The Impact of Embodiment and Avatar Sizing on Personal Space in Immersive Virtual Environments

Lauren E. Buck, Soumyajit Chakraborty, and Bobby Bodenheimer

Abstract—In this paper, we examine how embodiment and manipulation of a self-avatar's dimensions — specifically the arm length — affect users' judgments of the personal space around them in an immersive virtual environment. In the real world, personal space is the immediate space around the body in which physical interactions are possible. Personal space is increasingly studied in virtual environments because of its importance to social interactions. Here, we specifically look at two components of personal space, interpersonal and peripersonal space, and how they are affected by embodiment and the sizing of a self-avatar. We manipulated embodiment, hypothesizing that higher levels of embodiment will result in larger measures of interpersonal space and smaller measures of peripersonal space. Likewise, we manipulated the arm length of a self-avatar, hypothesizing that while interpersonal space would change with changing arm length, peripersonal space would not. We found that the representation of both interpersonal and peripersonal space change when the user experiences differing levels of embodiment in accordance with our hypotheses, and that only interpersonal space was sensitive to changes in the dimensions of a self-avatar's arms. These findings provide increased understanding of the role of embodiment and self-avatars in the regulation of personal space, and provide foundations for improved design of social interaction in virtual environments.

Index Terms—Virtual reality, Perception, Interpersonal space, Peripersonal space, Proxemics

1 Introduction

Interaction in an immersive virtual environment (IVE) typically takes place in a 3D space. Users can reach out, grasp, and manipulate objects and interact with the representations of other individuals. A way of understanding and parsing interactions that take place in an IVE is to look at how users maintain personal space, commonly conceptualized as the immediate space around the body in which we interact with external stimuli. The maintenance of personal space is an essential cognitive function that defines how we interact with the world around us. It reveals how interactions affect us and how we feel about our environment. This work considers personal space in two different categories: *interpersonal* and *peripersonal* space. Interpersonal space is the spatial distance that one maintains between themselves and another individual, and it is a foundational element of social interaction [3, 35]. Interpersonal distance is correlated with bodily dimensions, particularly height and arm length [35, 64]. Peripersonal space is the near space around the body that the brain encodes as the perceived reaching and grasping distance around oneself [21]. Both interpersonal and peripersonal space have been shown to change based on differing interactions [39, 68, 80].

We are motivated to study personal space since it reveals interaction distances in differing scenarios. Understanding these interaction distances builds a foundation for designers and developers to build experiences in IVEs with a higher level of realism. There are several characteristics about virtual reality that have potential to change the interaction between a user and the environment. For example, self-avatars (the bodily representation of the user) can be a complete mismatch from the actual physicality of the user and this can affect the way that the environment is perceived [56, 60]. The availability of haptics can change the way people interact [10], and so can the distribution of the environment (meaning whether or not users are collocated in the same tracking space) [16, 67]. Given the degrees of freedom that are allowed for virtual reality experiences, we chose to hone in on how two different aspects of self-avatars – embodiment and sizing – might affect the spatial perception of the user.

We study these issues in two separate experiments by varying the embodiment and arm dimensions of participants. The effects of these factors on personal space are measured by assessing their effect on (1) comfort distance judgments, the judged distance at which one is no longer comfortable with an agent entering the "private space" around one's body [22, 36], and (2) peripersonal space, the functional reaching space that has been previously measured in IVEs and mixed reality [15, 74].

Ultimately, our experiments show that interpersonal space changes when both the level of embodiment and arm dimensions of the user's self-avatar are changed. We found that peripersonal space changes with the level of embodiment, but not when the arm dimensions of the user's self-avatar are changed. These findings thus inform the development of IVEs by providing information about how embodiment and self-avatars influence the quality of the experience by mimicking how people react to personal space in a way that approaches that of the real world. More broadly, our work has implications for the the neuroscience community, where there has been some debate over the link between peripersonal space and perceived arm-reaching space [88].

2 Related Work

2.1 Personal Space

Interpersonal space is social space that is emotionally charged and cannot be invaded without some level of discomfort [36, 39]. It expands or contracts depending on the characteristics of the interaction partner like age, gender, race, personality, etc. [36]. In virtual reality, interpersonal space has been shown to be affected by shared external characteristics [7, 72], mutual gaze [5, 6], and studied in the context of affordance judgments [16]. Wilcox et al. [82] has shown that virtual reality users are sensitive to images that violate their personal space. Zibrek et al. [90] found that the attractiveness of an anonymized human motion affects interpersonal space, while the gender of the anonymized motion does not [90]. Duverne et al. [23] suggests social setting does not affect interpersonal space in virtual reality. Interpersonal space is measured in different ways depending on the exact goals of the experiment. Consistent with significant work in both psychology and virtual reality, we measure it using a comfort distance judgment [40, 71, 90], that is, a participant indicates at what distance they first become uncomfortable with the approach of a virtual human.

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Peripersonal space can be thought of as a safety zone around the body [19] that allows for the motor control of the body toward or away from potentially threatening stimuli. Real world studies show that, as interpersonal space, peripersonal space is dynamic and it has been shown to extend with tool use [9] and to contract when social interaction takes place, behaving congruently with how the behavior of another individual is perceived [80]. Peripersonal space has been mapped in mixed reality [74] and in immersive virtual reality [15], and these mappings are consistent with those in neurophysiological studies. This work measures peripersonal space in the same way (See Section 4.3).

None of this prior work addresses how technical characteristics of virtual reality in relation to a user's own bodily self representation might affect personal space. In this work, we hope to understand how manipulations of embodiment and the self-representation affect personal space. These are unique characteristics of virtual reality that can change from environment to environment, and it is important to understand how the spatial representation changes as these environments vary so that the fidelity of interaction can be preserved. We discuss how embodiment and the self-avatar manipulation can have an impact on personal space in the next two sections.

2.2 Embodiment

The sense of embodiment refers to "the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body" [47] and it can be easily induced in immersive virtual environments [76]. It affects the way people feel about self-avatars [81], and it affects the mediation of the space around the body [55]. There are several factors that contribute to the sense of embodiment such as self-location, body ownership, agency and motor control, and external appearance [32]. In this work, we focus on all but body ownership. In our work, as has been done in other work [29, 30, 49, 59], we manipulate these factors to control the overall sense of embodiment that a user experiences.

Specifically, self-location describes the physical collocation of the body with the self. Naturally, we have the sensation that our self-location and physicality are in the same determinate volume of space [55]. Gonzalez-Franco and Peck [32] noted that a self-avatar must be collocated with the user for the sense of embodiment to be induced. Kilteni et al. [47] also noted that the viewpoint of the avatar is important to self-location. Visuospatial perspective is typically egocentric, hence the origin of this perspective is important [12, 24]. More work backs these findings in that physiological responses to perceived threat are stronger when one is given a self-representation in the first person perspective rather than the third [66, 77].

