This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

Did I Hit the Door? Effects of Self-Avatars and Calibration in a Person-Plus-Virtual-Object System on Perceived Frontal Passability in VR

Ayush Bhargava, *Key Lime Interactive,* Roshan Venkatakrishnan, *Clemson University,* Rohith Venkatakrishnan, *Clemson University,* Hannah Solini, *Clemson University,* Kathryn Lucaites, *Clemson University,* Andrew C. Robb, *Clemson University,* Christopher C. Pagano, *Clemson University,* and Sabarish V. Babu, *Clemson University*

Abstract—The availability of new and improved display, tracking and input devices for Virtual Reality experiences has facilitated the use of partial and full body self-avatars in interaction with virtual objects in the environment. However, scaling the avatar to match the user's body dimensions remains to be a cumbersome process. Moreover, the effect of body-scaled self-avatars on size perception of virtual handheld objects and related action capabilities has been relatively unexplored. To this end, we present an empirical evaluation investigating the effect of the presence or absence of body-scaled self-avatars and visuo-motor calibration on frontal passability affordance judgments when interacting with virtual handheld objects. The self-avatar's dimensions were scaled to match the participant's eyeheight, arms length, shoulder width and body depth along the mid section. The results indicate that the presence of body-scaled self-avatars produce more realistic judgments of passability and aid the calibration process when interacting with virtual objects. Also, participants rely on the visual size of virtual objects to make judgments even though the kinesthetic and proprioceptive feedback of the object is missing or mismatched.

Index Terms—Virtual Reality, Self-Avatars, Virtual Objects, Affordance Perception, Passability.

1 Introduction

Recent advancements in display and tracking technology have made Virtual Reality (VR) increasingly popular in homes and at work. As a result, several commodity devices are being utilized to recreate unique virtual experiences like skydiving, combat training, underwater exploration and axe throwing. One of the most common interactions that immersive virtual environments (IVE) afford is object manipulation. Users are often allowed to grab and manipulate virtual objects when performing actions like shooting, throwing and carrying. This is usually facilitated with the use of controllers that provide 6 degrees of freedom (DoF) tracking and several DoF for interaction using buttons, joysticks 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 [1], [2], [3].

Holding and carrying objects in the real world creates a person-plus-object (PPO) system which has been shown to affect the perception of affordances in the surrounding environment [4], [5]. Originally coined by J.J. Gibson, affordances are a relationship between properties of an object and the capabilities of a user that determine what actions can be enacted on the object [6]. For instance, chairs afford sitting on and gaps afford crossing. Therefore, we expect the virtual object system formed as a result of carrying virtual objects to change the action capabilities of the user within the IVE. Affordance judgments in IVEs have also been previously reported to be affected by the size of the self-representation [7], [8]. However, to the best of our knowledge, the combined effect of virtual object interaction and self-representation on affordance perception (aperture passability in particular) in VR has not been investigated.

Furthermore, the perceived kinesthetic and proprioceptive properties of handheld virtual objects (e.g., sensing what the object feels like, how its positioned or held, how it moves when force is applied, etc.) in IVE interactions lack the associated weight and inertial feedback as compared to real objects, which has been shown to affect action capabilities in the real world as well [2], [4]. Any such feedback associated with virtual objects is provided by the device being used for the interaction, which may produce a mismatch between the expected and the perceived kinesthetic and proprioceptive properties. Previous literature also suggests the use of calibration to better incorporate tools into our body schema [3], [5], [9]. However, this direction of virtual object interaction and calibrating to them has remained unexplored. This is particularly intriguing as understanding how users account for this mismatch or absence of information to make aordance judgments in VR may have significant implications on how interactions are

- *Dr. A. Bhargava works as an XR User Experience Researcher for Key Lime Interactive in Brooklyn, NY and can be contacted via email (ayush.bhargava92@gmail.com).*
- *R. Venkatakrishnan, R. Venkatakrishnan, Dr. A.C. Robb, Dr. S.V. Babu - School of Computing, Clemson University*
- *H. Solini, K. Lucaites, Dr. C.C. Pagano - Department of Psychology, Clemson University*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

facilitated in IVEs. A relevant example would be the use of VR for training the construction workforce or distribution center workers who are often tasked with maneuvering heavy objects on a daily basis. Inaccurate perceptuo-motor calibration (act of adapting limb movement in response to perceived stimuli for better outcomes) to such stimuli during VR training could result in harmful accidents in the real world.

Previous research has shown that we rely on an internal representation of our body, referred to as "body schema", for perception and motor control [10], [11]. The body schema is fluid and is perceived continuously on-line or (re)calibrated as the dispositions of the limbs and its attachments change [2], [3], [12]. The same mechanism underlie both the perception of hand-held/attached objects and the perceptions of the body itself [3]. Furthermore, previous works also suggest that self-avatars promote an embodied body schema that is influenced by the visual properties of the self-avatar and any alteration made to it, in turn affecting the perceived action capabilities when interacting in IVEs (i.e. reachability and depth perception) [13], [14]. The use of self-avatars is becoming increasingly popular in VR as recent advancements have made tracking technology more affordable with motion capture suits and commodity tracking solutions that cost a fraction of some high-end tracking systems like Vicon. In addition, several software products now provide inverse kinematics (IK) tracking solutions for joint based animations out of the box. This combined with the affordability of low-cost hardware has given rise to a new wave of VR simulations capable of generating human-like self-avatars in a matter of minutes. However, previous literature suggests that the presence of self-avatars affects the perception of the spatial properties of the environment, the objects in the IVE, and the affordance judgments associated with them [7], [13], [15], [16], [17], [18], [19]. Self-avatars have also been shown to affect object interaction tasks [20] and cognitive load in VR [21].

An interesting facet with respect to self-avatars in IVEs is that individuals may 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 may simply collide with virtual objects that they may perceive as being avoided (especially in the absence of haptic feedback), may view collision events as intersecting meshes, or may be provided with some visuo-auditory information indicating collision with another virtual object. This is unlike the real world where people often try to wiggle or squeeze through openings especially while carrying objects, and may use their innate sense of malleability or adaptability in successfully passing through apertures that they may extend into VR experiences [22], [23]. This inability to squeeze through may result in greater collisions with openings when carrying virtual objects in the presence or absence of embodied self-avatars. This could further complicate VR training procedures for maneuvering heavy objects.

Thus, this work potentially extends this notion that users' body schema is not only malleable in the presence of self-avatars, but also during virtual object interaction in IVEs. The virtual objects may be integrated into the body schema (just like tools) forming a person-plus-virtual-object (PPVO) system, and have a corresponding effect on the perceived action capabilities in VR. Based on previous research [3], [13], [14], visuo-motor calibration, the act of improving one's accuracy and precision to a perceptual stimuli with repeated feedback, may further enhance the integration of the PPVO system into the body schema. We then posit that the presence of the self-avatar may moderate this effect in altering the perceived affordance in pre and post calibration in IVEs. Therefore, it is essential to study how users behave when perceiving affordances while carrying objects of different sizes in IVEs with or without a self-avatar, and to understand how repeated experience calibrates or attunes the perceived affordances.

Although the effect of self-avatars on perception and object interaction has been studied previously, the combined effect of the use of self-avatars with virtual handheld objects on affordance judgments has been relatively unexplored. To this effect, in a novel empirical evaluation we investigated how a person-plus-virtual-object (PPVO) system, with or without a full body self-avatar, affects frontal passability judgments in VR. We further investigated how the effects of calibration to virtually wielded objects in virtual reality (PPVO) and receiving feedback affected users' passability judgements from pre-test (before calibration) to post-test (after calibration) session. In the process, we instructed participants to interact with virtual objects of different sizes using both hands and to judge if they can pass through apertures of different sizes while holding the virtual object.

