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Comparative Evaluation of Viewing and Self-Representation on Passability Affordances to a Realistic Sliding Doorway in Real and Immersive Virtual Environments

Ayush Bhargava*
Key Lime Interactive

Hannah Solini†
Department of Psychology
Clemson University

Kathryn Lucaites‡
Department of Psychology
Clemson University

Jeffrey W. Bertrand§
Clemson University Center
for Workforce Development

Andrew Robb¶
School of Computing
Clemson University

Christopher C. Pagano‖
Department of Psychology
Clemson University

Sabarish V. Babu**
School of Computing
Clemson University

Abstract

As Virtual Reality (VR) devices become more accessible, a multitude of VR applications engage users in highly immersive virtual environments that feature realistic graphics, real-life scenarios, and self-avatars. Many of these simulations require users to make spontaneous affordance judgments such as stepping over obstacles, passing through gaps, etc. which are shown to be affected by the nature of our self-representation in the virtual world. As the technology for creating self-avatars becomes more widely available, it is important to explore how various affordance judgments are affected by the presence of self-avatars. In this work, we investigate the effects of body-scaled self-avatars on the affordance of passability in a natural setting. We implemented a gender-matched body-scaled self-avatar using HTC Vive trackers and evaluated how passability judgments for a sliding doorway in VR, with and without an avatar, compared to the real world judgments. The results suggest that passability judgments are more conservative in VR as compared to the real world. However, the presence of a self-avatar does not significantly affect passability judgments made in VR. This does not align with previous findings which show that having a self-avatar improves judgments and estimates.

Keywords: Self-Avatars, Affordance, Passability, Virtual Reality

Index Terms: Human-centered computing—Empirical studies in HCI—; Human-centered computing—Interaction design—

1 Introduction

In the last decade, Virtual Reality (VR) has undergone several 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, new VR applications are being developed for a wide range of fields like entertainment, health care, education, etc. 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 [4], rock climbing [26], etc. A combination of these factors have brought forth a new era of virtual realism ready to be exploited by researchers and businesses alike.

*e-mail: ayush.bhargava92@gmail.com
†e-mail: hsolini@g.clemson.edu
‡e-mail: klucait@g.clemson.edu
§e-mail: jbertra@clemson.edu
¶e-mail: arobb@clemson.edu
‖e-mail: cpagano@clemson.edu
**e-mail: sbabu@clemson.edu

To successfully recreate scenarios like the ones described above without breaking immersion, it is necessary that the perceived spatial information is veridical [31]. This information is relayed via size, distance and depth estimations made by individuals 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 [19, 32, 40, 48]. However, past studies made use of VR devices that offered much lower fidelity of rendering, field of view and resolution as compared to current devices, and this could have been the cause of the inaccuracies reported in [7, 25, 41, 50]. It is thus important to revisit these results when newer and more promising commercial products are introduced.

When investigating how well VR systems support the perception of visual space, it is important to recognize that properties such as size, distance, height, slant, etc., are not typically perceived as such, but rather people are perceiving what actions they can perform within a given environment [19, 34, 53, 54]. 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 large enough to be walked through, or if a raised surface is low enough to be stepped onto. The relationship thus formed between the environmental properties and the perceiver is referred to as affordances [17], and it results in the perception of actions that can be performed with the primary objects when one needs to interact with the environment [13, 19, 54]. The relevant metrics for describing affordances are intrinsic, they pertain to the action capabilities of the perceiver. For example, the affordances of step-on-able and sit-on-able depend on the height of a surface relative to the length of the legs and their parts [34, 53]. Similarly, the affordance of passability depends on the width of the gap relative to the width of the actor [13, 54]. Given that the affordances of environmental surfaces are perceived relative to one's action capabilities, it is possible that the inclusion of an appropriately scaled self-avatar in a virtual scene will enhance the perception of affordances [29].

A high fidelity self-avatar is one of the most challenging aspects of making VR simulations immersive. Self-avatars have been reported to greatly affect a user's decision making, behavior and presence in IVEs [9, 10, 30, 39]. The most popular way of tracking humans in real time for self-representations has been through the use of optical tracking system like VICON; These systems usually cost thousands of dollars, need a large area to setup, and are cumbersome. These factors, coupled with the complex scripts required to map real-life motion to virtual characters in real time, make self-avatars non-trivial and somewhat inaccessible. However, recent advancement in tracking hardware and software has made it possible to track users in real time using sensors like accelerometers, gyroscopes, and lighthouse trackers like the HTC Vive trackers. Many companies,

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like Perception Neuron[1] and Synertial[2], have thus developed real time 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 avatar using inverse kinematics (IK) based on positional data received from trackers like the HTC trackers. As a result, VR applications have seen an increase in the use of self-avatars for entertainment and research alike.