The sense of agency refers to the feeling that one has "global motor control, including the subjective experience of action, control, intention, motor selection, and the conscious experience of will" [47]. The sense of agency is reduced when the visual feedback of an action and the actual movement are mismatched [11, 28, 73]. Franck et al. [28] show that the sense of agency is reduced when virtual reality users experience latency greater than or equal to 150 ms. The sense of agency further enhances the experience of embodiment [32] and can be increased when people view themselves in a virtual mirror [33]. It is not uncommon, however, for the sense of agency to be disrupted and influenced by the interruption of networking and graphical computations.

There are mixed results about how the appearance of a self-avatar affects the sense of embodiment; appearance can either enhance or inhibit levels of embodiment [32, 46, 63, 84, 86]. There is evidence that suggests that personalized avatars increase embodiment and presence [81] (although the avatars in this work were highly personalized). Recent work suggests that it does not have primary impact on embodiment [29, 52]. Nonetheless, avatar appearance is an easy experimental parameter to vary.

2.3 Avatar Manipulation

Since physical characteristics of humanoid models are readily manipulated in virtual reality, a body of work has emerged to understand how changes in self-representation affect interactions in immersive virtual environments. This literature suggests that users adapt to the size of their given self-avatar and behave accordingly. For example, Linkenauger et al. [57] showed that users adjust the perception of what they can grasp with their virtual hands when they vary in size. Jun et al. [43] also showed that people perceive that they can step over gaps according to the size of their virtual foot. Other works demonstrate results similar to these [20, 48, 56, 78, 79]. Work has shown that the perception of the self changes when users are given avatars of different heights (i.e., people given taller avatars act more confidently) [86], and the sense of embodiment can be affected [32]. Kammerlander et al. [44] showed that actors have greater success embodying characters of different proportions when they can visualize them in virtual reality. Additionally, there is work showing that perception of immediate reaching and grasping space extends when tools are used that increase arm length [9, 25, 37, 42, 50, 83] and can vary when virtual reality users are given self-avatars of different volume [63]. This body of literature suggests that manipulating the dimensions of a self-avatar's arms could lead to a change in the way users perceive the personal space around them in an immersive virtual environment.

3 Rationale and Hypotheses

As pointed out in the preceding discussion, it is common for users to embody their self-avatars in IVEs, but there are different factors that affect the level of embodiment felt [32]. Users also readily adapt their spatial perception to the dimensions of self-avatars that do not match their own [56, 57]. These lead to the research questions that we sought to answer:

R1 Does the level of embodiment affect the interpersonal and peripersonal space of users in an immersive virtual environment?

R2 Do an avatar's physical characteristics, such as arm length, affect the interpersonal and peripersonal space in an immersive virtual environment?

In our first experiment, we vary embodiment in three levels by varying a user's self-avatar, the latency and responsiveness of their movements, and their perspective. In the real world, the social psychology literature generally indicates that when people are in uncomfortable situations, their interpersonal space contracts, and vice-versa, expands when in comfortable contexts [35, 36, 39] Conversely, the cognitive science field generally finds that peripersonal space acts opposite to this, reducing when in emotionally charged or dangerous situations [19, 80]. This work led us to our hypotheses for the first experiment:

H1 Our conditions would be sufficient enough to evoke differing levels of embodiment.

H2 Comfort distance judgments would increase with higher embodiment levels while peripersonal space would contract.

In the second experiment, we vary the arm dimensions of the user's self-avatar in three conditions: *shorter* than the arm length of the user, the *normal* arm length of the user, and *longer* than the arm length of the user. Cognitive science literature finds that both interpersonal and peripersonal space extend during tool use that extends reach [68], and the virtual reality community has widely found users of IVEs to adapt interactions to the dimensions of a given self-avatar [43, 56, 57]. There is work that links arm reaching space with comfort distance in that they share a common motor nature [39]. However, with regard to the peripersonal space, recent literature has shown that peripersonal space has been decoupled from arm reaching space; peripersonal space does not cover the extent of arm reaching space, and arm reaching space is not sensitive to multisensory stimulation [88]. Thus, the hypotheses for the second experiment were:

H3 As arm dimensions decrease, comfort distance will decrease.

H4 As arm dimensions increase, comfort distance will increase.

H5 Lengthened or shortened arms will not change the representation of peripersonal space.

4 Experiment 1

In this experiment, we examine how embodiment affects the representation of personal space. We generated three levels of embodiment and had users react to agents entering their personal space while experiencing each level of embodiment.

4.1 Power and Experimental Participants

Prior to conducting our study, we ran an a priori power analysis using G Power[1] to determine an appropriate sample size. We chose two effect sizes of $d = 0.25$ and 0.5, accounting for small and medium effect sizes, to compute an appropriate range for the sample size, as well as an alpha error probability $\alpha = 0.05$, and power $\beta = 0.8$. The number of measurements given to G Power was 150, since this experiment would consist of 150 trials, and the number of groups was dependent upon the within subjects factors, which were in this case 3. Finally, the correlation among repeated measures was left as the default value of 0.5. The power analysis revealed that we would need 24 participants to obtain a medium effect size. We also considered the experiment conducted by Serino et al. [74], which is similar to our own, and had a similar number of participants. Thus, 24 participants (13 female, 11 male) between the ages of 18-30 (20.7 ± 3.1) were recruited and took part in this experiment. Participants were recruited through our institution's sign up system for psychology studies as well as through flyers that were placed around campus. All participants had no prior knowledge of the study and had normal or corrected-to-normal vision. The protocol was approved by our institution's IRB and sanitation measures were taken to protect participants and experimenters against COVID-19. There was no reported transmission of COVID-19. Participants gave informed, written consent and were paid $10/hour.

4.2 Apparatus

We used an HTC Vive Pro head-mounted display with two HTC SteamVR base stations, version 2.0, in addition to handheld controllers and two Vive trackers attached to a pair of shoes. The computer driving the HTC Vive Pro contained a 4.0 GHz Intel i7 6700K Quad-Core CPU equipped with 32GB RAM and an Nvidia GeForce GTX 1080 Ti graphics card. We measured the end-to-end latency of this system for one tracker using the technique described by Feldstein and Ellis [26] using an iPhone XS Max in Slo-Mo mode as our 240 frame per second camera. Over five tests the maximum latency was 12.5 ms, which is roughly consistent with the latency of the Vive system reported in Le Chénéchal and Chatel-Goldman [53], and we will assume that as our system latency.