2 Related Work

2.1 Affordance Perception

The differences between the perception of an individual's surrounding environment in the real world and an IVE has been extensively studied with the aim of providing veridical experiences in virtual worlds. The vetting process of such investigations either involves comparing estimations made in IVEs against true measurement [24], [25] or comparing affordance judgments made for similar stimuli in the real world and the IVE [19], [26], [27]. Affordances refer to the action capabilities of the perceiver in the surrounding environment based on his/her own intrinsic units [28]. For example, grasping an object if it is within reach and fits the size of the hand, leaping over a gap between two surfaces based on stride length, and climbing a step if it is not too high to step on. Affordances have been suggested as a more reliable way to compare perception of spatial properties in IVEs to the real-world as they allow users to perceive the environment in terms of their own ability to act rather than explicit units (such as inches or centimeters), and are considered more task relevant [26]. When systems are designed properly, affordances are perceived directly, without the need for cognitive deliberations or internal mental representations [28], [29], [30], [31]. This approach has been adopted by several others to investigate how various affordances in virtual worlds compare to the real world [32].

One of the most common affordances that we encounter everyday is passability through openings like doors, hallways, obstacles and crowds [33]. Warren and Whang analyzed how small and large participants walked through different sized apertures under static and dynamic condi-

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

tions [34]. They reported that participants use their widest frontal dimension, i.e. shoulder width in this case, to make judgments and need the critical ratio (a ratio between the opening and the widest frontal dimension at which the opening is perceived as passable 50% of the time) to be greater than 1 to pass through. They explained that this ratio was expected and can be considered realistic as our bodies sway from side to side when we walk and need a margin of safety to pass through openings without hitting them. Franchak et al. studied passability with pregnant women and adults wearing pregnancy packs and 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 [35].

Such scenarios are very popular in VR simulations and are often presented in the form of portals, puzzle doors, crawl spaces, hurdles and sliding doors [33]. Therefore, the affordance of passing through openings and apertures is a popular area of investigation in the VR perception research community. Geuss et al. compared passability judgments made for an opening between two poles in the real world and a virtual replica of the environment and found them to be similar [26]. Bhargava et al. recently studied passability perception to a sliding doorway aperture with newer display devices but allowed participants to walk closer to the opening before making a judgment to investigate behavioral differences [27]. Although both works found the judgments to be comparable, Bhargava et al. found that participants needed to walk closer to the door in VR to attain the same level of judgment accuracy as the real world.

Lin et al. investigated the affordance of stepping over or ducking under a pole in the real world and in an IVE and found the thresholds to be different between the two conditions in the absence of self-avatars [8]. More recently, Buck et al. compared the action of passing through apertures in a collaborative setting while embodying avatars [18]. 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 VR.

2.2 Affordance Perception with Objects

It has been previously established by Wagman et al. that handheld objects form a person-plus-object (PPO) system that affects affordance judgments in the real world and these judgments are influenced by the dynamic touch properties like inertia and weight even when the object is not in view [4]. The study evaluated how passability was influenced when wielding objects with different weights and widths that could not be seen, compared to when objects of different widths could be seen but not felt. The results suggest that individuals are sensitive to the affordance in either condition, without any significant differences, and the object is treated as an extension of the body. However, they reported a critical passability ratio of less than 1 in both conditions. Stefanucci et al. also studied the impact of one's own body on the perception of size in the surrounding environment [36]. The authors compared size estimations for an aperture made by broad and narrow shouldered participants. They reported that broad shouldered participants estimated the aperture width to be smaller as compared to the narrow shouldered participants. They also reported that just holding one's arms out wider than the shoulders affected the perception of size. Petrucci et al. evaluated the accuracy of passability for firefighters through different obstacles and reported a general lack of awareness of their personal protective equipment [22]. The largest error reported was with passing under or over obstacles because of the oxygen tank on their backs. This was perhaps because of the tank not being in view at the time of judgment.

Previous research has also demonstrated that outcome feedback can help calibrate the use of tools and further incorporate them into the body schema [3], [13], [14]. Day et al. investigated the use of perceptuo-motor calibration in the context of a near field reaching task while augmenting participant reach. Their results suggested that calibration occurred corresponding to the tool's dimensions. In another study by Hackney et al., the authors evaluated passability through openings of different sizes while holding onto an adjustable plastic tray [5]. Participants were asked to pass through or go around the opening presented. The authors reported that while crossing the opening, participants adjusted their judgments to the PPO system with the adjustable tray. The critical ratio reported in their experiment was over 1.2. Put in simple terms, participants were more likely to pass through the opening when it was 1.2 times wider than their widest frontal dimension when holding a tray. With respect to the firefighter study reported above, the authors also reported that years of experience (more calibration to the protective equipment while maneuvering) had a positive effect on the judgment error.

2.3 Virtual Object Perception

The studies mentioned above were completed in the real world but the perception of object size in IVEs seems to be dissimilar as compared to the real world [25], [37]. Stefanucci et al. had participants judge if they can grasp an object by fitting their hand through an opening in the real world and in an IVE viewed on a desktop monitor [25]. The authors reported that the size of objects seems to be underestimated in virtual environments as compared to the real world. In another experiment, Stefanucci et al. repeated the same comparison but with a large screen stereoscopic display and found similar results but the use of stereo vision reduced the underestimation [37]. Recently, Lougiakis et al. investigated the effect of virtual hand representation on interactions [38]. In their experiment, participants interacted with virtual cubes while embodying an abstract sphere, the 3D virtual controllers or human hands. The authors reported that the sphere had the worst performance and the hand had the highest level of ownership.

It is also important to note that the kinesthetic and proprioceptive sensations associated with objects are often absent and mismatched when interacting with virtual objects in IVEs as interaction is facilitated by gestures or devices rather than actual objects. Since previous literature suggests that we rely on kinesthetic and proprioceptive information like weight and inertia to incorporate objects or tools into our body schema [2], [4], their absence or mismatch may produce other unknown effects affecting affordance perception. However, this possibility and the effects of calibration to virtual objects remains unexplored.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

2.4 Self-Avatars

Recent investigations of affordance have seen a steady rise in the use of self-avatars due to the advancements in technology as described earlier. It has been reported that the presence of self-avatars affects the perception of the surrounding environment and the objects in it. Banakou et al. studied the effect of embodying a child avatar versus an adult avatar of the same height and observed that object sizes were overestimated by individuals who embodied a child avatar [15]. Investigations have also looked at 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 [39]. The authors had participants perform block pattern tasks in the real world and different versions of a virtual environment. They reported that visually faithful self-avatars had little effect on object interaction and cognitive task performance. However, 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 [21]. The authors evaluated the presence of self-avatars and the ability to rotate hands on the tasks listed above. The results suggested that participants performed significantly better with self-avatars, 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 [20]. The authors reported that participants performed tasks more quickly and accurately when they had animated self-avatars.

2.5 Affordance Perception with Self-Avatars

In a study by Priyankova et al., participants embodied static avatars that were either underweight or overweight and this manipulation had a significant effect on affordance judgments of passability [7]. Jun et al. manipulated the sizes of virtual feet and found that this affected participants judgements of whether they could step over a gap [40]. In a study by Linkenauger et al., participants were made to embody different sized virtual hands and this altered their estimated sizes of virtual objects in a direction consistent with the rescaling [41]. In the study by Lin et al. mentioned above, the use of self-avatars significantly reduced the difference in thresholds for judgments involving stepping over or ducking under poles [8]. In a separate study, Lin et al. further reported that embodying self-avatars that were 15% taller than the actual height of the participant shifted these thresholds [16]. They also showed that the use of self-avatars affects the threshold for stepping off a ledge in VR [42]. Recently, Bhargava et al. investigated how the affordance of passability from a fixed viewing distance differed between the real world and VR with or without a body-scaled self-avatar [19]. The self-avatar matched the participant's eye-height, arm length and shoulder width. Judgments in both VR conditions were different from those made in the real world, however the presence of a body-scaled self-avatar did not make a significant difference in VR.

