self-avatars results in safer crossing behavior, however scaling the eye height or the avatar does not seem to affect the perceived walking speed. A detailed discussion on all the findings can be found in the manuscript.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

In the last decade, Virtual Reality (VR) has undergone numerous advancements in terms of technology and has thus seen renewed popularity. With the recent decline in the prices of displays, tracking technologies and graphics cards, and the competitive nature of the consumer market, a wide variety of new VR applications are being developed for entertainment, health care, training and education. These applications are often multimodal, highly realistic and enable users to experience some of the most extreme activities in VR with multi-sensory stimuli, for example, underwater VR exploration [5] or rock climbing [46]. A combination of these factors have brought forth a new era of virtual realism ready to be exploited by researchers and businesses alike.

To successfully recreate scenarios like the ones described above without breaking immersion, it is necessary that the perceived spatial information is veridical [55]. This information is relayed via size, distance, depth and volume perception within the virtual environment. Previous research has shown that these estimates are often inaccurate in immersive virtual environments (IVE) when they are viewed through a Head-Mounted Display (HMD) or via large screen stereoscopic displays in VR or augmented reality environments [26, 56, 85]. However, past studies made use of VR devices that offered much lower fidelity of rendering, field of view (FOV) and resolution as compared to current devices, and this has been suggested as a cause of the inaccuracies reported in previous work [44, 87, 74]. It is thus important to revisit these results when newer and more promising commercial products are released.

When investigating how well VR systems support the perception of spatial properties in virtual spaces, it is important to recognize that properties such as size, distance, height, slant, etc., are not typically perceived as such, but rather people perceive what actions they can perform within a given environment exploiting the spatial attributes [26, 93, 61, 92]. People need to perceive, for example, if an object is close enough to be reached and small enough to be grasped, if a gap between two surfaces is small enough to leap across, or if a surface is low enough to be stepped on. The actions possible for a given set of environmental objects and surfaces are referred to as affordances [35], and they are the primary objects of perception when one needs to interact with the environment [26, 93, 20]. Therefore, the perception of affordances or action capabilities is a relation between the actor and the object of focus and the relevant metrics for describing affordances are intrinsic to the perceiver. For example, the affordances of step-on-able and sit-on-able depend on the height of a surface relative to the leg length of the actor [61, 92], a box is lift-able if its width is smaller than the arm span of the actor. Similarly, the affordance of passability depends on the width of the gap relative to the width of the actor [93, 20]. The intrinsic metrics of the perceiver or the actor is a representation of their body dimensions and its potential for action which is referred to as body schema [30, 29]. More recently, it has been suggested that the body schema is malleable and is perceived as the body moves and is equipped with items [67]. Due to the malleable nature of the schema, it adapts as our bodies go through permanent and temporary changes throughout life and any calibration needed happens spontaneously [12].

Given that the affordances in a given environment are perceived relative to one's action capabilities represented by their body schema, it has been demonstrated that the inclusion of an appropriately scaled self-avatar in a virtual world can enhance the perception of affordances [54, 57]. Any alterations to the self-avatar can recalibrate the embodied body schema in turn changing the perception of the spatial properties of the environment [49, 13, 12]. Although the use of self-avatars in VR makes it extremely easy to alter one's body schema and has been shown to greatly affect a user's perception of the environment, decision making, behavior and presence in IVEs [13, 54, 71, 11], generating a high fidelity self-avatar is one of the most challenging aspects of making VR simulations immersive. The most popular way of tracking humans in real time for self-representations has been through the use of optical tracking systems, for example VICON; These systems usually require tens or hundreds of markers to be placed on the user and make use of several infrared (IR) cameras that cost thousands of dollars. As a result, they need a large area to setup and are cumbersome. These factors, coupled with the complex scripts required to filter and map real-life motion to virtual characters in real time makes self-avatars non-trivial and somewhat inaccessible. However, recent advancements in hardware and software have made tracking users in real time more accessible with the help of sensors like accelerometers, gyroscopes, and lighthouse trackers like the HTC Vive trackers. Many companies, like Perception Neuron [1] and Synertial [2], have thus developed tracking solutions that utilize suits with integrated accelerometers worn by users that cost a fraction of what optical tracking systems cost. Other companies like Ikinema [3] and Root Motion [4] have developed software applications and APIs that can generate a real time tracked self-avatar using inverse kinematics (IK) based only on a few positional data points received from trackers like the HTC Vive trackers. The results obtained may not be as accurate as the ones from optical systems due to the reduced number of data points, but they seem to be acceptable as an increasing number of VR applications are making use of them to create self-avatars. Nevertheless, generating body-scaled self-avatars is a challenging process and as a result various simulations opt for generic self-representations that may not have the same body proportions as the user or only depict certain body parts like hands, head or feet. Some even use non-human entities like robots or controllers. Considering that self-avatars can affect perception, a logical next step is to understand how alterations to the embodied body schema influence the perception of affordances.

Previous research has examined both direct estimates of depth, size, and scale, as well as affordance judgments in virtual reality with and without the presence of self-avatars and how they compare to the real world [76, 13, 64, 23]. However, few have explored passability judgments [93, 23, 73]. Passability is one of the most common affordances utilized every day while crossing hallways, walking through doorways, maneuvering between crowds, traffic crossing, etc. The affordance of passability is also common in VR simulations and appears in the form of portals, doorways, puzzle doors, gaps between obstacles, avoiding moving objects, etc. Considering how estimations and affordances are not perceived similarly in IVEs and embodying self-avatars can further influence it, it is imperative to evaluate how the perception of affordances like passability changes in the presence of gender matched body-scaled self-avatars.

Another facet of VR is natural and intuitive interaction. One of the most common forms of interactions that are afforded in VR is object manipulation. Users are often allowed to grab and operate virtual objects during the experience like shooting, throwing balls, levers, etc. This is usually

[1]https://neuronmocap.com/
[2]https://www.synertial.com/mocapsuit
[3]https://www.ikinema.com/
[4]http://www.root-motion.com/final-ik.html

facilitated with the help of controllers that provide 6 degrees of freedom (DoF) tracking and several DoF for interaction using buttons and touch sensors. Picking up and carrying virtual objects in IVEs augments the virtual representation of the user with objects of varying dimensions depending on the object itself and how the user holds it. In the real world, a handheld object is functionally incorporated into the physical body of the wielder and is treated as an extension of the body [4]. Holding and carrying objects in the real world creates a person-plus-object (PPO) system which has been shown to influence affordance perception in the surrounding environment [91, 28]. Similarly, carrying virtual objects forms a person-plus-virtual-object (PPVO) system which is expected to change the action capabilities of the user within the IVE. Affordance judgments in VR have been previously reported to be affected by the size of the self-representation [71, 54], however the effect of virtual handheld objects on affordance perception in IVEs has not been investigated. Apart from picking up and grabbing different objects, individual often have to interact with moving objects as well. For example catching objects in sports, crossing traffic, throwing objects in motion, etc. Perceiving affordances in such scenarios becomes complex as they change overtime. What was afforded a fraction of a second ago may not be credible anymore. Such scenarios involve perceiving moving objects and synchronizing self-motion with the predicted trajectory of the moving object. Affordance perception in cases such as these is influenced by the action-scaling properties of the body schema such as reflexes, reach, walking speed, etc. Previous works in this area have evaluated traffic crossing behavior in pedestrians and bicyclists across different age groups [72, 65], regulation of self-motion with respect to moving doors [7], perceiving reachability while jumping [69], etc. Although IVEs have been used to study regulatory perception of affordances in the past, the impact of altered action capabilities as a result of embodying generic self-avatars on dynamic affordance perception has not been investigated.

Understanding how individuals react or interact when faced with the situations described above is especially important as inconsistencies in expected outcomes while making static and dynamic affordance judgments in the virtual world might lead to break in immersion and presence. With the industrial sector progressively incorporating VR into games and thrilling experiences where carrying and avoiding objects is common and split second decision may change the outcome of the situation like FPS and RPG games, it is imperative to understand how interacting with virtual objects of different sizes in the presence of self-avatars affects the affordance of passability. This is especially true when replicating challenging real life scenarios like PTSD rehabilitation, combat training, etc.

Therefore, in a series of investigations, we empirically examine how newer displays and tracking technologies can be used to generate fully tracked body-scaled self-avatars and their effect on action capabilities in static and dynamic virtual environments via passability affordance judgments. In the presented works, we compare judgments made in the real world to those made in their virtual counterparts in the presence and absence of self-avatars. We explore how the presence of self-avatars affects the perception of action capabilities associated with the PPVO system formed as a result og carrying virtual objects. To further understand the effect of embodying self-avatars on action capabilities, the final study investigates the effect of embodying self-avatars with altered anthropometric properties on dynamic affordances. This series of studies, to the best of our knowledge, takes the next step towards exploring several unique effects of embodying self-avatars on perceived action capabilities in both static and dynamic affordance scenarios.

Chapter 2

Related Work

2.1 Comparing Real and Virtual Worlds

To maintain high levels of immersion in VR simulations, it is imperative that the veridicality of the environment is preserved by making sure that the perceived size of objects and the action capabilities associated with them are comparable to the real world. The perceived distance, depth and size of objects in IVEs or VR has been studied by researchers previously and reported as comparable or underestimated based on the task presented and the technology used to present the virtual environment [85, 23, 24, 82, 76, 13]. For example, Lin et al. [56] asked participants to blind walk to a target and found no differences in estimated distances between the real and virtual environments. However, Stefanucci et al. [85] asked participants to judge the size of objects in real and virtual environments and reported that the perceived size of objects was smaller in VR as compared to the real world. These underestimations and differences have been attributed to the capabilities of the underlying hardware and software used to render the IVE and human perception error [44, 87, 76]. Klein et al. found that participants underestimated distances more when viewing a virtual environment on a large screen as compared to a CAVE [45]. The authors attributed this increased underestimation in the large screen condition to its restricted FOV. For those studies investigating FOVs in HMDs, it was found that wider FOVs resulted in improved distance estimates [26, 39, 51]. In a separate study by Stefanucci et al., authors reported that the difference in the actual and perceived size of virtual objects was reduced when using stereoscopic large screen displays [82].

2.2 Estimation Techniques

Most of the research on size and distance estimation in VR has utilized procedures that involve verbal estimation or visually directed actions [76]. Verbal estimation requires the participant to report their estimates in standardized units (i.e., feet, meters), while visually guided action requires the participant to perform a secondary movement to indicate their estimate (i.e., toss a bean bag to the perceived distance). These methods for estimating distance and size have been shown to be biased by cognitive factors [59, 47, 60, 66]. Importantly, verbal estimates are subjective measurements of distance estimates because they rely on the participant's knowledge of standardized units of measure. As such, these distance estimates are a measure of the participant's experience with standardized units of measure as opposed to their actual perception of distance.

2.3 Affordances

An alternative method to evaluating veridical perception of environments by gauging the perceiver's size and distance estimates is through affordance perception [23]. Affordances are possibilities for action [35], which are determined by the relationship between characteristics of the environment and properties of the organism's action system. Importantly, affordances are scaled to the individual organism, determined by each individual's morphology and physical capabilities (body schema). A large body of research has examined affordances and how they are influenced by the body schema moderated by body-scaling and action-scaling. Body-scaling is the use of information that is scaled to an individual's geometric properties and physical morphology to perceive what actions can be successfully completed [34]. For example, a doorway is pass-through-able if the width of the opening is larger than the actor's widest frontal dimension - their shoulder width [93]. Similarly, action-scaling refers to considering one's dynamic properties, i.e., the properties of one's own movements, to determine action possibilities [78]. Given these intrinsic units and their suggested influence, size of different parts of the body have been reported to affect action capabilities.

2.3.1 Static Affordances

Stefanucci et al. [83] conducted a series of experiments in the real world examining how changes to the body can affect the perception of extrapersonal space and aperture widths and found that the dimensions of the body plays a role in the scaling of environmental parameters in extrapersonal space. Franchak et al. demonstrated that changes to body proportions affects affordance judgments in the real world and may require perceptual recalibration based on the task and the environment [20]. In another set of experiments involving handheld objects, Wagman et al. showed that carrying objects creates a person-plus-object (PPO) system which affects affordance judgments and is influenced by properties like weight and inertia experienced during dynamic touch [91]. The study evaluated how passability was influenced when wielding objects with different weights and width but not seeing them and when seeing objects of different widths but not wielding them. The results suggest that individuals are sensitive to the affordance in either condition without any significant differences and treat the object as an extension of their body.

In a study comparing affordance judgments made in the real world to those in an IVE, Geuss et al. asked participants to make size estimates, affordance judgments, and blind walking distance estimates to an aperture in both the real world and a virtual replica [23]. Participants viewed two poles and used their hands to indicate the gap width between the two poles (size estimate), judged (yes/no) whether they could pass through the two poles (affordance judgment), and blindly walked to the poles (distance estimate). Differences in blind walking distance estimates were found between the real world and the virtual environment. However, size estimates and affordance judgments did not significantly differ between the real world and the virtual environment. Since this was a within subjects study, performing the size estimation task first may have biased responses on the affordance task. Thus, an unbiased assessment of affordance perception in IVEs is merited. Pointon et al. investigated passability affordance in an augmented reality environment and reported the judgments to be similar to those made in the real world and IVEs [73]. More recently, Buck et al. compared the action of passing through apertures in a collaborative setting [6]. The authors investigated how dyads cross an opening together in the real world and in a collaborative IVE. They reported that gendered social dynamics were not as prevalent in VR as in the real world, however participants required wider gaps to cross together in the IVE.

2.3.2 Dynamic Affordances

Several works have extended these investigations to study dynamic action-scaled affordances. Action-scaled affordances are more complicated as they change overtime and require the actor to synchronize their own movement to that of the moving object [14, 72]. Fajen et al. studied ball catching behavior to determine an actor's sense of his locomotion behavior [15]. They concluded that actors are fairly aware of their locomotor abilities and do not entirely rely on information on the fly. Buekers et al. examined the regulation of human motion based on external dynamic stimuli; namely oscillating doors [7]. The authors reported that actors postpone regulating behavior until the very last stage where the action becomes necessary to successfully overcome an affordance judgment. In another study by Grechkin et al., participants were asked to board a train with automatic doors in a virtual environment using natural walking versus joystick and while experiencing the simulation in an HMD or a CAVE [27]. The authors reported that perception of affordances in IVEs was profoundly affected by the medium of presentation of the virtual world and the use of HMD while walking seemed to increase the difficulty of the task. Traffic crossing has been a fairly popular approach for studying dynamic affordances in IVEs. Simpson et al. evaluated child and adult road crossing behavior utilizing a HMD based VR simulation [80]. The results suggested that pedestrians rely on distance between cars rather than speed to make traffic crossing decisions. Chihak et al. compared and contrasted child and adult cyclists behavior for intersecting moving gaps in an IVE [8]. The authors reported that adults always had more time to spare before contact but slowing down helped increase the time to spare for both children and adults resulting in safer crossing behavior. In a more recent work, Plumert et al. studied child cyclist traffic crossing behavior to understand how they learn to perceive dynamic affordances [72]. They report that synchronizing self motion to the lead car for a particular gap seems to be a key factor in crossing moving gaps. Moreover, experience seems to play a significant role in perceiving moving objects with respect to oneself as adults always made safer decisions in comparison to children. These results were also confirmed by O'Neal et al. in recent study investigating pedestrian road crossing behavior in different age groups [65]. The authors reported that children's ability to perceive and act on dynamic affordances goes through a prolonged period of development. Through this period they adjust their gap crossing decisions to account for their poor initiation timing.

2.4 Avatar Embodiment

The use of self-avatars in VR makes it easier to temporarily manipulate one's body schema. Embodying a synchronously tracked self-avatar even for short periods of time can generate high levels of body-ownership and influence the embodied body schema [3, 77, 12, 13]. Since affordances are considered a useful perceptual measure of size in virtual worlds [23], the use of self-avatars in VR is an excellent way to study affordances and evaluate the fidelity of contemporary VR devices as compared to the real world. Past work shows that embodying self-avatars in IVEs can affect size and distance estimations as well as affordance judgments [71, 64, 57, 3]. Banakou et al. examined the effects of embodying a child body versus an adult body of the same height in an IVE on object size and attitude changes [3]. They found that participants who embodied a child's body significantly overestimated object sizes as a consequence of the difference between the embodied body schema associated with the child versus the adult avatar. In another study by Jun et al., participants embodied virtual feet in an IVE that were either much smaller or much larger than their own feet and judged if they could step across gaps of varying widths [40]. They found that participants with smaller foot width had a reduced ability to step over gaps and participants with larger foot width perceived they could step over larger distances.

Piryankova et al. examined the effects of embodying overweight and underweight bodies on the affordance of passability in women [71]. Even though the self-avatar used in this study was static and only had head-tracking, they saw a significant difference in the participants' passability judgment based on the size of the body they embodied. There have been other studies that use a full-body tracked avatar to study affordances. In a study by Lin et al., experimenters studied the affordance judgment of stepping over or under a pole and stepping off a ledge in an IVE with and without a fully tracked self-avatar [54]. They found that having a self-avatar significantly affected the threshold at which participants changed their judgments. Lin et al. also demonstrated how the presence of a self-avatar affected participants' threshold of stepping off of a ledge in VR [55]. They reported the judgments to be more realistic in the presence of self-avatars.

Apart from affordances, investigations have also evaluated the effect of self-avatars on interaction and cognition. Lok et al. investigated how handling real objects and self-avatar visual fidelity affected performance for a spatial cognitive task in an IVE [58]. The authors had participants perform block pattern tasks in the real world and different versions of a virtual environment. They reported that a visually faithful self-avatar had little effect on object interaction and cognitive task performance. In a more recent study by Steed et al., participants were asked to perform cognitive tasks involving memorizing letters and performing spatial rotations in an IVE [81]. The authors evaluated the presence of self-avatars and the ability to rotate hands on the tasks listed above. The results suggested that participants with self-avatars performed significantly better than those without, however these results were not compared to the real world. McManus et al. evaluated the influence of animated self-avatars on a distance estimation, an object interaction and a stepping stone locomotion task [62]. The authors reported that participants with animated self-avatars performed tasks quickly and more accurately as compared to the other conditions.

2.5 Altered Action Capabilities

Embodying self-avatars in IVEs might often be associated with illusionary changes to the anthropometric properties like altered eye height, limb size, action-scaling etc. as has been demonstrated in some of the studies mentioned above. Such alterations have been shown to affect the perception of object size, distance estimates and performance. Lin et al. demonstrated that embodying a self-avatar with altered leg length significantly influenced participants' affordance judgment thresholds [53]. Leyrer et al. studied the effect of altering the eye height of the participant in the virtual environment viewed through an HMD and found that it affected both the egocentric distances and perceived room dimensions [49]. In a more recent study, Hoort et al. attempted to understand the mechanism underlying visual rescaling of the external environment based on an individual's body [90]. Participants experienced the illusion of having a small or a large body and the authors reported that the size of test-objects was determined by the size of the body in an inverse relation. In a recent study, Lin et al. studied the effect of embodying virtual hands smaller or larger than the user's actual hands on object interaction and ownership using tracked gloves and controllers [52]. Although the results did not report any significant differences in performance efficiency based on the hand size embodied, using controllers for interaction resulted in better performance even though using gloves induced higher levels of ownership.

Chapter 3

Preliminary Evaluation of Affordance in Contemporary Virtual Reality

In this experiment, we empirically investigate the extent to which body-scaled information that is available in real-world viewing is both available and salient in contemporary IVEs. Specifically, we compare perception of passability through a doorway in the real world against a virtual world replica of the same stimuli in an HTC Vive based virtual environment.

For the present experiment, participants completed an affordance perception task to determine whether they could pass through doorways of various widths. Warren et al. showed that individuals compare their shoulder width, the widest frontal dimension, to the width of the gap to perceive passability [93]. Participants judged the boundary between passable and impassable door widths to be a ratio of 1.16 times their shoulder width. Additionally, they found that perceptions of aperture passability are a function of the width of the door relative to the individual's static eye-height. Geuss et al. asked participants to make size estimates, affordance judgments, and blind walking distance estimates of an aperture in both the real world and a virtual environment [23]. Although this was evaluated in a within subjects fashion and performing the size estimation task first may have biased responses on the affordance task, the findings suggested that affordance perception tasks may be a more appropriate method to assess the perceptual fidelity of a virtual environment.

Thus, an unbiased assessment of affordance perception in IVEs is merited. Moreover, Pointon et al. explored passability affordance in an augmented environment by replicating the tasks described above and observed a trend similar to Geuss et al. [73].

While Geuss et al. used a static affordance perception task (participants stood in one spot for the duration of the task), Fath et al. identified multiple sources of dynamic information that can be utilized when perceiving aperture passability [16]. They exposed participants to a virtual environment in which static eye-height scaled information was unavailable. When walking was initiated, two dynamic sources of information became available: head-sway scaled and stride-length-scaled information. Participants utilized these sources of dynamic information to accurately perceive their passability boundary. In each, participants were scaling the size of the opening to intrinsic units of head sway amplitude and stride length. If static eye-height scaled information is insufficient for accurate spatial perception in VEs, the utilization of dynamic information may improve estimates. Importantly, newer VR hardware systems allow for wide area tracking that would allow a user to walk around their environment and produce dynamic sources of information. Task-specific exploration of the environment may also improve affordance perception by means of exposure to the optic flow and motion parallax produced by such movements.

Unlike prior work, we allow participants to walk towards the aperture if they are uncertain of their ability to pass through the door. This allowed them to utilize dynamic information when making their affordance judgments. The virtual world sliding doorway apparatus and experiment room were carefully created and calibrated to exactly match the size and scale of the real world counterpart using a conjunction of tracking, scaling and adjustment techniques described in this chapter.

3.1 Experiment Design

The study utilizes a between-subjects design with a real world (RW) condition and an immersive VR condition. No viewing restrictions were introduced in the real world condition in order to examine passability judgements in natural setting of the real world viewing, and to maintain ecological validity. The VR condition encompassed viewing that was typical of best existing, popular, commercial VR systems (HTC Vive, Oculus Rift and Touch etc.), and did not have any additional tracking technology or rendering enhancements such as self-avatars. In this manner, we aim to capture a baseline measure of passability perception between typical VR and RW viewing situations, before examining the importance of other intrinsic (self-representations) or external reference information on participants' perceptual judgments. Participants' position in the IVE was marked on the floor by a circle which was updated based on the position of the HMD. The conditions were set up in this manner as we wanted to compare a typical real life scenario to a typical VR setup that many commercial HMD VR systems provide out of the box. The experiments were conducted in a 7.5 X 4.5 m room (see Figure 3.1). A sliding doorway was used for both the conditions. The doorway was adjusted to produce 14 pre-determined widths, 3 times each, in random order for a total of 42 trials. The sliding doorway and a judgment line were positioned on opposite sides of the room 4.42 meters apart. A curtain was hung behind the door to block any background visuals that could be seen through the opening, as they might provide additional perceptual cues.

A 3D replica of the physical room and the experiment apparatus matching in size and scale was modelled using Maya for use in the VR condition. Images matching the patterns from the physical space were used to texture the door, curtain, walls, etc., see Figure 3.2. The Unity 3D game engine was used to render the simulation at 90 frames per second on a HTC Vive HMD (110° horizontal FOV) utilizing a desktop computer with a dedicated NVIDIA GeForce GTX 1080 graphics card and an Intel i7 processor. The same physical room was used for both conditions and the virtual environment was mapped exactly onto the physical space.

The verification of the one-to-one mapping of the virtual environment onto the physical space was a 2-step process involving tactile feedback from the HTC Vive controllers, tracker recordings and the visual angle subtended in the HMD. For the first step, we touched the virtual aperture at multiple locations with the controller and checked for tactile feedback. If a tactile feedback was received, we checked if the location overlapped with the exact location on the real door, and verified the tracker logs. In case a tactile feedback was not received or the location was off, an offset was calculated based on the controller's position and the door's position. This offset was applied to the tracking space in Unity. The second step involved verifying the visual angle subtended. We visually aligned the Vive controller to an edge of the door in the virtual world first and then took off the HMD to see if the real controller visually aligned with the same edge of the real door. This process was repeated for all horizontal and vertical edges of the door from different viewing distances and aperture widths.

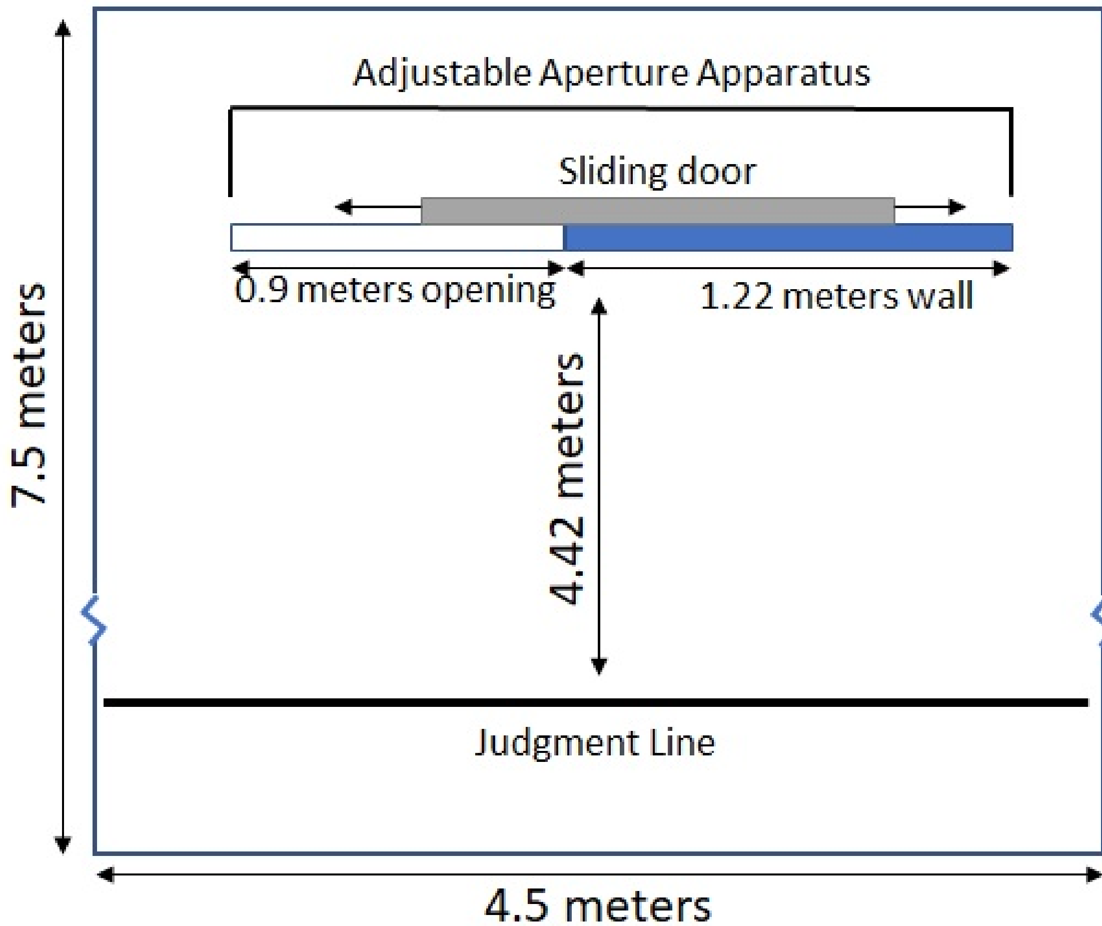

Figure 3.1: Experimental setup with details of the adjustable aperture

3.1.1 Participants

35 participants were recruited from Clemson University, 17 in real world and 18 in VR, for this experiment with 25 females and 10 males. The age ranged from 17 to 33 years with an average of 20.4 years. All participants were checked for normal or corrected-to-normal vision. The participants were either paid $10 or given course credit.

3.1.2 Procedure

In both conditions, participants read and signed a consent form and were asked to fill out a small demographic survey. Then their height and shoulder widths were measured in centimeters.