We built the 3D immersive virtual environment using the Unity Game Engine (Version 2019.1.7f1), and all scripts were written in C#. The experiment was conducted in three different virtual rooms (see Figure 1) that were designed to be neutral, but different from one another, so that participants would not become accustomed to landmark cues that could affect their performance. Room 1 was 8 m x 7.7 m x 3.5 m, Room 2 was 9 m x 9 m x 3.5 m, and Room 3 was 6 m x 6 m x 3.5 m. Each room contained a virtual mirror, a marker on the floor where the user stood during the trials, five doors, some windows and various furniture items, pictures and plants. The items placed in the room were either modelled in Unity or taken from CGTrader.

The agent that was consistently used in all embodiment conditions and self-avatar used in the low and medium embodiment conditions (pictured in Figure 2) were taken from Adobe Mixamo. The self-avatars used in the high embodiment condition (see Figure 2 as well) were gender and race matched and made using Adobe Fuse, which has since been discontinued. The agent executed a walking animation that was also taken from Adobe Mixamo. The self-avatars that were used were all driven by Final IK, which uses inverse kinematics to compute the motions and positions of the self-avatar. Tracking data was used from the feet (Vive trackers), hands (Vive controllers), and head-mounted display to drive the self-avatar. The tracker positioning and full set up of equipment that users wore is depicted in Figure 3. All data was recorded immediately into a text file as users participated in the experiment, and was extracted into a csv file for analysis.

4.3 Experimental Design

Before beginning the study, participants were instructed on how to wear the virtual reality equipment and were allowed to adjust the head-mounted display and IPD to their comfort. They donned the head-mounted display, tracking shoes, and controllers and were given instructions on how to respond to each trial. We asked the participant their height to calibrate the self-avatar, and refined the dimensions as needed. Once the avatar was calibrated, the experiment began.

Low Embodiment	Medium Embodiment	High Embodiment
Avatar: Generic Humanoid	Avatar: Generic Humanoid	Avatar: Gender and Race Matched
Latency: 500 ms	Latency: 250 ms	Latency: System, 12.5 ms
Slow Down: 0.350 (30 Hz)	Slow Down: None	Slow Down: None
Viewpoint: Third	Viewpoint: First	Viewpoint: First

Table 1. This table describes the embodiment manipulations for each condition.

The same experimental protocol was followed for each block, and each block was done in a different room (Figure 1) with a different degree of embodiment. First, users were asked to perform an egocentric pointing task in the mirror so they would acclimate to their virtual body, and they were then asked to move and interact with their body while looking at themselves in the mirror. This period lasted 2 minutes, as prior literature shows that users can be primed and acclimate to a virtual body during priming phases that last from 1-5 minutes [1, 62, 85]. After this initial priming phase, users were asked to perform the same multisensory task as in [15] with a few differences to fit the experiment. Users were asked in one set of trials to report their comfort distance and another set to respond to a tactile stimulus. These sets of trials were counterbalanced to prevent an order effect. In the comfort distance trials, a virtual agent would approach the user from one of five doorways, which were placed at different angles around the user (0°, 45°, 90°, -45° and -90°). We had the virtual agent approach from these angles because personal space surrounds the body. If an agent approaches from the same direction every time, there is concern that participants could adopt a strategy and responses would become practiced and artificial. The appropriate door made a sound to indicate an avatar was approaching from it and the agent made audible footsteps when approaching, so that the particular doorway the agent was coming through could be discerned.

When the user became uncomfortable with the agent being in their personal space, they would pull either of the triggers on the controllers and the agent would disappear. There were 25 total randomized comfort distance trials, where each user experienced the agent approaching from each doorway five times. In the trials were the user exclusively responded to the tactile stimulus, which was a vibration delivered by one of the handheld controllers, the user would pull one of the triggers on the controllers each time the visual stimulus (the agent) approached in their direction. The agent walked towards the user at a speed of 75 cm/s until making contact with the user. There were a total of 25 randomized trials in which the tactile stimulus was delivered when the agent was 0.75 m, 1 m, 1.25 m, 1.45 m, or 1.85 m away from the user. The tactile stimulus was delivered five times at each distance and angle. Once the comfort distance and tactile response trials were complete, the user would answer an embodiment questionnaire to determine how embodied they felt during each condition. We used a modified questionnaire from Gonzalez and Peck [32], omitting two questions not relevant to the current experiment (see Supplementary Material for exact questions used). A single subject experienced a total of 150 trials and answered the embodiment questionnaire 3 times. All comfort distances and response times were logged as they were completed. It took participants 30-45 minutes to complete the experiment.

The experiment was done in three different blocks for each condition (low, medium, and high embodiment). The details of the embodiment manipulations are as follows and can be seen in Table 1. In each condition, we varied three components that have been shown to affect the degree of embodiment felt by users of IVEs: agency, self-location, and external appearance [32].

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

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

Fig. 2. The avatars used in both experiments. Top, from left to right: humanoid, Asian female, Black female, Caucasian female and Indian female. Bottom, from left to right: Asian male, Black male, Caucasian male and Indian male.

Fig. 3. The equipment used in both experiments. As seen, the Vive Pro HMD was worn, along with the handheld controllers and two Vive Trackers placed on the feet.

In the **low embodiment** condition, we manipulated agency by implementing 500 ms of latency in addition to the inherent system latency and by applying a scalar value of 0.35 to slow down the avatar and simulate a frame rate of about 30 Hz. Next, to manipulate self-location, the user was given the third person viewpoint (see Figure 4). And finally, to manipulate the external appearance, the self-avatar given in this condition was the generic, androgynous humanoid seen in Figure 2.

In the **medium embodiment** condition, we applied 250 ms of latency to the self-avatar. No slow down was applied to the self-avatar. The user saw their self-avatar from the first person viewpoint and the self-avatar given was the generic, androgynous humanoid.

Finally, in the **high embodiment** condition, no latency or slowdown was applied to the self-avatar. Users saw their self-avatar from the first person viewpoint and the self-avatar given was one of the gender and race matched avatars seen in Figure 2.

Latency refers to network latency that causes a disturbance between the action and visual feedback of users in an environment, and we applied latency by delaying updates of the self-avatar's position and rotation. Slow down refers to GPU overload, i.e., GPU throttling that introduces drops in performance that affect frame rate. We implemented slow down by forcing the linear interpolation of the position and rotation from one point to the next to occur over a fixed time period, thus slowing down the movements of the user's self-avatar. It is important to note that both latency and slow down were *only* applied to the self-avatar, and not to the surrounding environment. The degree of latency and slow down applied were chosen to be noticeable by the user and greater than the level of latency that affects embodiment [28, 47]. We tested these levels of latency and slow down ourselves when building the environment to determine what would be greatly noticeable in the low embodiment condition and less so but still noticeable in the medium embodiment condition. We felt that by generating a higher level of latency and including slow down in the low embodiment condition, users would experience little to no agency over the self-avatar, and that by generating some latency in the medium embodiment condition users would experience only disturbed agency.