A large amount of previous research has examined both direct estimates of depth, size, and scale, as well as affordance judgments in virtual reality and how they compare to the real world [42]. However, few have looked at passability judgments [15, 40, 54]. Passability is one of the most common affordances utilized every day while crossing hallways, walking through doorways, maneuvering between crowds, etc. Passability judgments are also common in VR simulations, such as when passing through portals and doorways, or when moving between obstacles. Therefore, in this work, we empirically examine how newer displays and tracking technologies affects affordance judgments in an IVE with and without a body-scaled self-avatar as compared to the real world by means of passability judgments. To the best of our knowledge, ours is the only work that investigates the effects of a body-scaled self-avatar, especially shoulder width scaled, on aperture passability judgments.

In the experiment, we asked participants to judge the passability of a sliding doorway apparatus in real life and in a to-scale virtual replica of the same apparatus with and without a gender-matched body-scaled self-avatar. 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.

2 Related Work

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 size of objects and affordances in Immersive Virtual Environments (IVEs), or more commonly known as Virtual Reality (VR), has been studied by researchers previously and they have been reported as comparable or underestimated based on the task presented and the technology used to present the virtual environment [15, 16, 45, 48]. For example, Lin et al. [32] had participants blind walk to a target and found no differences in estimated distances between the real and virtual environments. However, Stefanucci et al. [48] had participants 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 also been attributed to the underlying hardware and the software used to render the IVE [25, 50]. In a recent study, Buck et al. evaluated distance estimation in older HMDs and newer Oculus HMDs and found that newer commercial HMDs helped reduce distance underestimations but it was not fully mitigated [7]. A similar observation was reported by Kelly et al. and Peer et al. evaluating distance estimations in contemporary HMDs [24, 37]. Therefore, in light of recent advancements in the hardware and software domains, it is timely to reevaluate the effects of contemporary VR displays and rendering technology on the perception of objects and affordances in virtual worlds.

A large body of research has examined affordances and how they are influenced 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 [22]. 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 [54]. Similarly, action-scaling refers to considering one's dynamic properties, i.e., the properties of one's own movements, to determine action possibilities [43]. The size of different parts of the body have been reported to affect action capabilities. Stefanucci et al. [46] 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.

The use of self-avatars in VR makes it easier to manipulate the size and perception of one's own body. Given that embodying a synchronously tracked self-avatar even for short periods of time can generate high levels of body-ownership and that affordances are considered a useful perceptual measure of size in virtual worlds [15], 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 the presence of self-avatars can affect size and distance estimations as well as affordance judgments [2, 33, 36, 39]. 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 [2]. They found that participants who embodied a child's body significantly overestimated object sizes. In another study, Jun et al. had participants embody virtual feet in an IVE that were either much smaller or much larger than their own foot and had them judge if they could step across gaps of varying widths [23]. They found that participants with smaller foot widths had a reduced ability to step over gaps and participants with larger foot widths 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 [39]. Even though the self-avatar used in this study 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 and found that having a self-avatar significantly affected the threshold at which participants changed their judgments [31]. The authors reported the use of optical tracking system to track a full-body self-avatar which is expensive and cumbersome to implement. More recently, Buck et al. reported the use of IK based self-avatars with scaled height and arm length in a study that investigated the effects of social dynamics on affordances in collaborative virtual environments [6]. Buche et al. investigated the effect of changing virtual body size viewed from a third person perspective on affordance judgments and found that the passability through doors was significantly affected by the reduction in avatar size [5]. Another study investigating passability affordance by Bhargava et al. reported no differences between judgments made in the real world and VR [3]. However, they allowed participants to walk closer to the door and did not regulate the distance from which judgments were made. They reported that even though the judgments were comparable, participants in the VR condition needed to walk closer to the door to be more certain of their judgments.