Although the effects of self-avatars has been studied previously, the effect of virtual object interaction in the presence or absence of body scaled self-avatars on affordance judgments has been relatively unexplored. To investigate this phenomenon, we conducted a study in which participants were asked to judge if they could pass through different sized virtual apertures while holding an extended virtual object in front of themselves with both hands. Furthermore, to understand how the presence of self-avatar affects the perception of affordances while interacting with virtual objects, half of the participants embodied a gender matched body-scaled self-avatar whose eye height, arm length, shoulder width and body depth along the mid section matched that of themselves. It has been previously demonstrated that perceptual recalibration, which continuously occurs as we perform actions [14], [35], can be achieved in VR [3] and is influenced by a self-representation [13], [14]. Therefore, we also evaluated the effect of multisensory feedback during a calibration phase on passability judgments for the PPVO system. To the best of our knowledge, this is the first study that has investigated this phenomenon.

3 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 an empirical evaluation that examined frontal passability judgments for the PPVO system. When making frontal judgments, the object may not always dictate the width of the PPVO or the PPO systems as it might not be wider than the shoulders. In other words, the object being held (virtual or real) might not be wider than the shoulder width of the participant, in which case the frontal width would be determined by the shoulder width of the participant and not the object wielded. We utilized a mixed factorial design with one independent between-subjects variable, presence or absence of self-avatar, and one within-subjects variable, object size, presented in a randomized fashion. A circular virtual bar with two handles similar to a log bar was used as the interaction object.

The bar length was randomized between trials. The length was either .8 times (narrower), the same size (matched) or 1.2 times (wider) participants' shoulder width. The diameter of the bar remained the same across all trials. The participants were instructed to hold the bar using both 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 participants' shoulder width or 1.2 times their shoulder width. This is because participants' shoulders were wider than the bar in the condition with the narrower bar, thus making their shoulders the widest frontal dimension of the system.

All experiments were conducted in a 6.8 m X 7 m virtual room with a sliding doorway aperture setup, see Figure 1. 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 ranged from .7 to 1.3 times the shoulder width of the participant (at .1 intervals). The ratios are referred to as door width ratios in the manuscript from here on. For each participant the same door widths were used across all three bar sizes to compare how judgments varied for the same sized door with different sized bars. The calibration phase had the same

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

bar sizes with door width ratios ranging from .7 to 1.3 at .15 intervals. Each door width was presented three times for each of the three bar sizes in each of the three phases, resulting in 63 trials in the pretest and posttest phases (7 x 3 x 3) and 45 trials in the calibration phase (5 x 3 x 3), for a total of 171 trials per participant. The experiment lasted on average about 75 minutes.

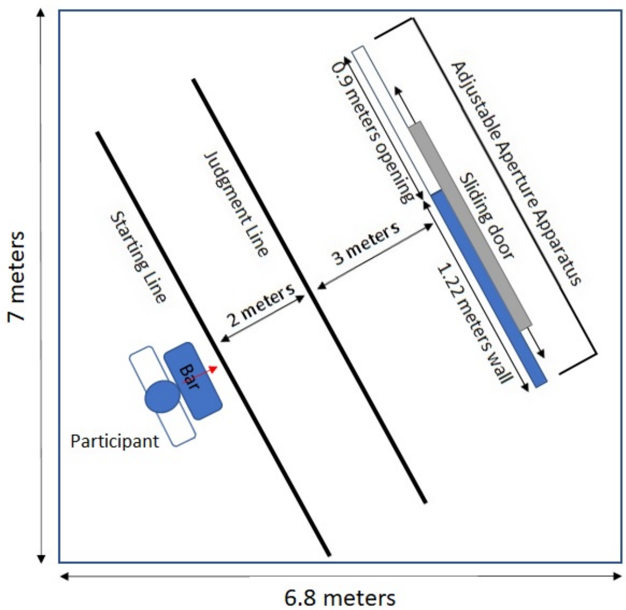


Fig. 1. Top down view of the experiment room setup with the sliding doorway aperture and bar.

3.1 Apparatus

The hardware setup used an HTC Vive Pro HMD, HTC wand 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 graphics card for rendering at 90 frames per second.

3.2 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 2. The sliding doorway was placed along the diagonal in the room to maximize the walking space for the experiment. The virtual space was calibrated so that it overlapped 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 opposite end of the sliding experiment 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 and perform certain exercises as explained in the next sections.

3.3 Object Interaction

The interaction with the virtual bar was facilitated with the help of the HTC Vive wand 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

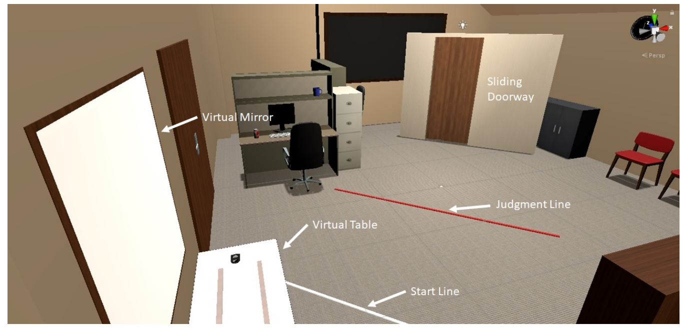


Fig. 2. The virtual space where participants performed all the trials.

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 the 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 the 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.

3.4 Avatar Generation and Tracking

We utilized the avatar system described by Bhargava et al. in [19]. Their system utilized 8 tracking points (HMD, 2 controllers and 5 HTC Vive trackers) and a mixture of an inverse kinematics (IK) Unity plugin, FinalIK, and an extension of the avatar generation Unity plugin, Unity Multipurpose Avatar, to create self-avatars that matched the user's gender, eyeheight, shoulder width and arm length. In the system, two trackers are placed behind the elbows, 1 tracker is placed on the lower back and the other two trackers are placed on the feet. For our study, we extended their system to adjust the stomach and gluteus of the avatar to match the body depth of the participant along the midsection as measured by the experimenter.

3.5 Calibration Phase Feedback

The calibration phase provided perceptual information as feedback to the participants. In this phase, the participant was asked to try and pass through the virtual door with the bar without hitting it to confirm their judgment. In case they 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 3) and a "thud" sound was played from the same side. The highlight showed the participant the farthest extent of the bar or their virtual body that had or would intersect with the door on that side. This was achieved using a conjunction of collision detection and ray casting algorithms 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 cast collisions for the vertical

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

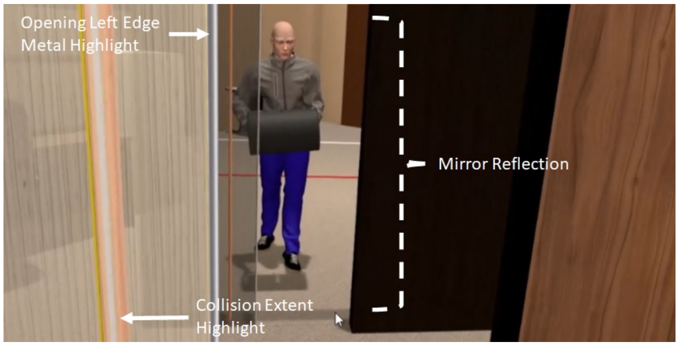


Fig. 3. Perceptual information provided as feedback to the participant upon colliding with the door in the calibration phase

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 they passed through the door while holding onto the bar.