Additionally, the third person perspective was implemented by having the camera always follow directly 1.25 m behind the self-avatar at eye height. This could cause the user's vision to be occluded by the self-avatar, so users were allowed to adjust the position of the camera left or right in small increments of 0.1 m as needed to see over the shoulder before the trials began.

4.4 Analysis and Results

Our data consist of the comfort distances and reaction times measured as agents approached during the different conditions (low, medium, and high embodiment) as well as the responses to the embodiment questionnaires. We perform three primary analyses: first, we determine how both the comfort distance and reaction times were influenced by the conditions of the study, second we determine the peripersonal space boundaries and how they were influenced by the conditions of the study, and finally we determine the difference in embodiment experienced during the three conditions. The data contained outliers, which was expected, as there were trials where participants either reacted too quickly by accident or had a delayed reaction where they would forget to pull the trigger in response to the stimuli. In these instances, the comfort distance or reaction time recorded was a positive floating point number. We systematically removed these instances using Tukey's method of fences. The upper fence for each reported comfort distance and reaction time were calculated and we removed any distance or reaction time that was greater than the upper fence. The upper fence was the boundary at which a data point would be three standard deviations

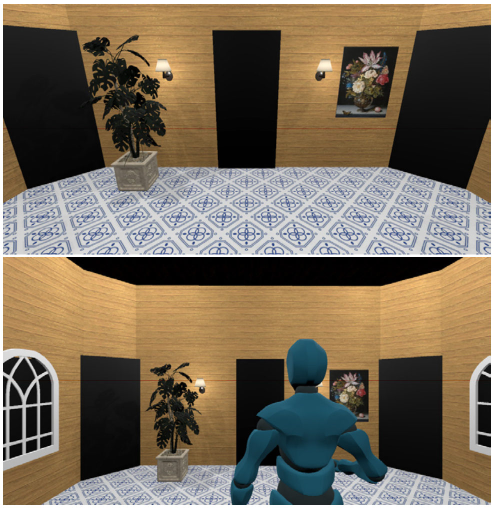

Fig. 4. A view of the environment from the first person viewpoint (top) and the third person viewpoint (bottom).

from the mean. We did not remove values below the lower fence since these were negative values and there were no negative distances at which someone could report their comfort distance and no negative reaction times. This process removed 2.8% of the data; as noted, the outliers removed were typically instances where the participant did not respond correctly during the trials.

Comfort Distance. We first performed an analysis to determine if comfort distances were different based on the level of embodiment. Using SPSS, we ran an analysis of variance (ANOVA) with condition (embodiment: low, medium, high) as the within-participant independent variable. All assumptions were checked and corrected for by SPSS. The ANOVA found a main effect of condition $F(2,46) = 3.242$, $p = 0.048$, $\eta_p^2 = 0.12$. Post hoc pairwise analyses were run using Fisher's LSD. This method controls controls for type I error among three groups at the nominal rate and thus additional significance correction was not needed [61]. The LSD test revealed statistically significant differences between the comfort distances in the high embodiment condition ($M = 0.986$ m, $SE = 0.019$) and both the low ($M = 0.817$ m, $SE = 0.018$) and medium ($M = 0.857$ m, $SE = 0.023$) embodiment conditions. There was no significance in the comfort distances between the low and medium embodiment conditions. Table 2 shows the post hoc comparisons.

Level of Embodiment		Mean Difference	Significance
Low (0.817 m)	Medium (0.857 m)	0.040	$p = 0.619$
	High (0.986 m)	0.170*	$p = 0.027$
Medium (0.857 m)	High (0.986 m)	0.129*	$p = 0.028$

Table 2. Fisher's LSD post hoc comparisons of the comfort distances between the three levels of embodiment for Experiment 1. Mean comfort distance for each condition are denoted in parenthesis. *Denotes statistical significance.

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

Level of Embodiment		Mean Difference	Significance
Low (0.319 s)	Medium (0.368 s)	0.049*	$p = 0.008$
	High (0.314 s)	0.005	$p = 0.598$
Medium (0.368 s)	High (0.314 s)	0.054*	$p = 0.004$

Table 3. Fisher LSD post hoc comparisons of the reaction times between the three levels of embodiment for Experiment 1. Mean reaction time in seconds for each level are in parenthesis. *Denotes statistical significance.

Distance		Mean Difference	Significance
0.75 m (0.267 s)	1 m (0.291 s)	0.024*	$p = 0.002$
	1.25 m (0.325 s)	0.058*	$p < 0.001$
	1.45 m (0.354 s)	0.087*	$p < 0.001$
	1.85 m (0.431 s)	0.164*	$p < 0.001$
1 m (0.291 s)	1.25 m (0.325 s)	0.033*	$p < 0.001$
	1.45 m (0.354 s)	0.063*	$p < 0.001$
	1.85 m (0.431 s)	0.140*	$p < 0.001$
1.25 m (0.325 s)	1.45 m (0.354 s)	0.029*	$p < 0.001$
	1.85 m (0.431 s)	0.106*	$p < 0.001$
1.45 m (0.354 s)	1.85 m (0.431 s)	0.077*	$p < 0.001$

Table 4. Fisher's LSD post hoc comparisons of the reaction times at each distance for Experiment 1. Mean reaction time in seconds for each distance are in parenthesis. *Denotes statistical significance.

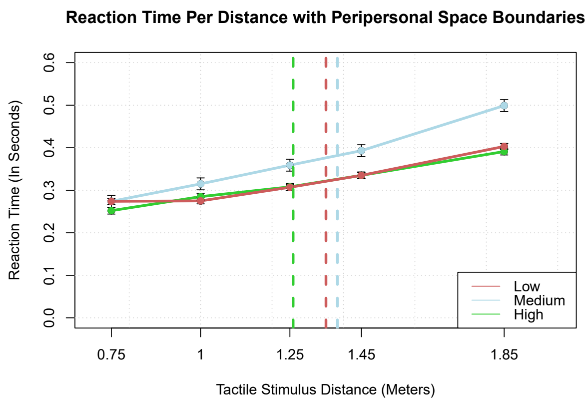

Fig. 5. This figure depicts the average reaction time per distance for each condition at each distance. Peripersonal space boundaries (not directly correlated with reaction time here) are represented by the dotted lines ($M = 1.351$ m, 1.383 m, and 1.259 m for low, medium and high embodiment respectively). Error bars represent the standard error.