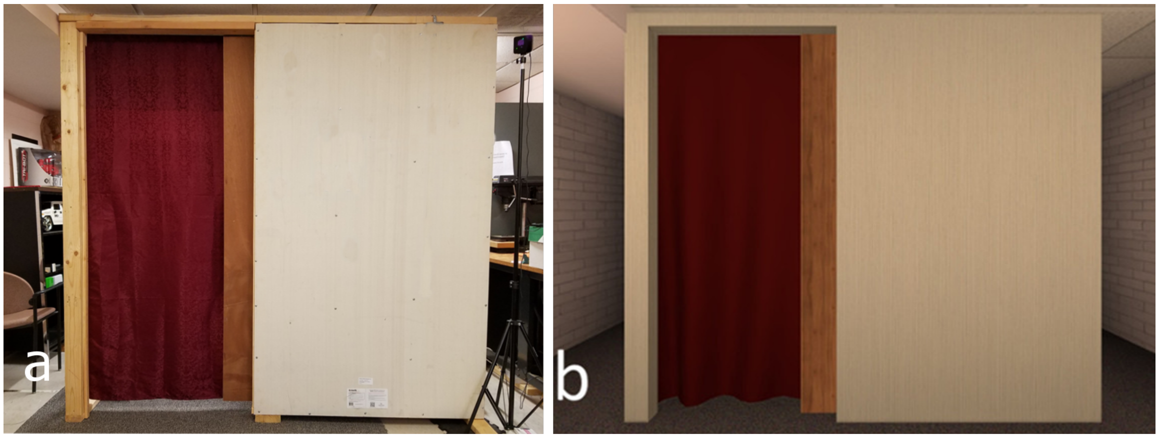

Figure 3.2: (a) Real world widest aperture (72 cms) (b) VR replica of the widest aperture (72 cms)

Visual acuity was also measured using a modified Snellen visual acuity test [1]. Interpupillary Distance (IPD) and Stereo Acuity [2] was also measured for each participant in the VR condition. All participants had normal 20/20 visual acuity, and were able to perceive stereo normally.

Following the survey and the measurements, participants were explained how to make judgments and were positioned behind the judgment line. They were instructed, for every door width presented, to communicate to the experimenter if they could pass through it without turning their shoulders. They were allowed to walk closer to the door if uncertain but were not permitted to walk through it. Walking was allowed to maintain consistency with natural interaction and to provide participants with ample spatial information by incorporating motion parallax and optic flow, especially in the IVE. Since walking through the door was not allowed, they never receive feedback about the accuracy of their judgments. For each trial, we recorded the participant's judgment (yes or no), the door-width presented, if they walked closer to the door (0 or 1), and the distance between the door and the participant if they walked. These were recorded using a pen and a paper for the real world condition and using a keystroke logging script for the VR condition.

The protocol followed was slightly different in the 2 conditions and is explained below in detail. Participants were allowed to take breaks especially in the VR condition as some of them were experiencing VR for the first time.

[1] http://www.allaboutvision.com/eye-test/snellen-chart.pdf

[2] https://www.good-lite.com/cw3/Assets/documents/100050_StereoFlyManual.pdf

3.1.2.1 Real World (RW)

After the participant was instructed on how to make judgments, he/she was asked to close their eyes. The experimenter then adjusted the sliding door to a random width. For every trial, the door was slid back and forth thrice before sliding to the actual width to avoid any bias from the sound of the door sliding. Once the door was at the desired width for that trial, the participant was asked to open their eyes and make a judgment. If the participant was uncertain of their judgment, he/she could walk towards the door until they were certain. If the participant walked during a trial, the distance between his/her feet and the door was recorded. The participant was then instructed to walk back to the line and close their eyes for the next trial. The procedure above was repeated for 42 trials.

3.1.2.2 Virtual Reality (VR)

In the VR condition, before the participants were asked to stand behind the line, their IPD was measured and they were tested for stereo perception. The experimenter then gave participants some information about the HMD, adjusted the IPD to match the participants' measured eye separation, and helped them don the HMD. To familiarize participants with the depth cues present within the IVE, a small acclimation phase was added. The acclimation phase included participants being situated in a virtual room similar to the testing room, but without the virtual apparatus. They were asked to walk up to a virtual cube randomly placed in the room and read out loud a number that was placed on one of its surfaces. They repeated this task 6 times and the cube was randomly placed at a different location each time with a randomly generated number on it. This forced them to naturally walk with the HMD to the objects and read the information they contained. After the acclimation phase, participants were given the same instructions as in the real world condition in the testing phase. In the VR condition, instead of having the participant close their eyes, a virtual curtain blocked their view as the aperture's width was adjusted for the next trial. When the participants' view was restored, they had to make a judgment about the aperture's passability. The testing phase procedure above was then repeated for 42 trials.

3.1.3 Research Questions and Hypotheses

The research questions addressed in this study were as follows:

1. Are perceptions of aperture passability different in the real world and IVEs?
2. To what extent do participants in IVEs require task-specific exploration of the environment in order to perceive their passability?

Our hypotheses in this study were as follows:

H1: Participants in both the real world and virtual reality condition will scale their perceptions of passability to their individual shoulder widths

H2: Participants in the real world condition will produce more accurate judgments than those in the virtual reality condition

H3: Participants in the virtual reality condition will be more uncertain of their judgments and thus walk towards the door more often than participants in the real world condition

H4: On trials where participants walked, participants in the virtual reality condition will require more task-relevant exploration of the environment (i.e., they will walk farther) than participants in the real world

3.1.4 Variable Transformation

For each trial, a binary judgment variable was computed, such that judgments of the door being passable were coded as 1 and judgments of the door being impassable were coded as 0. Second, a binary movement variable was created such that trials where participants walked towards the door prior to making their judgment were coded as 1, and trials where participants did not walk towards the door were coded as 0. Third, a binary accuracy variable was created to address whether participants correctly judged each door to be passable or impassable. When participants judged a door that was larger than their shoulders to be passable, or a door that was smaller than their shoulders to be impassable, they made a correct judgment (coded 1). When participants judged a door that was larger than their shoulders to be impassable, or a door that was smaller than their shoulders to be passable, they made an incorrect judgment (coded 0). It was necessary to dichotomize this categorical variable that otherwise had four categories due to the unequal distribution of occasions in some of those categories.

For each participant, every presented door width was converted into a passability ratio calculated by dividing the door width by the individual participant's shoulder width. Thus, a passability ratio of 1 indicates that the door width and the participant's shoulder width are equal. A passability ratio less than 1 indicates that the door width is smaller than the participant's shoulder width (and should thus be impassable), while a passability ratio greater than 1 indicates that the door width is larger than the participant's shoulder width (and should thus be passable).

Lastly, after viewing raw data scatter plots, a quadratic term was created for the passability ratio variable. A significant quadratic effect would indicate that a quadratic function fits the data better than a traditional linear function.

3.2 Results

3.2.1 Hierarchical Linear Model (HLM)

Since the experiment uses a repeated measures design, there was considerable nesting in the variables. That is, since each participant completed 42 trials, a portion of the variance in their responses can be attributed to a common source – the fact that the same participant was responding to each trial. This created multiple levels of variance. In a mixed-model regression, Level 1 (within-participant) variables represent those that change from trial to trial (for this study: Passability Ratio and Trial Number). Level 1 variables explain residual variance from the regression line, indicated by the difference between actual values and predicted values for each trial. Level 2 (between-participant) variables represent those that change from participant to participant (for this study: Condition). Level 2 variables explain intercept variance, indicated by the difference between the overall regression intercept and the intercepts of each participant's individual regression equation. Level 1 by Level 2 interactions occur when within-participant effects are moderated by between-participant variables. These cross-level interactions explain slope variance, indicated by the difference between the overall regression slope and the slope of each participant's individual regression line.

In order to confirm that there was nesting in the data, the Intraclass Correlation (ICC) was calculated from the baseline model. The ICC is a ratio of between-subjects variance / total variance. Results showed that 42% of the total variance in participant responses resided between-participants, and 58% of the total variance resided within-participants. This confirms the nestedness of the data, and supports the mixed model approach.

Typical statistical analyses, such as those involving disaggregation or aggregation of data, cannot simultaneously account for multiple levels of variance (i.e., relationships between and across levels) [75, 32]. Hierarchical Linear Modeling (HLM) is a method that can appropriately identify differences that occur at between-subject levels and within-subject levels [75, 32, 94]. In addition, HLM requires fewer assumptions and is more tolerant of missing data and differences in group sizes [75, 94]. Therefore, to account for variance at every level, HLM was used for this analysis. For a more detailed explanation of HLM, see [32].

When using HLM, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, all continuous variables were grand-mean centered. Thus, the intercept coefficient of the regression equation represents the predicted outcome when all continuous variables are held at their average.

Additionally, the use of dichotomous dependent variables produced a nonlinear cubic distribution. Since nonlinearity violates an assumption of linear regression, the raw scores were transformed into logit values, which have a linear distribution. By using a binary logistic regression [68], the model will predict the linear logit value, which can later be transformed into the odds and probability of an event occurring. Interpretation of main effects will utilize the odds ratio; Instead of having an additive effect on the logit, the odds ratio has a multiplicative effect on the odds (i.e., a one-unit increase in the predictor results in the odds being multiplied by the odds ratio).

Effect sizes for each fixed effect will be presented as the change in R2 (proportion of explained variance) comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect.

3.2.2 Judgment

To investigate whether virtual reality alters the perception of door passability, a binary logistic regression was run with judgment as the dependent variable. Participants judged each doorway to be either passable or impassable. Table 3.1 shows results of the model predicting passable judgments.

As expected, the passability ratio (presented door width / shoulder width) significantly predicted judgments and accounted for 75% of the variance in judgments. Participants became more likely to judge a presented door width passable as it increased with respect to their shoulder widths. Notably, participants' passability judgments in the VR condition were not significantly different from the ones in the real world condition (F = .48, p = .49). The perceived critical boundary (the smallest ratio judged as passable) was 1.03 for the real world condition and 1.0 for the virtual reality condition.

Table 3.1: Full model fixed coefficients and standard errors predicting judgment

Predictors	Coefficients (SE)	sr^2
Intercept	3.30 (.81)	-
Passability Ratio	28.47 (1.97)***	.75
Condition	.77 (1.12)	-
Passability Ratio X Condition	-4.42 (4.01)	-

note: * p <.05, ** p <.01, *** p<.001

3.2.3 Movement

To further investigate the effect of virtual reality on a participant's perception of affordances, a binary logistic regression was run with movement as the dependent variable. Recall that for each trial, participants were asked to walk towards the door if they were uncertain of their passability judgment. See Table 3.2 for results of the model predicting when participants walked towards the door prior to making their judgment.

Table 3.2: Full model fixed coefficients and standard errors predicting movement

Predictors	Coefficients (SE)	sr^2
Intercept	-3.09 (.30)	-
Trial	-.04 (.01)***	.04
Passability Ratio	34.83 (5.54)***	.05
Passability Ratio Squared	-16.95 (2.61)***	.26
Condition	-.31 (.36)	-
Passability Ratio Squared X Condition	-1.30 (.57)*	.02

note: * p <.05, ** p <.01, *** p<.001

In predicting the likelihood of movement, the main effect of trial showed that participants were less likely to walk towards the door over time. For each additional trial, the odds of walking towards the door were reduced by a multiplicative factor of .96. Again, there was a main effect of the passability ratio. However, upon inspection of the plotted data, a quadratic term was included in the model. The significant effect of passability ratio squared suggests that the relationship between movement and the passability ratio is best explained by a quadratic function rather than a linear one. That is, the probability of walking was highest when the passability ratio was close to 1, and lowest when the passability ratio was very high or very low (see Figure 3.3).

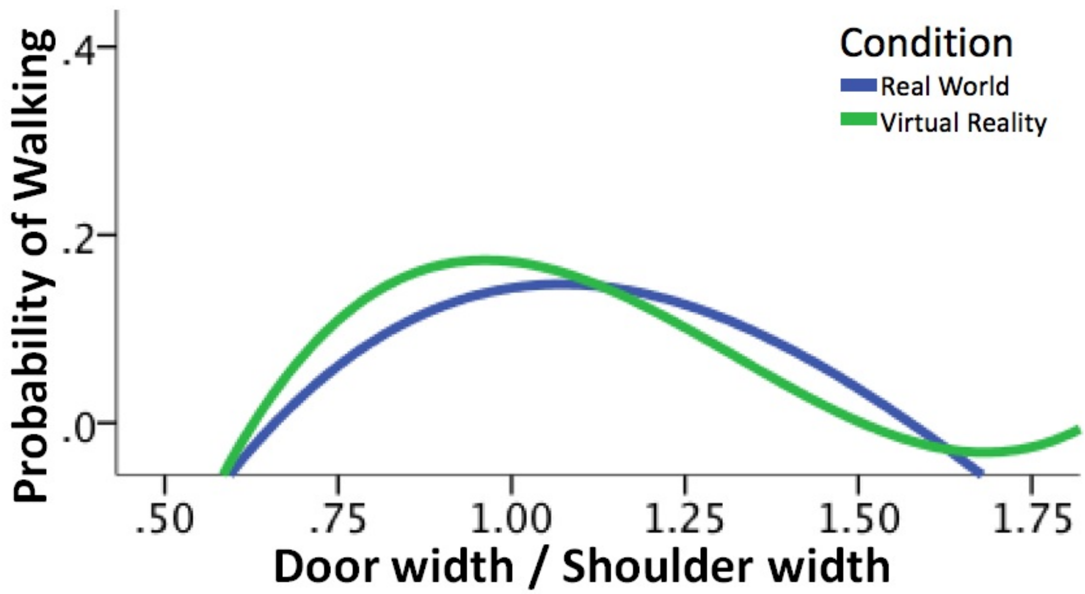

Figure 3.3: Interaction of passability ratio by condition predicting the probability of walking towards the door

Again, there was no main effect of condition on a participant's likelihood to walk towards the door ($F = .77$, $p = .39$). However, condition was a significant moderator of the quadratic ratio term. Figure 3 shows that at high and low values of the ratio, participants were unlikely to walk for both the VR and real world conditions. However, participants in VR were more likely to walk towards the door for ratios slightly less than 1, while participants in the real world were more likely to walk towards the door for ratios slightly above 1.

3.2.4 Distance

Next, we selected only the cases in which participants walked towards the door ($n = 140$ trials), and ran an HLM regression to assess the effects of virtual reality on the distance walked. Recall that for this variable, a small distance from the door indicates that the participant walked farther before making their judgment with certainty, and a large distance from the door indicates that the participants walked a short distance before making their judgment. Table 3.3 shows results for the model predicting the participant's distance from the door at the time of their judgment.

There was a significant main effect of passability ratio which accounted for 6% of the residual

Table 3.3: Full model fixed coefficients and standard errors predicting distance

Predictors	Coefficients (SE)	sr^2
Intercept	142.54 (19.78)	-
Passability Ratio	-847.71** (312.57)	.06
Passability Ratio Squared	347.22* (135.99)	.06
Condition	56.33* (27.35)	.1
Passability Ratio X Condition	101.17 (147.04)	-
Passability Ratio Squared X Condition	-31.28 (61.08)	-

note: * p <.05, ** p <.01, *** p<.001

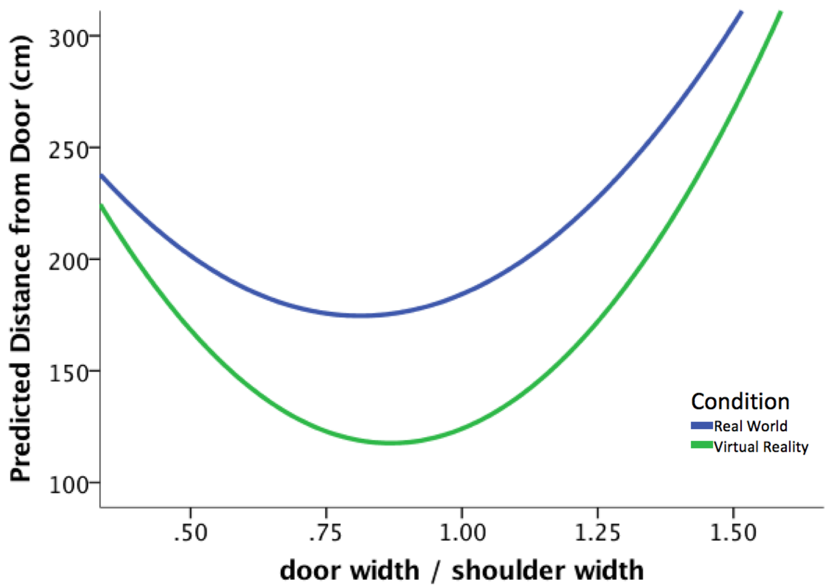

Figure 3.4: Predicted distances from the door plotted against the participant's passability ratio, displaying a quadratic effect of passability ratio and a main effect of Condition

variance in the model. Again, plots of the data suggested a quadratic trend, so the passability ratio squared term was included in the model. This suggested that the distance from the door was smallest when the ratio was close to 1 (see Figure 3.4). Additionally, there was a significant main effect of condition, such that participants in the virtual reality condition (M = 133.67 cm, SD = 18.25) were closer to the door when they made a judgment as compared to the ones in the real world condition (M = 190.01 cm, SD = 20.42). The effect of condition accounted for 10.3% of the intercept variance in the model.

3.2.5 Accuracy

To test whether virtual reality affected participants' accuracy of judgments, a binary logistic regression was run with judgment accuracy as the dependent variable. Table 3.4 shows results from the model predicting incorrect judgments.

Table 3.4: Full model fixed coefficients and standard errors predicting incorrect judgments

Predictors	Coefficients (SE)	sr^2
Intercept	-7.38 (.81)	-
Trial	.01 (.01)	-
Passability Ratio	165.99 (17.24)***	.06
Passability Ratio Squared	-81.34 (8.43)***	.78
Movement	-1.16 (.27)***	.04
Condition	-.10 (.37)	-
Trial X Condition	.03 (.01)*	.01
Passability Ratio X Condition	-1.79 (1.78)	-
Passability Ratio X Movement	-58.21 (37.51)	-
Passability Ratio Squared X Condition	-1.40 (.98)	-
Passability Ratio Squared X Movement	-1.38 (1.20)	-

note: * p <.05, ** p <.01, *** p<.001

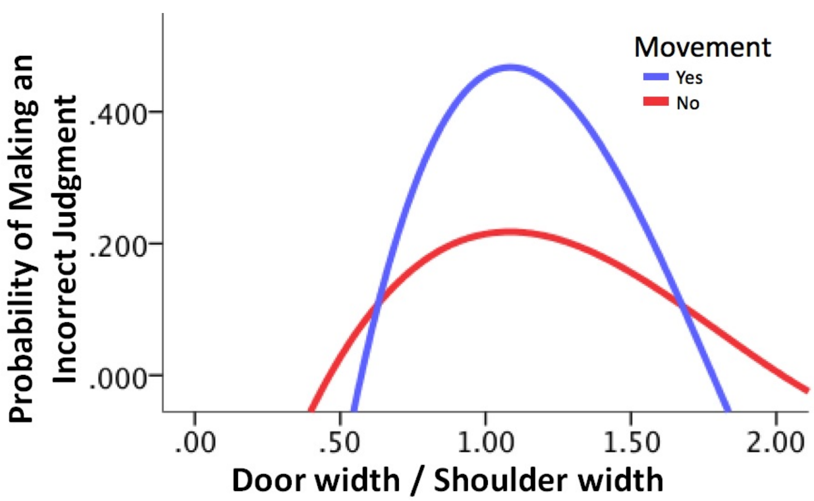

Figure 3.5: Predicted probability of making an incorrect judgment plotted against the participant's passability ratio, showing the quadratic effect of passability ratio and the main effect of movement

There was a significant main effect for both the linear and quadratic passability ratio term, accounting for over 78% of the variance in accuracy. Participants were much more likely to make an incorrect judgment when the door width was close to the participant's shoulder width (see Figure

3.5). Additionally, the main effect of movement was significant. Participants were more likely to be incorrect when they chose to walk towards the door (probability of incorrect judgment M = .3, SD = .25) than when they did not walk towards the door (M = .09, SD = .16), t (151) = -9.53, p <.001. Although condition was not a significant predictor of accuracy, it was a significant moderator of the effect of trial. In the virtual reality condition, there was no improvement in accuracy across trials. But for the real world condition, accuracy improved over time; Every increase in trial number resulted in the odds of an incorrect judgment decreasing by a multiplicative factor of .97.

3.3 Discussion

In the following section, we will discuss our findings based on the ordinal structure of each trial. Upon presentation of a door width, participants determined if they could make a passability judgment with certainty. 1) If uncertain, participants initiated movement towards the door. 2) On trials in which participants initiated movement, they were instructed to continue walking until they were certain of their passability, and then stop. 3) Once participants stopped moving, they gave a verbal judgment of their ability to pass through the door. 4) Offline, experimenters calculated the accuracy of each judgment by comparing the participant's shoulder width to the presented door width.

3.3.1 Movement

Overall, the likelihood of walking towards the door - an index of uncertainty in participants' initial static judgment - was equal in both the real world and in VR. This suggests that static information that informs affordance perception in VR adequately replicates the same static information that is available in the real world. Interestingly, this occurred despite the absence of a self-avatar in the VR condition. As mentioned before, perceptions of aperture passability rely largely on geometric perceptual matching. That is, perceiving one's ability to pass through a doorway relies on the relation between one's shoulder width and the width of the opening [93, 92]. Since participants in VR had no virtual shoulders to reference when determining their passability, they could not directly compare virtual shoulder width and virtual door width. Despite that, passability judgments in VR were made with the same certainty as those made in the real world. While virtual shoulder width was not optically available in VR, static eye-height information was available and true to the participants' eye-height in the real world. This information was likely utilized to determine passability [93, 92]. This result is not supportive of our third hypothesis, but is a positive outcome for contemporary VR technology's ability to replicate real world sources of information.

When the presented door widths were close to the participant's shoulder width (and thus their critical passability boundary), participants were more likely to be uncertain of their judgment and walk towards the door. As shown in Figure 3.3, participants in VR were more likely to walk towards the door when the door was slightly smaller than their shoulder width, while participants in the real world were more likely to walk towards the door for door widths slightly larger than their shoulder width. Participants in the real world walked most often when the door width was 1.2 times their shoulder width. This ratio value closely replicates the perceptual boundary for verbal judgments of passability in the real world found by [93]. However, the finding that in VR, participants walk towards the door most often when the door is slightly smaller (.9) than their shoulder widths is unexpected. We present two possible explanations. First, perhaps participants in VR are perceiving the door to be larger than it is. In this case, a presented ratio of .9 was perceived as a ratio of 1. We find this unlikely due to the robust body of research indicating size underestimation in IVEs [76, 82, 85], along with findings from the present study that passability judgments were equivalent in VR and the real world. A second possible explanation is that doorways smaller than one's shoulder width present harmful consequences for misperception compared to doors larger than one's shoulder width. To wrongfully perceive a smaller door as passable would result in possible collision with the door, while there is no consequence for wrongfully perceiving a larger door as impassable. Thus, perhaps participants in VR were more cautious of their judgments in potentially harmful scenarios. Compared to previous VR work that utilized two poles to create an aperture [16, 23], this experiment used a virtual replica of a wooden doorway, which increased both its ecological validity and its potential for harm given a collision. Further research is necessary to investigate the ultimate cause of this finding.

3.3.2 Distance from Door

Although there was no difference between VR and the real world in the likelihood of initiating a walk towards the door, there were differences once they walked. On all walking trials, participants initiated their walk because they were uncertain of their ability to pass through the door. In this instance, the available static information (eye-height scaling) was insufficient, and walking exposed the participants to additional sources of dynamic information. These sources include the motion parallax of the door relative to the environment and intrinsic scaling of the door relative to kinematic properties of the participant's self-produced head sway and stride length [16]. Participants in VR walked further before making their judgment than participants in the real world. Thus, participants in VR required more exposure to sources of dynamic information before gaining certainty in their passability judgment than those in the real world. This supports our fourth hypothesis, and falls in line with past research that suggests continuous visual feedback when walking through an IVE may improve judgments of size and distance by allowing participants to rescale perceived space [42, 43, 79]. In the case of this experiment, interaction with the IVE improved participants' certainty of passability judgments, and participants in VR required more dynamic exploration of the environment to reach certainty than participants in the real world.

3.3.3 Judgment

Despite walking differences between the real world condition and the virtual reality condition, there were no significant differences in participants' judgments of perceived passability. It is possible that additional exploration of the optic flow in the VR condition allowed performance to equal that of the real world condition. As the passability ratio increased (i.e. as the width of the opening became wider than the participants' shoulder width) the probability of judging the doorway as passable increased in both the real world condition and virtual reality condition. This finding suggests that individuals engage in body-scaling in both the real world and VR when determining if they can pass through a doorway.

3.3.4 Accuracy

For trials where participants decided to walk, the likelihood of making an incorrect judgment was higher. That is, participants were less likely to make an accurate affordance perception when they chose to walk towards the door. This was expected, however, because participants walked towards the door on trials that were close to the passability boundary, and thus they were less certain of their judgments.

Importantly, no significant effect of condition was observed. That is, the likelihood of making an incorrect judgment was similar in the real world condition and virtual reality condition. This finding does not support our second hypothesis that participants in the real world condition will produce more accurate judgments than participants in the virtual reality condition. While previous research has thoroughly documented issues of depth compression and subsequent underestimation in virtual environments [76], the lack of difference in accuracy between conditions found in the present study suggests that participants in the virtual reality condition did not experience depth compression. As such, it's possible that advancements in newer VR hardware have successfully mitigated the issue of depth compression. More specifically, this may be attributed to the wider FOV in the HTC Vive. The FOV for the HTC Vive is similar to that used by Jones et al. who found that estimates improved when FOV was wider [39].

Additionally, the use of a virtual sliding doorway that both mimicked a real world scenario and matched the sliding doorway used in the real world condition may explain the similarity in performance between the real world condition and virtual reality condition. For instance, Interrante et al. claims that maintaining high fidelity between the real world and virtual environment (i.e., matching the virtual environment to the real world) reduces issues of depth compression [33]. Thus, our findings are in agreement with those documented by Interrante et al. Lastly, the similarity in accuracy between the real world and virtual reality is consistent with [23] suggesting that affordance perception tasks are more appropriate measures of size and distance, as they result in similar performance between the real world and VR.

Further analysis revealed that as the trials progressed, the likelihood of making an incorrect judgment decreased in the real world condition. For the virtual reality condition, however, the likelihood of making an incorrect judgment remained similar as the trials progressed. Though the overall likelihood of making an incorrect judgment was similar for both conditions, the significant interaction between condition and trial suggests there was a learning effect in the real world condition, but not for the virtual reality condition. Previous research has found that individuals' gaits in virtual environments are less stable than in the real world [36]. More specifically, individuals have been shown to walk slower, take shorter steps, and take more steps in virtual environments [36]. It's possible that our participants in the virtual reality condition experienced reduced gait stability, which inhibited a learning effect.

3.4 Conclusion

The present study sought to revisit spatial perception in IVEs to determine if the advancements of newer VR hardware (wider FOV, high resolution fidelity, and wide-area tracking) reduce or eliminate underestimation. Participants were presented with various door widths in VR or the real world and judged whether they could pass through the door. If uncertain of their ability to pass through the door, participants were instructed to walk towards the door (but not through it) until they were certain of their response. This movement towards the door provided task-specific exploration of the environment that allowed them to pick up additional sources of intrinsically scaled dynamic information. This allowed us to compare affordance perception (as a surrogate for size estimation), accuracy, certainty, and reliance on dynamic information between VR and the real world.

Overall, participants in VR were no different from participants in the real world in terms of aperture passability judgments, accuracy of judgments, and certainty of judgments. This suggests that overall, the information necessary to determine one's affordances (size and distance of the aperture relative to one's own geometric and dynamic properties) is available and salient in VR. However, in order to achieve a comparable level of judgment accuracy to that of the real world, VR participants required additional exposure to dynamic sources of information by walking closer to the door. Further, even though participants never received explicit or experiential feedback about the accuracy of their judgments, participants in the real world improved in accuracy over time, while participants in VR did not. Ultimately, improvements in resolution, graphic fidelity, and FOV offered by newer VR hardware allow users to accurately perceive their action capabilities.

Some key takeaways for developers of complex virtual reality applications with environments involving locomotion are provided here. When developing virtual replicas of a real world environment, it is beneficial to use devices that provide a wider FOV and the ability to physically navigate towards the aperture. It may be additionally beneficial to create a highly realistic environment so that performance on tasks in both the real world and virtual environment is comparable. For VR applications, games, and other immersive training scenarios that require users to maneuver through obstacles, it may be useful to provide more optic flow via inclusion of arbitrary objects and increased travelable distance. This will be especially useful in scenarios where improvements in affordance judgments is desired, such as walking rehabilitation, athletic training for hurdle races, combat training for stealth missions involving maneuvering through pits, etc.