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

[1]https://neuronmocap.com/

[2]https://www.synertial.com/mocapsuit

[3]https://www.ikinema.com/

[4]http://www.root-motion.com/final-ik.html

al. compared passability using 2 poles in the real world and in VR but found no significant differences between the two conditions [15]. In the work by Priyankova et al., participants embodied an underweight or overweight avatar while judging aperture passability [39]. 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 [30]. 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].

2.1 Our Contribution

In this contribution, we compared passability judgments 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 from a specific distance. We follow a methodology similar to Warren et al.'s real world experiment, where participants walk a certain distance before making a judgment [54], for both the real world and VR. For the VR condition, we 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. The setup uses HTC Vive devices to track eight points on 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 for a realistic doorway in VR in the presence of a body-scaled head and limb tracked self-avatar. Previous works have often used poles to evaluate affordances [30, 40, 54], however it has been noted that maintaining realism between the real world and VR stimuli improves the perception of the scale of the environment [21]. We also provide extensive details on the calibration technique used to map the virtual replica of the experiment setup exactly onto the real world and the self-avatar generation system.

3 Experiment Setup

3.1 Study Design

Our goal is 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 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.

3.1.1 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

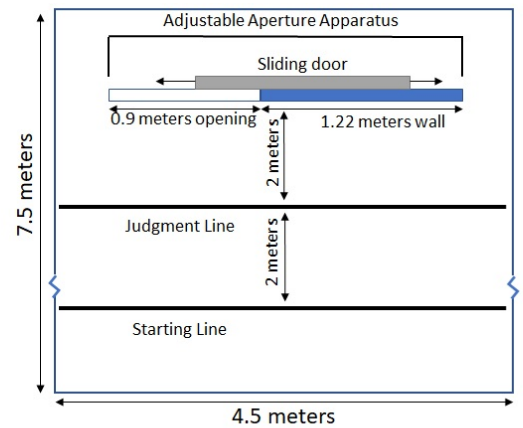

Figure 1: Experiment room setup with the sliding doorway aperture

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[5] 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 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.

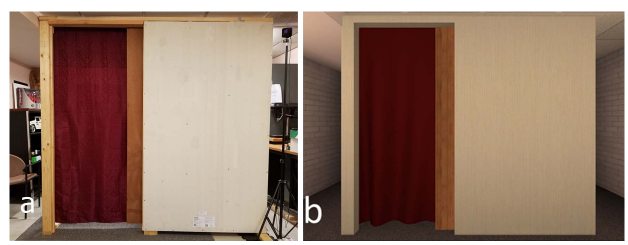

Figure 2: Figure shows a particular aperture width in the real world (a) and the virtual world (b)

To precisely map the virtual room onto the real world environment, we started by manually aligning the camera rig in the Unity scene to the virtual room that was imported. Once a satisfactory result was achieved (determined by walking around the room), we recorded the position and orientation of one of the base stations as reported by the simulation and used those as reference values for recalibrating the room if needed later on. To further fine-tune and verify the overlap of the virtual room onto the real room, we used two methods in the order they are described below:

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

[5]https://unity3d.com/

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*
   To verify the visual angle subtended between the real and virtual doorway apertures, 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. The results were visually accurate in most cases. In case the apertures were slightly off visually but the tactile feedback was accurate, priority was given to adjustments based on visual matching. This was done as participants were told to make judgments based on visual perception and were never allowed to touch or go through the door.

Every time adjustments were made to the scene during the steps described above, the position and orientation of the base station recorded earlier was updated with the latest simulation reported values. After this process was completed, a custom script periodically checked for misalignment based on an euclidean distance calculated between the reported and recorded position of the base station in 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 disturbed during the experiment.

3.1.2 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 3.

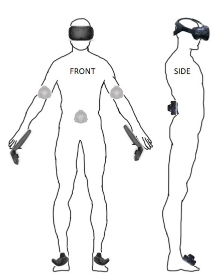

Figure 3: HTC Vive HMD, controller and tracker placement on participant. Grayed out trackers were placed on the lower back and just above the elbows on the back of the arm of the participant.

The basic avatar for each gender was generated using the Unity Multipurpose Avatar (UMA)[6] 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 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.

3.1.3 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 [7] 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 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

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

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

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.

3.2 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 [20]. To determine the Level 2 sample size (number of participants), a power analysis using Cohen's medium effect size of .3 [8] 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 Clemson 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 nested-ness 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 [51]. 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.