Peripersonal Space Boundaries. To determine the peripersonal space boundaries we employed a method that has been used in several previous works [15, 17, 45, 74]. This method involves fitting the data to a a sigmoid function to extract the boundaries. The fitting equation is as follows:

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

where x is the *independent* variable, or the distance of the agent, y is the *dependent* variable, or the reaction time; $y_{\min}$ and $y_{\max}$ are the upper and lower saturation levels of the sigmoid, or the minimum and maximum reaction times recorded across trials; x_c is the value of the abscissa at the central point of the sigmoid; and b is the slope of the sigmoid at the central point. Both x_c and b vary dependent on the data and are estimated during the fitting. The parameter x_c represents the midpoint of the region of greatest increase in reaction time to the visual stimulus, i.e., the boundary of peripersonal space. Note that this boundary is based on the rate of change of reaction times, but not on the absolute values of the reaction times. To determine each peripersonal space boundary, all reaction times for each trial were averaged at each distance per subject, providing a set of (x,y) data points to fit the sigmoid to. The coefficient of determination (R^2) was extracted as a goodness-of-fit measure. For this experiment, the average peripersonal space boundary was 1.33 m. The exact boundaries for each condition are as follows: low embodiment was 1.35 m, medium embodiment was 1.38 m, and high embodiment was 1.26 m. The average goodness-of-fit measure was 0.81.

We ran an ANOVA with condition (embodiment: low, medium, high) as the independent variable to determine if the peripersonal space boundaries changed based on level of embodiment. A main effect of condition was found $F(2,46) = 4.206, p = 0.021, \eta_p^2 = 0.16$. We again used Fisher's LSD for post hoc analyses. A significant difference in the peripersonal space boundaries were found between the low and high embodiment conditions as well as the medium and high embodiment conditions, while there were no other differences between the other conditions. The comparisons can be seen in Table 5. We next performed a Bayes factor analyses. Bayes factors provide support for the null hypothesis through an odds ratio[2]. The method that we used is described by Rouder et al. [70], which takes into account the sample size and adjusts for power. Prior odds were set to 1, which favors neither the null nor the alternative hypothesis. Comparing the low and high conditions gives a Jeffrey-Zellner-Siow (JZS) Bayes factor of 2.01 in favor of the alternative, and comparing the medium and high conditions gives a JZS Bayes factor of 3.96 in favor of the alternative. Finally, comparing the low and medium conditions gives a JZS Bayes factor of 5.26 in favor of the null hypothesis.

Level of Embodiment		Mean Difference	Significance
Low (1.351 m)	Medium (1.383 m)	0.032	$p = 0.533$
	High (1.259 m)	0.093*	$p = 0.023$
Medium (1.383 m)	High (1.259 m)	0.125*	$p = 0.011$

Table 5. Fisher LSD comparisons of the peripersonal space between the three levels of embodiment for Experiment 1. Mean peripersonal space boundaries for each level are in parenthesis. *Denotes statistical significance.

Embodiment. Finally, we analyzed the results from the embodiment questionnaires to determine if users experienced differing levels of embodiment during each condition. Embodiment questionnaire scores ranged from -3 to 3 with -3 being the lowest level of embodiment and 3 being the highest. We performed an ANOVA with condition (embodiment: low, medium and high) as the independent variable and found a main effect, $F(2,46) = 32.824$, $p < 0.001, \eta_p^2 = 0.61$. Post hoc analyses using Fisher's LSD showed a significant difference in the embodiment scores between the low ($M = -0.519$, $SE = 0.198$) and both the medium ($M = 0.523$, $SE = 0.156$) and high ($M = 0.708$, $SE = 0.137$) embodiment conditions, but no difference between the medium and high embodiment conditions. Table 6 shows the comparisons.

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

Level of Embodiment		Mean Difference	Significance
Low (-0.519)	Medium (0.523)	1.042*	$p < 0.001$
	High (0.708)	1.227*	$p < 0.001$
Medium (0.523)	High (0.708)	0.185	$p = 0.135$

Table 6. Fisher LSD comparisons of the embodiment questionnaire scores between the three levels of embodiment for Experiment 1. Mean scores for each condition are in parenthesis. *Denotes statistical significance.

4.5 Discussion

In this experiment, the level of embodiment had an effect on both interpersonal and peripersonal space. We were able to confirm or partially confirm all hypotheses. Our conditions evoked differing levels of embodiment (H1), and users experiencing the highest degree of embodiment regulated interpersonal and peripersonal space differently than those experiencing lower degrees of embodiment (H3). There was a significant difference in the reported comfort distance between the high embodiment condition and both the low and medium embodiment conditions. Additionally, peripersonal space boundaries generated were similar to those generated in previous literature [15, 74], with a bound of 1.35 m for the low condition, 1.38 m for the medium condition, and 1.26 m for the high condition. Another noticeable result is that interpersonal and peripersonal space were inversely correlated; the interpersonal distance expanded as embodiment increased while the peripersonal space contracted as embodiment increased.

While the embodiment scores were only statistically significant between the low condition and both the medium high conditions, we were still able to manipulate embodiment. Users that experienced the third person avatar often commented that they did not think of the avatar as themselves, and this is reflected in previous literature [34, 65, 77]. Additionally, users seemed to respond positively to the avatars that were gender and race matched. One even commented that the hair and skin color of the avatar made it feel like the avatar was customized. There has been work that has shown avatar personalization to positively impact the sense of embodiment [81]. However, it is important we treat this result with caution, considering the fact that there are some instances in which avatar customization adversely affects embodiment [58] and has the potential to not affect it at all [52]. Any of the other factors, such as the omission of lag and slow down combined with the first person viewpoint, could be the key to the increased level of embodiment in the high embodiment condition. The lack of statistical significance between the medium and high embodiment scores could be due to the fact that latency was only applied to the self-avatar, and that users were not paying attention to the self-avatar during the actual trials since they were given the first person viewpoint and they were not actively moving about the environment. The degree of latency could have also affected this, since latency traditionally only produces a sharp decline in embodiment at 500 ms. We additionally note that the variance in scores increased with the level of embodiment, with the highest variance occurring in the low embodiment scores and lowest in the high embodiment scores. The clothing of the self-avatars could have an impact on embodiment and interaction, but note that users can embody avatars that do not remotely possess the same characteristics as themselves [8, 86] and that users solely interacted with the humanoid avatar (Figure 2), which was devoid of any definitive characteristics.

Another interesting finding to note is the interaction of distance and embodiment on reaction time. Figure 5 shows that the reaction times are slower at all distances in the medium embodiment condition. This can be attributed to a few different factors. In the low embodiment condition, the third person perspective gave participants a wider field of view. This field of view allowed users to see, and thus react more quickly to the approaching avatars. In the medium embodiment condition, the first person perspective afforded users a more restricted field of view that required users to turn their heads to find the approaching avatars. This, coupled with the applied latency, slowed the reaction times of the users. Latency beyond the system latency was not present in the high embodiment condition to evoke slower reactions.