A limitation of our work is that the technique used to calibrate the room relies on the underlying HTC Vive libraries to render the tracked objects and graphics accurately within the tracking boundary. Though this technique provided satisfactory results for our study, further testing should be conducted to ensure that it is robust and without fault. Another limitation is that we did not investigate the effects of embodied viewing afforded by self-avatars. As previously mentioned, participants in the virtual reality condition engaged in more task-relevant exploration of the environment, suggesting that the static information available to them was insufficient. Addition of a self-avatar will increase the static information available and may influence individuals' perceptions of passability. Therefore, in future research, we aim to investigate the effects of self-avatars on passability judgments in IVEs. We plan to explore how passability judgments are affected when the dimensions of the self-avatar like height, width, etc. are modified in an IVE. Finally, we plan to explore the effects of visual fidelity of the environment and aperture, as well as the HMD's FOV on passability judgments in an IVE.

Chapter 4

Affordance Perception Mediated by Body-Scaled Self-Avatars

In this contribution, we compared passability judgment for an adjustable aperture made in the real world to those made in a to-scale virtual replica with and without a gender-matched body-scaled self-avatar. Given that several high definition display devices and trackers have been released since most of the studies described in the related work section were conducted, we believed it was timely to reevaluate the perception of affordance in an IVE as compared to the real world. This gave us an opportunity to develop a more widely accessible self-avatar system using off-the-shelf tracking devices available for widespread VR use. The self-avatar was created using the HTC Vive HMD, 2 HTC Vive controllers, 5 HTC Vive trackers and modified versions of 2 Unity plugins. Our study evaluates the level of immersion offered by contemporary devices and a relatively cost effective and less intricate approach of implementing self-avatars with full-body tracking. Thus, this contribution aims to fill a much needed void in the research literature on how commodity VR viewing devices and body-scaled self-avatars impact affordance judgements in immersive virtual environments as compared to the real world.

Although previous works have investigated passability judgments in IVEs, none report using a fully-tracked self-avatar with scaled height, arm-length and, more importantly, shoulder width. Geuss et al. compared passability using 2 poles in the real world and in VR but found no significant differences between the two conditions [23]. In the work by Priyankova et al., participants embodied an underweight or overweight avatar while judging aperture passability [71]. Although the avatar embodied only mapped head movement, participants' judgments were significantly affected by the anthropomorphic properties of the avatar. As described above, Lin et al. used a tracked self-avatar to study the affordance of stepping over or ducking under but only scaled the legs of the self-avatar [54]. Buck et al. studied the interplay of social dynamics in collaboratively passing through apertures, however, the shoulder width of the self-avatars was not scaled to match the participants [6].

We follow a methodology similar to [54, 23] but make use of a head and limb tracked self-avatar matching the eye height, arm length and widest frontal dimension (i.e. shoulder width) of the participant during passability judgments. Our experiment uses eight HTC Vive trackers for tracking the participant's body. This is significantly cheaper, much easier to set up, and is less tedious to put on. To the best of our knowledge, this is the only work that evaluates passability judgments in VR in the presence of a body-scaled head and limb tracked self-avatar. We also provide extensive details on a calibration technique used to map the virtual replica of the experiment setup exactly onto the real world. The empirical evaluation comparing the real world and the VR conditions helps analyze the comparative effects of the presence or absence of the body-scaled self-avatars on action capabilities in VR in contrast to real world judgments.

4.1 Experiment Design

Our goal was to empirically evaluate how passability judgments made in the real world differ from passability judgments made in an IVE, and how the presence of a body-scaled self-avatar further influences passability judgments made in an IVE. In this study, we compared passability judgments of a sliding doorway aperture made in the real world at a fixed viewing distance to those made in an IVE with and without an articulated self-avatar. A between-subjects design with 3 conditions was employed with the conditions as follows:

1. Real World (RW)
2. Virtual Reality without Avatar (VR-NA)
3. Virtual Reality with Avatar (VR-A)

All conditions were conducted in a 7.5 X 4.5 m room with a sliding doorway aperture at one end, see Figure 4.1 for details. During the experiment, the doorway was randomly slid to 1 of

13 widths that ranged from .7 to 1.3 times the shoulder width of the participant, with increments of .05 times the shoulder width. Each door width was presented 5 times for a total of 65 trials per participant. An exact to-scale virtual replica of this room was created for the VR conditions.

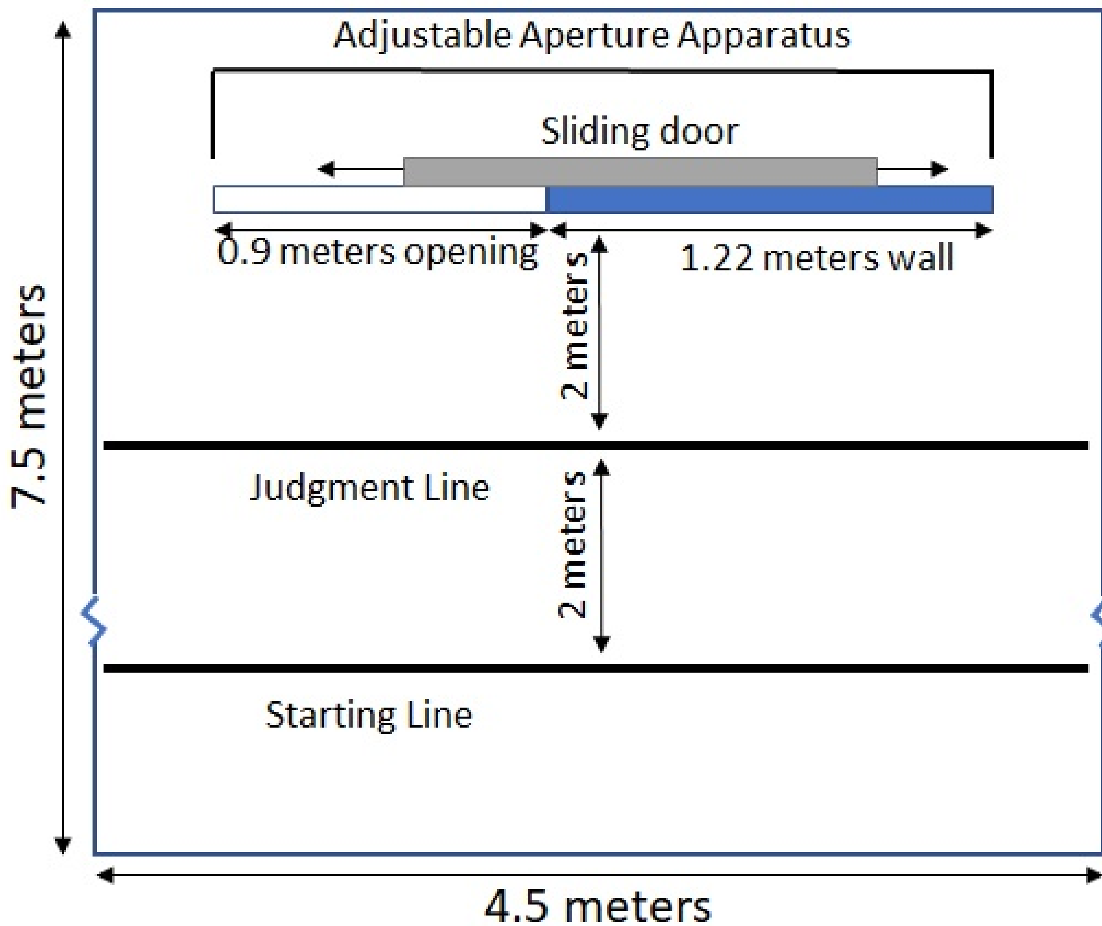

Figure 4.1: Experiment room setup with the sliding doorway aperture

4.1.0.1 Virtual World Construction

For both the VR conditions, the virtual world was created and mapped exactly onto the room and the adjustable apparatus in the real world using multiple calibration techniques described below. The IVE was rendered onto an HTC Vive head-mounted display (HMD) with a field of view of 110°, 1080x1200 pixels per eye, at 90 frames per second. The desktop computer had an Intel i7 quad-core processor and an NVIDIA GeForce GTX 1080 graphics card.

The basic room environment was modeled in Blender based on the measurements taken from the real room and was imported into the Unity[1] game engine. Textures used for the door, curtain, walls, ceiling, carpet, and miscellaneous objects were created from images that closely resembled the real world textures (see Figure 4.2). Once a rough copy of the environment was created, the virtual room was precisely aligned with the real room so as to match the visual angle subtended by the doorway. Matching the visual angle subtended was an important step as it ensured that door widths in the real world occupied the same field of view in the virtual world.

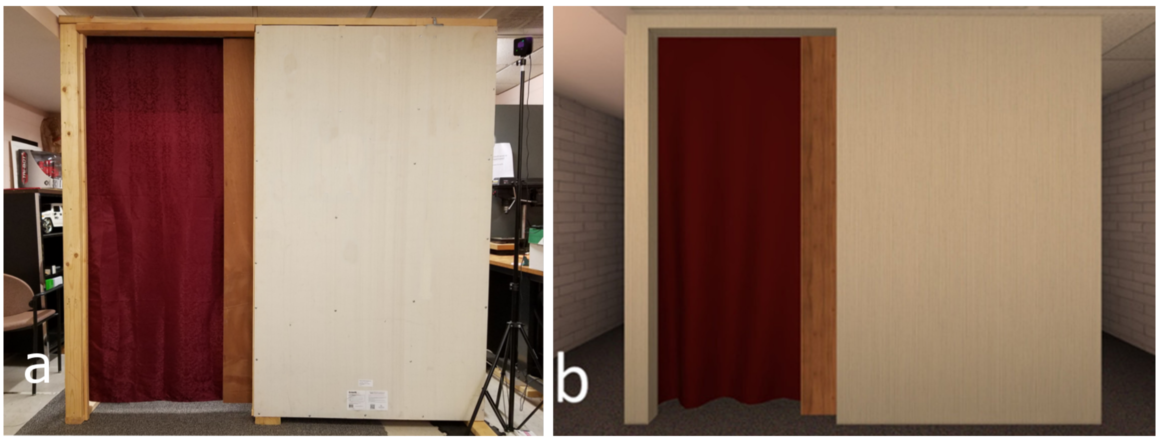

Figure 4.2: Figure shows a particular aperture width in the real world (a) and the virtual world (b)

We used the position and orientation of one of the HTC Vive base stations, as reported by the simulation, to align the room as it remains stationary and usually does not accumulate drift overtime. We compared this reported position and orientation of the base station to where it should be with respect to the room in the simulation and calculated positional and rotational offsets. These offsets were then applied to the virtual room to get better overlap results. This process was repeated several times to get positional and rotational offsets which were then averaged and applied to the objects in the Unity scene for the final rendering. After this process was completed, a custom script periodically checked for misalignment based on an Euclidean distance calculated between the reported position of the base station and the position with respect to the room. The room was automatically calibrated if a drift greater than 1 cm occurred. The room rarely needed additional calibration after the original alignment step, however this functionality was implemented in case the base station was accidentally moved during the experiment.

[1] `https://unity3d.com/`

To further fine-tune and verify the overlap of the virtual room onto the real room, we used two methods:

1. *Checking for tactile feedback (touch based verification) from different parts of the sliding doorway*
   We physically examined the virtual aperture via tactile interaction at multiple locations with the HTC Vive controller and checked for visual and tactile congruence or mismatch. If tactile feedback was received, we checked if the location overlapped with the exact physical location on the real door, and verified the tracker logs. In case tactile feedback was not received or the location was off, an offset was calculated based on the controller's position and the door's position. This offset was applied to the tracking space in Unity. This was usually a very small adjustment in the range of millimeters.

2. *Comparing the visual angle subtended for the door and aperture widths between the IVE to the real world from different locations in the room*
   We performed the following step to verify if the visual angle subtended between the real and virtual doorway apertures matched. We visually aligned a virtual marker rendered on the left and right Vive controllers to the edges of the doorway in the virtual world first and then took off the HMD to examine if the real controller visually aligned with the corresponding edges of the real doorway. This process was repeated for all horizontal and vertical edges of the doorway from different viewing distances and aperture width trials of the experiment.

4.1.0.2 Avatar Generation

For the VR condition with self-avatar (VR-A), we used a gender-matched body-scaled avatar tracked in real time using the HTC Vive HMD, two controllers and five additional HTC Vive trackers strapped onto the participant's body as seen in the Figure 4.3.

The basic avatar for each gender was generated using the Unity Multipurpose Avatar (UMA)[2] framework from the Unity asset store. The plugin allows for the creation of a wide range of characters including humans with a large number of adjustment parameters for the limbs, bodily features like stomach, waist, etc., and facial features like cheekbones, lips, etc. These adjustments are made using a slider on a GUI or in the avatar generation scripting framework. All adjustment

[2] https://assetstore.unity.com/packages/3d/characters/uma-2-unity-multipurpose-avatar-35611

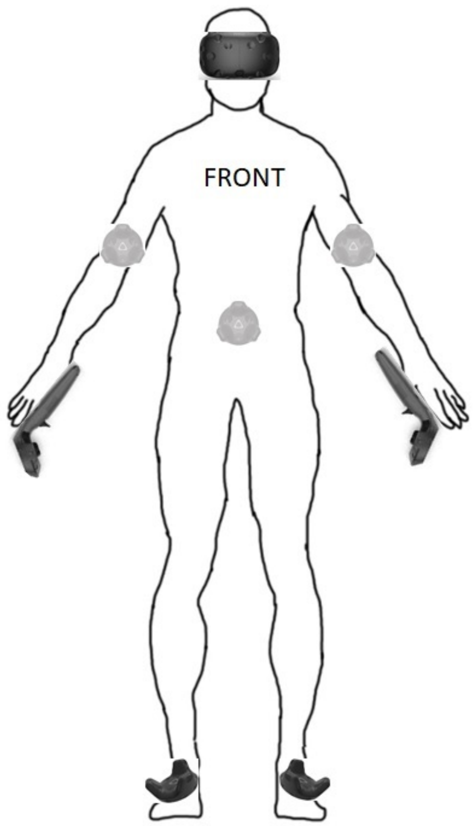

Figure 4.3: HTC Vive HMD, controller and tracker placement on participant. Grayed out trackers were placed on the lower back and just above the elbows on the back of the arm of the participant.

parameters use a normalized scale ranging from 0 to 1, and do not have a way of setting exact values in defined absolute units like meters or inches.

In order to scale the self-avatar to match the participant's body proportions, we use an HTC Vive controller to record the global position of the participant's eyes, left and right shoulder, elbow of either arm, and the wrist position of the same arm we recorded the elbow position for. The measurements were performed by placing the tip of the HTC Vive controller at these locations and pulling the trigger on the controller. Based on these positions, we calculated the participant's eye height, shoulder width, upper arm length, and forearm length in meters. Since the UMA plugin does not allow for direct adjustment of body parameters for an avatar using measurements made in absolute units, the measurements were converted into a normalized value based on the range that the corresponding adjustment slider provides. For example, to calculate the value for the forearm length slider that would match our measurement, we set the slider value to 0 and calculated the resultant Euclidean distance between the elbow bone and the wrist bone of the avatar and repeated the process with the slider set to 1. This gave us the range for the slider and we used that to convert the recorded forearm length into a normalized value that fits the adjustment scale. Upon running pilots, we realized that the lower range of the shoulder width adjustment scale (referred to as the upper muscle in the plugin) did not account for about 30% of participants. To solve this issue, some of the core scripts of the UMA plugin that handle body adjustments based on the gender of the character were directly modified or overwritten. This helped account for 100% of the participants' shoulder widths within the range thus attained.

The lower limbs of the participant were not particularly measured to scale the self-avatar's lower limbs as the avatar generated by matching the eye height provided close enough lower limb proportions and length. Also, the task utilized in the experiment requires participants to utilize their widest frontal dimension, namely their shoulder width, to make judgments rather than lower limb proportions, especially with the eye height being matched.

4.1.0.3 Avatar Tracking

Once the avatar was scaled to match the participant's body proportions, especially the upper torso and shoulder width, we used the FinalIK [3] Unity plugin to map the participant's body position onto their self-avatar in real time, based on the position of the HTC Vive HMD, the two controllers (one on each hand), and the five HTC Vive trackers strapped onto the participant's body. In total, we used eight points of tracking to track the participant's body to render the body-scaled self-avatar, namely head, left and right hand, hip, left and right elbow, and left and right foot. The plugin provides an out-of-the-box script to animate a humanoid avatar based on the trackers assigned for different body parts using inverse kinematics (IK) solvers. The script also has adjustment parameters in the form of positional and rotational weights for each target tracker assigned which factor into the IK solving algorithm as the avatar is animated. These weights need to be adjusted based on the device being used and the realism of the movements being produced.

The script moves different joints of the scaled avatar to animate it based on the corresponding tracker position. Sometimes the tracker placed on the participant's body may not be exactly on the right spot in relation to the joint being moved, especially the hip and the head, resulting in an unrealistic animation. In such cases, a secondary empty game object parented to the tracker object

[3] `https://assetstore.unity.com/packages/tools/animation/final-ik-14290`

in Unity was used as target and an offset was added to this object to position it appropriately. For example, the hip tracker is often placed slightly higher or lower than where the corresponding hip joint is located on the avatar skeleton. To account for this, an empty object with a vertical offset was parented to the hip tracker object in Unity and was used as a target instead of the tracker object itself. This step gave us satisfactory results in terms of the animations produced based on the participant's movements.

4.1.1 Participants

Simulation studies investigating the power of Hierarchical Linear Models suggest that the number of participants and the number of trials are both important for establishing sufficient power [32]. To determine the Level 2 sample size (number of participants), a power analysis using Cohen's medium effect size of .3 [9] and an alpha of .05 revealed that a sample size of 52 participants will produce power above .85.

Thus, a total of 52 participants were recruited from [blinded for review] University graduate and undergraduate programs, 16 for the real world condition, 18 for the VR no avatar condition and 18 for the VR avatar condition. The average age of participants was 21.4 years and the distribution comprised of 27 females, 24 males, and 1 participant who preferred not to say. All participants had normal or corrected-to-normal vision and could perceive stereo.

To determine the Level 1 sample size (i.e., number of trials), we need to consider the nestedness of the data. The Intra-Class Correlation (ICC) is an index of nesting that can be used to identify the number of trials needed to represent the effective sample size of independent observations [88]. Power analyses using a effect size of .3, alpha of .05, and a typical range of ICC values (.25-.35) revealed that 65 trials would produce power levels above .9. This is sufficient power to detect cross-level interactions.

4.1.2 Procedure

In all three conditions, participants were greeted and asked to read and sign a consent form. Once the participant finished signing the consent form, he or she was asked to fill out a demographics questionnaire. After the questionnaire, we recorded the participant's shoulder width and height in centimeters using a tape measure. We then performed a modified Snellen visual acuity test[4] and

[4]http://www.allaboutvision.com/eye-test/snellen-chart.pdf

recorded the results. If the participant was going to experience one of the VR conditions, then their Interpupillary Distance (IPD) and Stereo Acuity[5] was recorded. The basic protocol for the remainder of the experiment was similar across all 3 conditions but the VR conditions involved a few extra steps. The protocol details per condition are described below.

4.1.2.1 Real World (RW)

1. After the above mentioned pre-experiment procedure, the participants were told that they will be judging if they can pass through an opening presented to them without turning their shoulders.

2. They were told to stand behind the starting line (4 meters from the door) with their eyes closed and wait for the experimenter's signal.

3. At this time, the experimenter would adjust the sliding doorway to one of the 13 widths chosen at random and then signal the participant by saying "Okay" or "Go". To eliminate any bias related to the doorway width previously presented, as trials progressed, the door was slid back and forth thrice before adjusting to the actual width.

4. After receiving the signal from the experimenter, the participants would open their eyes, walk to the judgment line 2 meters from the door (thus obtaining optic flow and motion parallax information with respect to the aperture while walking to the judgment line) and say yes or no indicating if they thought that they could pass through the aperture opening or not without turning their shoulders. Their response was recorded by the experimenter using keystrokes and subsequently logged to a data file.

5. Once they said yes or no, they would walk back to the starting line, close their eyes and wait for the experimenter's signal for the next trial. Participants were not given any feedback about their judgment during the trials. There were a total of 65 trials (13 door widths presented five times each).

4.1.2.2 Virtual World without Avatar (VR-NA)

After step 1 described above in the procedure for the real world condition, the VR simulation was run and the experimenter helped the participant don the HMD. The participants then went

[5] https://www.bernell.com/product/SOM150/Depth-Perception-Tests

through an acclimation phase before step 2 described above. In the acclimation phase, participants were asked to stand behind the starting line and were shown a blue cube, with a number on one of its faces, somewhere in the room. The participant was asked to walk up to the cube, read the number out loud and then walk back to the starting line. This was repeated 5 times before progressing any further. This step was added as the majority of the participants had not experienced VR before and it was necessary to make sure that participants knew that visual information such as motion parallax, binocular disparity, occlusion, etc., present in the real world were also present and salient in VR.

Since participants could not see their body in this condition, a small circle with an arrow pointing in the direction they were looking was provided on the floor where they were standing. This circle's position and rotation on the floor was updated based on the movement of the HMD donned by the participant. This helped participants align themselves behind the line during the trials to make judgments. Another small difference in the VR conditions was that instead of closing their eyes, the participant's view was blocked or removed using a sliding opaque GUI when the door width was being adjusted.

4.1.2.3 Virtual World with Avatar (VR-A)

This condition had a calibration and ownership induction phase since it involved using a full-body tracked self-avatar. Before being instructed on the task in step 1 from the RW condition, participants were asked to sit in a chair and were instructed on how to place the trackers on their body. The experimenter helped them if they needed assistance in putting the trackers on.

Once the trackers were strapped onto the participant, they were asked to stand in the center of the room facing the doorway. At this time, the experimenter used an HTC Vive controller to record positions as described in the avatar generation section. Although we already had a measurement of the participant's shoulder width, we again recorded the position of the participant's shoulders to calculate a shoulder width. The two are different in the sense that the one taken towards the beginning is from the edges of the shoulder and is used to calculate door widths but the one calculated based on the recorded positions is based on the position of the shoulder joint as it would be placed on a humanoid skeleton rig, which is slightly inside the avatar mesh and not on the edges of the mesh. This was necessary as the shoulder width of the avatar was calculated and verified by the distance between the two shoulder joints in the avatar skeletal rig generated.

After the measurements were taken, the experimenter helped the participant don the HMD and handed him/her the controllers. The participant was then asked to make a T-pose with their body, see Figure 4.4, so the trackers could be calibrated using an automatic script that checks for the relative position of the trackers to identify which tracker is strapped to which part of the body. The participant was asked to hold this pose until he/she was asked to relax. Once the trackers were calibrated, an avatar was generated that matched the shoulder width, height and the arm lengths of the participant.

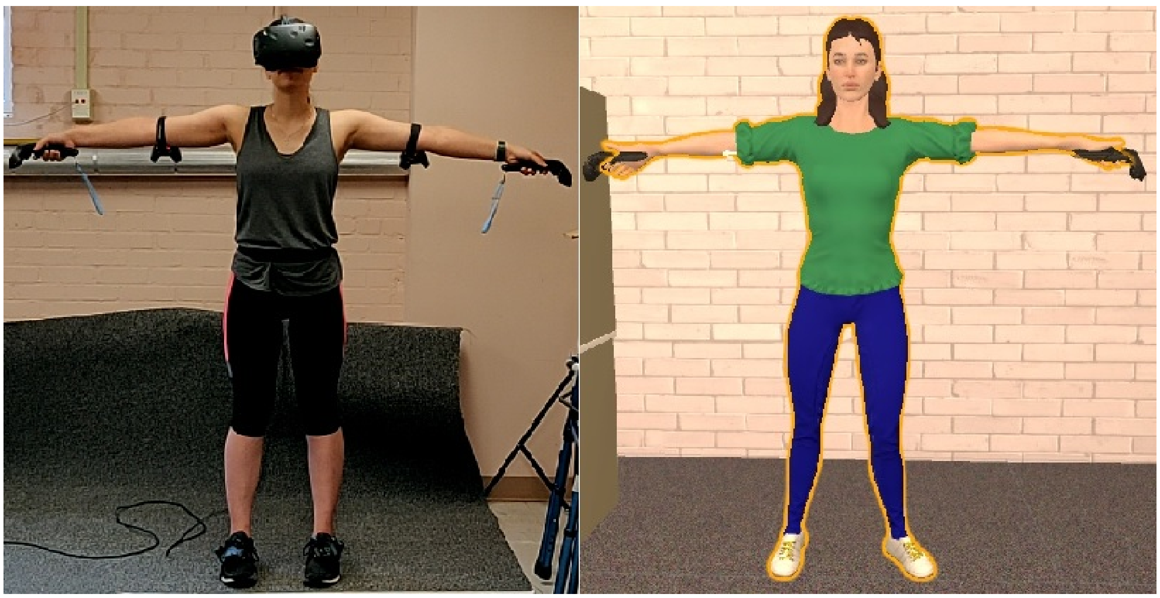

Figure 4.4: T-pose made by participants for tracker calibration and avatar generation.

Immediately after the avatar generation process, the targets were assigned for the FinalIK avatar animation retargeting script as described in the avatar tracking section. The assignment involved automatically calculating offsets for the hip, eyes and the feet, and assigning the correct tracking object in Unity to the correct solver on the script. The participant was then told to relax. This process of avatar generation, automatic tracker assignment and calibration during which the participant was holding the T-pose lasted about 7-10 seconds as sometimes the assigned indices for the HTC trackers needed to be swapped which incorporated a small delay between the swap and when the change would start reflecting in the simulation. After this, the avatar was ready and the participant could see their avatar in a large virtual mirror present in the scene in front of them. As a final step to ensure that the avatar's shoulder width matched that of the participant, the participant was asked to touch their shoulders in VR with the controllers, and see if their shoulders felt the same size as their own as well as if they received tactile feedback from their real shoulders in the same spot. If there were any discrepancies, the shoulder width of the avatar was adjusted until the participant and the experimenter were satisfied.

Once the avatar generation process was complete, the participant entered the body-ownership induction phase. In this phase, they were told to explore their virtual body and the virtual world with a virtual mirror in front of them for about 5 minutes. After this, the virtual mirror was replaced with the adjustable doorway apparatus and the experiment progressed as described in the RW and VR-NA conditions above. After all the trials were completed, the participants in this condition were asked to fill out an avatar embodiment questionnaire [25]. Although participants spent about 5 minutes longer in the VR conditions before they started their first trial as compared to the real world, the real world condition took longer to run as each trial required physically moving the door to adjust the aperture width precisely. Therefore, we believe that any calibration experienced by a participant due to the duration of the experiment would be similar in all three conditions.

We wanted participants to walk in the virtual reality condition as it gave them an opportunity to explore motion parallax, optic flow and stereoscopic viewing as it helps improve their perception of size of the environment, as they would in the real world [79]. To maintain consistency across all conditions, we had participants walk 2 meters to the judgment line in the real world condition as well as the VR conditions prior to making a judgment in every trial.

4.1.3 Data Collection

The survey responses and the measurements taken towards the beginning of the experiment were stored on secure university servers without any identifying information. Participants' passability judgment responses to doorways were recorded using keystrokes and a data logging script that was incorporated into the simulation. When a key was pressed to record the participant's response, the logging script also recorded the trial number, the passability ratio associated with the trial, the door width associated with the trial and the time since the beginning of the experiment. The log files were stored on the servers mentioned above as well. In the two VR conditions, the position and rotation of any tracked object like the HMD and the HTC Vive trackers was also logged in every frame along with the variables mentioned above.

4.1.4 Research Questions and Hypotheses

The research questions this study explores are as follows:

1. How do passability judgments from fixed distances differ between real world and virtual reality simulations?

2. How does the presence of a body-scaled self-avatar affect passability judgments from fixed viewing distances?

Our hypotheses based on the research questions above are as follows:

H1: When the aperture width is close to the participant's shoulder width, passability judgements will be different in the virtual world as compared to the real world.

H2: For VR experiences, passability judgments will be different in the avatar condition as compared to the no-avatar condition.

4.2 Results

Due to the repeated measures design of the experiment, there was considerable nesting of variables. The nested-ness of the data indicated that there were multiple levels of variance. To account for variance at each level, Hierarchical Linear Modeling (HLM) was used [32], and to hold the intercept constant across all models, all continuous variables were grand-mean centered.

Further, the use of dichotomous dependent variables produced a nonlinear cubic distribution. Because nonlinearity violates an assumption of linear regression, we transformed the raw scores into logit values to obtain a linear distribution. In using a binary logistic regression [68], the model will predict the linear logit value, which can later be transformed into the odds and probability of an event occurring. Interpretation of main effects will utilize the odds ratio. Instead of having an additive effect on the logit, the odds ratio has a multiplicative effect on the odds (i.e., a one-unit increase in the predictor results in the odds being multiplied by the odds ratio).