3.6 Participants

Studies investigating the power of Hierarchical Linear Models suggest that the number of participants and the number of trials are both important for establishing sufcient power [43]. To determine the Level 2 sample size (number of participants), a power analysis using Cohen's medium effect size of .3 [44] and an alpha of .05 revealed that a sample size of 22 participants will produce power of .85. Thus, a total of 22 participants were recruited from Clemson University graduate and undergraduate programs, 11 for each of the two conditions. The average age of participants was 18.7 years and the distribution consisted of 16 females and 6 males. All participants had normal or corrected-to-normal vision and could perceive stereo.

3.7 Research Questions

The research questions that this study explores are as follows:

1) Do virtual handheld objects affect frontal passability in VR?
2) Does the presence of body scaled self-avatars affect the perception of passability with virtual handheld objects?
3) In the absence of haptic or inertial feedback, does the size of virtual handheld objects affect affordance perception in IVE?
4) Does calibration affect frontal passability judgments with handheld objects in VR?

3.8 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 VR.
2) Next, the experimenter measured the participant's visual acuity using a modified Snellen visual acuity test[1], Stereo Acuity[2] and Interpupillary Distance (IPD). Previous research has shown that IPD can affect spatial perception in IVEs [45], [46] and to make sure that the participant was seeing the most accurate imagery, the measured IPD was adjusted on the HMD.
3) 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 their back against it and hold 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 to get the participant's body depth.
4) Following the measurements, the participant was briefed on what VR is, all the devices they would be using and what they would be doing.
5) The participant was then immersed in the IVE and underwent 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 interaction (rubbing their forearms with the controllers while viewing their self-avatar).
6) Then the participant was acclimated to the IVE by walking up to 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.
7) Next, the participant was instructed on how to interact with the virtual bar using both controllers while facing a virtual mirror. They were also taught four quick exercises that they needed to perform before every trial in order to fully acclimate to the dimensions of the virtual bar. These exercises were included as we wanted the participant to notice the change in bar lengths between trials and compare it to their real or virtual body depending on the condition. The exercises were as follows: 1) moving the bar away from the body and bringing it back, 2) pushing the bar above the head and bringing it back, 3) turning to either their left or right, moving the bar away from the body and bringing it back, and 4) While facing the mirror, rotating the bar to look at it from the sides.
8) 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 in front of the mirror, then 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 passing 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.
9) At this point, the participant was allowed to take a break if they wanted.

1. http://www.allaboutvision.com/eye-test/snellen-chart.pdf
2. https://www.bernell.com/product/SOM150/Depth-Perception-Tests

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

10) 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 their judgment. Upon hitting the door, the multi-modal feedback described in the earlier section was provided to the participant to show to what extent they and their virtual handheld object collided or penetrated the left and right extent of the doorway. 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 through and then walk back to the white line. They were allowed to take a break after calibration but were not allowed to take the HMD off. This was done to ensure that they do not lose the calibration effect by being in a different environment before going into the posttest phase.
11) Next was the posttest or post-calibration phase. In this phase, the participant followed the exact same instructions as the pretest phase.
12) After finishing all the trials in the three phases, the participant was asked to fill out a presence questionnaire, a body-ownership questionnaire [47] if they were given a self-avatar and the NASA-TLX workload questionnaire.

3.9 Hypotheses

Based on the research questions listed above and motivated by the theoretical underpinning discussed in earlier sections, we tested the following hypotheses:

1) Frontal passability judgments with virtual handheld objects will be made in a more realistic manner (with passability ratios greater than 1.0 being judged as passable) in the presence of self-avatars.
2) Frontal passability judgments will scale based on the virtual bar length being held.
3) Calibration will aid virtual object integration into the embodied body schema resulting in more realistic frontal passability judgments (with passability ratios greater than 1.0 being judged as passable).

3.10 Data Analysis

Due to the repeated measures design of this experiment, variables had considerable nesting within participants. That is, since each participant completed multiple 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, along with other manipulated within-participant factors, created multiple levels of variance.

In a mixed model regression, Level 1 (within-participant) variables represent those that change from trial to trial, producing residual variance from the regression line. Level 2 (between-participant) variables represent those that change from participant to participant, producing variance in the intercept of the regression equation. Level 1 by Level 2 interactions occur when within-participant effects are moderated by between-participant variables, producing variance in the slope of the regression equation. In order to account for variance at the within-participant and between-participant levels, hierarchical linear modeling was used [43].

When using hierarchical linear modeling, it is important to hold the regression coefficient of the intercept constant across all models. 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 and all categorical variables are held at a baseline condition (phase = pretest, Bar Length = 1.2, Avatar = present).

Effect sizes for each fixed effect will be presented as the change in R^2 (a measure of how close the data is to the resultant regression line) comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 (a measure of the unique amount of variance a predictor variable brings to the model) can be interpreted as the percentage of variance accounted for by the fixed effect (for more on measuring effect sizes for dichotomous variables, see [48]).

The dependent variable for this analysis 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 [49]. 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. The odds ratio is a measure of success; odds ratios with values greater than 1 indicate that successes are more likely than failures. For example, an odds ratio of 2 would indicate that a success (i.e., judging the door as passable) is twice as likely than a failure (i.e., judging the door as impassable). The success probability can be derived from the odds ratio via the following equation [50], $Pi = odds/(odds + 1)$. Thus, an odds ratio of 2 would have a success probability of 2/(2+1) = 0.667. The corresponding probability of failure would be 0.333. Significant results will be graphed using a probability function, such that the probability of a participant judging a presented door to be passable (judgment = "yes") will be plotted against various levels of the predictor variables. We will highlight two key aspects of the probability function. First, we will extract the critical ratio, which is a threshold value at which the door is perceived as passable 50% of the time [51]. This indicates the average door width ratio at which participants switch their passability judgments from "no" to "yes". Second, the shape of the probability function, indicated by its slope coefficient, represents the reliability of participant's judgments across trials [52]. Steeper slope coefficients indicate a reliable and abrupt transition from impassable judgments to passable judgments, while a shallower slope indicates more variability and uncertainty in participant's judgments [33], [53].

4 Results

4.1 Body Ownership

We used the recommended Principal Component Analysis (PCA) method to calculate the body ownership scores for participants using the avatar embodiment questionnaire [47], M = .89, SD = .95. The range for the scores was -3 to 3.

4.2 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

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

on their frontal judgment data. See Table 1 for the results of the omnibus F test. For significant effects of categorical variables, a comparison of estimated marginal means using a bonferroni-corrected t-test are presented below. For significant effects of continuous variables, the slope coefficient, odds ratio, and t-test comparing the slope coefficient to zero are also included below.

TABLE 1
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 Width 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*

As a reminder, this analysis is being done only on the pretest data, at this stage we are not considering the post test or the difference between the pretest or the posttest. The largest predictor of frontal passability judgments was the presented Door Width Ratio (B = 15.46, SE = .62, odds = 5.2E+6). As the door width relative to the PPVO increased by .1 ratio units (e.g., the incremental change in the experiment), the odds of judging the door as passable increased by a multiplicative factor of 4.69. This accounted for 29% of the variance in frontal passability judgments.