3.3 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[8] and recorded the results. If the participant was going to experience one of the VR conditions, then their Interpupillary Distance (IPD) and Stereo Acuity[9] was recorded. The HMD's IPD was set to the recorded IPD using the knob provided. Since, no such adjustments was necessary for the real world, the IPD and stereo acuity were not measured for the real world participants. 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.

3.3.1 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).

3.3.2 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 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 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 are 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.

3.3.3 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, 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, 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

[8]http://www.allaboutvision.com/eye-test/snellen-chart.pdf
[9]https://www.bernell.com/product/SOM150/Depth-Perception-Tests

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.

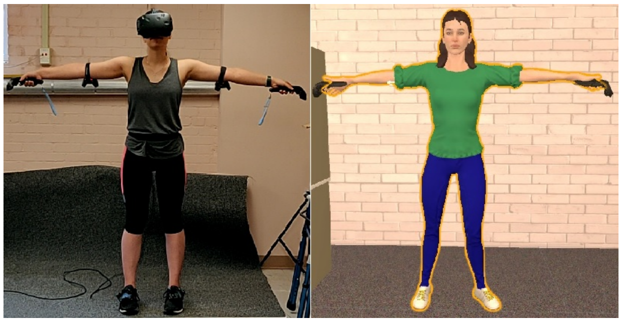

Figure 4: T-pose made by participants for tracker calibration and avatar generation.

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 [18]. 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 [44]. 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.

3.4 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.

3.5 Research Questions and Hypotheses

Recent investigations with newer HMDs have reported differences in behavior in the real world and VR to achieve comparable judgments [3] and differences in the estimates of distance in VR [7, 24, 37]. However, the introduction of self produced optic flow via walking in IVEs has been shown to improve estimations [44]. Therefore, we asked the research question how do passability judgments after walking a fixed distance differ between the real world and IVEs. Moreover, the use of self-avatars has been shown to improve these estimates and judgments [28, 29, 31]. Therefore, we wanted to explore how the presence of a body-scaled self-avatar affects 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 significantly better in the avatar condition as compared to the no-avatar condition.

4 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 [20], 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 [38], 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).

4.1 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 Demographics

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. A one-way ANOVA revealed no significant differences in height across the three conditions, F(2,51) = 1.226, *p* = .302. All participants had normal or corrected to normal vision and all participants in the VR conditions could perceive stereo.

4.3 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 1 shows results from the model predicting judgments of passability (participant responses of "yes").

Table 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).

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 [49]. As shown in Figure 5, perceived critical ratios in the VR conditions were .99 for the no-avatar condition and 1.02 for the avatar condition. However, the perceived critical ratio was .9 for participants in the RW condition.

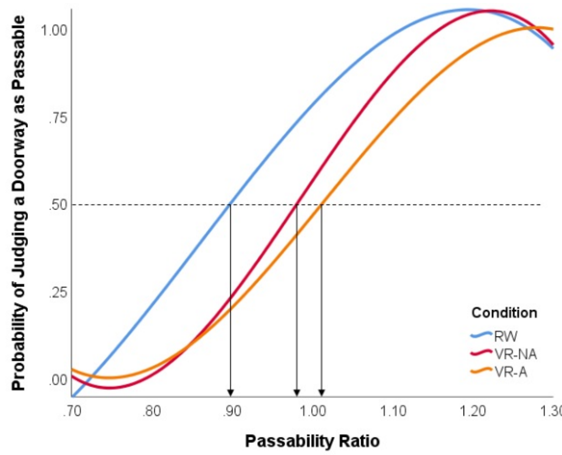

Figure 5: Probabilities of making a passable judgment plotted against the passability ratio for each condition.

4.4 Embodiment Score

Using the embodiment questionnaire, we calculated the subscore for the "Ownership" factor [18], M = 1.81, SD = 2.42. Participants show a medium to high level of embodiment.