4.2.1 Variable Transformation

For each trial, we computed judgment as a binary variable. It was created such that judgments of the door being passable were coded as 1 and judgments of the door being impassable were coded as 0. A passability ratio variable was calculated by dividing the presented door width by the participant's shoulder width. There were thirteen passability ratios (.7, .75, .8, .85, .9, .95, 1, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3), which were created by manipulating the door widths for each participant based on his or her shoulder width. Passability ratios less than one corresponded to doorways that were impassable for participants, and passability ratios equal to or greater than one corresponded to doorways that were passable for participants.

Lastly, after viewing scatterplots of the logit values (the linear data used in the logistic regression), a visible quadratic trend was evident. As with any regression, curvilinear trends in the data are represented by significant effects of a quadratic term. To test this in our data, we created a quadratic term by squaring the passability ratio.

4.2.2 Demographics

Analyses were conducted to check for any differences with respect to the shoulder width and gender distribution between the three conditions. A one-way ANOVA revealed no significant differences in shoulder width across the three conditions, $F(2,49) = .46$, $p = .63$. A Pearson chi-square test revealed no significant difference in gender distribution across the three conditions, chi-square $(4) = 6.55$, $p = .16$.

4.2.3 Judgment

To identify whether virtual reality altered participants' perceptions of whether doorways were passable, we conducted a binary logistic regression with judgment as the dependent variable. Table 4.1 shows results from the model predicting judgments of passability (participant responses of "yes").

Table 4.1: F-values and effect sizes for the full model predicting passable judgments

Predictors	F	df1	df2	sr^2
Passability Ratio	340.45***	1	57	.71
Condition	5.98**	2	39	.02
Condition * Passability Ratio	1.33	2	56	-

note: * p <.05, ** p <.01, *** p<.001

There was a significant main effect of passability ratio, accounting for 71% of the variance in judgments of passability. As the passability ratio increased (i.e., as doorways became passable), participants were more likely to judge that the doorway was indeed passable. For every .05 unit increase in the passability ratio (that is, an increase in the door width equivalent to 5% of the participant's shoulder width), the odds of judging the door as passable increased by a multiplicative factor of 6.25. This effect occurred across all conditions.

There was also a significant main effect of condition, which accounted for an additional 2% of variance in judgments of passability. A main effect indicates differences in the intercept of the regression line across conditions. Due to our mean-centering procedures, the intercept for this analysis was placed at passability ratio = 1. Post hoc pairwise comparisons indicated that when the presented door width was equivalent to the participant's shoulder width (i.e., ratio = 1), participants in the RW condition (probability of passable judgments: M = .98, SE = .02) were significantly more likely to judge doorways as passable compared to the VR-A condition (M = .42, SE= .20; t(39) = 3.37, p = .002). It was also found that participants in the RW condition were significantly more likely to judge doorways as passable compared to the VR-NA condition (M = .68, SE= .18; t(39) = 2.48, p = .017). There was no significant difference in judgments of passability between the VR-A and VR-NA conditions (t (39) = -.946, p = .35).

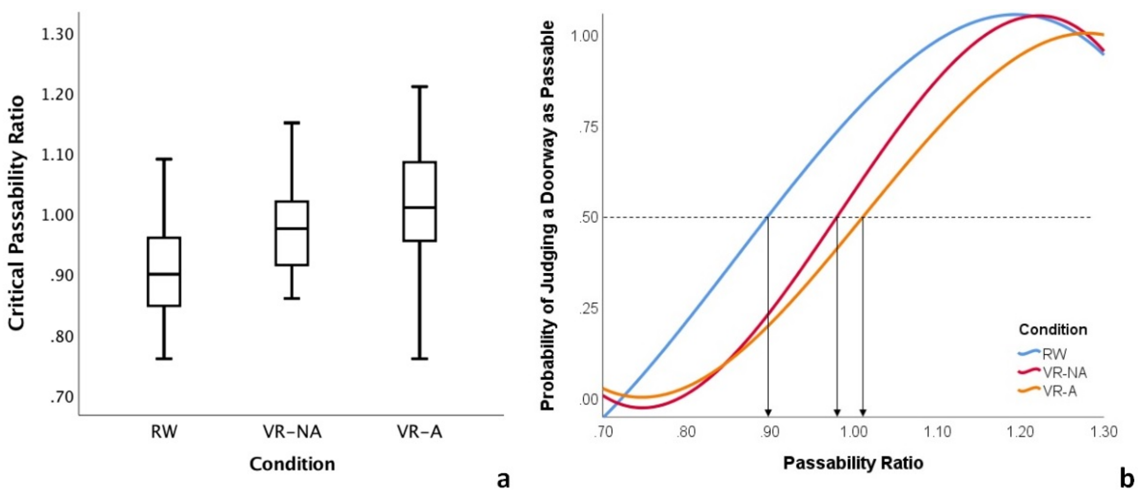

Figure 4.5: (a) A box plot of each individual participant's critical ratio. This plot shows the median (the horizontal line), the 25th-75th percentile range (the box), and outliers exceeding M +/- 3SD (there are none in our data) (b) Probabilities of making a passable judgment plotted against the passability ratio for each condition.

This main effect can be further understood by extracting the perceived critical ratios. In psychophysical experiments, the perceived critical ratio represents the ratio at which participants have a .5 probability of making a passable judgment. The perceived critical ratio also indicates the smallest ratio that participants perceive they can pass through [86]. As shown in Figure 4.5b, perceived critical ratios were close to 1 for participants in the VR conditions. However, the perceived critical ratio was .9 for participants in the RW condition.

4.2.4 Embodiment Score

Using the embodiment questionnaire, we calculated the subscore for the “Ownership” factor [25], M = 1.81, SD = 2.42. Participants show a medium to high level of embodiment.

4.3 Discussion

The statistical analysis of the judgment variable revealed that as the passability ratio increased (i.e. the door width increased), the probability of making a passable judgment also increased. This suggests that participants engage in body-scaling similarly in both the real world and the virtual world and provides evidence that the simulation effectively provides salient perceptual information regarding the aperture. However, a closer look at differences across condition revealed that the ratio threshold at which participants' judgments change from passable to impassable is significantly higher for both of the VR conditions compared to the real world condition. That is, door widths had to be larger before participants in VR judged them to be passable. This supports our first hypothesis which states that passability judgments will be different in the real world condition as compared to the VR conditions when aperture width is close to the shoulder width of the participant. This result is different from the passability results reported by Geuss et al. [23], who found no differences in aperture passability judgments between RW and VR-NA conditions. Aperture passability judgments in [23] were made from a static position (standing still), whereas judgments in our experiment were made after participants walked towards the door. Since it has been previously reported that walking through IVEs improves size perception [79], perhaps the introduction of self-produced optic flow in our experiment provided additional information that increased the margin of safety for participants to walk through the door in both VR conditions.

The analysis of the judgment variable did not reveal any significant differences between the virtual reality no-avatar and the avatar conditions. This is unsupportive of our second hypothesis which states that passability judgments will be different in the avatar condition as compared to the no-avatar condition. This contradicts the results reported by Lin et al. [54]. Lin et al. reported that providing a tracked self-avatar helped participants better determine what actions can and cannot be performed in an IVE. This is perhaps because of the difference in affordances used to study the effect of self-avatars between the two studies. Lin asked participants to duck under or step over a horizontal pole whereas we asked participants if they could walk through a doorway. This could also be an outcome of the different tracking solutions used for the fully-tracked self-avatar. Therefore, further investigation with different affordance judgments and a comparison of the two tracking solutions is required to fully evaluate this effect.

Although we made participants walk towards the door before making a judgment similar to the protocol followed by Warren et al. [93], we report a critical ratio of .9 for the real world condition which is different from what has previously been reported. Warren et al. reported a critical ratio of 1.16 from a distance of 5 meters from the aperture. Geuss et al. [23] had participants make judgments from a distance of 3 meters from the aperture without walking and reported a critical ratio 1.08. Considering that the reported critical ratio decreased with the judgment distance between the two investigations reported above, and that our experiment allows for both an even smaller distance of judgment (2 meters) and an opportunity for self-produced optic flow, it is plausible that the combination of the two may have resulted in a lower critical ratio of .9. Our study also utilized a real life aperture scenario (a sliding doorway) instead of poles. The sliding door might have acted as a frame of reference and provided more optic flow when making judgments. This aligns with the observations reported by Interrante et al. suggesting that maintaining high fidelity between the real world and VR helps improve estimations [33]. Therefore, the increased optic flow and familiarity of the door could have further influenced the reported outcome. Moreover, both Warren et al. and Geuss et al. used 5 cm increments, whereas our increments were 5% of the participant's shoulder width which ranged from 2 to 2.9 cms depending on the participant (shoulder widths ranged from 40 cms to 58 cms). These increments are half of what has been previously used and may have contributed to the observed threshold. Other studies that report a critical ratio of 1 or higher for passability judgments often provide feedback to participants by letting them squeeze through or allowing shoulder rotation as they pass through the presented opening [20, 63, 48, 21]. In addition to the above mentioned plausible explanations, our study provided no feedback to the participants about their judgments. The absence of feedback during affordance judgments provides more leeway for error to creep in even with a reasonable sample size.

There have been other studies that report a threshold of less than 1. A critical ratio of less than 1 was also observed by Wagman et al. when they had participants make passability judgments while holding rods that were wider than their shoulder width [91]. The authors explained that perception does not guarantee accuracy metrically rather puts the perceiver of affordance in "the ballpark" such that perceptually guided behavior can be regulated (or halted) online as it unfolds in real time. Thus, the ratios may have resulted from participants assuming that they would make such on-line postural adjustments as they approached the aperture. This also applies to our study as participants may have made their judgments on the assumption that they could squeeze through the opening with scrunched shoulders. It was not specified to the participants that they cannot shrug or scrunch their shoulders, only that they cannot rotate their shoulders. Therefore, judgments made on the basis of scrunched shoulders could have resulted in a threshold of .9. A more recent study by Favela et al. also shows a critical ratio of less than 1 when making stationary passability judgments, although the critical ratio while walking through the aperture at normal speeds was reported to be 1.36 [17].

However, this raises the question about why the ratios were close to or higher than 1 in the VR conditions. For the VR-NA condition, it is possible that participants were making conservative judgments as they could not see their body and wanted to leave room for error indicating the application of margin of safety. In the case of the VR-A condition, participants could see their scaled bodies but the tracking system could not replicate complex shoulder movements like shrugging or scrunching. Therefore, the passability judgments could have been based on relaxed shoulders with no room for scrunching which may be slightly larger than the shrugged shoulder width of the participant. An alternate explanation is that participants in VR-A could see a synchronous virtual body from a first person perspective and perhaps their actions appeared to have stronger physical consequences (i.e., 'since I can see my avatar body, I can harm my avatar body'), which led to more conservative judgments of passability in order to keep the avatar safe. This is in line with observations made by Sanz et al. in their experiment comparing virtual hands with varying levels of realism. They noticed that participants with realistic (human-like) virtual hands were more protective and less reckless when completing a dangerous task compared to those with unrealistic (robot-like) virtual hands [2].

A limitation of our study, as mentioned above, is that although the tracking system developed for the body-scaled self-avatar in our study was robust and provided satisfactory results, as is evident from the embodiment scores, the placement of trackers on the participant's body did not allow replication of complex shoulder movements like shrugging, shoulder scrunching, etc. Secondly, we did not compare the performance of the avatar system implemented against other systems like the optical tracking system.

4.4 Conclusion

In an empirical evaluation, we compared passability judgments for an adjustable aperture made in the real world to those made in a virtual to-scale replica with and without a gender-matched body-scaled self-avatar in the IVE. Although participants engage in body-scaling similarly in all three conditions, the results indicate that passability judgments differ in an IVE as compared to the real world. This is different from what previous literature reports and can be attributed to the difference in devices, the tracking solutions or the methodology adopted for the investigation. Also, the presence of a self-avatar does not seem to significantly affect judgments as reported in previous literature. Perhaps this is a result of participants not being able to replicate complex shoulder movements like shrugging but more work is needed to draw meaningful conclusions. Besides the results reported above, we present a relatively accessible self-avatar system that lets one create body-scaled avatars in a matter of minutes without spending thousands of dollars that can be used for future perceptual studies with self-avatars.

Some useful guidelines to follow while developing simulations that recreate real world scenarios and make use of self-avatars are; 1) when recreating doorways, portals, hallways, etc. in VR, it may be beneficial to model these slightly larger than their real world counterparts to provide users a comparable level of judgment accuracy, 2) when implementing self-avatars, it might be advantageous to gauge the importance of complex joint motions for the interactions afforded in the simulation, especially in situations where one has to maneuver through tight spaces in the virtual world, 3) checking for tactile feedback using tracking devices like the HTC Vive controllers and verifying the visual angle subtended could help accurately map virtual worlds onto real world counterparts especially for simulations like architectural walkthroughs, fine-motor tasks, etc.

High-end motion capture systems have frequently been used for real time avatar tracking for years yet we do not fully understand how this contributes to the experience. This, however, is not the focus of our current work as it would require comparing our body tracking solution to other high-end motion capture systems. Therefore, we believe that extending the current avatar system to mimic more complex joint movements and comparing it to other implementations will prove to be a fruitful direction for future work. Another future research direction can be to evaluate the effects of anthropomorphic and anthropometric fidelity of self-avatars on affordance judgments.

Chapter 5

Affordance Perception Mediated by the Person-Plus-Virtual-Object System

It has been previously established that handheld objects form a person-plus-object system that affects aperture passability judgments in the real world but these judgments are influenced by the dynamic touch properties like inertia and weight [91] even when the object is not in view. However, the haptic sensations associated with weight and inertia are often absent or mismatched when interacting with objects in IVEs. This is due to the fact that interaction in IVEs is facilitated by the use of controllers or gestures. The haptic feedback thus received, if any, may not match the virtual object being interacted with causing a mismatch. This particular aspect is intriguing as understanding how users account for this absence of information, if at all, to make affordance judgments can have great implications on how interactions are handled in IVEs in the presence of self-avatars.

The literature also suggests that holding objects wider than ones own body affects size perception in the surrounding environment [83]. The studies mentioned above were completed in the real world and the perception of size of objects in IVEs seems to be dissimilar as compared to the real world [85, 82, 3]. The size of objects seems to be underestimated in virtual environments as compared to the real world [85, 82] but can be heavily influenced by the avatar embodied [3, 57, 90].

Although, the effect of self-avatars on the perception of size has been exhaustively studied, the effect of interacting with perceived virtual objects on affordance judgments remains unexplored. Another interesting facet with respect to self-avatars in IVEs is that individuals lose the ability to squeeze through openings in VR. Since virtual objects and self-avatars in IVEs are made up of rigid meshes that usually do not deform on contact, users of such environments are often able to simply pass through obstacles, see intersecting meshes or given some form feedback that they have collided with another mesh. This is unlike the real world where people often try to wiggle or squeeze through opening especially when carrying objects [70, 10]. It is thus essential to study how users behave when perceiving such an affordance in IVEs.

With the industrial sector progressively incorporating VR into games and thrilling experiences along with replicating challenging real life scenarios where carrying virtual objects is common and split second decisions may change the outcome of the situation like combat training, PTSD rehabilitation, FPS and RPG games, etc., it is imperative to understand how interacting with virtual objects of different sizes in the presence of self-avatars, forming the PPVO system, affects frontal and lateral passability judgments. We wanted to examine both judgment types as individuals frequently switch between the two when trying to maneuver through openings while carrying objects, however they are fundamentally different. Unlike frontal judgments where the virtual object may not always moderate the width of the PPVO or the PPO for that matter, the width of the PPVO and the PPO are determined by both the person and the object being held at all times when making lateral passability judgments. Moreover, it has been previously noted that performing affordance tasks facilitates scaling of body dimension and improves judgment accuracy [22]. Thus, we wanted to further evaluate the saliency and efficacy of visual and auditory feedback in the presence of virtual objects. To the best of our knowledge, this is the first study that investigates this phenomenon.

5.1 Experiment Design

To investigate the effect of interaction with different sized objects in IVEs in the presence and absence of body-scaled self-avatars, we conducted a two part study. The first part evaluated frontal passability judgments and the second part evaluated lateral passability judgments for the object system. Each of the parts utilized a mixed factorial design with one independent between-subjects variable, presence or absence of self-avatar, and one within-subjects variables, object size, presented in a randomized fashion, see Table 5.1. A circular virtual bar with two handles similar to a log bar [1] was used as the interaction object for the study.

Table 5.1: Study 2 Design

Part 1 (Frontal Judgment)		Part 2 (Lateral Judgment)	
No-Avatar (F-NA)	Avatar (F-A)	No-Avatar (L-NA)	Avatar (L-A)
Pre-test | Calibration | Post-test			

All experiments were conducted in a 6.8 m X 7 m virtual room with a sliding doorway aperture setup, see Figure below. The experiment had three phases, a pretest phase, a calibration phase and a posttest phase. During the pretest and posttest phases, the order of the bars presented was randomised between trials and for each sized bar, the doorway was randomly slid to 1 of 7 widths that range from .7 to 1.3 (at .1 intervals) times the shoulder width of the participant or the body depth plus the diameter of the bar in the matched condition. The same door widths were used across all three bar sizes for a participant as we wanted to compare how judgments varied for the same sized doors with different sized bars. The calibration phase had the same bar size ratios and the door width ratios presented ranged from .7 to 1.3 at an interval of .15. Each door width was presented three times for each of the bar sizes in each of the phases. Given the door widths above, the pretest and posttest phases had 63 trials each (3 x 7 x 3) and the calibration phase had 45 trials (3 x 5 x 3) for a total of 171 trials per participant. The experiment lasted about one hour and 15 minutes on average.

5.1.1 Apparatus

The hardware setup used an HTC Vive Pro HMD, associated controllers and HTC Vive Pro trackers for the self-avatar. The desktop computer configuration included an Intel i7 quad-core processor and an NVIDIA GeForce GTX 1080 dedicated graphics card for seamless rendering at 90 frames per second.

[1] https://www.titan.fitness/strongman/log-bars/10%22-strongman-log-bar-%7C-v2/430061.html?cgid=log-bars

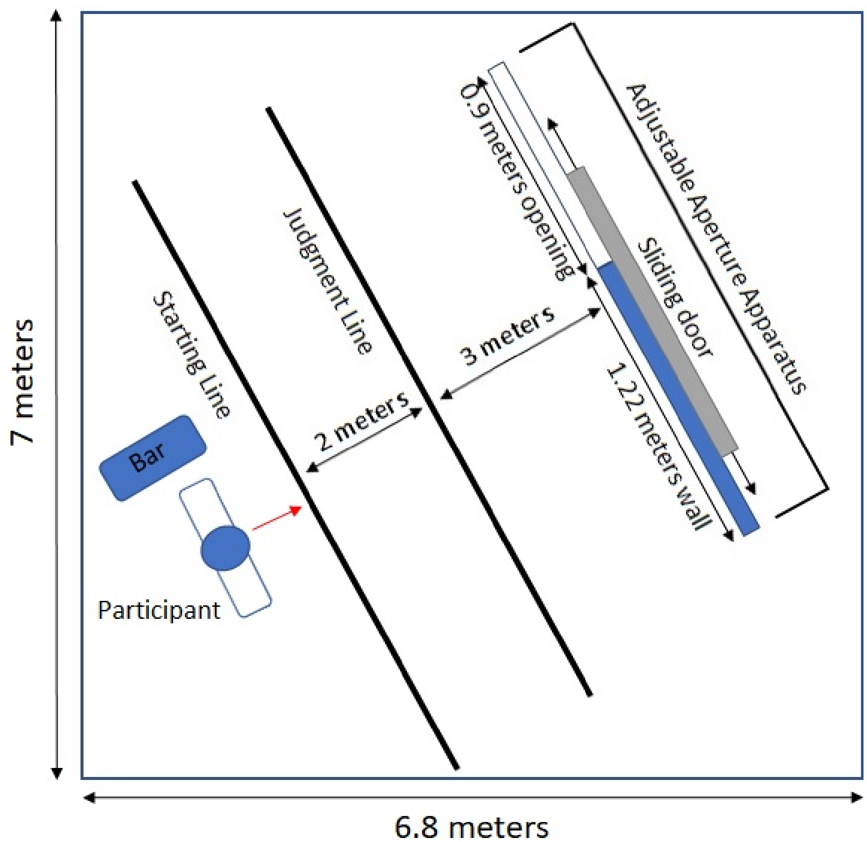

Figure 5.1: Top down view of the experiment room setup with the sliding doorway aperture and bar

5.1.2 Virtual Environment

The virtual environment was based on the physical room the experiment was conducted in and had the same dimensions in terms of height, width and length. Various objects in the room were modeled in Blender and imported into Unity to create the virtual space, see Figure 5.2. The sliding doorway was placed along the diagonal in the room so we would get more walking room for the experiment. The virtual space was calibrated so that it overlapped with the physical space to make sure that participants did not run into other physical objects in the room. The participants were instructed to start at the end opposite to the door (at the white line in the figure). A virtual table and a virtual mirror were placed at the start location. This is where the participant was instructed to pick up the virtual bar from and perform certain exercises as mentioned in the next sections.

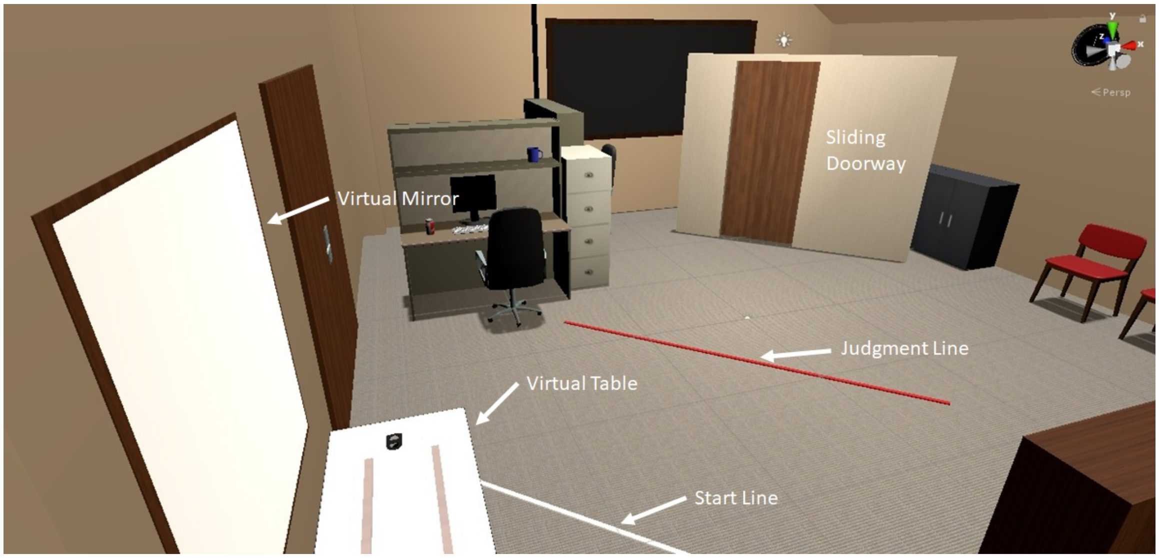

Figure 5.2: The virtual space where participants performed all the trials

5.1.3 Object Interaction

The interaction with the virtual bar was facilitated with the help of the HTC Vive Pro controllers. The interactions were programmed such that the user could touch any of the handles of the bar with the controllers they were holding and press and hold the trigger on the respective controller to pick up the bar. Since the object was supposed to be lifted using both hands, we used two configurable physics joints, one on each handle, to provide a dual wielding interaction with the bar. Therefore, if the participant tried to grab the bar by only one handle, the bar would dangle in air with the pivot attached to the controller in contact. Since we wanted the bar to behave like a real object but it was virtual and had a mismatched sense of haptic feedback associated with holding it, we made sure that the joint at the contact point broke if the controller went more than 15 cms away from the associated handle on the bar making it dangle in air. This also reinforced a sense of the width of the bar by making sure that participants were maintaining the distance between their hands when holding the virtual bar.

5.1.4 Avatar Generation and Tracking

Techniques used to generate, calibrate and track the gender-matched body-scaled self-avatar using the trackers and a combination of Unity plugins from the last study were employed for the self-avatar in this study as well. The previous body-ownership phase that involved simply exploring the avatar in front of the mirror was replaced with more extensive exercises, namely egocentric pointing, exocentric pointing and visuo-haptic stimulation. The system was also extended to modify the body depth of the self-avatar based on the measurements of the participants. The avatar's gluteus and belly were equally adjusted to

5.1.5 Calibration Phase Feedback

The calibration phase provided several feedback cues to the participant. In this phase, the participant was asked to try and pass through the virtual door with the bar without hitting it to confirm his/her judgment. In case s/he hit the door, it was turned translucent, a vertical highlight was shown on the side of the door they hit, the edge of the opening on the same side was highlighted with a metal like texture (see Figure 5.3) and a "thud" sound was played from the same side. The highlight showed the participant the extent of the bar or their virtual body that had or would hit the door on that side. This was achieved using a conjunction of collision detection and ray casting to calculate the farthest extent in Unity. Several rays capable of colliding only with the self-avatar or the virtual bar were cast from behind the door on the side that was hit. Then a point was selected from all the ray collisions for the vertical highlight to pass through that was farthest from the center of the opening depending if it was the left or right side of the door. A virtual mirror was also placed behind the door so that the participant could observe their virtual body and the bar as s/he passed through the door while holding onto the bar.

5.1.6 Participants

Simulation studies investigating the power of Hierarchical Linear Models suggest that the number of participants and the number of trials are both important for establishing sufficient power [32]. To determine the Level 2 sample size (number of participants), a power analysis using Cohen's medium effect size of .3 [9] and an alpha of .05 revealed that a sample size of 44 participants will produce power of .85. Thus, a total of 44 participants were recruited from Clemson University graduate and undergraduate programs, 11 for each of the two conditions in the frontal and lateral judgment conditions. The average age of participants was 19.2 years and the distribution comprised of 31 females and 13 males. All participants had normal or corrected-to-normal vision and could

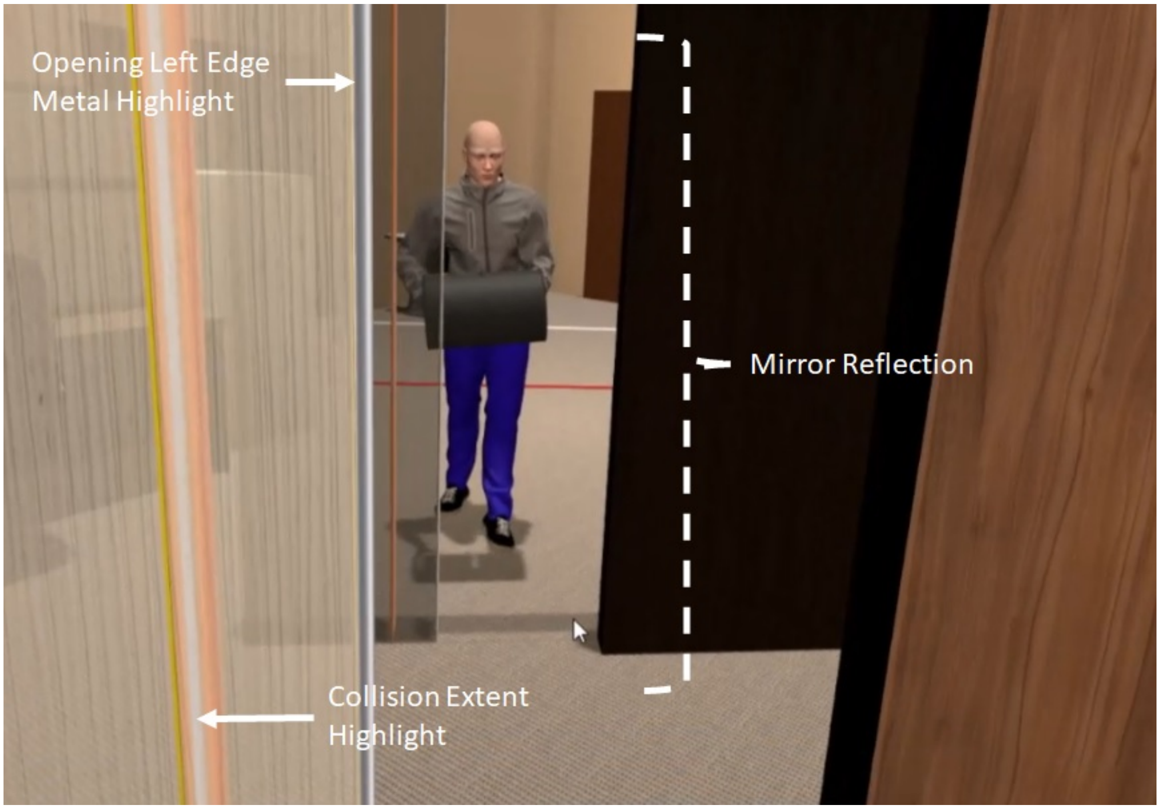

Figure 5.3: The different feedback cues provided to the participant upon collision with the door in the calibration phase

perceive stereo.