5 Experiment 2

In this experiment, we examined how personal space would change when the arm dimensions of a self-avatar change. The same task as in Experiment 1 was given to users, except this time the arm dimensions of the self-avatar were either the user's own arm dimensions, shorter, or longer.

5.1 Power and Experimental Analysis

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

5.2 Apparatus

The apparatus and experimental setup in this experiment was the same as in Experiment 1.

5.3 Experimental Design

The experimental design paralleled that of Experiment 1. There were three conditions: shorter arm, normal arm, or longer arm. Experimental trials were done in three blocks. In the first block, the dimensions of the avatar were always calibrated to those of the user (normal arm length). In the second and third block, which were counterbalanced, the dimensions of the self-avatar's arms were calibrated to either be 12.5% longer or shorter than the natural arm length of the user. The different arm lengths are pictured in Figure 6. This design was chosen so that participants would accustom themselves to the task and understand their natural arm length in the virtual environment, so that they could then understand and see the affect of a perturbed limb length. We were motivated in this design by our prior experience with recalibration studies [1] and studies of the effect of feedback in mixed reality [31]. Users were given the generic humanoid avatar as their self-avatar. We chose this avatar since we felt that users would be able to detect changes in arm length easier. We did not want characteristics from a more detailed self-representation distracting from this change.

The same experimental protocol was followed for each block of trials. First, users were asked to perform an egocentric pointing task in the mirror so that they would acclimate to their virtual body, and they were then asked to move and interact with their body while looking at themselves in the mirror. This period lasted 2 minutes. After this initial priming phase, users were asked to complete a "block task" in which they would reach towards blocks that were placed in front of them at different heights so that they could acclimate to their given arm length. This task also lasted 2 minutes. A user can be seen performing this task in Figure 7. After this task, they were asked to either report their comfort distance or to respond to a tactile stimulus (as in Experiment 1, the same task used in Buck et al. [15]) as they were approached by an agent. The protocol of the experiment from here on out was the exact same that was used in Experiment 1 with one exception. Every 5 trials, a yellow cube that was 0.15 m x 0.15 m x 0.15m would appear 0.5 m away directly in front of the user at a height of 1.25 m, and the user would reach toward the cube to receive a quick reminder of their arm length. Once the user touched the cube, it would disappear and trials would resume. Again, each user experienced a total of 150 trials. Along with the embodiment questionnaire, users were asked about their arm length after each set of trials. They were asked if they noticed their arms to be longer or shorter than their actual arm length. It took participants 45 minutes to 1 hour to complete the study.

5.4 Analysis and Results

The data for this experiment consist of comfort distances and reaction times measured as agents approached during the different conditions (normal, shorter, and longer arm dimensions). Our method of analysis generally parallels the methods used in Experiment 1, Section 4.4. Thus, we first determined and removed the outliers. This process removed 2.8% of the data again.

Comfort Distance. We ran an ANOVA with condition as a factor (dimension: normal, shorter, longer arms) to determine how condition affected comfort distance, checking and correcting all the ANOVA's assumptions as needed. We found a main effect of condition $F(2,46) = 4.596$, $p = 0.015$, $\eta_p^2 = 0.17$. Post hoc analyses were run using Fisher's LSD. The results revealed that the comfort distance for the normal arm dimension manipulation ($M = 1.269$ m, $SE = 0.111$) was significantly different from both the short ($M = 1.154$ m, $SE = 0.095$) and long ($M = 1.161$ m, $SE = 0.094$) arm dimension manipulations. There was no significant difference in the comfort distance when the arm dimensions were longer versus shorter. Table 7 shows the post hoc comparisons.

Dimension Manipulation		Mean Difference	Significance
Normal (1.269 m)	Short (1.154 m)	0.115*	$p = 0.038$
	Long (1.161 m)	0.108*	$p = 0.026$
Short (1.154 m)	Long(1.161 m)	0.007	$p = 0.791$

Table 7. Fisher's LSD comparisons of the comfort distance between the three arm dimension manipulations for Experiment 2. Mean comfort distance for each manipulation are in parenthesis. *Denotes statistical significance.

Reaction Time. Next, we ran a 3 (dimension: normal, shorter, longer arms) x 5 (distance) factorial ANOVA to determine if the reaction times were different based on the different arm dimensions as well as when the tactile stimulus was delivered at different distances. We found a main effect of distance $F(4,92) = 80.268$, $p < 0.001$, $\eta_p^2 = 0.78$, but no effect of condition. The post hoc analysis with Fisher's LSD revealed a significant difference between all reaction times for each distance. The average reaction times for each distance are as follows: 0.250 s ($SE = 0.011$) at 0.75 m, 0.266 s ($SE = 0.010$) at 1 m, 0.290 s ($SE = 0.011$) at 1.25 m, 0.313 s ($SE = 0.011$) at 1.45 m, and 0.367 s ($SE = 0.013$) at 1.85 m. The significance comparison can be seen in Table 8. Figure 8 provides a visual supplement to these results.

Distance		Mean Difference	Significance
0.75 m (0.250 s)	1 m (0.266 s)	0.017*	$p = 0.003$
	1.25 m (0.290 s)	0.040*	$p < 0.001$
	1.45 m (0.313 s)	0.064*	$p < 0.001$
	1.85 m (0.367 s)	0.117*	$p < 0.001$
1 m (0.266 s)	1.25 m (0.290 s)	0.024*	$p < 0.001$
	1.45 m (0.313 s)	0.047*	$p < 0.001$
	1.85 m (0.367 s)	0.100*	$p < 0.001$
1.25 m (0.290 s)	1.45 m (0.313 s)	0.023*	$p < 0.001$
	1.85 m (0.367 s)	0.077*	$p < 0.001$
1.45 m (0.313 s)	1.85 m (0.367 s)	0.054*	$p < 0.001$

Table 8. Fisher's LSD post hoc comparisons of the reaction times at each distance for Experiment 2. Mean reaction time in seconds for each distance are in parenthesis. *Denotes statistical significance.

Peripersonal Space Boundaries. We determined the peripersonal space boundaries using the same fitting equation used in Section 4.4. For this experiment, the average peripersonal space boundary was at 1.39 m. The exact boundaries for each condition are as follows: normal arm dimensions at 1.429 m ($SE = 0.044$), longer arm dimensions at 1.404 m ($SE = 0.044$), and shorter arm dimensions at 1.350 m ($SE = 0.041$). The average goodness-of-fit measure was 0.87.