5 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. [15], who found no differences in aperture passability judgments between RW and VR-NA conditions. Aperture passability judgments in [15] 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 [44], 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 improve for participants in the avatar condition as compared to the no-avatar condition. This contradicts the results reported by Lin et al. [30]. 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. [9], 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. [15] asked 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. It has been previously noted that maintaining realism between the real world and VR helps improve estimations [21]. Therefore, the sliding door might have acted as a frame of reference and provided more optic flow when making judgments. 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 [13, 14, 27, 35]. 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 recent study by Favela et al. reported 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 [11]. Wagman et al. observed a critical ratios of less than 1 when they asked participants to make passability judgments while holding rods that were wider than their shoulder width [52]. 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 online 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 them. Therefore, judgments made on the basis of scrunched shoulders could have resulted in a threshold of .9. Moreover, Franchak et al. noted that researchers have used varying methods to measure critical ratios in the past, some have measured it to be the upper or lower limit of performance and some as the cutoff point marking success on some proportion of trials [12]. They state that "although the cutoff method locates the affordance threshold between upper and lower limits, the performance criterion is arbitrary". Therefore, it is possible that our critical points were different due to the operational definition for calculating them. We define critical ratios as the point in the graph where probability of saying yes is .5. A comparison of IPDs across conditions could have also helped to explain this result, however the IPDs for the real world participants were not recorded as mentioned in the procedure section. This can thus be considered a limitation of our work.

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 [1]. A similar trend was observed by Stefanucci et al., where participants were more careful of their judgments when they could see bodily cues [47].

6 Conclusion and Future Work

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.

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. This is a limitation of our work and 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.

REFERENCES

[1] F. Argelaguet, L. Hoyet, M. Trico, and A. Lécuyer. The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *Virtual Reality (VR), 2016 IEEE*, pp. 3–10. IEEE, 2016.

[2] D. Banakou, R. Groten, and M. Slater. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, 110(31):12846–12851, 2013.

[3] A. Bhargava, K. M. Lucaites, L. S. Hartman, H. Solini, J. W. Bertrand, A. C. Robb, C. C. Pagano, and S. V. Babu. Towards revisiting passability judgments in real and immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 513–514. IEEE, 2018.

[4] F. Bruno, A. Lagudi, L. Barbieri, M. Muzzupappa, M. Cozza, A. Cozza, and R. Peluso. A vr system for the exploitation of underwater archaeological sites. In *Computational Intelligence for Multimedia Understanding (IWCIM), 2016 International Workshop on*, pp. 1–5. IEEE, 2016.

[5] C. Buche and N. Le Bigot. Revam: a virtual reality application for inducing body size perception modifications. In *2018 International Conference on Cyberworlds (CW)*, pp. 229–236. IEEE, 2018.

[6] L. E. Buck, J. J. Rieser, G. Narasimham, and B. Bodenheimer. Interpersonal affordances and social dynamics in collaborative immersive virtual environments: Passing together through apertures. *IEEE transactions on visualization and computer graphics*, 25(5):2123–2133, 2019.

[7] L. E. Buck, M. K. Young, and B. Bodenheimer. A comparison of distance estimation in hmd-based virtual environments with different hmd-based conditions. *ACM Transactions on Applied Perception (TAP)*, 15(3):21, 2018.

[8] P. Cohen, S. G. West, and L. S. Aiken. *Applied multiple regression/correlation analysis for the behavioral sciences*. Psychology Press, 2014.

[9] S. H. Creem-Regehr, J. K. Stefanucci, and W. B. Thompson. Perceiving absolute scale in virtual environments: How theory and application have mutually informed the role of body-based perception. In *Psychology of Learning and Motivation*, vol. 62, pp. 195–224. Elsevier, 2015.

[10] E. Ebrahimi, A. Robb, L. S. Hartman, C. C. Pagano, and S. V. Babu. Effects of anthropomorphic fidelity of self-avatars on reach boundary estimation in immersive virtual environments. In *Proceedings of the 15th ACM Symposium on Applied Perception*, p. 2. ACM, 2018.

[11] L. H. Favela, M. A. Riley, K. Shockley, and A. Chemero. Perceptually equivalent judgments made visually and via haptic sensory-substitution devices. *Ecological Psychology*, 30(4):326–345, 2018.

[12] J. Franchak and K. Adolph. Affordances as probabilistic functions: Implications for development, perception, and decisions for action. *Ecological Psychology*, 26(1-2):109–124, 2014.

[13] J. M. Franchak and K. E. Adolph. Gut estimates: Pregnant women adapt to changing possibilities for squeezing through doorways. *Attention, Perception, & Psychophysics*, 76(2):460–472, 2014.