5.1.7 Research Questions

The research questions that this study explores are as follows:

1. Is the perception of passability with virtual handheld objects affected by the presence of body scaled self-avatars?

2. In the absence of haptic or inertial feedback, does the size of virtual handheld objects affect the affordance perception in IVE?

3. Does calibration affect passability judgments with handheld objects in VR?

4. How do virtual handheld objects affect frontal and lateral passability in VR?

5.1.8 Data Analysis

Due to the repeated measures design of this experiment, variables had considerable nesting within participants. In order to account for variance at the within-participant and between-participant levels, hierarchical linear modeling was used [32]. When using hierarchical linear modeling, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, all continuous predictors were grand-mean centered. Thus, the intercept coefficient of the regression equation represents the predicted outcome when all continuous variables are held at their average.

Further, the dependent variable was a binary yes/no judgment, which created a nonlinear cubic distribution. Raw scores were transformed into a linear distribution using a binary logistic regression [68]. To interpret the effects of continuous variables in a logistic regression, the slope coefficients are converted into odds ratios, which have a multiplicative effect on the outcome variable (i.e., a one-unit increase in the predictor results in the odds of "Yes" judgments being multiplied by the odds coefficient).

Effect sizes for each fixed effect will presented as the change in R2 comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect (for more on measuring effect sizes for dichotomous variables, see [89]).

5.2 Part 1: Frontal Judgments

In the frontal judgment conditions, the bar length was changed between trials. The width was either .8 times the shoulder width of the participant, the same size as the participant shoulder width or 1.2 times the participant shoulder width. The diameter of the bar remained the same across all trials. The participants were instructed to hold the bar using both the handles in a horizontal fashion in front of their body. As a result of the interaction, the PPVO system formed had a frontal dimension that was either the same size as the participant's shoulder width or 1.2 times the participant's shoulder width. This is because the participant's shoulders are wider than the bar in the condition with the narrower bar and thus the widest frontal dimension of the system is the participant's shoulder width.

5.2.1 Procedure

The following protocol was followed for the experiment

1. Upon arrival, the participant was asked to fill out a demographics survey which also gauged their experience with gaming in VR.

2. Next, the experimenter measured the participant's visual acuity using a modified Snellen visual acuity test, Stereo Acuity and Interpupillary Distance (IPD). The experimenter also measured the participant's height, shoulder width and body depth in centimeters. To measure the body depth, we asked the participant to stand against a wall with his/her back against it and hold on to a box in front of their midsection. We then measured how far the box extended from the wall and subtracted the depth of the box from it to get the participant's body depth.

3. Following the measurements, the participant was briefed on what VR is, all the devices they would be using for the simulation and in general what they would be doing in the simulation.

4. The participant was then put into the virtual environment and went through a body ownership phase if they had a self-avatar. The ownership phase involved exocentric pointing (pointing to various objects in the scene), egocentric pointing (pointing to various body parts) and visuo-haptic calibration (rubbing their forearms with the controller in the opposite hand while viewing their self-avatar).

5. Then the participant was acclimated to the IVE by having them walk upto a cube that appeared in a random location in the virtual room and reading the number on one of its faces out loud to the experimenter. This was repeated 5 times.

6. After the acclimation phase, the participant was instructed on how to interact with the virtual bar using both the controllers while facing a virtual mirror. The instruction phase also involved teaching the participant four quick exercises that they had to perform before every trial. These exercises were included as previous works suggest that it is important to spend time learning the perception-action dynamics of the PPO in order to adapt perceptual boundaries to it [28, 22]. This gave participant a good sense of how the bar lengths changed between trials and it matched up to their real or virtual body depending on the condition they were in. The exercises were as follows.

(a) Moving the bar away from the body and bringing it back.

(b) Pushing the bar up and bringing it back

(c) Turning to their left or right and moving the bar away from the body and bringing it back

(d) While facing the mirror, rotating the bar to observe it from the sides

7. Once the acclimation and the instruction phases were complete, the pretest phase commenced. For each trial in the pretest phase, participants were asked to pick up the bar from the virtual table, perform the exercises, walk two meters towards the virtual door from the starting line (white line) to the judgment line (red line) and then make a judgment about passability through the opening presented while holding onto the bar in front of their body. The particular instruction given to them in the frontal conditions was "While standing at the red line, you have to tell the experimenter if you can pass through the opening in the door if you were to walk straight through it while holding the bar in front of you in a horizontal fashion. You cannot rotate your shoulders or the bar to pass through". After making a judgment, the participant was asked to simply drop the bar and walk back to the white line and wait for the next trial to begin.

8. The calibration phase followed next and used instructions similar to the pretest phase. In addition to the previous instructions, after making a judgment, the participant was asked to walk towards the door and try to pass through it without hitting it to confirm his/her judgment. Upon hitting the door, the feedback described in the previous section was provided to the participant. The participant was instructed to always pass through the door and drop the bar behind it once both the bar and the body had passed the door. The participant was asked to walk back to the white line after dropping the bar.

9. Next was the posttest phase. In this phase, the participant followed the exact same instructions as the pretest phase.

10. After finishing all the trials in the three phases, the participant was asked to fill out a presence questionnaire, a body-ownership questionnaire [25] if they were given a self-avatar and the NASA-TLX workload questionnaire.

5.2.2 Hypothesis

Based on the research questions listed above, we tested the following hypotheses.

H1: Frontal passability judgments with virtual handheld objects will be more accurate in the presence of self-avatars

H2: Frontal passability judgments will scale based on the virtual bar length being held

H3: Calibration will improve frontal passability judgment accuracy with virtual handheld objects

5.2.3 Results

5.2.3.1 Body Ownership

We used the recommended Principal Component Analysis (PCA) method to calculate the body ownership scores for participants using the avatar embodiment questionnaire [25], M = .89, SD = .95. The range for the scores was -3 to 3.

5.2.3.2 Judgments

In order to assess the effects of avatar presence, bar length, and door width ratio on frontal passability judgments, a binary logistic hierarchical linear model was run on pre-test frontal judgments. This analysis used only the pre-test data in order to understand participants' affordance perceptions prior to receiving any feedback about the accuracy of their judgments. See Table 5.2 for the results of the omnibus F test.

Table 5.2: Omnibus F test results predicting frontal passability judgments

Predictor	df1	df2	F	sr^2
Trial	1	1378	1.42	–
Bar Length	2	1378	42.34***	.04
Door Width Ratio	1	1378	308.19***	.23
Avatar	1	25	2.31	–
Presence	1	25	.07	–
Bar Length x Door Width Ratio	2	1376	.1	–
Avatar x Bar Length	2	1376	2.49	–
Avatar x Door Width Ratio	1	1377	5.49*	.01
Avatar x Presence	1	26	.01	–
Avatar x Bar Length X Door Width Ratio	2	1371	3.25*	.03

*Note: * denotes p <.05, *** denotes p <.001*

The largest predictor of frontal passability judgments was the presented Door Width Ratio. As the door width relative to the PPVO increased by 1 ratio unit, the odds of judging the door as passable increased by a multiplicative factor of 2.4E+7. This coefficient seems exceptionally large, but can be explained by the large unit increase in the door width that accompanies the coefficient (an increase in 1 ratio unit means adding the width of the entire PPVO to the current door width). This accounted for 23% of the variance in frontal passability judgments.

The size of the bar also impacted frontal judgments. Holding all other variables at their average, participants were more likely to judge a door as passable when holding the .8 Bar Length (M prob = .67, SE = .12) compared to the 1.0 Bar Length (M prob = .15, SE = .07, t = 7.57, p <.001) and the 1.2 bar length (M prob = .33, SE = .12, t = 6.35, p <.001). Interestingly, the 1.2 Bar Length was more likely to judge a door as passable compared to the 1.0 Bar Length (t = 2.76, p = .007). This main effect was not moderated by presented door width, meaning the group differences in judgment were the same across all door widths.

At the average presented door width, there was no significant difference between passability judgments for the Avatar (M prob = .20, SE = .12) and the No-Avatar condition (M prob = .55, SE = .18, t = 1.61, p = .12). However, the effect of Avatar was significantly moderated by Door Width Ratio. The slope for the effect of Door Width Ratio was steeper for the No-Avatar condition (B = 19.25, SE = 1.76, odds = 2.3E+8) than the Avatar condition (B = 15.13, SE = 1.16, odds = 3.7E+6, t = 2.34, p = .02, see Figure 5.4. This suggests that the No-Avatar condition was more likely to judge larger door widths as passable compared to the Avatar Condition. This effect can be further understood by extracting the perceived critical ratios. In psychophysical experiments, the perceived critical ratio represents the ratio at which participants have a .5 probability of making a passable judgment. The perceived critical ratio also indicates the smallest ratio that participants perceive they can pass through [86]. As shown in Figure 5.4, the perceived critical ratio for the No-Avatar condition was .92 and the perceived critical ratios for the Avatar condition was .99.

The Avatar X Door Width interaction was further moderated by Bar Length. When the Bar Length was .8, the effect of Door Width Ratio on frontal passability judgments was significantly stronger (indicated by a steeper slope) for the No-Avatar condition compared to the Avatar condition (t = 2.5, p = .02). The perceived critical ratio was .82 for the No-Avatar condition and .92 for the Avatar condition. The slopes were marginally stronger when the Bar Length was 1.0 (t = 1.89, p = .058), with the critical ratios being .97 for the No-Avatar condition and 1.08 for the Avatar condition.

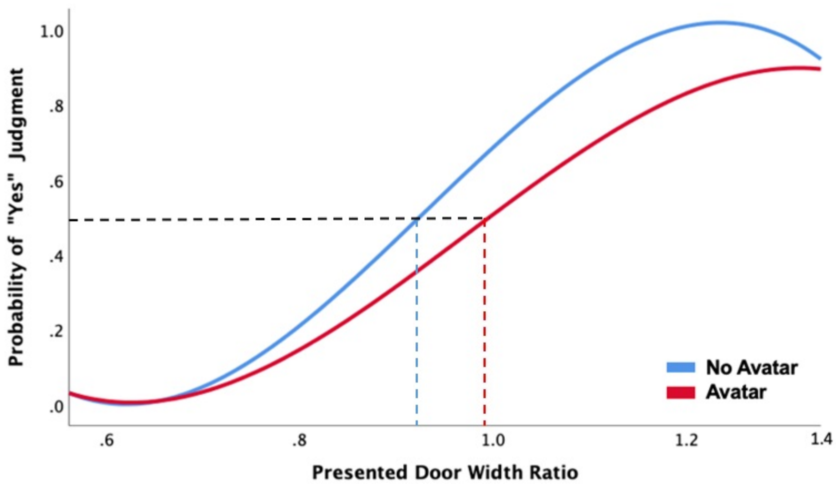

Figure 5.4: Effect of Door Width Ratio on Frontal passability judgments, moderated by Avatar presence

However, the slopes were not significantly different when the Bar Length was 1.2 ($t = 1.49$, $p = .137$). The critical ratios were .95 and .98 for the No-Avatar and Avatar conditions respectively.

To assess the effect of calibration on frontal passability judgments, a second model was run utilizing both the pretest and posttest data. Only those effects related to phase are discussed below. Other significant effects are discussed in the previous model. See Table 5.3 for the results of the omnibus F test.

At the average presented door width, participants were more likely to judge the door as passable in the pretest (M prob = .42, SE = .08) compared to the posttest (M = .12, SE = .06, $t = 5.63$, $p < .001$). The effect of Phase was moderated by Door Width Ratio. The slope for the effect of Door Width Ratio was steeper for the Pretest (B = 17.95, SE = 1.01, odds = 6.2E+7) than the Posttest (B = 13.88, SE = .69, odds = 1.0E+6, $t = 6.09$, $p < .001$, see Figure 5.5A). This suggests that participants were more likely to judge larger door widths as passable in the pretest as compared to the posttest. The perceived critical ratio was .96 for the pretest and 1.05 for the posttest.

The effect of Phase was moderated by Bar Length. For all Bar Lengths, participants were more likely to judge doors as passable in the Pretest compared to the Posttest. The .8 Bar Length resulted in the largest difference in mean probability between the Pretest (M prob = .79, SE = .06) and Posttest (M prob = .43, SE = .22, $t = 1.97$, $p = .049$). The 1.0 Bar Length resulted in a smaller difference in mean probability between the Pretest (M prob = .38, SE = .1) and Posttest

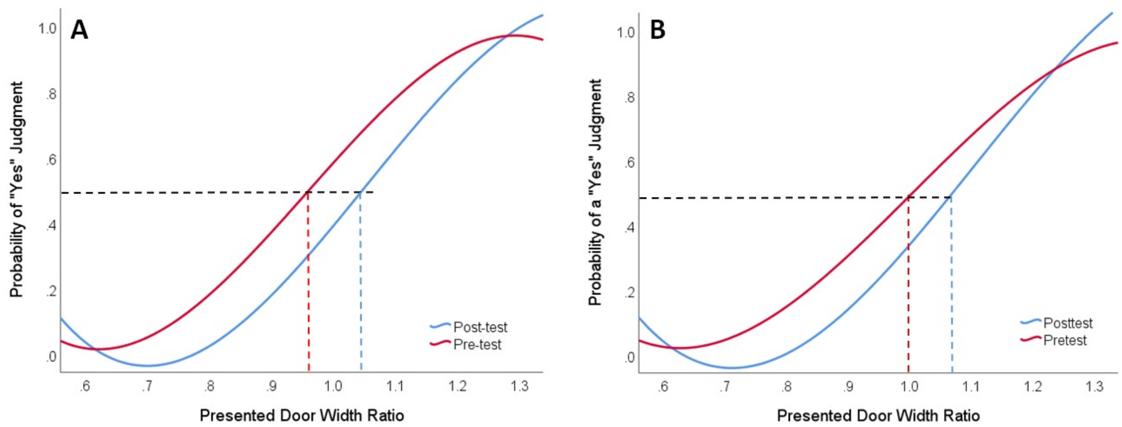

Figure 5.5: A) Interaction b/w Door Width Ratio and Phase B) Interaction b/w Door Width Ratio and phase for Avatar condition

(M prob = .12, SE = .1, t = 3.5, p = .001). The effect of Phase was smallest for the 1.2 Bar Length. Participants were only slightly more likely to judge doors as passable in the Pretest (M prob = .09, SE = .04) as compared to the Posttest (M prob = .01, SE = .01, t = 2.22, p = .032). Interestingly, there were no significant differences in judgments among all Bar Lengths for the Posttest. Significant differences among Bar Lengths in the Pretest are reported above.

The effect of Phase was also moderated by Avatar. For both the Avatar and No-Avatar conditions, participants were more likely to judge doors as passable in the Pretest compared to the Posttest. The effect of Phase was greatest for the No-Avatar condition, as evidenced by a larger difference in mean probabilities between the Pretest (M prob = .62, SE = .14) and Posttest (M prob = .15, SE = .13, t = 4.72, p <.001). For the avatar condition, participants were only slightly more likely to judge doors as passable in the Pretest (M prob = .29, SE = .08) as compared to the Posttest (M prob = .08, SE = .05, t = 3.98, p = .001). This interaction was further moderated by Door Width Ratio.

In the Avatar condition, the effect of Door Width Ratio on frontal passability judgments was significantly stronger for the Posttest (B = 16.97, SE = 1.38, odds = 2.3E+7) compared to the Pretest (B = 10.88, SE = .79, odds = 5.3E+4, t = 4.41, p <.001, see Figure 5.5B). In the No-Avatar condition, the effect of Door Width Ratio on passability judgements did not significantly differ between the Pretest and Posttest.

Lastly, there was a four-way interaction among Phase, Door Width Ratio, Avatar, and Bar

Table 5.3: Omnibus F test results predicting frontal passability judgments

Predictor	df1	df2	F	sr^2
Trial	1	2759	.43	–
Phase	1	2759	15.72***	.003
Bar Length	2	2759	90.3***	.06
Door Width Ratio	1	2759	624.32***	.29
Avatar	1	24	2.51	–
Phase X Door Width Ratio	1	2758	16.4***	.01
Phase X Bar Length	2	2757	4.97*	.002
Bar Length X Door Width Ratio	2	2757	.76	–
Avatar X Phase	1	2758	5.16*	.001
Avatar X Door Width Ratio	1	2758	5.64*	.001
Avatar X Bar Length	2	2757	12.5***	0.007
Phase X Bar Length X Door Width Ratio	2	2752	2.18	–
Avatar X Phase X Door Width Ratio	2	2755	8.57*	0.002
Avatar X Phase X Bar Length	2	2752	2.93	–
Avatar X Bar Length X Door With Ratio	2	2752	4.95*	0.03
Avatar X Phase X Bar Length X Door Width Ratio	2	2741	3.71*	0.03

*Note: * denotes p <.05, *** denotes p <.001*

Length. To assess this interaction, the file was split by Avatar condition and Bar Length condition to assess differences between Pretest and Posttest.

For the No-Avatar condition, the effect of Phase was not moderated by Door Width Ratio for the .8 Bar Length nor for the 1.0 Bar Length. In other words, the slopes for the effect of Door Width Ratio were similar for both the Pretest and Posttest in the .8 Bar Length as well as the 1.0 Bar Length. For the 1.2 Bar Length, however, the effect of Phase was moderated by Door Width Ratio. The slope for the effect of Door Width Ratio for the No-Avatar condition when the Bar Length was 1.2 was steeper for the Posttest (B = 39.88, SE = 7.23, odds = 2.1E+17) than the Pretest (B = 20.96, SE = 2.82, odds = 1.3E+9, t = 2.61, p = .009, see Figure 5.6).

For the Avatar Condition, the effect of Phase was moderated by Door Width Ratio for the .8 Bar Length and the 1.0 Bar Length. The effect of Phase was not moderated by Door Width Ratio for the 1.2 Bar Length condition. The slope for the effect of Door Width Ratio for the Avatar condition when the Bar Length was .8 was steeper for the Posttest (B = 14.41, SE = 2, odds = 1.8E+6) compared to the Pretest (B = 9.18, SE = 1.13, odds = 9,701, t = 2.76, p = .006, see Figure 5.7A). The slope for the effect of Door Width Ratio for the Avatar condition when the Bar Length was 1.0 was steeper for the Posttest (B = 20.76, SE = 2.92, odds = 1.0E+9) compared to the Pretest (B = 11.79, SE = 1.45, odds = 1.3E+5, t = 3.07, p = .002, see Figure 5.7B).

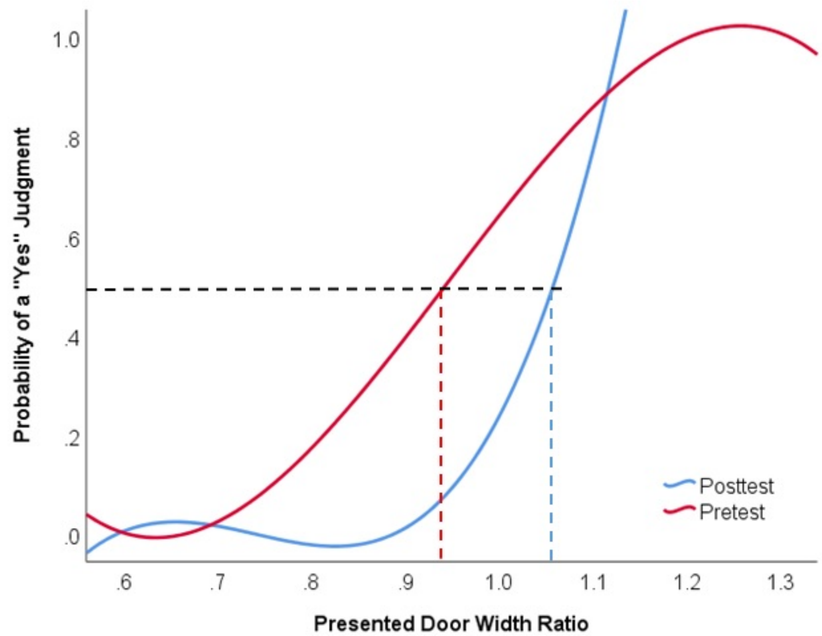

Figure 5.6: Interaction b/w phase and ratio for No-Avatar & 1.2 bar length conditions

5.2.4 Discussion

The results suggest that participants were more likely to judge an opening as passable while holding the smaller bar with length .8 times the shoulder width as compared to the matched and longer bars. This suggests that they were using the visual size of the bar to make passability judgments and were not relying on the mismatched haptic feedback. These results are similar to those observed by Hackney et al. where participants adapted to the different tray sizes being held while crossing apertures [28]. This supports our second hypothesis which states that passability judgments will be scaled to the length of the virtual bar being held. However, participants were more likely to judge openings as passable with the 1.2 bar length as compared to the matched bar. This is unexpected but can be explained with the help of the interaction effects. Taking a closer look at the interactions, a significant interaction between avatar and door width ratio was observed. Although participants were more likely to judge openings as passable in the absence of self-avatars, the critical ratio for the avatar condition was closer to 1 suggesting that they were more accurate in the presence of self-avatars. This supports our first hypothesis stating that judgments will be more accurate in the presence of self-avatars. This aligns with previous research that suggests that the presence of self-avatars significantly affects the affordance thresholds and results in more realistic

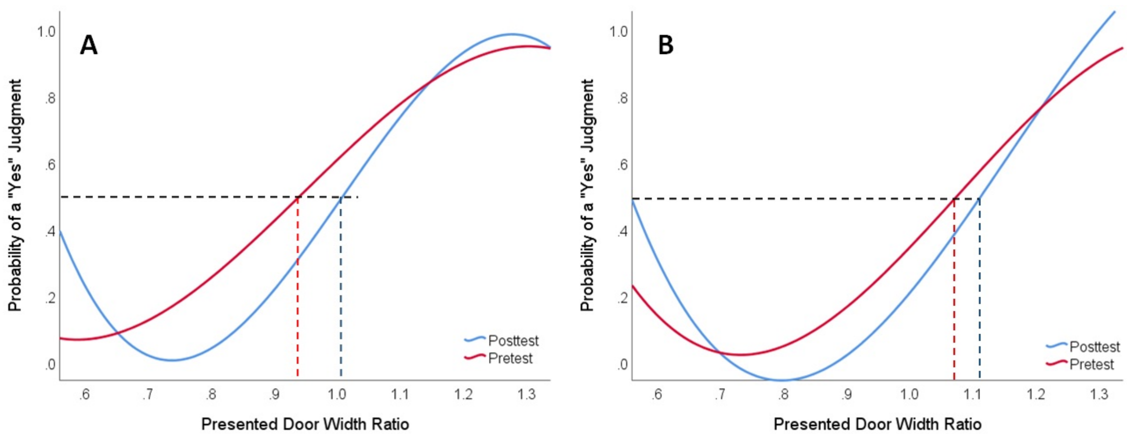

Figure 5.7: A) Interaction b/w phase and ratio for Avatar and .8 bar length conditions B) Interaction b/w phase and ratio for Avatar and 1.0 bar length conditions

judgments [53, 55]. Furthermore, this interaction was moderated by the length of the virtual bar being held. When interacting with the smaller and matched bars, the slopes were significantly different for the avatar and the no-avatar conditions. The slopes did not significantly differ for the longer bar. Although closely examining the critical ratios for different bar sizes revealed that they fell within the range reported by Wagman et al. [91], the ratios were higher for the avatar condition as compared to the no-avatar condition for the narrower and matched bar sizes but were only slightly different for the wider bar size. This suggests that participants were able to comprehend if their body or the virtual bar determined the width of the PPVO when the bar size was close to the shoulder width in the presence of the self-avatar, but when the object was distinctively wider than the shoulders, participants relied on the width of the virtual object in either condition. This is similar to the findings reported by Higuchi et al. [31]. The authors studied speed and shoulder rotations for successfully passing through apertures and found that individual judgments scale to the width of the object being held if it is wider than the shoulders. Moreover, since it is easier to compress the shoulder width by scrunching them or hunching over than expanding it, the presence of a self-avatar representing the true shoulder width in the narrower and matched conditions helped participants make more accurate judgments. This also supports our second hypothesis.

Comparing the pretest and posttest data, we observed that participants were more likely to judge openings as passable in the pretest as compared to the posttest. Closely examining the critical ratios, we see a shift from .96 to 1.05. The posttest ratio is closer to what we would expect to be passable when performing the action as we need the opening to be slightly larger to pass through without grazing it and also to account for body sway when walking. The ratio is similar to what has previously been reported in several other works [93, 23, 73]. This supports our third hypothesis which states that calibration will improve the accuracy of frontal passability for the PPVO system. This effect was observed across all bar lengths between pretest and posttest. Considering only the posttest data, no significant differences were observed in the slopes of the different bar lengths. This further supports our third hypothesis. We also observed that the difference in slope was largest between pretest and posttest for the no-avatar condition but the slopes were only slightly different for the avatar condition. This suggests that participants were more accurate with self-avatars from the start and further improved their judgments post calibration, supporting our first hypothesis. This is similar to what was reported by Lin et al. in their study involving stepping off a ledge in the presence and absence of self-avatars [55]. They observed that judgments for stepping off the ledge more realistic in the presence of self-avatars. Performing exercises with the bar in front of a virtual mirror before making a judgment could have also played a role in accurately determining the dimensions of the bar with respect to their body further facilitating accurate judgments.

Interestingly, the analysis also suggested that for the no-avatar condition, the slopes for the door width ratio were significantly different for the longer bar length but not for the smaller and matched bar lengths between the pretest and posttest. Perhaps in the absence of self-avatars participants were not able to determine if the frontal dimension of the PPVO system was defined by the bar length or their shoulders for the smaller and matched bars and not knowing what to calibrate judgments to, the slopes were not significantly different between phases. Since, the longer bar was undoubtedly wider than the shoulders, participants were able to successfully calibrate. This aligns with the results reported in a study by Franchak [19]. The author investigated the role of vision in recalibration to altered body dimension and saw a significant decrease in the judgment accuracy for without vision calibration trials. The opposite was true for the avatar condition. There was a significant shift in the slopes from pretest to posttest for the smaller and matched bar lengths but not for the longer bar length. Since, participants were able to accurately determine the size of the bar in the presence of a self-avatar they were able to successfully calibrate to a realistic threshold based on the PPVO dimension for the smaller and matched bars. For the longer bar, being able to determine that the PPVO width was defined by the virtual object from the start, judgments were not significantly different pre and post calibration. This suggests that the presence of self-avatars aided in calibration as well, further strengthening the support for all our hypotheses.

5.3 Part 2: Lateral Judgments

In the lateral judgment conditions, the bar diameter was changed between trials and the length of the bar remained unchanged. The bar diameter was based on the body depth of the participant. The bar diameters were .8 times the body depth, the same as the body depth or 1.2 times the body depth. As a result, the PPVO system formed had a depth of 1.8 times the body depth, 2 times the body depth or 2.2 times the body depth. The participants were instructed to hold the bar in front of their bodies to make sideways passability judgments to the presented openings.

5.3.1 Procedure

We followed the exact same protocol for the lateral passability condition as the frontal conditions except, participants were asked to make judgments sideways at the judgment line. For the lateral conditions, the instruction given to the participants was "When you stop at the red line to make a judgment, you have to turn sideways and tell the experimenter if you can pass through the opening in the door if you were to walk sideways through it while holding the bar in front of your body. You cannot hold the bar on top of your head". In the calibration phase, participants were told to try and pass through the opening while walking sideways.

5.3.2 Hypothesis

The same set of hypotheses as the frontal judgments were tested for lateral judgments.