The size of the bar also impacted pretest frontal judgments. Holding all other variables at their average, participants were more likely to judge a door as passable when holding the narrower bar (M prob = .67, SE = .12) compared to the matched bar (M prob = .15, SE = .07, t = 7.57, p <.001) and the wider bar (M prob = .33, SE = .12, t = 6.35, p <.001). Interestingly, participants were more likely to judge a door as passable when holding the wider bar as compared to the matched bar (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 = .18, SE = .08) and the No-Avatar condition (M prob = .33, SE = .11, t = 1.33, p = .20). However, the Avatar variable significantly moderated the effect of Door Width Ratio. The slope for the effect of Door Width Ratio was steeper for the No-Avatar condition (B = 16.803, SE = 1.05, odds = 1.9E+7) than the Avatar condition (B = 14.3, SE = .76, odds = 1.6E+6, t = 2.38, p = .02, see Figure 4). As shown in Figure 4, the perceived critical ratio for the No-Avatar

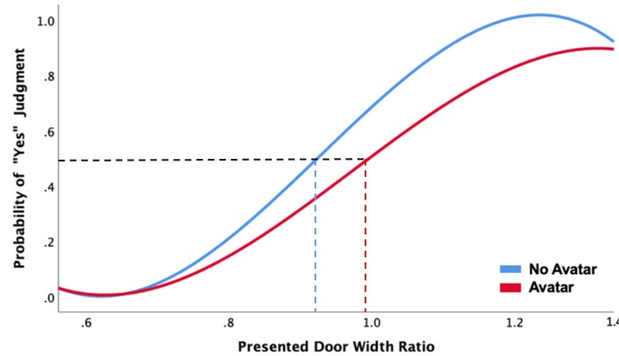


Fig. 4. Effect of Door Width Ratio on Frontal passability judgments, moderated by Avatar presence.

condition was .92 and the perceived critical ratios for the Avatar condition was .99. This suggests that participants in the No-Avatar condition were more consistent and reliable in their passability judgments compared to participants in the Avatar condition, even though the no-avatar participants were misperceiving some door widths that were smaller than their PPVO width as passable.

The Avatar x Door Width interaction was further moderated by Bar Length. To explore this interaction, the data file was split by Bar Length and the model was rerun to assess the effect of the Avatar X Door Width interaction for each individual Bar Length. Results showed that the Avatar X Door Width interaction effect was significant only for the narrower bar condition. Following the pattern shown in Figure 4, for the narrower bar, the No-Avatar condition had a significantly steeper slope (B = 20.55, SE = 2.24) than the Avatar condition (B = 11.64, SE = 1.01, t = 3.97, p <.001). The perceived critical ratio was .82 for the No-Avatar condition and .92 for the Avatar condition. For both the matched bar condition and the wider bar condition, there was no significant difference between the slopes of the Presented Door Width for the Avatar and No-Avatar condition (Matched Avatar: B = 15.66, SE = 1.42, Critical Ratio = 1.08, Matched No-Avatar: B = 16.92, SE = 2.01, Critical ratio = .97, t = .63, p = .53; Wider Avatar: B = 16.65, SE = 1.84, Critical Ratio = .98, Wider No-Avatar: B = 19.85, SE = 2.62, Critical Ratio = .95, t = 1.22, p = .22).

By including phase (pretest vs. posttest) in the model, we were able to assess any calibration effects on frontal passability judgments. 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 5A). This suggests that participants made more consistent judgments in the pretest compared to the posttest. However, 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 significantly more likely to judge doors as passable in the Pretest compared to the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

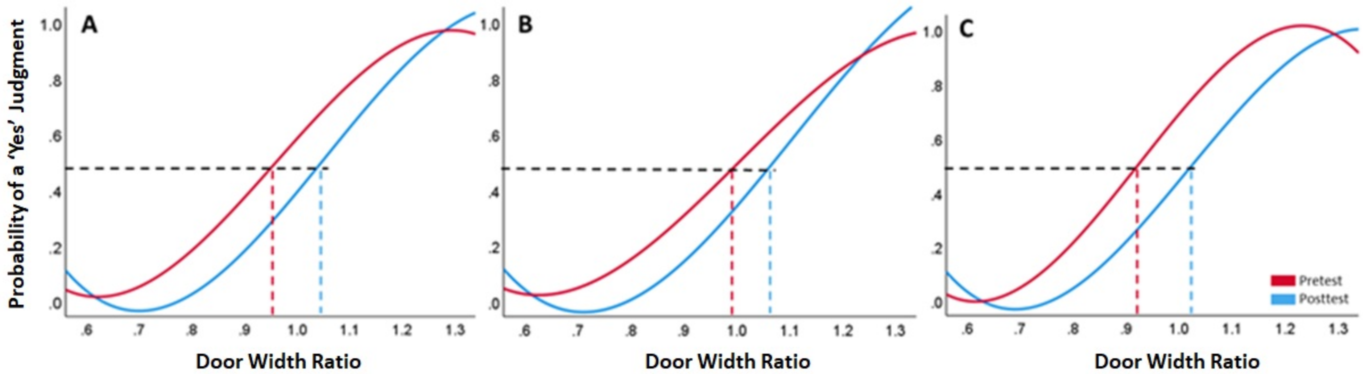


Fig. 5. A) Interaction b/w Door Width Ratio and Phase. B) Interaction b/w Door Width Ratio and phase for Avatar condition. C) Interaction b/w Door Width Ratio and Phase for the No-Avatar condition.

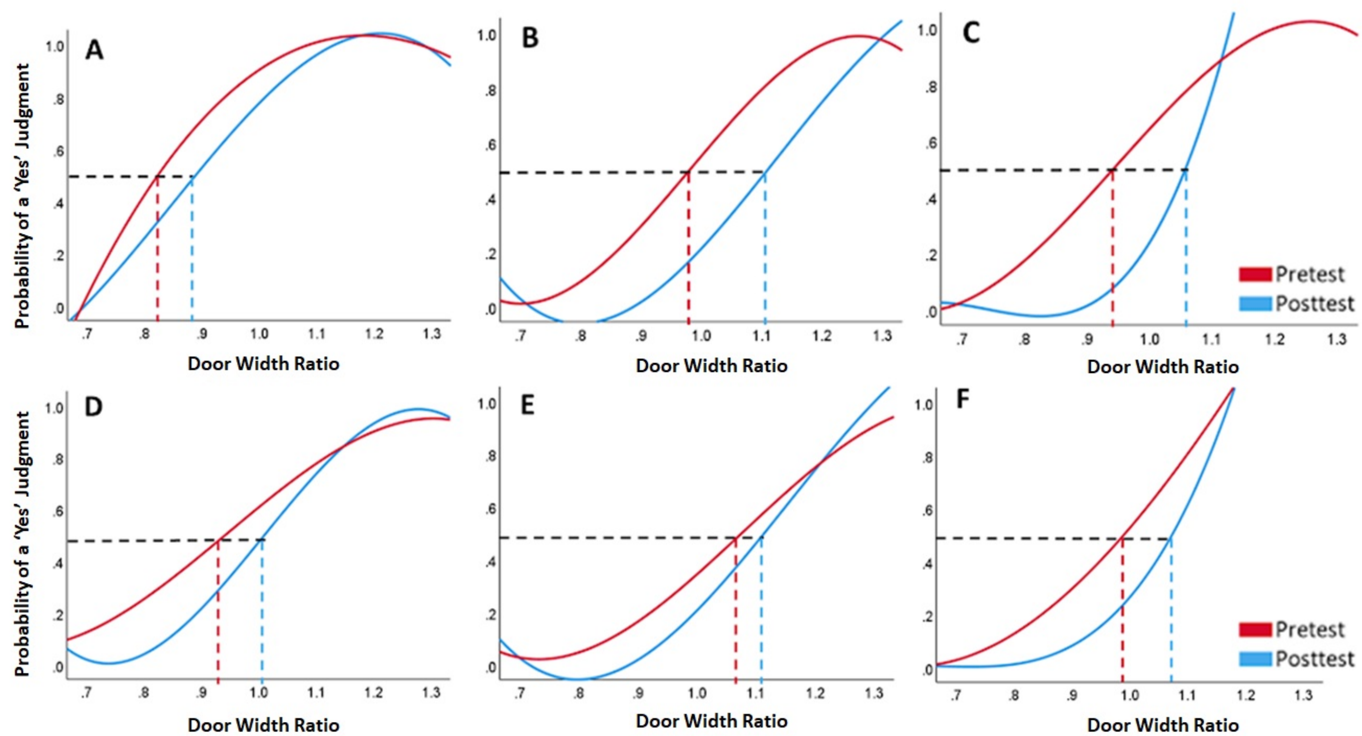


Fig. 6. A) Interaction b/w phase and ratio for No-Avatar and .8 bar length condition. B) Interaction b/w phase and ratio for No-Avatar and 1.0 bar length condition. C) Interaction b/w phase and ratio for No-Avatar and 1.2 bar length condition. D) Interaction b/w phase and ratio for Avatar and .8 bar length conditions. E) Interaction b/w phase and ratio for Avatar and 1.0 bar length conditions. F) Interaction b/w phase and ratio for Avatar and 1.2 bar length conditions.