[14] J. M. Franchak and F. A. Somoano. Rate of recalibration to changing affordances for squeezing through doorways reveals the role of feedback. *Experimental brain research*, 236(6):1699–1711, 2018.

[15] M. Geuss, J. Stefanucci, S. Creem-Regehr, and W. B. Thompson. Can i pass?: using affordances to measure perceived size in virtual environments. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, pp. 61–64. ACM, 2010.

[16] M. N. Geuss, J. K. Stefanucci, S. H. Creem-Regehr, W. B. Thompson, and B. J. Mohler. Effect of display technology on perceived scale of space. *Human factors*, 57(7):1235–1247, 2015.

[17] J. Gibson. The ecological approach to visual perception. *Dallas: Houghtom Mifflin*, 1979.

[18] M. G.-F. Gonzalez-Franco and T. C. Peck. Avatar embodiment. towards a standardized questionnaire. *Frontiers in Robotics and AI*, 5:74, 2018.

[19] T. Y. Grechkin, T. D. Nguyen, J. M. Plumert, J. F. Cremer, and J. K. Kearney. How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM Transactions on Applied Perception (TAP)*, 7(4):26, 2010.

[20] D. A. Hofmann. An overview of the logic and rationale of hierarchical linear models. *Journal of management*, 23(6):723–744, 1997.

[21] V. Interrante, B. Ries, and L. Anderson. Distance perception in immersive virtual environments, revisited. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 3–10. IEEE, 2006.

[22] S. Ishak, K. E. Adolph, and G. C. Lin. Perceiving affordances for fitting through apertures. *Journal of Experimental Psychology: Human Perception and Performance*, 34(6):1501, 2008.

[23] E. Jun, J. K. Stefanucci, S. H. Creem-Regehr, M. N. Geuss, and W. B. Thompson. Big foot: Using the size of a virtual foot to scale gap width. *ACM Transactions on Applied Perception (TAP)*, 12(4):16, 2015.

[24] J. W. Kelly, L. A. Cherep, and Z. D. Siegel. Perceived space in the htc vive. *ACM Transactions on Applied Perception (TAP)*, 15(1):2, 2017.

[25] R. V. Kenyon, M. Phenany, D. Sandin, and T. Defanti. Accommodation and size-constancy of virtual objects. *Annals of biomedical engineering*, 36(2):342–348, 2008.

[26] F. Kosmalla, A. Zenner, M. Speicher, F. Daiber, N. Herbig, and A. Krüger. Exploring rock climbing in mixed reality environments. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 1787–1793. ACM, 2017.

[27] J.-C. Lepecq, L. Bringoux, J.-M. Pergandi, T. Coyle, and D. Mestre. Afforded actions as a behavioral assessment of physical presence in virtual environments. *Virtual reality*, 13(3):141–151, 2009.

[28] M. Leyrer, S. A. Linkenauger, H. H. Bülthoff, U. Kloos, and B. Mohler. The influence of eye height and avatars on egocentric distance estimates in immersive virtual environments. In *Proceedings of the ACM SIGGRAPH symposium on applied perception in graphics and visualization*, pp. 67–74. ACM, 2011.

[29] Q. Lin, J. Rieser, and B. Bodenheimer. Stepping over and ducking under: The influence of an avatar on locomotion in an hmd-based immersive virtual environment. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 7–10. ACM, 2012.

[30] Q. Lin, J. Rieser, and B. Bodenheimer. Affordance judgments in hmd-based virtual environments: Stepping over a pole and stepping off a ledge. *ACM Transactions on Applied Perception (TAP)*, 12(2):6, 2015.

[31] Q. Lin, J. J. Rieser, and B. Bodenheimer. Stepping off a ledge in an hmd-based immersive virtual environment. In *Proceedings of the ACM Symposium on applied perception*, pp. 107–110. ACM, 2013.

[32] Q. Lin, X. Xie, A. Erdemir, G. Narasimham, T. P. McNamara, J. Rieser, and B. Bodenheimer. Egocentric distance perception in real and hmd-based virtual environments: the effect of limited scanning method. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, pp. 75–82. ACM, 2011.

[33] S. A. Linkenauger, M. Leyrer, H. H. Bülthoff, and B. J. Mohler. Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PloS one*, 8(7):e68594, 2013.

[34] L. S. Mark. Eyeheight-scaled information about affordances: A study of sitting and stair climbing. *Journal of experimental psychology: human perception and performance*, 13(3):361, 1987.