H1: Lateral passability judgments with virtual handheld objects will be more accurate in the presence of self-avatars

H2: Lateral passability judgments will scale based on the virtual bar diameter being held

H3: Calibration will improve lateral passability judgment accuracy with virtual handheld objects

Table 5.4: Omnibus F test predicting lateral passability judgments

Predictor	df1	df2	F	sr^2
Trial	1	1376	7.187**	.006
Bar Diameter	2	1376	.754	–
Door Width Ratio	1	1376	266.023***	.37
Avatar	1	25	.171	–
Presence	1	25	.606	–
Bar Diameter X Door Width Ratio	2	1374	.971	–
Avatar X Bar Diameter	2	1374	.072	–
Avatar X Door Width Ratio	1	1375	.712	–
Avatar X Presence	1	26	.008	–
Avatar X Bar Diameter X Door Width Ratio	2	1369	4.047*	.009

*Note: * denotes p <.05, ** denotes p <.01, *** denotes p <.001*

5.3.3 Results

5.3.3.1 Body Ownership

We used the recommended Principal Component Analysis (PCA) method to calculate the body ownership scores for participants using the avatar embodiment questionnaire [25], M = .85, SD = .73. The range for the scores was -3 to 3.

5.3.3.2 Judgments

In order to assess the effects of avatar presence, bar diameter, and door width ratio on lateral passability judgments, a binary logistic hierarchical linear model was run on pre-test lateral judgments. See Table 5.4 for results of the omnibus F test.

There were two main effects predicting pretest lateral judgments. As expected, Door Width Ratio was a significant predictor, explaining 37% of the variance in judgments (B = 23.44, SE = 1.43, t = 16.31, p <.001). As the Door Width Ratio increased by 1 unit, the odds of judging the door as passable increased by a multiplicative factor of 1.52E+10. Additionally, as trials in the pretest increased, participants were slightly less likely to judge doors as passable (B = -.02, SE = .006, t = 2.68, p = .007, odds = .938).

Neither Bar Diameter nor Avatar condition significantly predicted lateral judgments. However, there was a significant 3-way interaction between Avatar condition, Bar Diameter, and Door Width Ratio accounting for <1% of the variance in judgments. For the Avatar condition, there was no difference in Door Width Ratio slopes across the different Bar Diameters (F(2,683) = 1.08, p = .34). The perceived critical ratio was 1 for both the .8 and 1 bar diameters and 1.02 for the 1.2

bar diameter. For the No-Avatar condition, there were differences in slope across Bar Diameters (F(2.684) = 3.92, p = .02). The 1.0 Bar Diameter slope (B = 32.31, SE = 3.74, odds = 1.1E+14) was significantly steeper than the 1.2 Bar Diameter (B = 22.88, SE = 2.69, odds = 8.6E+9, t = 2.75, p = .006, see Figure 5.8), but not significantly different from the .8 Bar Diameter (B = 27.46, SE = 3.12, odds = 8.4E+11, t = 1.29, p = .19). There was also no difference in slope between the 1.2 and .8 Bar Diameter (t = 1.46, p = .14). The perceived critical ratios for the .8 bar was .96, for the 1 bar was .97 and for the 1.2 bar was 1.

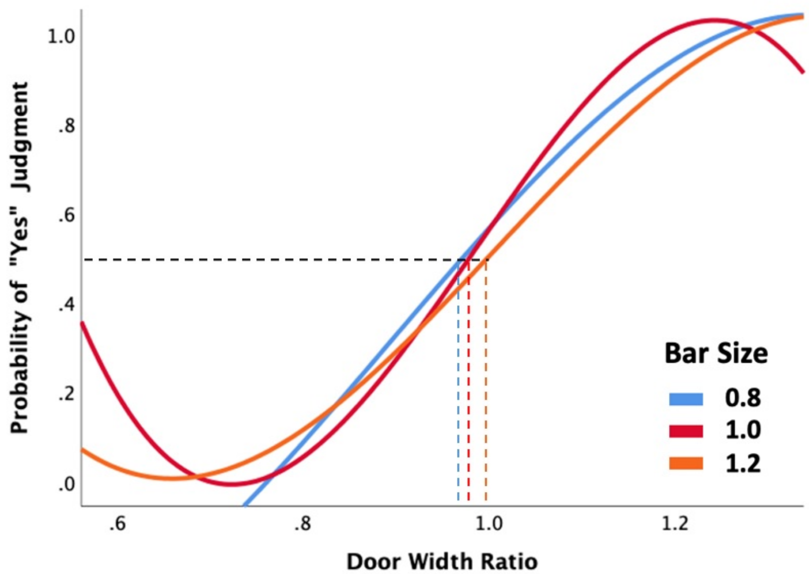

Figure 5.8: Interaction b/w Bar Diameter and Door Width Ratio for the No-Avatar Condition only. Slope for 1.0 Bar Diameter significantly steeper than 1.2 Bar Diameter.

Again, to assess the effect of calibration on lateral passability judgments, a second model was run utilizing both the pretest and posttest data. Only those effects related to phase are discussed below. Other significant effects are discussed in the previous model. See Table 5.5 for the results of the omnibus F test.

The main effect of Phase was not a significant predictor of lateral passability judgments. At the average presented door width, there was no significant difference between passability judgments in the pretest compared to the posttest. The effect of Phase, however, was moderated by Avatar. For the No-Avatar condition, there was no significant difference in participants' judgments of passability between the Pretest and Posttest. For the Avatar condition, participants were more likely to judge the door as passable in the Pretest (M prob = .58, SE = .13) compared to the Posttest (M prob = .15, SE = .12, t = 4.6, p <.001), see Figure 5.9A. The perceived critical ratio for the pretest was 1.01 and for the posttest was 1.15.

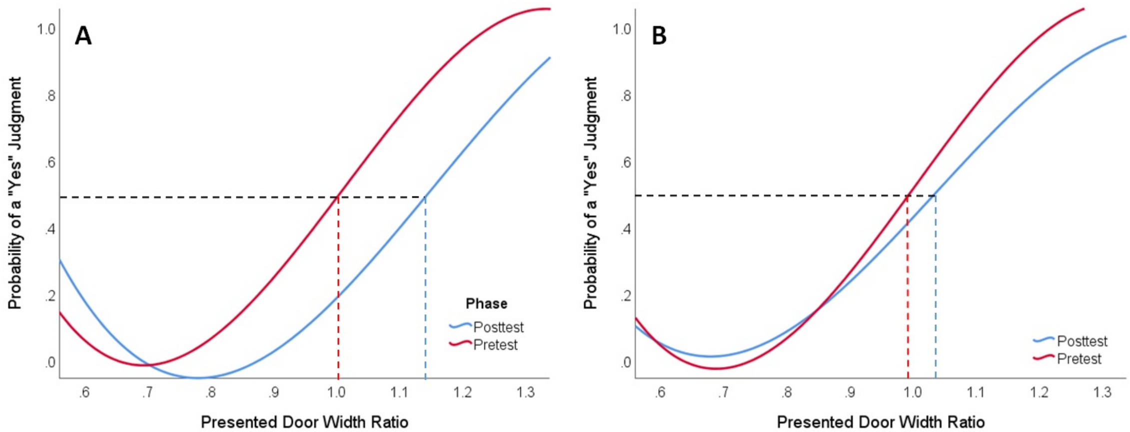

Figure 5.9: A) Interaction between phase and door width ratio for the avatar condition B) Interaction between Phase and Door Width Ratio

Additionally, the effect of phase was moderated by Door Width Ratio. The slope for the effect of Door Width Ratio was steeper for the Pretest (B = 19.71, SE = 1.01, odds = 3.6E+8) than the Posttest (B = 12.72, SE = 1.1, odds = 3.3E+5, t = 6.48, p <.001), see Figure 5.9B. The perceived critical ratio for the pretest was calculated to be 1 and for the posttest was 1.04. This interaction was further moderated by Bar Diameter.

In the .8 Bar Diameter condition, the effect of Door Width Ratio on lateral passability judgments was significantly stronger for the Pretest (B = 20.87, SE = 1.9, odds = 1.2E+9) compared to the Posttest (B = 12.29, SE = 1.93, odds = 2.2E+5, t = 4.3, p <.001), see Figure 5.10A. In the 1.0 Bar Diameter condition, the effect of Door Width Ratio on lateral passability judgments was significantly stronger for the Pretest (B = 21.86, SE = 1.9, odds = 3.1E+9) compared to the Posttest (B = 12.31, SE = 2.02, odds = 2.2E+6, t = 4.73, p <.001), see Figure 5.10B. The effect of Door Width Ratio on lateral passability judgments did not significantly differ between the Pretest and Posttest for the 1.2 Bar Diameter condition with the perceived critical ratios being 1.01 and 1.04 respectively.

Lastly, there was a four-way interaction among Phase, Door Width Ratio, Avatar, and Bar Diameter. To assess this interaction, the file was split by Avatar condition and Bar Diameter

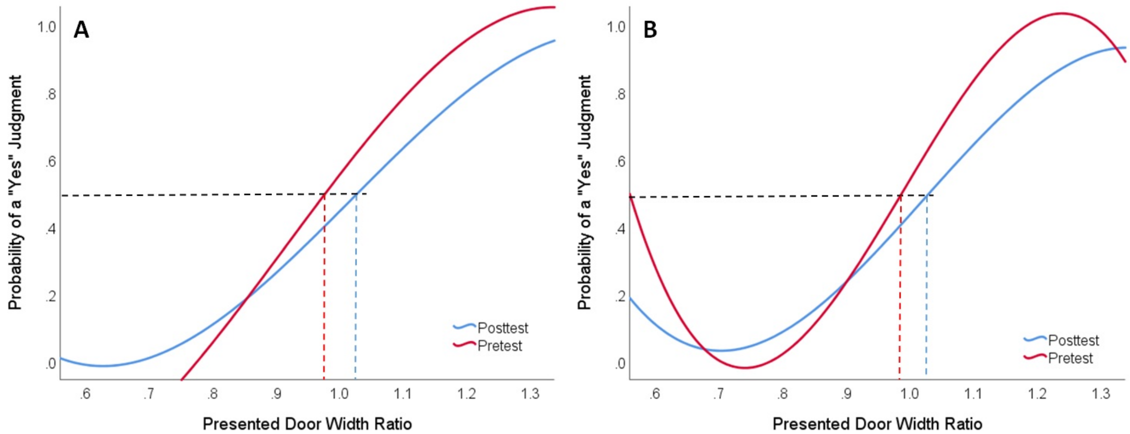

Figure 5.10: A) Interaction between Phase and Door Width Ratio for the .8 Bar Diameter B) Interaction between Phase and Ratio for the 1.0 Bar Diameter

condition to assess differences between Pretest and Posttest.

For the No-Avatar condition, the effect of Phase was moderated by Door Width Ratio for all Bar Diameters. The slope for the effect of Door Width Ratio for the No-Avatar condition when the Bar Diameter was .8 was steeper for the Pretest (B = 18.13, SE = 2.44, odds = 7.4E+7) than the Posttest (B = 11.96, SE = 2.81, odds = 1.6E+5, t = 2.2, p = .028, see Figure 5.11A). The perceived critical ratios were .96 and .89 for the pretest and posttest respectively. The slope for the effect of Door Width Ratio for the No-Avatar condition when the Bar Diameter was 1.0 was steeper for the Pretest (B = 18.6, SE = 2.4, odds = 1.2E+8) than the Posttest (B = 12.85, SE = 2.8, odds = 3.8E+5, t = 2.06, p = .04, see Figure 5.11B) with critical ratios being .975 and .925 respectively. The slope for the effect of Door Width Ratio for the No-Avatar condition when the Bar Diameter was 1.2 was steeper for the Posttest (B = 19.1, SE = 2.7, odds = 1.9E+8) than the Pretest (B = 11.79, SE = 1.5, odds = 1.3E+5, t = 2.72, p = .007, see Figure 5.11C) with critical ratios being .93 for posttest and 1 for pretest.

For the Avatar condition, the effect of Phase was moderated by Door Width Ratio for the 1.0 Bar Diameter. The effect of Phase was not moderated by Door Width Ratio for the .8 and 1.2 Bar Diameter conditions. Interestingly, the critical ratio for the .8 bar diameter shifted from 1.048 to 1.11 and the critical ratio for the 1.2 bar diameter shifted from 1.07 to 1.11 from the pretest to the posttest phase. The slope for the effect of Door Width Ratio for the Avatar condition when the Bar Diameter was 1.0 was steeper for the Pretest (B = 23.35, SE = 2.94, odds = 1.4E+10) compared to

Table 5.5: Omnibus F test results predicting lateral passability judgments

Predictor	df1	df2	F	sr^2
Trial	1	2753	.37	–
Phase	1	2753	1.08	–
Bar Diameter	2	2753	.85	–
Door Width Ratio	1	2753	675.48***	.32
Avatar	1	25	13.45*	.04
Phase X Door Width Ratio	1	2752	41.97***	.03
Phase X Bar Diameter	2	2751	.69	–
Bar Diameter X Door Width Ratio	2	2751	1.26	–
Avatar X Phase	1	2752	130.33***	.04
Avatar X Door Width Ratio	1	2752	.53	–
Avatar X Bar Diameter	2	2751	.8	–
Phase X Bar Diameter X Door Width Ratio	2	2746	3.58*	.008
Avatar X Phase X Door Width Ratio	1	2749	3.12	–
Avatar X Phase X Bar Diameter	2	2746	.42	–
Avatar X Bar Diameter X Door With Ratio	2	2746	1.87	–
Avatar X Phase X Bar Diameter X Door Width Ratio	2	2735	3.42*	.01

*Note: * denotes p <.05, *** denotes p <.001*

the Posttest (B = 16.59, SE = 3.22, odds = 1.6E+7, t = 2.1, p = .036, see Figure 5.11D). A trend similar to the other two bar diameter conditions was observed in terms of the critical ratios. The ratios shifted from 1.01 to 1.15 from the pretest to the posttest.

5.3.4 Discussion

Analyzing the pretest data revealed a three way interaction between avatar, bar diameter and presented door width ratio. There were no significant differences between the three bar diameters in the presence of self-avatars. Perhaps participants were able to accurately perceive the diameter of the bar in the presence of a self-avatar similar to what was observed in the frontal conditions and were accurate in their judgments across all bar sizes from the start. This is evident from the critical ratios of the three bar diameter conditions. The ratios are either 1 or 1.02 across all three bar diameters. This strengthens our previous argument for using exercises to more accurately perceive the size of the virtual bar in relation to the body. However, for the no-avatar conditions, the slope for the matched bar diameter condition was significantly different from the thinner and thicker bar conditions. Taking a closer look at the critical ratios revealed that they were all less than or equal to 1. This supports our first hypothesis which states that participants will make more accurate judgments in the presence of self-avatars. As stated above, this aligns with previous research suggesting that judgments are more accurate in the presence of self-avatars [55].

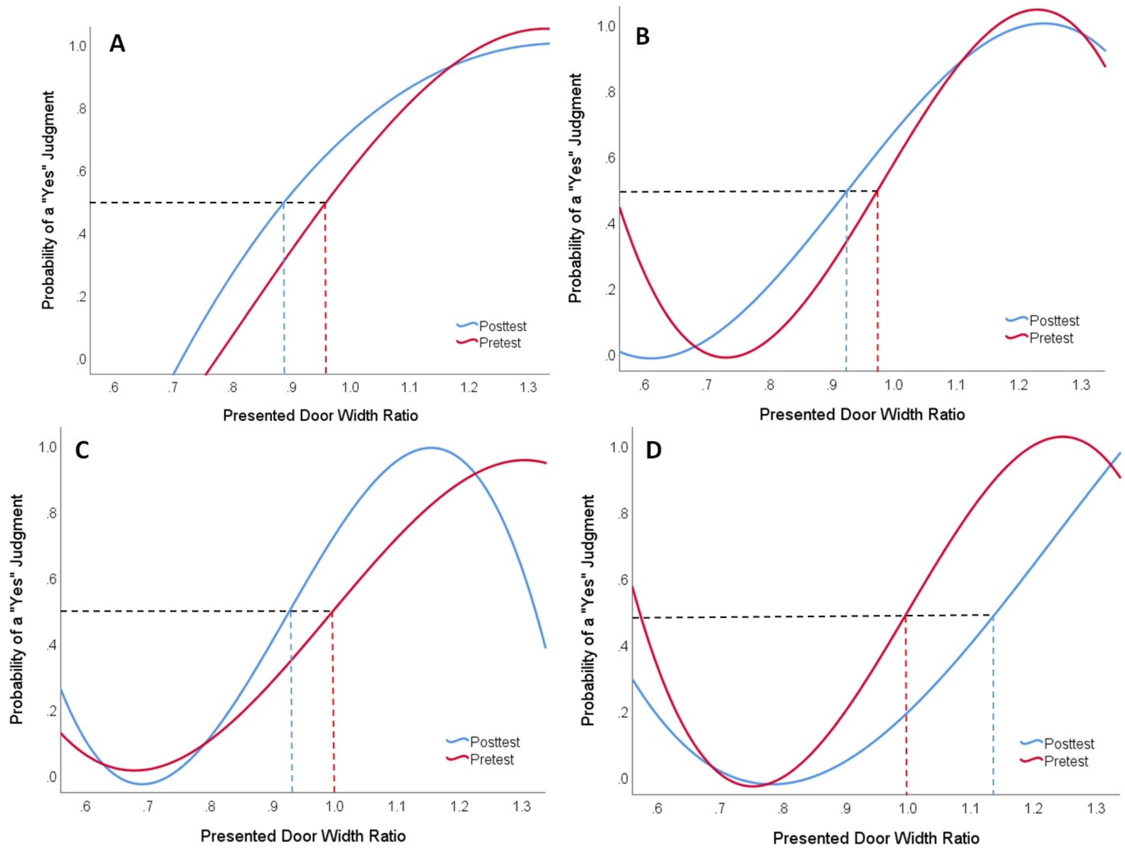

Figure 5.11: A) Interaction between Phase and Door Width Ratio for the .8 Bar Diameter and No-Avatar B) Interaction between Phase and Door Width Ratio for the 1 Bar Diameter and No-Avatar C) Interaction between Phase and Door Width Ratio for the 1.2 Bar Diameter and No-Avatar D) Interaction between Phase and Door Width Ratio for the 1.0 Bar Diameter and Avatar

Comparing the data between phases, no main effect was observed between phases overall. This does not support our third hypothesis which states that calibration will improve the accuracy of lateral passability judgments. A reason for this could be the way participants were adapting their bar holding behavior to different door widths in the calibration phase as observed by the experimenters. The door widths were based on the body depth along the midsection of the participant. However, we observed that participants often held the bar between their chin and their chest rather than in front of their midsection to pass through narrower openings. This was valid based on the instructions given to them and in terms of the natural adjustment behavior expected when it comes to making lateral judgments. Holding the bar in this position helped participants avoid their elbows sticking as compared to holding the bar close to their midsection and it also reduced the effective body depth as compared to the midsection. In this case, calibration did help participants with their judgments but not in the manner the experimenters expected.

The main effect of phase was moderated by the presence and absence of self-avatars. There was no significant difference pre and post calibration in the absence of self-avatars. This is perhaps due to the same reason we stated in part 1 and similar to the no vision investigation by Franchak [19]. Since, participants did not have an avatar they were not sure how much of the PPVO system's widest dimension was defined by their body and could not calibrate properly. To get through narrow openings during the calibration phase, participants were perhaps holding the virtual bar such that it was partially intersecting with their body but could not see it as there was no avatar or they were holding the bar in front of the body but were not able to determine how much of the body was intersecting with the door while crossing. We believe the latter to be more probable as holding on to the bar with the help of the controllers provided some haptic sensation to the participants of where the bar would be if they had a body. Another plausible explanation is that participants thought that they could compress their body and squeeze through the opening with the bar. This aligns with previous research suggesting that laterally squeezing through apertures is depends on how much the torso can compress [10, 34]. Being unaware of the fact that self-avatars in IVEs do not have the capability to compress the body, it is highly likely that participants calibrated to their compressed body depth in the absence of self-avatars. The authors investigated lateral passability judgments for older and younger adults and reported their affordance thresholds to be closer to their compressed body dimensions. In the presence of a self-avatar, participants were more readily judging doors as passable in the pretest as compared to the posttest when they had a self-avatar. Examining the critical ratios revealed a shift from 1.01 to 1.15 from the pretest to the posttest, suggesting that calibration was effective in the presence of self-avatars supporting the first and the third hypotheses. Having realized that self-avatars did not afford compressing the body, individuals calibrated to the static body depth yielding a critical ratio similar to Warren et al. [93]. A similar phenomenon has been reported by several others in cases where all the information about a surface is not available from the visuals alone. For example, Adolph et al. demonstrated that the slipperiness of surface can only perceived by actually walking on it and the rigidity of a surface can be perceived by pressing against it [1, 37, 38].

The results also suggest that the door widths presented moderated the effect of phase, where we see a shift in the critical ratios from 1.0 to 1.04 overall. This would infer that the calibration phase aided in accurately assessing the width of the PPVO in comparison to the door widths in turn supporting the third hypothesis. This effect was further influenced by the different bar diameter conditions. For the thinner and matched bar conditions, participants were significantly more accurate in the posttest with critical ratios shifting in the positive direction. A similar trend in the critical ratio was observed for the thicker bar condition but the slopes did not differ significantly pre and post calibration. This supports our second hypothesis which states that passability judgments will scale based on the bar being held.

The three way interaction discussed above was further mediated by self-avatars. In the absence of a self-avatar, all three bar conditions saw a dip in the critical ratios suggesting that participants were not able to accurately perceive when and where their bodies would collide with the bar or the door. This is perhaps a byproduct of both the behaviors discussed above; 1) holding the bar between the chin and the chest to reduce effect body depth in comparison to the midsection of the body and 2) not realizing when the body intersected with the door in the absence of self-avatars, hence judging narrower openings as passable. In the presence of the self-avatar, only the slopes for the matched bar condition were different pre and post calibration, however the critical ratios revealed a larger shift moving further away from 1 in the positive direction across all bar diameters. The resultant critical ratios were closer to what was reported by Warren et al. [93]. This supports our first hypothesis and reinforces the importance of a self-avatar for calibration and judging affordances.

5.4 Comparing Judgments Overall

5.4.1 Hypotheses

Other than the hypotheses for each of the parts of the experiment, we also tested the following to expose any differences based on the judgment type and effect of self-avatars on them.

H1: Frontal passability will be significantly different from lateral passability for the PPVO system

H2: Frontal passability for the PPVO system in the presence of self-avatars will be significantly different from lateral passability for the PPVO system

Table 5.6: Omnibus F test predicting passability judgments

Predictor	df1	df2	F	sr^2
Trial	1	5457	131.96***	.02
Door Width Ratio	1	5457	1281.81***	.35
Judgment Type	1	47	.21	–
Avatar	1	48	13.64***	.02
Judgment Type X Door Width Ratio	1	5456	6.65*	.004
Avatar X Door Width Ratio	1	5456	1.7	–
Judgment Type X Avatar	1	48	1.52	–
Judgment Type X Avatar X Door Width Ratio	1	5453	.19	–

*Note: * denotes p <.05, ** denotes p <.01, *** denotes p <.001*

5.4.2 Results

To assess differences between Judgment Type (i.e., frontal and lateral passability judgments), a binary logistic hierarchical linear model was run. See Table 5.6 for results of the omnibus F test. There were three main effects predicting passability judgments. As expected, Door Width Ratio was a significant predictor, explaining 35% of the variance in judgments (B = 16.81, SE = .47, t = 35.8, p <.001). As the Door Width Ratio increased by 1 unit, the odds of judging the door as passable increased by a multiplicative factor of 1.99E+7. Additionally, as trials increased, participants were slightly less likely to judge doors as passable (B = -.01, SE = .001, t = -11.49, p <.001, odds = .99).

There was an effect of Avatar, such that at the average presented door width, participants were less likely to judge doors as passable in the Avatar condition (M prob = .37, SE = .07) as compared to the No-Avatar condition (M prob = .73, SE = .06, t = -4.04, p <.001), see Figure 5.12A. The perceived critical ratio for the No-Avatar conditions was .97 and for the Avatar conditions was 1.06.

Lastly, there was a significant interaction between Judgment Type and Door Width Ratio. The slope for the effect of Door Width Ratio was slightly steeper for Lateral Judgments (B = 18.09, SE = .71, odds = 7.18E+7) compared to Frontal Judgments (B = 15.75, SE = .91, odds = 6.9E+6, t = 2.58, p = .01, see Figure 5.12B). The effect of this interaction was trivial, accounting for .4% of the variance in passability judgments.

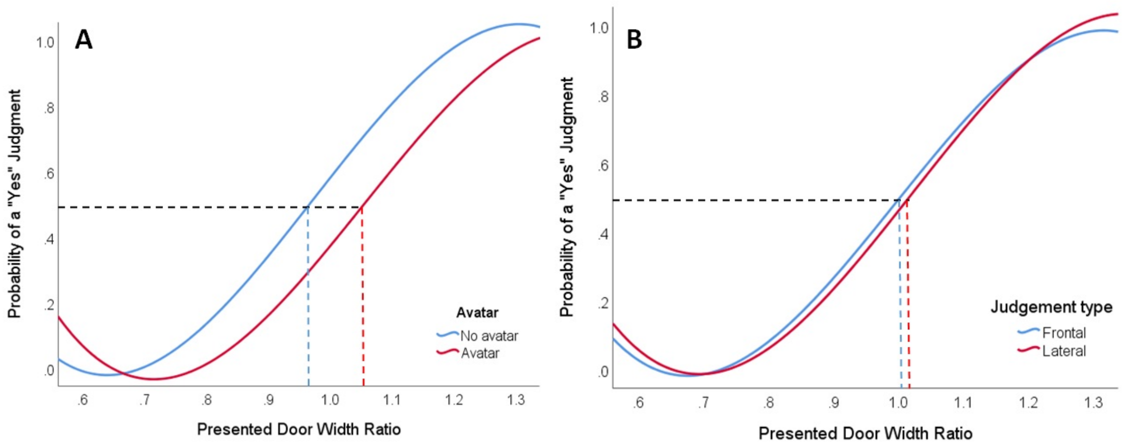

Figure 5.12: A) Main effect of avatar overall B) Interaction between Judgment Type and Door Width Ratio

5.5 General Discussion

Inferring from the overall comparison of conditions, judgments were overall more accurate in the presence of self-avatars. This aligns with our results from the two parts of the study separately and with previous research suggesting that judgments are more realistic and accurate in the presence of self-avatars [53, 55]. However, the effect was not moderated by judgment type. This does not support for second overall hypothesis which states that frontal and lateral judgments will differ in the presence of self-avatars. This is interesting considering that the two judgment types are fundamentally different as a higher proportion of the width of the PPVO is defined by the body in the lateral judgments as compared to the frontal judgments. Perhaps this is due to the fact that the lateral judgments did not fully afford natural interaction as participants could not compress their avatar or wiggle their way through the opening similar to the real world. Therefore, for scenarios affording lateral passability, it crucial to have a self-avatar to indicate to users that body compression is not yet afforded in IVE. This caveat could both help keep and break immersion in VR as it provides critical cues about body dimensions aiding in affordance judgments but also suggesting that natural interaction is not fully afforded.

We also observed a significant interaction of judgment type by door width ratio presented. The observed slope for the lateral judgments was steeper as compared to the frontal judgment, however the perceived critical ratios for the two slopes are very close suggesting that the two judgments were not very different from each other. This does not support out first overall hypothesis that states that passability judgment will differ based on the judgment type. This is perhaps due to the same reason as the one stated above. Since lateral judgments did not afford natural interaction as compared to the real world lateral judgments, they did not significantly differ from frontal judgments overall. This is also evident from the similarity in the critical ratios reported separately for different conditions in the two parts of the full investigation. This is an important finding as it infers that users can comprehend that compressing their body may not be fully afforded in IVEs and thus quickly adapt to their embodied body schema in conjunction to the virtual object. Interestingly this happens even in the absence of accurate haptic sensations like inertia and weight. This is similar to what was found by Wagman et al. where they examined the adaptation of critical boundaries as a result of holding objects with different lengths, weight and inertial properties [91]. The authors demonstrated that the perception of affordance was mediated by haptic cues only. Our work takes this one step further by examining how mismatched visual and haptic cues affect affordance perception especially for a use case where such cases are more probable.

5.6 Conclusion and Future Work

In a two part study, this work investigates how the perception of affordance changes when interacting with virtual handheld objects in an immersive environment. We explore this phenomenon by means of frontal and lateral passability judgments while holding virtual bars of different sizes with both hands in front of the body in the presence or absence of gender matched body-scaled self-avatars. This is the first work that compares and contrasts frontal and lateral passability judgements for a PPVO system in virtual reality.