Posttest. The narrower bar 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 matched bar resulted in a smaller difference in mean probability between the Pretest (M prob = .38, SE = .1) and Posttest (M prob = .12, SE = .1, t = 3.5, p = .001). The effect of Phase was smallest for the wider bar. 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).

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).

Further, there was a statistically significant three-way interaction among Phase, Door Width Ratio, and Avatar. Post hoc comparison revealed that for the Avatar condition, the slope for the effect of Door Width Ratio on frontal passability judgments was steeper for the Posttest (B = 16.97,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

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 5B). In the No-Avatar condition, the slope effect of Door Width Ratio on passability judgments did not significantly differ between the Pretest and Posttest, see Figure 5C.

Lastly, there was a four-way interaction among Phase, Door Width Ratio, Avatar, and Bar Length. To assess this interaction, the file was split by Avatar and Bar Length conditions 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 narrower bar (Figure 6A) nor for the matched bar (Figure 6B). In other words, the slopes for the effect of Door Width Ratio were similar for both the Pretest and Posttest in the narrower as well as the matched bar conditions. For the wider bar, 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 was wider 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 6C).

For the Avatar Condition, the effect of Phase was moderated by Door Width Ratio for the narrower and the matched bars. The effect of Phase was not moderated by Door Width Ratio for the wider bar. The slope for the effect of Door Width Ratio for the Avatar condition with the narrower bar 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 6D). The slope for the effect of Door Width Ratio for the Avatar condition with the matched bar 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 6E).

4.3 Presence

We analyzed the sense of presence scores of the Witmer and Singer Presence survey [54] between the avatar and no-avatar condition via non-parametric statistical analysis. Although we did not find a significant difference between the avatar and no-avatar condition overall on the mean presence scores, we found some significant differences between the conditions in specific relevant items of the questionnaire. A Mann-Whitney U test indicated that the participants could actively survey or search the virtual environment using touch significantly more in the self-avatar condition (Mdn = 6) as compared to the No-Avatar condition (Mdn = 2), U = 29.5, p = .039. Analysis also revealed that participants could control the interface provided to successfully accomplish the task significantly higher in the self-avatar condition (Mdn = 3) as compared to the No-Avatar condition (Mdn = 1), U = 31.0, p = .041. Interestingly, the analysis revealed that the visual display quality interfered with the task significantly more in the self-avatar condition (Mdn = 3) as compared to the No-Avatar condition (Mdn = 1), U = 28.0, p = .027.

5 Discussion

The results from the pretest suggest that participants were more likely to judge an opening as passable while holding the narrower bar with length .8 times the shoulder width as compared to the matched (bar length = shoulder width) and wider (bar length = 1.2 x shoulder width) bars. This suggests that in making passability judgements, participants tend to rely more on the visual information of the bar as compared to the mismatched kinesthetic and proprioceptive feedback. 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 scaling judgments to the PPVO width. These results are similar to those observed by Wagman et al. and Hackney et al. where participants calibrated to the different object sizes being held or viewed while making passability judgments [4], [5]. This supports our second hypothesis, which states that passability judgments will scale to the length of the virtual bar being held. However, participants were more likely to judge openings as passable with the wider bar as compared to the matched bar. This is unexpected but it is possible that participants struggled to determine if the PPVO width was determined by their shoulder width or the virtual bar when they were the same. This is similar to Bhargava et al.'s findings that participants struggle to make passability judgments when the ratio between the shoulder width and the opening is close to 1.

Taking a closer look at the interaction effects, a significant interaction between avatar and door width ratio was observed. Although participants were more consistent with their judgment in the absence of self-avatars, the critical ratio for the avatar condition was closer to 1 suggesting that their judgments were more realistic in the presence of self-avatars. Perhaps participants were more cautious with their passability judgments since they could see their virtual body along with the bar [19]. This supports our first hypothesis stating that judgments would be more realistic in the presence of self-avatars. This also aligns with previous research that suggests that self-avatars significantly affect the affordance thresholds and results in more realistic judgments [16], [42].

Furthermore, the interaction between avatar and door width was moderated by the length of the virtual bar being held. When holding the narrower bar, participants were more consistent with their judgments in the no-avatar condition compared to the avatar condition. The judgments did not differ for the matched and the wider bars. Closer examination of the critical ratios for the different bar sizes revealed that they were comparable to the ranges reported for the PPO by Wagman et al. [4], but the ratios for all avatar conditions were closer or above 1 which is what is needed to successfully cross an opening as reported by Warren et al. [34]. This suggests that in the presence of the self-avatar participants more accurately perceived whether their body or the virtual bar determined the width of the PPVO. Since it is easy to compress one's shoulder width by scrunching them or hunching over rather than expanding them, the presence of a self-avatar representing the true shoulder width probably helped participants make more realistic judgments. This further strengthens the support for our first hypothesis.

Comparing the pretest and posttest judgments for different door widths, we observed that participants were more consistent with their pretest judgments compared to the posttest. Closely examining the critical ratios, we see a shift from .96 to 1.05, producing a posttest ratio closer to what

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

would be expected given than an opening slightly larger than the PPVO is required to pass through without contact. This also better accounts for body sway when walking. The latter ratio is similar to what has previously been reported in several other experiments [19], [26], [34]. This supports our third hypothesis, which states that calibration will aid virtual object integration into the embodied body schema, resulting in more realistic passability judgments for the PPVO.

An interaction of Avatar and Phase was observed such that participants became less likely to judge doors as passable in the posttest as compared to the pretest. This difference was larger for the no-avatar condition. Since we observed a more realistic critical ratio in the posttest overall and participants without a self-avatar had a larger difference, it is possible that participants with no avatar were less conservative pre calibration and improved more as compared to the participants with an avatar. This strengthens the support for the first hypothesis and the reasoning that participants were more cautious and were able to better determine the width of the PPVO in the presence of a self-avatar. This is similar to what was reported by Lin et al. in their study involving stepping off a ledge in the presence or absence of self-avatars [42].

Further analysis of the calibration effects with avatars across the different bar sizes suggested that with the no-avatar conditions, participants produced less consistent judgments in the posttest with the narrower and matched bars compared to the wider bar. Perhaps in the absence of self-avatars, participants were less able to determine if the frontal dimension of the PPVO system was defined by the bar length or their shoulders for the narrower and matched bars. Not knowing what to calibrate judgments to, for these object sizes the slopes were not significantly different between phases. Since, the wider bar was undoubtedly broader than the shoulders, participants were able to successfully calibrate for that size. For the avatar conditions, participants were more consistent with their judgments in the posttest when holding the narrower and matched bars compared to the wider bar. Following the same reasoning, participants may have been more able to calibrate to the narrower and matched bars because they could more accurately determine if the PPVO width was dictated by the bar or their body in the presence of a self-avatar. For the wider 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 aligns with the results reported in a study by Franchak [9] investigating the role of vision during recalibration to altered body dimensions which observed a significant decrease in judgment accuracy without vision. This suggests that the presence of self-avatars aided in the calibration process, further supporting the third hypothesis.