[35] D. R. Mestre, C. Louison, and F. Ferlay. The contribution of a virtual self and vibrotactile feedback to walking through virtual apertures. In *International Conference on Human-Computer Interaction*, pp. 222–232. Springer, 2016.

[36] B. J. Mohler, S. H. Creem-Regehr, W. B. Thompson, and H. H. Bülthoff. The effect of viewing a self-avatar on distance judgments in an hmd-based virtual environment. *Presence: Teleoperators and Virtual Environments*, 19(3):230–242, 2010.

[37] A. Peer and K. Ponto. Evaluating perceived distance measures in room-scale spaces using consumer-grade head mounted displays. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 83–86. IEEE, 2017.

[38] C.-Y. J. Peng, K. L. Lee, and G. M. Ingersoll. An introduction to logistic regression analysis and reporting. *The journal of educational research*, 96(1):3–14, 2002.

[39] I. V. Piryankova, H. Y. Wong, S. A. Linkenauger, C. Stinson, M. R. Longo, H. H. Bülthoff, and B. J. Mohler. Owning an overweight or underweight body: distinguishing the physical, experienced and virtual body. *PLoS One*, 9(8):e103428, 2014.

[40] G. Pointon, C. Thompson, S. Creem-Regehr, J. Stefanucci, M. Joshi,

R. Paris, and B. Bodenheimer. Judging action capabilities in augmented reality. In *Proceedings of the 15th ACM Symposium on Applied Perception*, p. 6. ACM, 2018.

[41] E. D. Ragan, D. A. Bowman, R. Kopper, C. Stinson, S. Scerbo, and R. P. McMahan. Effects of field of view and visual complexity on virtual reality training effectiveness for a visual scanning task. *IEEE transactions on visualization and computer graphics*, 21(7):794–807, 2015.

[42] R. S. Renner, B. M. Velichkovsky, and J. R. Helmert. The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2):23, 2013.

[43] S. Runeson and G. Frykholm. Kinematic specification of dynamics as an informational basis for person-and-action perception: expectation, gender recognition, and deceptive intention. *Journal of experimental psychology: general*, 112(4):585, 1983.

[44] Z. D. Siegel and J. W. Kelly. Walking through a virtual environment improves perceived size within and beyond the walked space. *Attention, Perception, & Psychophysics*, 79(1):39–44, 2017.

[45] J. K. Stefanucci, S. H. Creem-Regehr, W. B. Thompson, D. A. Lessard, and M. N. Geuss. Evaluating the accuracy of size perception on screen-based displays: Displayed objects appear smaller than real objects. *Journal of Experimental Psychology: Applied*, 21(3):215, 2015.

[46] J. K. Stefanucci and M. N. Geuss. Big people, little world: The body influences size perception. *Perception*, 38(12):1782–1795, 2009.

[47] J. K. Stefanucci and M. N. Geuss. Duck! scaling the height of a horizontal barrier to body height. *Attention, Perception, & Psychophysics*, 72(5):1338–1349, 2010.

[48] J. K. Stefanucci, D. A. Lessard, M. N. Geuss, S. H. Creem-Regehr, and W. B. Thompson. Evaluating the accuracy of size perception in real and virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 79–82. ACM, 2012.

[49] S. S. Stevens. *Psychophysics: Introduction to its perceptual, neural and social prospects*. Routledge, 2017.

[50] W. B. Thompson, P. Willemsen, A. A. Gooch, S. H. Creem-Regehr, J. M. Loomis, and A. C. Beall. Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence: Teleoperators & Virtual Environments*, 13(5):560–571, 2004.

[51] A. Tom, T. A. S. R. J. Bosker, and R. J. Bosker. *Multilevel analysis: an introduction to basic and advanced multilevel modeling*. Sage, 1999.

[52] J. B. Wagman and K. R. Taylor. Perceiving affordances for aperture crossing for the person-plus-object system. *Ecological Psychology*, 17(2):105–130, 2005.

[53] W. H. Warren. Perceiving affordances: Visual guidance of stair climbing. *Journal of experimental psychology: Human perception and performance*, 10(5):683, 1984.

[54] W. H. Warren Jr and S. Whang. Visual guidance of walking through apertures: body-scaled information for affordances. *Journal of experimental psychology: human perception and performance*, 13(3):371, 1987.