The findings suggest that users are able to conform to the visual dimensions of the bar to make judgments even though the haptic feedback associated with is mismatched. Moreover, the presence of a self-avatar significantly benefits affordance judgment accuracy in both frontal and lateral passability. Being able to determine how much of the body mediates the widest frontal dimension of the PPVO is essential in making accurate judgments and having a scaled virtual body helps in achieving that. A virtual self-representation also helps in perceiving what is afforded with a virtual body as compared to the real world. For example, individuals rely more on their compressed body depth as compressed body depth rather than their static body depth when making lateral judgements [10] but this is not afforded in an computer mediated environment. However, users are able to quickly adapt to this change in the presence of self-avatars and conform their judgments accordingly. In the absence of self-avatars, users rely more on the object's dimensions for frontal passability, especially when the object width is close to their shoulder width. For lateral judgments, participants are more inaccurate as compared to frontal judgments in the absence of self-avatars but it is unclear if they make judgments based on their compressed body depth or if they simply do not pay attention to how much of their real body would intersect with the door since it is not visible. More work is needed to further investigate this phenomenon.

This work can provide several guidelines when it comes to developing highly realistic VR simulations. Firstly, for simulations that require users to perceive affordances in relation to their full body, it would be beneficial to have a self-avatar that resembles the user as much as possible. The self-avatar aids in comprehending what is afforded by a virtual body in an IVE and in accurately perceiving the size of objects. Secondly, since lateral judgments do not currently afford natural interaction in IVEs due to the lack of body compression, using a less conservative collision detection algorithm might be beneficial in scenarios where the learned behavior needs to accurately transfer to the real world. For scenarios where the goal is entertainment and not training, having slightly larger apertures to pass through might benefit the overall experience.

A limitation of our work is that we did not restrict where the virtual object was held in front of the body for lateral judgments. This makes it difficult to determine that exact cause of overestimation in the absence of self-avatars. Future work will aim to probe this effect further to assess the exact cause and to come up with strategies to better a more immersive experience. Evaluating how much visually inspecting a virtual object factors into accurately perceiving affordance can also prove to be a fruitful direction for future work.

Chapter 6

Dynamic Affordance Perception Mediated by Self-Avatars

Although the use of self-avatars in commercial VR simulations is becoming increasingly popular, generating a body-scaled self-avatar is still a daunting and tedious task that often requires taking several bodily measurements of the participant. This may not be feasible in every situation and might also make some individuals uncomfortable. Due to this reason several simulations provide generic avatars that do not match the user's eye height or limb proportions. The self-avatar might be shorter, taller, narrower, or could even be a different entity entirely like robots. The embodied body schema in such scenarios is moderated by the anthropometric properties of the self-avatar and may involve getting accustomed to different dynamic properties like changes in eye height, walking speed, vertical jump, ability to dodge, delayed responses, reach, etc. These factors might influence the perception of the scale of the virtual environment and in turn affect affordance perception.

Wraga et al. investigated the effect of eye height manipulation on affordance perception and object dimensions estimations [95]. The authors reported that both affordance perception and estimated height of objects were correspondingly biased by the change in eye height. In another study, Leyrer et al. studied the effect of eye height scaling and self-avatars on egocentric and exocentric estimates in a IVE [49]. The authors reported that eye height had a significant effect on both types of estimates but the presence of a self-avatars only affected egocentric distance estimates. In a separate study, Leyrer et al. proposed changes to the eye height in an virtual world as a solution to reduce underestimations on an individual basis [50]. More recently, Ebrahimi et al. evaluated the effect of avatar fidelity on near field depth perception [13]. The results suggested that the accuracy of judgments increased with the visual fidelity of the self-avatars.

Previous works have also investigated dynamic affordance perception as a function of self-motion or other navigation techniques with the help of simulated environments. Buekers et al. examined the regulation of self-motion with respect to oscillating doors and found that the participants walked at their preferred walking speed up tot he final phase and then regulated their walking to pass the door successfully [7]. Grechkin et al. evaluated dynamic affordances using joystick based navigation and natural walking in a CAVE and a HMD based IVE [27]. The authors reported that both independent variables affected performance with HMD+Walking significantly increasing the difficulty of the task. The use of IVEs to train and study pedestrian and bicyclist traffic crossing behavior has been of popular interests as IVEs provide a safe way to study such behavior across all age groups [8, 80, 72]. However, the focus of these works has been on understanding the development of dynamic affordance perception across different age groups and training children on safe road crossing behavior.

Although the effect of altered eye height and self-avatars on distance and depth estimates has been studied, the effect of altered anthropometric properties of self-avatars and eye height scaling on affordance judgments, especially dynamic affordances, has remained relatively unexplored. Since seeing a synchronous self-representation affects estimates [64, 13, 49], self-avatars may also affect dynamic affordance perception. Seeing a synchronous altered self-avatar may influence action-scaling of the embodied body schema with effects such as extended reach, higher vertical jump, better vantage point, etc. in turn affecting dynamic affordance perception. Therefore, it is important to study the effect of embodying mismatched self-avatars on dynamic affordance judgments in VR. To this end, in this study, we investigate how simply scaling the eye height and doing so in the presence of self-avatars with altered anthropometric properties affects dynamic gap perception in a traffic crossing scenario. We also explore if having a shorter or taller self-avatar induces an expectation of walking slower or faster as a result of shorter or longer stride length even through no alterations will be made to the walking speed in the virtual world.

6.1 Experiment Design

To investigate the effect of altered eye height and anthropometric properties of self-avatars on dynamic passability judgments, we utilized two between-subjects independent variables; presence and absence of self-avatars and eye height. This gives us a 3X2 factorial design with six conditions, see Table 6.1 below.

Table 6.1: Study 3 Design

Eye Height / Self-Avatars	**Shorter**	**Matched**	**Taller**
No-Avatar	S-NA	M-NA	T-NA
Avatar	S-A	M-A	T-A

The experiments were conducted in the same physical room as the previous study but utilized a cityscape environment with virtual cars moving in one direction as oncoming traffic. Each trial involved making dynamic passability judgments and performing the action to cross a one way virtual street, see Figure 6.1. The oncoming traffic consisted of sedans that appeared out of a parking garage one after the other at 1, 2, 3, 4, 5 or 6 seconds intervals presented in random order without repetition. Once all 6 time intervals had been used, the intervals repeated in a random order until the user crossed the street. The trial gaps were reset on the completion of a trial. Participants performed a total of 60 trials.

6.1.1 System Description

Similar to the previous study, the IVE was rendered on a HTC Vive Pro HMD with a diagonal FOV of 110°. HTC Vive Pro controllers and trackers were used to fully track the body-scaled self-avatar in real time. The same desktop computer with an Intel i7 quad-core processor and an NVIDIA GeForce GTX 1080 dedicated graphics card was used to render the simulation at over 90 frames per second.

6.1.2 Virtual Environment

The virtual world consisted of a long one way street with buildings on either side of it and was developed using the Unity 3D game engine. The buildings consisted of small housing complexes,

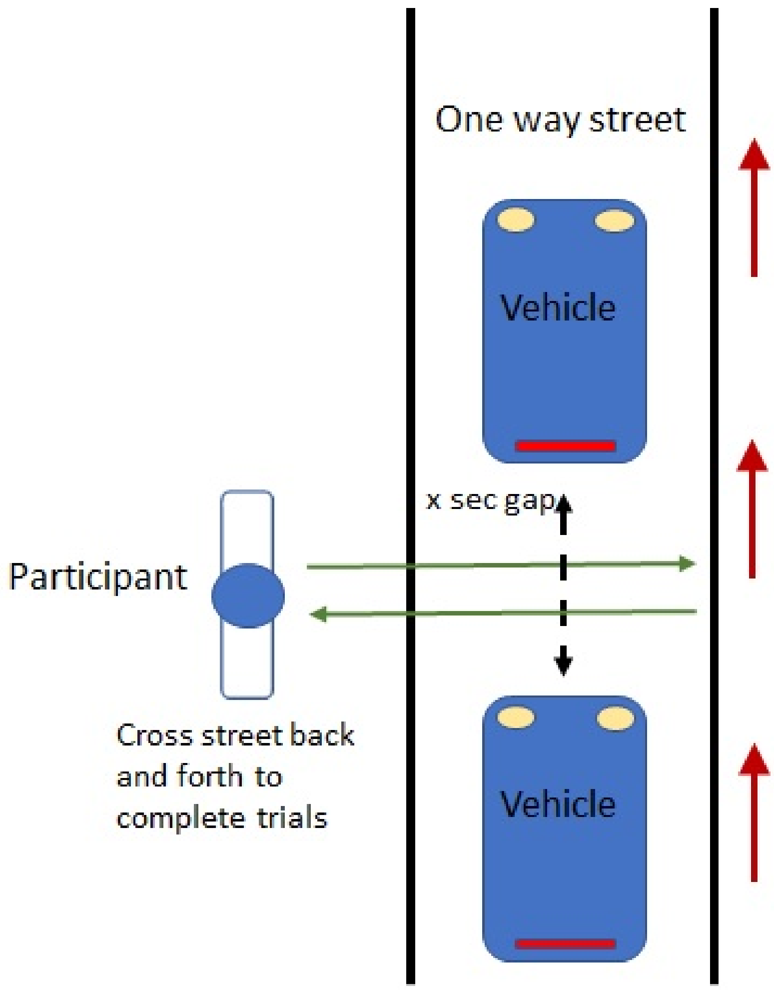

Figure 6.1: Top down view diagram of the experiment setup with one way oncoming traffic

Figure 6.2: Virtual environment with one way street and buildings

stores, hotel and a parking garage. The street consisted of a bus stop on one side of the street and a flower pot on the opposite side. These objects marked the bounds in which the participants was instructed to perform the task of crossing the street back and forth. The street was 3 meters wide from side walk to sidewalk and had about 1-2 meters of walking space on the side before they hit the virtual objects described above (see Figure 6.2). The oncoming traffic consisted of yellow or blue sedan cars 1.9 meters in width that spawned randomly out of the parking garage at one end of the street, driving autonomously to the other end at a constant speed of 25 mile per hour and disappeared at the other end of the street, see Figure 6.3. The vehicles were introduced at random time intervals as described above.

The simulation tracked the lower back HTC Vive tracker worn by the participant to monitor the participant's walking behavior through out the simulation. A set of box colliders were placed on either side of the street to signal the simulation when the participant had crossed the street for a particular trial.

Figure 6.3: One way oncoming traffic

6.1.3 Avatar Generation and Tracking

In the no avatar conditions, the height of the camera rig in Unity was simply raised or lowered by 20% based on the eye height of the participant. For the avatar conditions, techniques used to generate, calibrate and track the gender-matched body-scaled self-avatar from the previous studies were employed. The system was further extended to uniformly scale the self-avatar to be shorter or taller depending on the condition assigned. The self-avatar was first scaled to the participant's actual body dimensions and then scaled up or down uniformly on all three axes by 20% depending on the condition. This was necessary to maintain realistic limb proportions of the self-avatar and match them to the participant's real limb proportions. Participants in the shorter or taller conditions only saw the scaled avatars to avoid any priming effects.

The targets for the IK solver were adjusted proportionately based on the scaled self-avatar such that stretching the limbs in real life would result in stretching of the limbs of the self-avatars as well. This was achieved simply by adjusting the local positions of the targets while parented to the tracker objects themselves.

6.1.4 Participants

Simulation studies investigating the power of Hierarchical Linear Models suggest that the number of participants and the number of trials are both important for establishing sufficient power [32]. To determine the Level 2 sample size (number of participants), a power analysis using Cohen's medium effect size of .3 [9] and an alpha of .05 revealed that a sample size of 42 participants will produce power of .9. Thus, a total of 42 participants were recruited from Clemson University graduate and undergraduate programs, 7 for each of the six conditions. The average age of participants was 18.5 years and the distribution comprised of 29 females and 13 males. All participants had normal or corrected-to-normal vision and could perceive stereo.

6.1.5 Procedure

The procedure for the experiment was follows;

1. The participant started by filling out the demographics survey.

2. Once the survey was completed, the experimenter recorded the participant's visual acuity, stereo acuity, interpupillary distance, height and shoulder width.

3. The participant was then assigned to one of 6 conditions randomly and briefed on the task they were going to perform and the devices they were going to use.

4. The participant was then asked to put on the HTC Vive pro trackers and asked to stand in the center of the room so that the experimenter could record positions on his/her body for scaling the eye height.

5. Once the positions were recorded, the participants was asked to stand in a T-pose and the trackers were calibrated using a custom script that assigned the right Steam VR device index to the trackers in Unity based on their positioning on the body.

6. Next, the rig was moved up or down depending on whether the participant was in the shorter, matched or taller condition. If the participant was assigned to a self-avatar condition, a gender matched self-avatar was also generated based on the recorded positions and scaled appropriately.

7. Once the avatar was calibrated, the participant performed egocentric pointing and exocentric pointing while standing in front of a mirror as part of the body-ownership phase. Then they went through the cube acclimation task used in the previous experiments.

8. After the body-ownership and the acclimation phases were completed, the participant was placed at the edge of the one way street and was instructed on how to cross the street with on coming traffic. The exact instructions given were "Soon you will see cars coming down the street from your left one after the other and your task is to cross the street back and forth 60 times. Crossing the street one way finishes one trial. The beginning of each trial is marked by the passing of a yellow colored car. You can start thinking about crossing the street once the yellow car passes. When you cross the street and turn around to cross the street for the next trial, you again have to wait for the yellow car to pass. Please do not run, walk at your regular walking speed".

9. The experimenter then initiated the trials by pressing a key on the keyboard and kept track of the trial count as the participant crossed the street back and forth.

10. After the participant completed all the trials, s/he was asked to fill out the iGroup presence questionnaire, a body ownership questionnaire [25] (if assigned to a self-avatar condition) and were asked to rate their perceived walking speed. The question was "What did you think about your walking speed in the virtual world?" and the response was recorded on a Likert's scale with the following choices: "Walked slower than the real world", 2-4, "Walked at the same speed as the real world", 6-8 and "Walked faster than the real world".

6.1.6 Data Collection

For each of the trials that the participant completed the following variables were recorded;

- **Gap sizes**: This is the time interval between the two vehicles that the participant chose to cross the street. We also recorded all the gap sizes that the participant did not choose.
- **Gap Count**: This is a count of all the gaps that a participant saw across all trials.
- **Velocity at crossing**: This is the speed at which the participant crossed the street.

- **Time to spare**: This is time to contact between the participant and the oncoming car measured in seconds.

- **Safety**: Gaps crossed with more than 1.5 seconds to spare were considered as safe. This measure is based on a previous work investigating road crossing in IVEs by Simpson et al. [80]. There were only two instances of collisions with the car across all participants. Thus, the two trials were coded as unsafe.

6.1.7 Research Questions and Hypotheses

The specific research questions we investigated are as follows.

1. Is eye-height scaled information enough to affect action-scaling of embodied body schema?

2. What effect does an altered self-avatar have on the embodied body schema in addition to eye-height?

3. Does having an altered self-avatar change the perceived walking speed in VR?

4. What effect does eye height scaling have on dynamic affordance judgments?

5. How do anthropometric properties of self-avatars affect dynamic judgments of passability?

Based on the questions listed above, we formed the following hypotheses.

H1: Street crossing behavior will differ significantly based on eye height

H2: Participants in the self-avatar conditions will perform safer gap crossing behavior

H3: Participants' perceived walking speed will differ based on the scaled self-avatar

6.1.8 Data Analysis

Due to the repeated measures design of this experiment, variables had considerable nesting within participants. In order to account for variance at the within-participant and between-participant levels, hierarchical linear modeling was used [32]. When using hierarchical linear modeling, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, all continuous predictors were grand-mean centered. Thus, the intercept coefficient of the regression equation represents the predicted outcome when all continuous variables are held at their average.

Further, the dependent variable was a binary yes/no judgment, which created a nonlinear cubic distribution. Raw scores were transformed into a linear distribution using a binary logistic regression [68]. To interpret the effects of continuous variables in a logistic regression, the slope coefficients are converted into odds ratios, which have a multiplicative effect on the outcome variable (i.e., a one-unit increase in the predictor results in the odds of crossing being multiplied by the odds coefficient).

Effect sizes for each fixed effect will presented as the change in R^2 comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect (for more on measuring effect sizes for dichotomous variables, see [89]).

6.2 Results

6.2.1 Preliminary Analysis

To ensure that there was an equal distribution of participant height, age, shoulder width, and presence across levels of each condition, a 2(Avatar vs No Avatar) X 3 (taller, matched, shorter eye height) MANOVA was run. There were no significant differences across levels of each condition for Height (F = .14, p = .98), Age (F = .97, p = .45), Shoulder Width (F = .99, p = .44), and Presence (F = .56, p = .74). A Chi-square test showed that there were no differences in gender distribution across conditions (chi-square = 2.47, p = .78).

6.2.1.1 Body Ownership

We used the recommended Principal Component Analysis (PCA) method to calculate the body ownership scores for participants using the avatar embodiment questionnaire [25]. An ANOVA analysis revealed no significant differences between the avatar conditions (M = .83, SD = .68). The range for the scores was -3 to 3.

6.2.2 Predicting Road Crossing

A binary logistic hierarchical linear model was run to predict the likelihood that participants crossed the road for each presented gap. See Table 6.2 for results of the omnibus F test. Gap Size was the largest predictor of road crossing, accounting for 49% of the variance. As the gap between cars increased by 1 second, the odds of a participant crossing through that gap increased by a multiplicative factor of 35 (B = 3.56, SE B = .13, exp B = 35.06, t = 29.05, p <.001, see Figure 6.4). There were no significant moderators of this effect. Further, the Gap Count was a significant predictor of road crossing. As the Gap Count increased by 1, the odds of crossing that gap increased slightly by a multiplicative factor of 1.01 (B = .012, SE B = .005, exp B = 1.01, t = 7.69, p <.001).

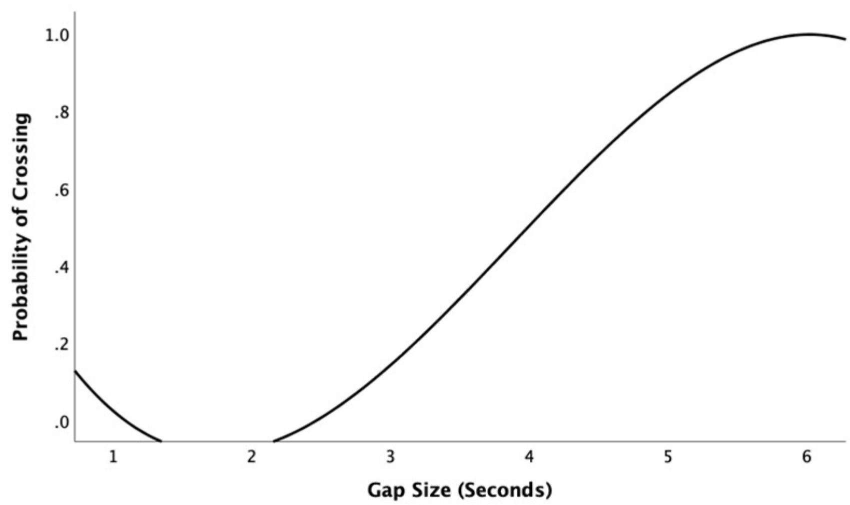

Figure 6.4: Probability of crossing the road as a function of Gap Size

There was not a main effect of Avatar or Eye Height Condition, suggesting that the likelihood of crossing a gap, when holding all other variables at their average, did not differ across these conditions. There were also no significant interactions across these variables.

6.2.3 Predicting Velocity

The dataset was reduced to only include gaps in which participants crossed the road. Using only these crossing trials, we ran a series of models predicting various properties of the crossing action (velocity at crossing, time to spare, and crossing safety).

To assess the effects of Gap Size, Gap Count, Avatar, Eye Height Condition, and Presence

Table 6.2: Omnibus F test results predicting road crossing

Predictor	df1	df2	F	sr^2
Gap Size	1	5367	870.341***	.49
Gap Count	1	5367	59.22***	.01
Avatar	1	47	.178	–
Eye Height Condition	2	47	2.512	–
Presence	1	47	.009	–
Avatar X Eye Height Condition	2	32	.014	–
Avatar X Gap Size	1	5366	.548	–
Eye Height Condition X Gap Size	2	5365	1.258	–
Avatar X Eye Height Condition X Gap Size	2	5360	1.036	–

Note: * denotes p <.05, *** denotes p <.001

Table 6.3: Omnibus F test results predicting velocity (m/s)

Predictor	df1	df2	F	sr^2
Gap Size	1	2449	54.92***	.02
Gap Count	1	2466	9.41*	.004
Avatar	1	36	.35	–
Eye Height Condition	2	36	1.51	–
Presence	1	36	.11	–
Avatar X Eye Height Condition	2	34	.75	–
Avatar X Gap Size	1	2448	12.82***	.02
Eye Height Condition X Gap Size	2	2446	2.18	–
Avatar X Eye Height Condition X Gap Size	2	2443	7.718***	.25

Note: * denotes p <.05, *** denotes p <.001

on participants' Velocity at crossing, a hierarchical linear model was run. See Table 6.3 for the results of the omnibus F test.

There was a main effect of Gap Size, such that for every one second increase in the gap size, velocity decreased by approximately .04 meters per second. In other words, participants walked slightly slower when gap sizes were larger. There was also a main effect of Gap Count, such that for every increase in Gap Count, velocity was estimated to decrease by approximately .0003 meters per second. That is, as participants walked slightly slower as they progressed through the experiment. There were no other significant main effects.

There was a significant interaction between Avatar and Gap Size. For both the Avatar and No Avatar conditions, participants' crossing velocities decreased as Gap Size increased. However, the slope for the Avatar condition was significantly steeper (B = -.05, SE = .01) than the No Avatar condition (B = -.02, SE = .01, t = 3.58, p <.001) see Figure 6.5. In other words, participant's crossing velocities in the Avatar condition decreased at a faster rate as gap size increased compared to the No Avatar condition. This effect was further moderated by Eye Height Condition, and accounted for 25% of the variance.

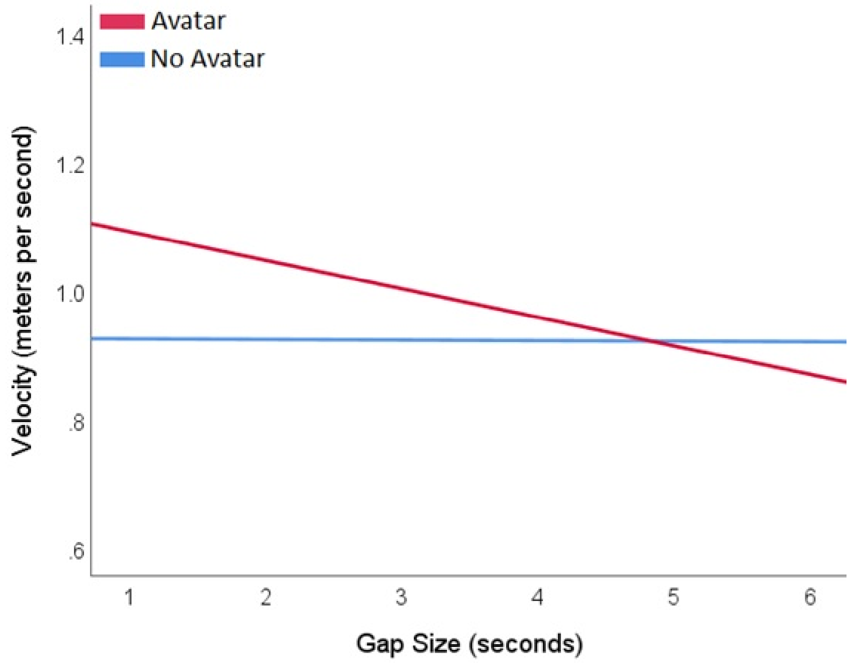

Figure 6.5: Significant interaction between Avatar and Gap size

To assess differences among the different Eye Height Conditions, the file was split by Avatar. For the no avatar condition, participants in the matched eye height condition walked faster as gap size increased (indicated by a positive slope), whereas participants in the shorter and taller eye height conditions walked slower as gap size increased (indicated by a negative slope). The slope for the matched eye height condition was significantly steeper (B = .13, SE = .01) than the slope for the shorter eye height condition (B = .09, SE = .02, t = 2.31, p = .021) and the slope for the taller eye height condition (B = .09, SE = .02, t = 2.4, p = .017), see Figure 6.6A. The slope for the shorter eye height condition was not significantly different than the slope for the taller eye height condition.

For the avatar condition, participants in all Eye Height Conditions walked slower as gap size increased. The slope for the shorter eye height condition was significantly shallower (B = -.02, SE = .02) than the slope for the matched eye height condition (B = -.08, SE = .01, t = -3.27, p = .001 and the taller eye height condition (B = -.07, SE = .02, t = -2.86, p = .004, see Figure 6.6B). This indicates that participants in the Shorter Eye Height condition decreased their walking velocities at a slower rate as the Gap Size increased. The slope for the matched eye height condition was not

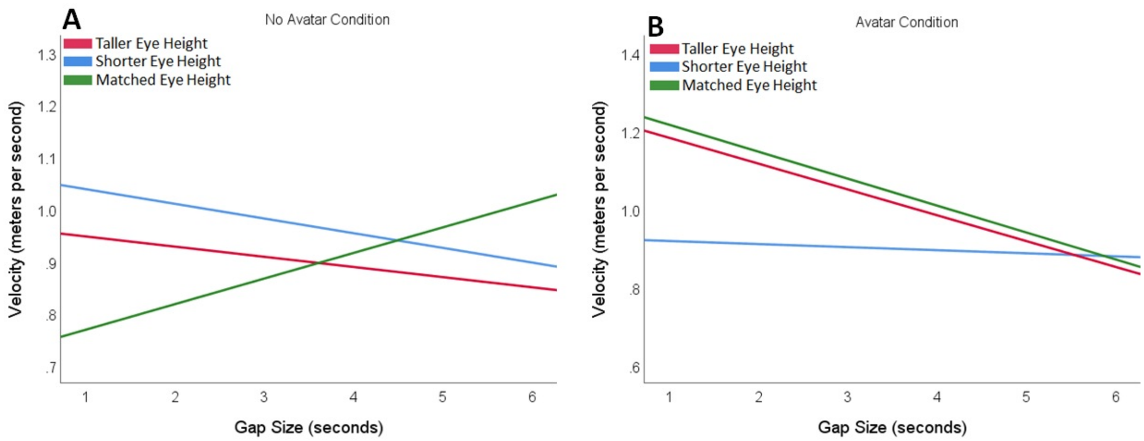

Figure 6.6: A) Interaction between Eye height condition and Gap size for the no avatar condition B) Interaction between Eye Height condition and Gap Size for the Avatar condition

significantly different from the slope for the taller eye height condition. That is, participants in the Matched and Taller Eye Height conditions decreased their walking velocities at a similar rate as the Gap Size increased.

The file was also split by Eye Height Conditions to assess differences between the two Avatar conditions. The slopes of the lines for the avatar and no avatar conditions were not significantly different in the shorter eye height condition. In the matched eye height condition, the slope for the the no avatar condition was significant steeper (B = -.08, SE = .01) than the slope for the avatar condition (B = .01, SE = .02, t = 4.31, p <.001). In the taller eye height condition, the slope for the no avatar condition was also significantly steeper (B = -.07, SE = .01) than the slope for the avatar condition (B = -.03, SE = .01, t = 2.37, p = .018), see Figure 6.7.

6.2.4 Predicting Time to Spare

To assess the effects of Gap Size, Gap Count, Avatar, Eye Height Condition, and Presence on Time to Spare, a hierarchical linear model was run on the data where participants crossed the virtual street (i.e., those trials where they physically walked). See Table 6.4 for the results of the omnibus F test.