6 Conclusion and Future Work

In this study, we investigated how the perception of an affordance changes when participants interact with virtual handheld objects in an immersive virtual environment. Frontal passability judgments were made in the presence or absence of a gender matched body-scaled self-avatar while holding virtual bars of different sizes in front of the body. This is the first work to investigate frontal passability judgments for a PPVO system in Virtual Reality.

The findings suggest that users can conform to the visual dimensions of the virtual object to make accurate judgments, even with mismatched kinesthetic and proprioceptive feedback. This aligns with a recent work by Gomes de Siqueira et al. where the authors demonstrated that participants have greater accuracy when estimating the size of tangible dials in VR when using vision versus haptics [55]. Moreover, the presence of a self-avatar significantly benefits affordance perception when interacting with virtual objects and when calibrating the embodied body schema for the PPVO, especially when the virtual object size is close to the individual's own shoulder width. Being able to determine if the virtual object or the shoulders dictate the widest frontal dimension of the PPVO is essential in making realistic passability judgments, and having a scaled virtual body helps in achieving that. Although we did not test cases where the kinesthetic and proprioceptive feedback were matched or stronger, we do believe that our results are generalizable because of the virtual object used and the different sizes it was scaled to. The participants were not given any information about what the bar was a replica of or what physical properties its real world replica would have. So, we do not know if the object was perceived heavier, lighter or matched by the participants, just that it would not be representative of holding it in the real world. Since participants focused on the virtual size, the results should hold in scenarios where the controller or other physical objects held in hand are heavier or lighter.

This work provides three guidelines for developing highly realistic VR simulations. First, self-avatars aid affordance perception for the PPVO and result in more realistic judgments. Therefore, providing users with a self-avatar when interacting with virtual objects could improve the overall user experience. Second, since self-avatars aid calibration to the PPVO, it would be beneficial to provide users with a closely matched self-avatar for VR training simulations when the goal is real world transference of learned skills. This is applicable to scenarios like construction and distribution center workforce training. Thirdly, using simple exercises or tasks to familiarize users with the virtual object they are interacting with could be beneficial to the overall user experience, especially when the kinesthetic and proprioceptive feedback is lacking or mismatched.

A limitation of our work is that we only studied frontal passability judgments. Users often change postures and perform maneuvers in real life situations. To address this limitation, we are currently conducting follow-up experiments to investigate lateral passability judgments for the PPVO in the presence and absence of body-scaled self-avatars. Another limitation is that we did not study PPVO effects for an invisible body with just hands and feet visible. Kondo et al. has previously demonstrated that such a body seems to elicit the same level of ownership as a full body in VR [56]. Although no-avatar condition participants in our experiment did see handheld controllers in VR, we did not attempt to induce ownership to them via visuo-motor synchronization, as was done by Kondo et al. This could be a fruitful direction for future research. Also, Ogawa et al. demonstrated that avatar appearance can affect how we

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3083423, IEEE Transactions on Visualization and Computer Graphics

perceive affordances [57]. Most VR simulations these days have partial or generic self-avatars that do not take the participant's bodily dimensions into account. Investigating how discrepancy in avatar appearance or dimensions as compared to the participant's body could affect affordances and calibration for the PPVO could result in valuable insights.

REFERENCES

[1] A. Berti and F. Frassinetti, "When far becomes near: Remapping of space by tool use," *Journal of cognitive neuroscience*, vol. 12, no. 3, pp. 415–420, 2000.

[2] C. C. Pagano and M. T. Turvey, "Eigenvectors of the inertia tensor and perceiving the orientations of limbs and objects," *Journal of Applied Biomechanics*, vol. 14, no. 4, pp. 331–359, 1998.

[3] B. Day, E. Ebrahimi, L. S. Hartman, C. C. Pagano, and S. V. Babu, "Calibration to tool use during visually-guided reaching," *Acta psychologica*, vol. 181, pp. 27–39, 2017.

[4] J. B. Wagman and K. R. Taylor, "Perceiving affordances for aperture crossing for the person-plus-object system," *Ecological Psychology*, vol. 17, no. 2, pp. 105–130, 2005.

[5] A. L. Hackney, M. E. Cinelli, and J. S. Frank, "Is the critical point for aperture crossing adapted to the person-plus-object system?" *Journal of motor behavior*, vol. 46, no. 5, pp. 319–327, 2014.

[6] J. J. Gibson, "The theory of affordances," *Hilldale, USA*, vol. 1, no. 2, 1977.

[7] 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*, vol. 9, no. 8, p. e103428, 2014.

[8] 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)*, vol. 12, no. 2, p. 6, 2015.

[9] J. M. Franchak, "Exploratory behaviors and recalibration: What processes are shared between functionally similar affordances?" *Attention, Perception, & Psychophysics*, vol. 79, no. 6, pp. 1816–1829, 2017.

[10] C. C. Pagano, S. R. Garrett, and M. Turvey, "Is limb proprioception a function of the limbs' intertial eigenvectors?" *Ecological Psychology*, vol. 8, no. 1, pp. 43–69, 1996.

[11] A. Maravita and A. Iriki, "Tools for the body (schema)," *Trends in cognitive sciences*, vol. 8, no. 2, pp. 79–86, 2004.

[12] B. Craske, "Perception of impossible limb positions induced by tendon vibration," *Science*, vol. 196, no. 4285, pp. 71–73, 1977.

[13] 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*. ACM, 2018, p. 2.

[14] B. Day, E. Ebrahimi, L. S. Hartman, C. C. Pagano, A. C. Robb, and S. V. Babu, "Examining the effects of altered avatars on perception-action in virtual reality." *Journal of Experimental Psychology: Applied*, vol. 25, no. 1, p. 1, 2019.

[15] 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*, vol. 110, no. 31, pp. 12 846–12 851, 2013.

[16] 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*. ACM, 2012, pp. 7–10.

[17] 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*, vol. 19, no. 3, pp. 230–242, 2010.

[18] 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*, vol. 25, no. 5, pp. 2123–2133, 2019.

[19] A. Bhargava, H. Solini, K. Lucaites, J. W. Bertrand, A. Robb, C. C. Pagano, and S. V. Babu, "Comparative evaluation of viewing and self-representation on passability affordances to a realistic sliding doorway in real and immersive virtual environments," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2020, pp. 519–528.

[20] E. A. McManus, B. Bodenheimer, S. Streuber, S. De La Rosa, H. H. Bülthoff, and B. J. Mohler, "The influence of avatar (self and character) animations on distance estimation, object interaction and locomotion in immersive virtual environments," in *Proceedings of the ACM SIGGRAPH Symposium on applied perception in graphics and visualization*. ACM, 2011, pp. 37–44.

[21] A. Steed, Y. Pan, F. Zisch, and W. Steptoe, "The impact of a self-avatar on cognitive load in immersive virtual reality," in *2016 IEEE Virtual Reality (VR)*. IEEE, 2016, pp. 67–76.

[22] M. N. Petrucci, G. P. Horn, K. S. Rosengren, and E. T. Hsiao-Wecksler, "Inaccuracy of affordance judgments for firefighters wearing personal protective equipment," *Ecological Psychology*, vol. 28, no. 2, pp. 108–126, 2016.

[23] D. Comalli, J. Franchak, A. Char, and K. Adolph, "Ledge and wedge: Younger and older adults perception of action possibilities," *Experimental brain research*, vol. 228, no. 2, pp. 183–192, 2013.

[24] R. S. Renner, B. M. Velichkovsky, and J. R. Helmert, "The perception of egocentric distances in virtual environments-a review," *ACM Computing Surveys (CSUR)*, vol. 46, no. 2, p. 23, 2013.