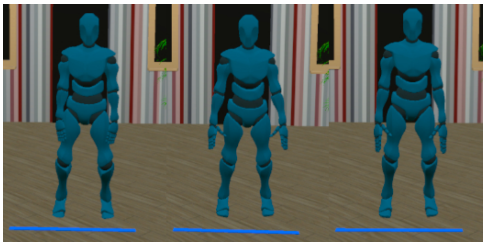

Fig. 6. The self-avatar with each arm length. From left to right: shortened, normal, and longer arms.

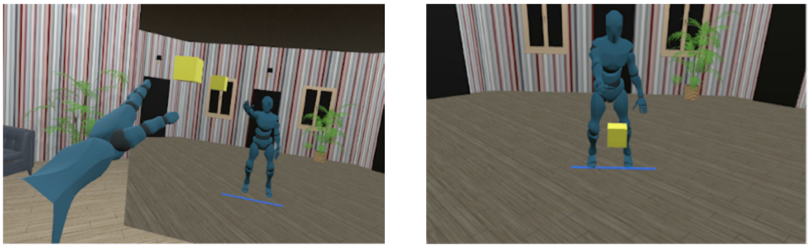

Fig. 7. A user performing the pre-trial block task.

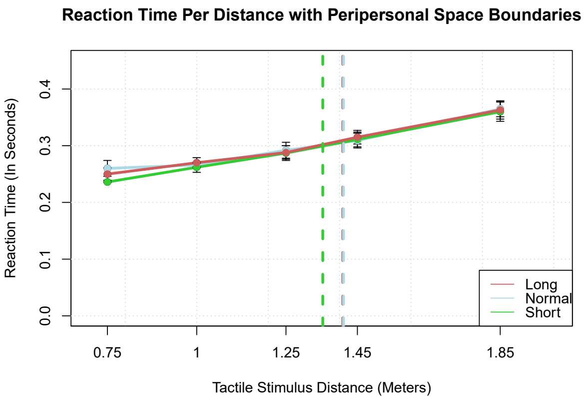

Fig. 8. This figure depicts the average reaction time per distance for each condition at each distance. Peripersonal space boundaries are represented by the dotted lines ($M = 1.429$ m, 1.404 m, and 1.350 m for normal, longer and shorter arm dimensions respectively). Error bars represent the standard error.

An ANOVA with condition (dimension: normal, shorter, longer arms) as the factor showed no significant difference in the peripersonal space boundaries between each manipulation. To further confirm these results we again performed Bayes factor analyses. Comparing the peripersonal space boundaries of those with normal versus long arm dimensions gives a JZS Bayes factor of 5.54 in favor of the null, those with normal versus short arm dimensions gives a JZS Bayes factor of 6.28 in favor of the null, and those with short versus long arm dimensions gives a JZS Bayes factor of 6.06 in favor of the null. Thus we can see that there are strong odds in favor of the peripersonal space boundaries of the users being the same even when the arm dimensions of the self-avatar are manipulated.

Embodiment. We ran an ANOVA with condition (dimension: normal, shorter, and longer arms) as the factor on the embodiment questionnaire data as in Experiment 1 and found a main effect of condition $F(2,46) = 3.262$, $p = 0.047$, $\eta_p^2 = 0.12$. Post hoc analysis using Fisher's LSD revealed a significant difference between the embodiment scores in the short versus long arm dimension manipulations, but no other significant differences. The average embodiment scores for each arm dimension manipulation are as follows: 0.451 ($SE = 0.112$) for the normal condition, 0.404 ($SE = 0.109$) for the short condition, and 0.250 ($SE = 0.125$) for the long condition. Table 9 shows the comparisons. We also note that 80% of participants accurately noticed their arm length was normal, 70% were able to note when their arms were longer, and 60% could note when there arms were shorter.

Order. To see if there were any effects caused by the ordering of conditions, we examined the difference between comfort distance for participants who experienced the short arm first and the long arm first (recall that the orderings were normal-short-long and normal-long-short). A two-tailed t-test showed a significant difference between

Dimension Manipulation		Mean Difference	Significance
Normal (0.451)	Short (0.404)	0.047	$p = 0.570$
	Long (0.250)	0.201	$p = 0.070$
Short (0.404)	Long (0.250)	0.154*	$p = 0.005$

Table 9. Fisher's LSD comparisons of the embodiment questionnaire scores between the three arm dimension manipulations for Experiment 2. Mean questionnaire scores for each manipulation are in parenthesis. *Denotes statistical significance.

the short and long arm first conditions, $t(598) = -3.351$, $p < .01$ ($M_S = 1.07$, $SE = 0.03$; $M_L = 1.20$, $SE = 0.29$). Likewise, when we examined the comfort distance between the short arm second and long arm second conditions, we found a significant difference between them, $t(598) = 3.183$, $p < .01$ ($M_S = 1.25$, $SE = 0.03$; $M_L = 1.12$, $SE = 0.03$). However, there was no difference between the peripersonal space boundaries between either of these conditions.

5.5 Discussion

Our data analyses presented some interesting, complex findings with regard to both interpersonal and peripersonal space. We confirmed H3, that when users experienced shorter arm dimensions the comfort distance would decrease. However, we did not confirm H4, that when users experienced longer arm dimensions the comfort distance would increase – the opposite occurred. Our analysis revealed that there was a significant difference between the normal comfort distance and both the longer and shorter arm dimension conditions. Our analysis also found no difference between the embodiment scores for the short and normal arm dimension conditions. The decrease in embodiment in the long arm dimension condition could explain why users allocated a shorter comfort distance between themselves and the agent, since we have seen in Experiment 1 (Section 4) that as embodiment decreases, so does comfort distance. Overall, users also responded that they noticed more when their arm dimensions were longer (they noticed the longer arm dimension manipulation 10% more than they noticed the shorter arm dimension manipulation).

The peripersonal space boundaries did not change based on the manipulation of the arm dimension, confirming H5. Note that the reaction times were not responsive to arm length changes, but did change significantly as the agent approached closer to the user. This response is expected, consistent with the previous experiment and prior work [15,74], as objects and agents approaching within the peripersonal space cause the reaction time of the user to the tactile stimulus to significantly decrease. A closer examination of our results reveals that some of our results may be due to order effects, in that we were not able to confirm H4, perhaps due to practice effects, but that H5 does not seem to be affected by the order. It is also interesting to note that the comfort distances and peripersonal space boundaries in this experiment were wider than those found in Experiment 1. This may be due to the age range of the participants used in this experiment, since there were older participants. Studies have shown that the representation of peripersonal space changes with age, with older adults allocating attention differently within this space [13]. Additionally, age is known to shape perception and acceptance of technology, and could have an impact on the way participants interacted with the environment [4].