There was a main effect of Gap Size, such that for every one second increase in Gap Size, Time to Spare increased by approximately .79 seconds. That is, participants had more time to spare

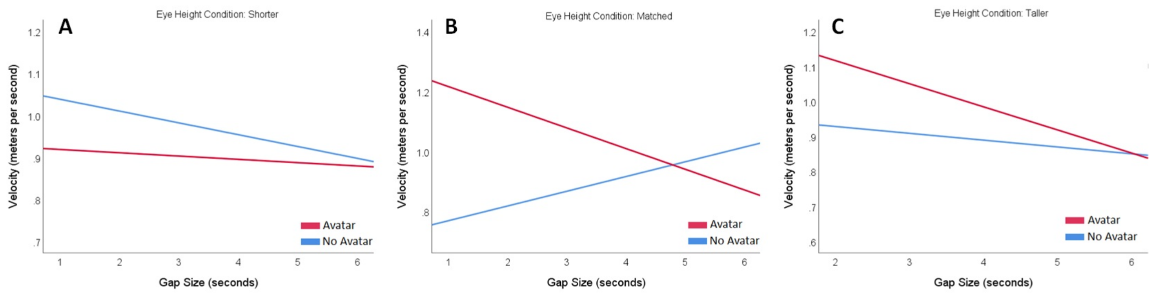

Figure 6.7: A) Interaction between Avatar and Gap Size for the Shorter eye height condition B) Interaction between Avatar and Gap size for the Matched eye height condition C) Interaction between Avatar and Gap size for the Taller eye height condition

Table 6.4: Omnibus F test results predicting time to spare (s)

Predictor	df1	df2	F	sr^2
Gap Size	1	2407	16,238.6***	.85
Gap Count	1	2415	246.44***	.01
Avatar	1	37	<.001	–
Eye Height Condition	2	37	.72	–
Presence	1	37	.06	–
Avatar X Eye Height Condition	2	35	.7	–
Avatar X Gap Size	1	2406	4.95*	.003
Eye Height Condition X Gap Size	2	2404	1.65	–
Avatar X Eye Height Condition X Gap Size	2	2401	.99	–

Note: * denotes p <.05, *** denotes p <.001

for larger gap sizes. This effect accounted for 85% of the variance. There was also an effect of Gap Count. For every increase in Gap Count, Time to Spare was estimated to decrease by approximately .002 seconds, indicated that as participants progressed through the experiment, time to spare values decreased. There were no other significant main effects.

There was an interaction between Gap Size and Avatar. For both the Avatar and No Avatar conditions, Time to Spare increased as Gap Size increased. However, the rate at which Time to Spare increased (i.e., the slopes) differed between the two conditions. The slope for the No Avatar condition was significantly steeper (B = .8, SE = .01) than the slope for the Avatar condition (B = .77, SE = .01, t = 2.22, p = .26, see Figure 6.8). Though this interaction was statistically significant, the effect was trivial, accounting for only .3% of the variance.

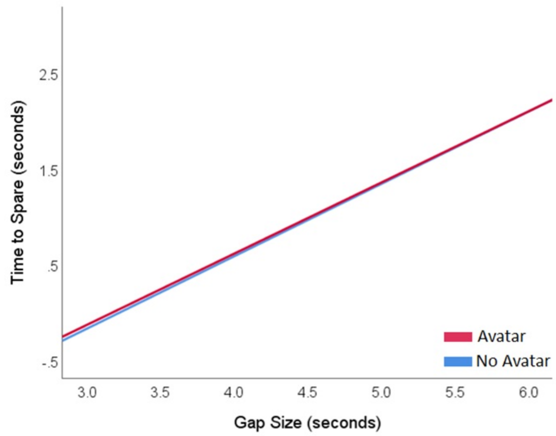

Figure 6.8: Interaction between gap size and avatar for the model predicting time to spare

Table 6.5: Omnibus F test results predicting safe crossing

Predictor	df1	df2	F	sr^2
Gap Size	1	2503	583.744***	.33
Gap Count	1	2503	29.969***	.01
Avatar	1	33	.244	–
Eye Height Condition	2	34	.539	–
Presence	1	33	.004	–
Avatar X Eye Height Condition	2	32	.656	–
Avatar X Gap Size	1	2502	1.34	–
Eye Height Condition X Gap Size	2	2501	2.89	–
Avatar X Eye Height Condition X Gap Size	2	2496	5.921**	.002

Note: * denotes p <.05, *** denotes p <.001

6.2.5 Predicting Crossing Safety

Lastly, we ran a binary logistic hierarchical linear model predicting whether or not the participant's street crossing behaviors were considered safe. All trials with a time to spare of less than 1.5 seconds were marked as unsafe as described in section data collection section. See Table 6.5 for results of the Omnibus F test.

As expected, the size of the gap was the largest predictor of safe crossing (B = 4.81, SE = .20, exp B = 122.96, t = 24.16, p <.001). As the gap size increased by 1 second, the odds of crossing safely increased by a multiplicative factor of 122.96. Further, Gap Count was also a significant predictor (B = -.01, SE = .002, exp B = .98, t = 5.47, p <.001). As Gap Count increased, participants were slightly less likely to cross safely.

There was not a main effect of Avatar or Eye Height Condition, however there was a significant 3-way interaction between Avatar, Eye Height Condition, and Gap Size. While the

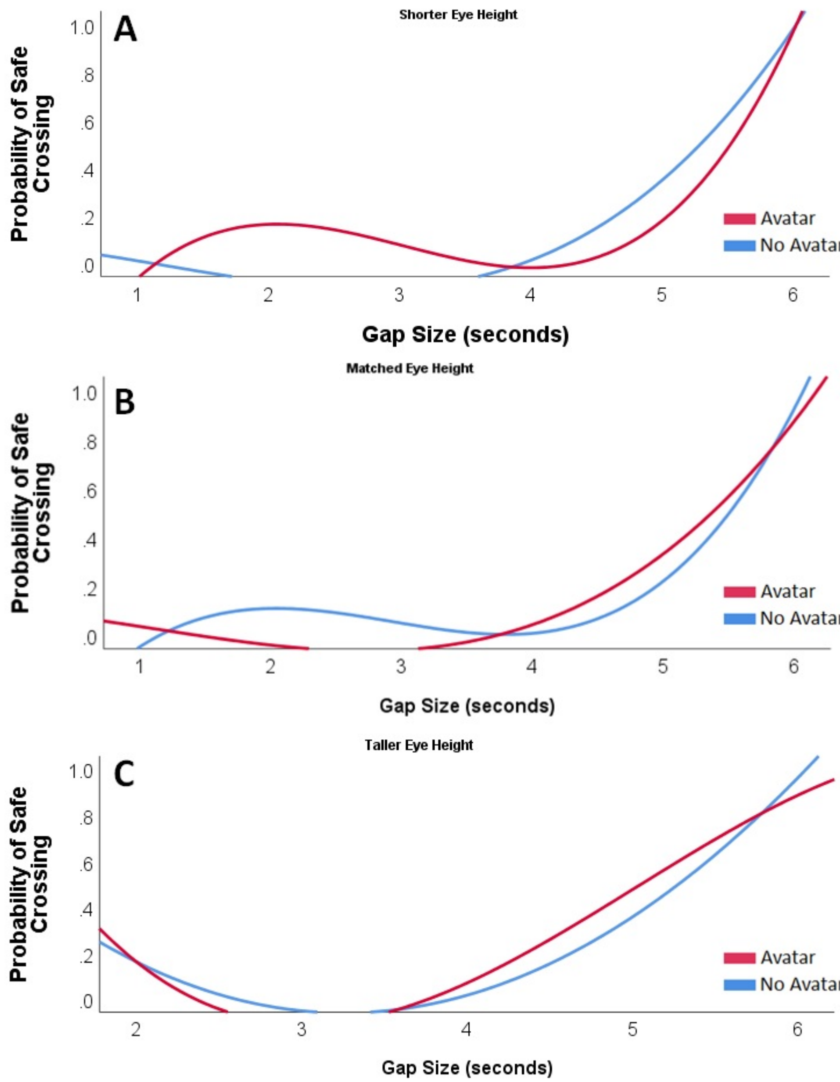

Figure 6.9: A) Graph predicting crossing safety for the shorter eye height condition in the presence and absence of self-avatars B) Graph predicting crossing safety for the matched eye height condition in the presence and absence of self-avatars C) Graph predicting crossing safety for the taller eye height condition in the presence and absence of self-avatars

effect of Gap Size was robust across all conditions, the steepness of the positive slope differed across levels of Avatar and Eye Height Condition. For participants viewing matched eye height, there was not a significant difference in the effect of Gap Size between the Avatar (B = 4.23, SE = .41) and the No Avatar (b = 4.70, SE = .58, p = .41) conditions. For participants viewing shorter eye height, the Avatar condition (B = 6.69, SE = .85) had a marginally steeper slope than the No Avatar condition (B = 4.88, SE = .87, p = .057). For participants viewing taller eye height, the No Avatar condition (B = 6.07, SE = .96) had a significantly steeper slope than the Avatar condition (B = 3.68, SE = .55, p = .002). See Figure 6.9.

6.2.6 Perceived Walking Speed

An ANOVA analysis of the perceived walking speed collected as part of the post experience surveys revealed no significant differences across conditions ($F(5, 36) = 1.61$, $p = .18$).

6.3 Discussion

The analysis revealed that as the gap size and the number of gaps seen (Gap Count) increased, participants became more likely to cross a presented gap. However, there were no main or interaction effects of eye height or self-avatar. This suggests that the participants were accurately perceiving gap sizes regardless of eye height and the presence or absence of self-avatars. This does not support any of our hypotheses but shows that the simulation was effective in eliciting natural crossing behavior. Previous research by Wraga et al. has also demonstrated that scaling of eye height only affects height estimates of objects but not width estimates [95]. Our results suggest that the same applies in dynamic scenarios as well. Another possible reason for the lack of effects related to eye height or self-avatars could be that the gap intervals were too large. Smaller gap sizes, similar to the ones chosen by O'Neal et al. [65] may yield different results.

A similar trend of gap size and gap count was observed for velocity at crossing. Participants crossed the street at a slower speed as the gap size and gap count increased. Furthermore, there was a significant interaction between avatar and gap size. The plotted graph (Figure 6.5) revealed that the difference in crossing velocities was largest for smaller gaps with the self-avatar line being higher but the velocities were almost equivalent for larger gaps. This suggests that participants with self-avatars have a better sense of action requirements for safe crossing when the gaps are small. This supports our second hypothesis. Having a self-avatar may have induced a higher sense of safety in participants for smaller gaps urging faster crossing velocities. This fall in line with previous research suggesting a higher margin of safety in the presence of body based cues [84]. The presence of a self-avatar gave participants a better sense of their limbs as they walked across the street. Being able to determine that they were safely crossing the street without hitting the car with any of their body's extremities, participants probably felt more comfortable slowing down. Grouping conditions based on eye height provided us with more insights into the effects on self-avatars on crossing velocity. The slopes for the shorter eye height conditions did not differ significantly in the presence or absence of self-avatars. However, participants in the no-avatar condition had a higher velocity at crossing for smaller gaps than participants in the self-avatar condition. The slope for the matched condition was steeper with an upward trend in the absence of a self-avatar but the slope for the self-avatar condition shows a downward trend as gap size increased. This suggests two very different trends for participants with and without a self-avatar in the matched conditions. Closely examining the graph shows that the difference was largest for very small gaps but the slopes converge for larger gaps. This could be a result of not having enough data for smaller gaps. Another plausible explanation is that the presence of self-avatars made participants have a higher sense of safety and made them walk faster to avoid getting hit by the traffic. This align with our previous argument. As they completed more trials and got more comfortable with their virtual body, they slowed down eventually converging to velocities similar to the no-avatar condition. Further investigation might be required to fully explore this relation. The slopes for the taller eye height conditions both showed a downward trend with the avatar one being steeper. This support our previous argument about participants reducing their crossing speed faster as a result of being more aware of their body. Participants in the avatar conditions crossed at a higher velocity than the participants with the no-avatar conditions suggesting a safer crossing behavior. This supports our second hypothesis. A similar trend was observed in a study by Leyrer et al. where the authors reported that distance estimates and affordance judgments were affected by the presence of self-avatars [49].

Grouping conditions based on the absence or presence of self-avatars, a significant difference based on eye height was observed. In the no-avatar condition, participants with the matched eye height had a significantly different upward trend as the gap size increased as compared to the shorter and taller eye height. However, the downward slopes of the shorter and taller conditions did not differ significantly. In the avatar conditions, the difference in crossing velocities was largest for smaller gaps with the shorter avatar participants crossing at slower speeds but the velocities were almost equivalent for all conditions for larger gaps. The velocities did not significantly differ at different gaps between the taller and matched eye height condition. Perhaps observing the cars from a vantage point lower than what participants are accustomed to affected the information perceived from the optic flow which negatively influenced regulatory self-motion. This supports our first hypothesis which states that crossing behavior will differ based on eye height.

The analysis of the time to spare variable revealed that participants in the self-avatar conditions had marginally more time to spare as compared to the no-avatar conditions for shorter gaps suggesting that participants in the avatar conditions had more time to spare at the time of crossing. This support our second hypothesis suggesting safer crossing behavior in the presence of self-avatars. Examining the safety of the gaps crossed revealed that the curve for the predicted probability of crossing a gap safely was not different for the matched eye height conditions but were significantly different for the shorter and taller eye height conditions. A steeper slope in graphs predicting the probability of affordances means less variability across trials [18], however in our case it would be beneficial to observe the overall trend of the curve as well. The slope for the avatar condition was steeper for the shorter eye height condition as compared to the no-avatar condition suggesting participants improved their crossing behavior more consistently with an avatar eventually reaching the same level of likely hood for safe crossing behavior as no-avatar. For the taller eye height condition, the slope for the no-avatar condition was steeper but overall the curve for the avatar condition was higher suggesting that participants with a self-avatar had a higher probability of crossing the street safely as compared to no-avatars. This further strengthens the support for our second hypothesis.

The analysis of the perceived walking speed revealed no significant differences. This is probably a result of collecting this variable post experience. This does not support our third hypothesis. Previous research suggests that optic flow generated as a result of body sway and exploring the environment while walking is sufficient to inform the user of the eye height and movement speed [92, 20, 96]. Therefore, the optic flow generated during the street crossing experience was likely enough to inform the user that their walking speed was a one to one match to the real world. Perhaps recording this in the beginning of the experiment right after the participant experienced a shift in eye height and before walking more than a few steps would yield different results. Another reason for this could be that the absence of haptic feedback received from devices used to raise one's eye height in the real world. Since such devices are not required to alter the eye height in VR, individuals do not sense or have to adapt to their altered leg length while walking. Therefore, users did not expect to have an altered walking speed.

6.4 Conclusion and Future work

In this work, we investigate the effect of eye height scaling and self-avatars on perception of dynamic affordances in VR. The study focuses on evaluating how users with mismatched eye height in the presence or absence of altered self-avatars synchronize self-motion to external moving objects to cross a gap. Participants were asked to cross a street with virtual oncoming traffic in the presence or absence of self-avatars. The virtual eye height in the IVE was either 20% shorter, taller or matched the participant's actual eye height. Participants in the avatar conditions were given a self-avatar that was uniformly scaled to match the virtual eye height. The results suggest that the presence of self-avatars results in safer road crossing behavior and helps participants synchronize self-motion to external stimuli quicker than in the absence of self-avatars. The perception of gap size does not seem to be affected by altered eye height or the self-avatar. This study to the best of our knowledge is the first ever to investigate the effect of eye height and scaled synchronous self-avatar on dynamic affordances.

Inferring from the observations and overarching trends, some takeaways for developers and researchers are; 1) VR simulations that involve synchronizing fully body motion to external dynamic stimuli would benefit from using self-avatars in turn improving immersion as having a self-avatar makes participants more aware of their body when trying to avoid hitting moving objects. 2) For simulations that involve perceiving and acting on dynamic affordances, it might be okay to alter the user's eye height as long as the interval between two moving objects is sufficiently large.

A limitation of our work, as mentioned earlier, is that we measured the perceived walking velocity after participants finished all the trials. The optic flow experienced during the experience could have easily provided them with enough information to realize that they were walking at the same speed as the real world. Also, the gaps size chosen might have been too large to see any meaningful differences between conditions. Any future research in this ares should consider using gaps with .5 second differences. A future direction of research following this study would be to evaluate how adding translation gain to the walking speed commensurate to the altered self-avatar would affect these judgments. Being taller or shorter also alters one's stride length in turn altering their walking speed. Investigating such an effect could provide various insights into how to best elicit a more immersive experience when altering action-scaled capabilities.

Chapter 7

Conclusion

This work describes in detail a series of experiments aimed at evaluating affordance perception in contemporary IVEs with and without the presence of self-avatars. We evaluated affordance perception in multiple virtual scenarios in the presence and absence of self-avatars. The self-avatar generation system developed as part of these efforts is capable of scaling the user's eye height, shoulder width, arm length and body depth along the midsection in a matter of seconds. The implementation details of the system have been thoroughly discussed and include techniques to map a self-avatar that is smaller or taller than the user to provide realistic movement behavior for an unencumbered immersive experience. The work also provides details on overlaying a to-scale virtual replica environment onto its real world counterpart with high precision.

In the initial experiments, we investigated how perception for an information rich stimuli differs in VR as compared to the real world. The results suggested that users need to explore more optic flow in VR as compared to the real world to produce the same level of accuracy when making affordance judgments. Restricting the behavior leading upto an affordance judgment revealed that there are significant differences between the real world and VR even with newer display and tracking technology. This aligns with other recent research reporting differences between estimates and judgements in the real and world and VR using contemporary VR devices [6, 11, 41].

This phenomenon was further explored in the presence of a body-scaled self-avatar. The presence of a self-avatar did not seem to significantly affect passability affordance perception through a realistic doorway but proved to be extremely helpful when making passability judgments while interacting with virtual objects. Users performed significantly better when interacting with virtual handheld objects in the presence of self-avatars. The self-avatar helped better perceive the size of the virtual objects especially with absent/mismatched weight and inertial feedback. Moreover, the use of self-avatars helped afford what the user's virtual representation is capable of in the virtual world. For example, the inability to compress one's body against other objects in VR can only be inferred with the help of a self-avatar. Users greatly overestimated passability through doorways while holding virtual objects in the absence of self-avatars.

Self-avatars also aid in regulating self-motion when synchronizing movement with external dynamic stimuli. Upon studying dynamic affordance perception and response, the results revealed that users with self-avatars were able to cross moving gaps with more time to spare as compared to no-avatar. Moreover, user with self-avatars were able to better regulate their walking speed based on the approaching gap size. The experiment also explored the effect of eye height and virtual body size alteration on dynamic affordance perception. The analysis did not reveal any effects suggesting that virtual eye height alteration changes the perception of moving gap size. This align with previous research reporting no changes in the perception of object width as a result of altering eye height [95]. Our work shows that the same is true for dynamic affordances.

Some key takeaways for developers of complex virtual reality applications with environments involving locomotion can be inferred from these works. For VR applications, games, and other immersive training scenarios that require users to maneuver through obstacles, it may be useful to provide more optic flow via inclusion of arbitrary objects and increased travelable distance. This will be especially useful in scenarios where improvements in affordance judgments is desired, such as walking rehabilitation, athletic training for hurdle races, combat training for stealth missions involving maneuvering through pits, etc. When implementing self-avatars, it might be advantageous to gauge the importance of complex joint motions for the interactions afforded in the simulation, especially in situations where one must maneuver through tight spaces in the virtual world. Using tactile feedback from tracking devices like the HTC Vive controllers and verifying the visual angle subtended could help accurately map virtual worlds onto real world counterparts especially for simulations like architectural walkthroughs.

This work can provide several guidelines when it comes to developing VR simulations involving natural object interaction with self-avatars. For simulations that require users to perceive affordances in relation to their full body, it would be beneficial to have a self-avatar that resembles the user as much as possible. Since lateral judgments do not currently afford natural interaction in IVEs due to the lack of body compression, using a less conservative collision detection algorithm might be beneficial in scenarios where the learned behavior needs to accurately transfer to the real world. For scenarios where the goal is entertainment and not training, having slightly larger apertures to pass through might benefit the overall experience. VR simulations that involve synchronizing fully body motion to external dynamic stimuli would could further benefit from using self-avatars in turn improving immersion as having a self-avatar makes participants more aware of their body when trying to avoid hitting moving objects.

Based on the limitations discussed following each of the experiments described in this work, there are several fruitful research directions that can be explored. An intriguing question that lingers is how commodity tracking solutions for self-avatars compare to high precision motion capture systems. Thus, an investigation comparing the effects of using a mocap systems to a system similar to what has been implemented in our work on body-ownership and agency could prove to be a fruitful contribution. Given the benefits of self-avatars in virtual object interaction, exploring how altered self-avatars affect virtual object interaction could help formulate implementation guidelines for simulations that make use of generic self-representations. When studying dynamic affordances, investigating the role of eye height and body proportions on varying acceleration and speed perception can yield new insights about how far the boundaries of VR can be pushed.

Appendices

Appendix A Consent Form

Information about Being in a Research Study
Clemson University

Perception for Action

Description of the Study and Your Part in It
You are invited to participate in a research study conducted by Dr. Chris Pagano, Katie Lucaites, and Hannah Solini. The purpose of this research is to investigate people's perception of their surrounding environment and what actions they can perform in their environment.

Your participation will involve perceiving one or more properties of things, such as whether or not you can reach something, step over something, walk through a gap, step onto and stand on a slope, etc. You may be asked to actually perform some actions, such as reaching to an object, stepping or leaping over markers on the floor, stepping onto a slope and standing on it, etc. Depending on the experimental group to which you are assigned, you may perform the actions yourself or you may operate a remote controlled vehicle through or over obstacles. Also, depending on which experimental condition you are participating in, you may be asked perform all or part of the experiment while wearing a blindfold and/or noise attenuating ear muffs. You will be asked to complete a brief questionnaire to determine your handedness and various dimensions of your body may be measured, such as the lengths of your arms and legs, your height, weight, etc. In some conditions we may record your behaviors in order to better understand the types of behaviors people perform under certain conditions. Depending on which experimental condition you are participating in, recording techniques may include photography, video, or electronic tracking devices and a computer.

It will take you about 45 minutes to participate in this study. Some participants may be asked to return for a second session.

Risks and Discomforts
Participation in this research involves performing everyday behaviors so the risks are minimal. Some participants will be asked to perform behaviors such as stepping, jumping, and/or reaching to various distances. Where appropriate risks will be minimized through procedures such as having participants perform behaviors on a rubber mat instead of on a hard surface and by ensuring that participants are wearing proper footwear and clothing.

Depending on your experimental group, you may be asked to perform the experiment while viewing the room virtually, through a head-mounted display. If so, Viewing the virtual reality display may cause you to experience none/some/all of the following symptoms: dizziness, weakness, nausea, headache, vomiting. These symptoms will go away when the virtual reality display is ended. You may ask to end the display at any time. If you continue to feel badly after the study, please contact Redfern Health Center at 656-2451.

Possible Benefits
There are no known benefits to you that would result from your participation in this research. Information that is obtained in this study may be used scientifically and may be helpful to others.

CLEMSON RESEARCH COMPLIANCE

IRB Number: IRB2014-320
Approved: 6/29/2018
Expiration: 6/28/2019

Incentives
Course/extra credit may be offered in some psychology courses for your participation in this study. You will receive one credit for every 15 minutes of participation. The same course/extra credit is available through a non-research activity that involves the same effort and time investment (please refer to your course instructor for more information). Subjects not receiving course credit will receive $10. For some experimental conditions involving multiple sessions subjects will receive either course credit for each session or payment of $10 per session**.**

Protection of Privacy and Confidentiality
We will do everything we can to protect your privacy and confidentiality. The records of your participation are confidential. The investigator will maintain your information, and this information may be kept on a computer. Your identity will not be revealed in any publication that might result from this study. All de-identified data will be maintained indefinitely and may be used in future research studies. If you do not want the data used in future studies you must notify one of the researchers in writing.

We might be required to share the information we collect from you with the Clemson University Office of Research Compliance and the federal Office for Human Research Protections. If this happens, the information would only be used to find out if we ran this study properly and protected your rights in the study.

Choosing to Be in the Study
Participation in this study is voluntary. You do not have to be in this study. You may choose not to take part and you may choose to stop taking part at any time. You will not be punished in any way if you decide not to be in the study or to stop taking part in the study. If you decide not to take part or to stop taking part in this study, it will not affect your grade in any way.

If you choose to stop taking part in this study, the information you have already provided will be used in a confidential manner.

Contact Information
If you have any questions or concerns about this study or if any problems arise, please contact Chris Pagano at Clemson University at 864-656-4984.

If you have any questions or concerns about your rights in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-0636 or irb@clemson.edu. If you are outside of the Upstate South Carolina area, please use the ORC's toll-free number, 866-297-3071.

Consent

I have read this form and have been allowed to ask any questions I might have. I agree to take part in this study.

Participant's signature: ____________________________________ Date: _________________

Printed name of participant: ________________________________

A copy of this form will be given to you.

CLEMSON
RESEARCH COMPLIANCE

IRB Number: IRB2014-320
Approved: 6/29/2018
Expiration: 6/28/2019

Appendix B Demographics Survey

Passability Judgement Demographics Survey

1.
Gender

Male	Female	Prefer not to say
○	○	○

2.
Age

3.
Before this study, have you ever worn a virtual reality headset? (E.g. HTC Vive, Samsung Gear VR, Google Cardboard)

○ Yes
○ No

4.
If you answered yes to the question above, approximately how many hours have you experienced VR for?

5.
Shoulder Width

6.
Height

7.
Interpupillary Distance (IPD)

8.
Visual Acuity

9.
Stereo Acuity

Appendix C Avatar Embodiment Questionnaire

Condition

- » 1
- » 2
- » 3
- » 4
- » 5
- » 6

Embodiment Questionnaire

I felt as if the virtual body was my body

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

It felt as if the virtual body I saw was someone else

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

It seemed as if I might have more than one body

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

I felt as if the virtual body I saw when looking at myself in the mirror was my own body

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

I felt as if the virtual body I saw when looking at myself in the mirror was another person

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

It felt like I could control the virtual body as if it was my own body

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

The movements of the virtual body were caused by my movements

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

I felt as if the movements of the virtual body were influencing my own movements

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

I felt as if the virtual body was moving by itself

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

It felt as if my (real) body were turning into an ‘avatar’ body

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

I felt like I was wearing different clothes from when I came to the laboratory

Strongly Disagree	Disagree	Somewhat disagree	Neither	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Appendix D Presence Questionnaire

PRESENCE QUESTIONNAIRE
(Witmer & Singer, Vs. 3.0, Nov. 1994)*
Revised by the UQO Cyberpsychology Lab (2004)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

|________|________|________|________|________|________|________|
NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?

|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

6. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|

NOT AT ALL | MODERATELY COMPELLING | VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|

NOT CONSISTENT | MODERATELY CONSISTENT | VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|

NOT COMPELLING | MODERATELY COMPELLING | VERY COMPELLING

11. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL | PRETTY CLOSELY | VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | EXTENSIVELY

13. How involved were you in the virtual environment experience?

|________|________|________|________|________|________|________|
NOT INVOLVED — MILDLY INVOLVED — COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|
NO DELAYS — MODERATE DELAYS — LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

|________|________|________|________|________|________|________|
NOT AT ALL — SLOWLY — LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|
NOT PROFICIENT — REASONABLY PROFICIENT — VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|
NOT AT ALL — INTERFERED SOMEWHAT — PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|
NOT AT ALL — INTERFERED SOMEWHAT — INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|________|________|________|________|________|________|________|
NOT AT ALL — SOMEWHAT — COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED SOUNDS:

20. How much did the auditory aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

21. How well could you identify sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

22. How well could you localize sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED HAPTIC (SENSE OF TOUCH):

23. How well could you actively survey or search the virtual environment using touch?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

24. How well could you move or manipulate objects in the virtual environment?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT EXTENSIVELY

Last version : March 2013

*Original version : Witmer, B.G. & Singer. M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, *7*(3), 225-240. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence*, *14*(3) 298-312.

Appendix E iGroup Presence Questionnaire

iGroup Presence Questionnaire (IPQ)

1. In the computer generated world I had a sense of "being there".
   7 point Likert's scale
   Anchors: Not at all – Very much

2. Somehow I felt that the virtual world surrounded me.
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

3. I felt like I was just perceiving pictures.
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

4. I did not feel present in the virtual space.
   7 point Likert's scale
   Anchors: Did not feel – Felt present

5. I had a sense of acting in the virtual space, rather than operating something from outside.
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

6. I felt present in the virtual space.
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

7. How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?
   7 point Likert's scale
   Anchors: Extremely aware – Moderately aware – Not aware at all

8. I was not aware of my real environment
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

9. I still paid attention to the real environment
   7 point Likert's scale
   Anchors: Fully disagree – Fully Agree

10. I was completely captivated by the virtual world.
    7 point Likert's scale
    Anchors: Fully disagree – Fully Agree

11. How real did the virtual world seem to you?
    7 point Likert's scale
    Anchors: Completely real – Not real at all

12. How much did your experience in the virtual environment seem consistent with your real world experience?
    7 point Likert's scale
    Anchors: Not consistent – Moderately consistent – Very consistent

13. How real did the virtual world seem to you?
    7 point Likert's scale
    Anchors: About as real as an imagined world – Indistinguishable from the real world

14. The virtual world seemed more realistic than the real world.
    7 point Likert's scale
    Anchors: Fully disagree – Fully Agree

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