[25] 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*. ACM, 2012, pp. 79–82.

[26] 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*. ACM, 2010, pp. 61–64.

[27] A. Bhargava, K. M. Lucaites, L. S. Hartman, H. Solini, J. W. Bertrand, A. C. Robb, C. C. Pagano, and S. V. Babu, "Revisiting affordance perception in contemporary virtual reality," *Virtual Reality*, pp. 1–12, 2020.

[28] J. J. Gibson, "The ecological approach to visual perception," 1979.

[29] B. R. Fajen, "Affordance-based control of visually guided action," *Ecological Psychology*, vol. 19, no. 4, pp. 383–410, 2007.

[30] W. H. Warren, "Direct perception: The view from here," *Philosophical Topics*, vol. 33, no. 1, pp. 335–361, 2005.

[31] W. Warren, "The dynamics of perception and action." *Psychological review*, vol. 113, no. 2, p. 358, 2006.

[32] C. C. Pagano, B. Day, and L. Hartman, "Ecological psychology: A theoretical framework for architecture and design," *Technology — Architecture + Design*, 2021.

[33] K. M. Lucaites, R. Venkatakrishnan, R. Venkatakrishnan, A. Bhargava, and C. C. Pagano, "Predictability and variability of a dynamic environment impact affordance judgments," *Ecological Psychology*, pp. 1–20, 2020.

[34] 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*, vol. 13, no. 3, p. 371, 1987.

[35] J. M. Franchak and K. E. Adolph, "Gut estimates: Pregnant women adapt to changing possibilities for squeezing through doorways," *Attention, Perception, & Psychophysics*, vol. 76, no. 2, pp. 460–472, 2014.

[36] J. K. Stefanucci and M. N. Geuss, "Big people, little world: The body influences size perception," *Perception*, vol. 38, no. 12, pp. 1782–1795, 2009.

[37] 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*, vol. 21, no. 3, p. 215, 2015.

[38] C. Lougiakis, A. Katifori, M. Roussou, and I.-P. Ioannidis, "Effects of virtual hand representation on interaction and embodiment in hmd-based virtual environments using controllers," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2020, pp. 510–518.

[39] B. Lok, S. Naik, M. Whitton, and F. P. Brooks, "Effects of handling real objects and avatar fidelity on cognitive task performance in virtual environments," in *IEEE Virtual Reality, 2003. Proceedings.* IEEE, 2003, pp. 125–132.

[40] 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)*, vol. 12, no. 4, p. 16, 2015.

[41] 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*, vol. 8, no. 7, p. e68594, 2013.

[42] 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*. ACM, 2013, pp. 107–110.

[43] D. A. Hofmann, "An overview of the logic and rationale of hierarchical linear models," *Journal of management*, vol. 23, no. 6, pp. 723–744, 1997.

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

[45] J. Kim and V. Interrante, "Dwarf or giant: the influence of interpupillary distance and eye height on size perception in virtual environments," in *27th International Conference on Artificial Reality and Telexistence, ICAT 2017 and the 22nd Eurographics Symposium on Virtual Environments, EGVE 2017*. Eurographics Association, 2017, pp. 153–160.

[46] D. Mine, N. Ogawa, T. Narumi, and K. Yokosawa, "The relationship between the body and the environment in the virtual world: The interpupillary distance affects the body size perception," *Plos one*, vol. 15, no. 4, p. e0232290, 2020.

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

[48] S. Tom and B. Roel, "Discrete dependent variables. multilevel analysis: an introduction to basic and advanced multilevel modelling," 2000.

[49] C.-Y. J. Peng, K. L. Lee, and G. M. Ingersoll, "An introduction to logistic regression analysis and reporting," *The journal of educational research*, vol. 96, no. 1, pp. 3–14, 2002.

[50] A. Agresti, *An introduction to categorical data analysis*. John Wiley & Sons, 2018.

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

[52] J. Franchak and K. Adolph, "Affordances as probabilistic functions: Implications for development, perception, and decisions for action," *Ecological Psychology*, vol. 26, no. 1-2, pp. 109–124, 2014.

[53] G. Watson, S. Brault, R. Kulpa, B. Bideau, J. Butterfield, and C. Craig, "Judging the passabilityof dynamic gaps in a virtual rugby environment," *Human Movement Science*, vol. 30, no. 5, pp. 942–956, 2011.

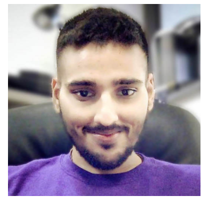
[54] B. G. Witmer and M. J. Singer, "Measuring presence in virtual environments: A presence questionnaire," *Presence*, vol. 7, no. 3, pp. 225–240, 1998.

[55] A. Gomes de Siqueira, R. Venkatakrishnan, R. Venkatakrishnan, A. Bhargava, K. Lucaites, H. Solini, M. Nasiri, A. Robb, C. C. Pagano, B. Ullmer, and S. V. Babu, "Empirically evaluating the effects of perceptual information channels on the size perception of tangibles in near-field virtual reality," in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2021.

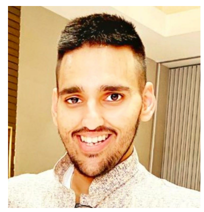
[56] R. Kondo, M. Sugimoto, K. Minamizawa, T. Hoshi, M. Inami, and M. Kitazaki, "Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity," *Scientific reports*, vol. 8, no. 1, pp. 1–8, 2018.

[57] N. Ogawa, T. Narumi, H. Kuzuoka, and M. Hirose, "Do you feel like passing through walls?: Effect of self-avatar appearance on facilitating realistic behavior in virtual environments," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–14.

Ayush Bhargava is a eXtended Reality (XR) user experience researcher at Key Lime Interactive in Brooklyn, New York. Before joining the research agency, he earned his PhD from Clemson University focusing on the effects of body-scaled self-avatars on affordance perception and natural interaction in VR. His research interests also include 3D interaction, cybersickness and tangibles.



Roshan Venkatakrishnan is a doctoral student in the Human-Centered Computing discipline at Clemson University. His research broadly spans areas under XR with a focus on human perception and user experience. Specifically, Roshan's immediate research interests and interdisciplinary pursuits lie in the areas of Cybersickness, temperature, depth, size and action-based perception capabilities in immersive virtual and augmented reality.



Rohith Venkatakrishnan is a graduate student pursuing a doctorate in Human-Centered Computing at Clemson University. His research interests include the study of human perception in virtual and mixed reality environments. He currently pursues research on the specific topics of Cybersickness, size perception, temperature perception, distance perception and perception based action capabilities in immersive virtual environments.

Hannah Solini is a Ph.D. candidate at Clemson University studying Human Factors Psychology. Her research interests include depth perception, affordance perception and calibration transfer in the real world and immersive virtual environments.

Kathryn Lucaites received her masters degree in applied psychology from Clemson University and is currently pursuing her Ph.D in human factors psychology. Her research investigates the impacts of complex dynamic movement patterns on affordance perception.

Andrew C. Robb is an assistant professor in the School of Computing at Clemson University. He earned his PhD in the Virtual Experience Research Group at the University of Florida. His research explores how the availability of consumer virtual reality will affect society, and seeks to ensure that this effect will be positive.

Christopher C. Pagano is a professor of human factors psychology at Clemson University. He received his PhD in experimental psychology with an emphasis in ecological psychology in 1993 from the University of Connecticut.

Sabarish V. Babu is an Associate Professor in the School of Computing at Clemson University. His expertise is in perception research in VR, virtual humans and avatars, and 3D human-computer interaction. He has authored or co-authored over 90 peer-reviewed publications in reputed journals and conferences, and have received 5 best paper awards.