6 General Discussion

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

Comfort distance and reaction time were both measured reliably based on previous metrics [15, 22, 36, 74], and our results reflected realistic interpersonal and peripersonal space measurements. It is interesting to see that we were able to reliably manipulate the sensation of embodiment in Study 1, but particularly so with regard to the appearance of the self-avatar since there is conflicting literature about the effects of increasing avatar realism on embodiment [32, 52, 58, 81]. Our embodiment manipulation provides the insight that gender and race matched avatars can perhaps be deployed to enhance embodiment, but we caution that there is a fine line that could be crossed into the uncanny valley [75] that might reverse this positive effect and there is still work to be done in this space with regard to embodiment in immersive virtual environments. In general, personal space behaved as expected in Study 1, and this gives credence to the importance of evoking embodiment in virtual reality users to support realistic interaction behaviors.

Study 2 also provided us with some interesting findings with regard to self-avatar manipulation. The change in interpersonal space when arm dimensions are manipulated show that, perhaps when users feel that some dimensions of self-avatars do not reflect their own, there is a decrease in the required interpersonal space around the body. No change in peripersonal space was experienced, and this result shows that peripersonal space can behave reliably in an immersive virtual environment. There is mounting evidence that peripersonal space requires separate cognitive processes from arm-reaching space [51, 88], and there is no reason for peripersonal space to change when one's arm dimensions change.

Ultimately, the combined results from Studies 1 and 2 can give guidance to designers of immersive virtual environments who are interested in creating specific interactions. The fidelity of collaborative interactions that occur in immersive virtual environments is still low [16,38,89] and this is a difficult area of study that must be addressed. Our results give some insight into the proper design decisions one needs to make in order to facilitate realistic, comfortable social and non-social interactions. Both measurements of comfort distance and reaction times to agents can give researchers and developers insight into how users interact within their personal space and what types of interactions users are particularly attentive to and comfortable with, and what needs to be changed and studied to increase the realism of these interactions. Study 1 shows that to create rich representations of personal space, users should be placed in the first person perspective and potentially provided with detailed self-representations, and environments should be strategically designed to prevent drops in frame rate and latency. Study 2 suggests that the dimensions of self-avatars, specifically those of the arms, are not particularly necessary to maintain high fidelity representations of personal space. However, future work should expand upon the limitations here to best understand how different environmental manipulations affect interactions.

7 Limitations and Future Work

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

Another area for further investigation regards why the results of the second experiment were not symmetric, i.e., why users are affected consistently by perturbations in arm length. An examination of Figure 6 shows a more pronounced exaggeration of the arms when they are longer versus shorter. This could explain why users felt less embodiment in the longer arm dimension condition. Additionally, we manually set a clipping plane on the camera view so that users could not see the inside of their virtual avatar. This caused the view of the upper arm to be clipped when the user looked down at themselves and this clipping changed to reveal more or less of the arm as the user rotated their head (this is illustrated somewhat in Figure 7). The clipping of the upper arm could have affected the perceived length of arm dimension. We also have to take into account the fact that comfort distance could have shortened for both the short and long arm dimension manipulation simply because users always received feedback from the normal arm condition first before ever experiencing both the short and long arm dimension manipulations. Users could have been more comfortable with the experiment after completing the first round of trials and felt less risk associated with the approaching avatars. A third possibility is that it is known that people typically overestimate how much they can reach, and thus seeing a longer arm in a self-avatar may look reasonable [18, 31, 69]. Regardless, our findings pertaining to H3 support previous literature that denotes that users of virtual reality adapt the way they interact with the space around them to the given dimensions of their self-avatar [43]. However, further study is needed in this area.

Other limitations are due to the nature of current commodity-level virtual reality systems that are readily available. Nonverbal cues (facial expressions, gaze behavior, precise tracking, etc.) can change the way people perceive personal space [3, 5, 6, 71, 87], and there are several nonverbal communication modes that commodity level systems simply cannot easily support. While highly personalized self-representations are possible to create [81], this process is tedious, and it is difficult to create an avatar that encapsulates the individual characteristics of a user like age, exact skin tone, hair color, clothing, etc., and this is a limitation that persists in our work as well as in the research community at large. Additionally, there are personality factors that affect the mediation of personal space [36], but this extends beyond the scope of our study and this area is still largely untouched in the virtual reality literature. However, it is important in the future that we consider how differences in personality affect the way users treat and maintain the personal space around their bodies. For example, those afflicted with different mental disorders treat personal space differently [2, 41, 54], and personality type shapes personal space [41].

More generally, the embodiment illusion is composed of many factors interacting in complicated ways [32]. It is possible that our manipulation of embodiment, composed as it was of several different components, simply provided a correlation between personal space and embodiment. Regardless, we feel that this work provides both guidance for future, more detailed investigations into individual components of embodiment and their relation to personal space, and some guidance for developers of social virtual spaces.

It would be particularly interesting to continue this line of work to shed light on how differing technical factors of virtual reality affect and support interpersonal interactions. In both experiments, we measured personal space from a variety of approach angles, but we did not actually determine the shape of personal space. This would be a good topic for future work. Additionally, it would be fascinating to understand how distributed environments affect the mediation of personal space. Previous work has introduced differing results with regard to how people treat their interpersonal space in these scenarios, with some users exhibiting caution around others [16] and others carelessly colliding with the avatars of other users [67]. It would also be interesting to understand how differing degrees of sentience, or interactions with human-driven avatars and computer-driven agents, affect personal space since we know that eye gaze increases sentience and changes the way users mediate interpersonal space [6]. It would be particularly interesting to understand how gender affects personal space in instances where embodiment changes, since some work alludes to the fact that gender affects personal space allocation [40]. There are many different avenues for this work to take.

8 Conclusions

Ultimately, this work has shown that personal space — both interpersonal and peripersonal space — are responsive to the level of embodiment that a user experiences in an immersive virtual environment. Interpersonal comfort distance expands when one feels highly embodied, and contracts when one does not feel embodied. Peripersonal space contracts when one feels highly embodied, and expands when one does not feel embodied. These results demonstrate the importance of embodied interaction to support high fidelity virtual reality experiences. Additionally, we have also shown that personal space is responsive to a manipulation of the dimensions of a self-avatar. Comfort distance changes when the arm dimensions of a self-avatar are not natural, but peripersonal space does not change significantly. These results give insight into how differing factors of immersive virtual environments can change the way users mediate personal space, a finding that can enable designers and developers to create these environments to convey the type of interaction they desire. High quality interaction is important for a diverse range of virtual reality applications, such as those meant for therapy and training in many differing venues such as medicine, defense, and education [2, 14, 27]. The findings from our second experiment on peripersonal space are relevant to the neuroscience community, where there has been debate about the link between peripersonal space and arm-reaching space [88]. Our work provides evidence for the theory that peripersonal space and arm-reaching space are two distinct spaces processed differently in the brain. Further research is needed to understand this distinction fully, however, and its implications for the design of virtual environments.

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