Does Hand Size Matter? The Effect of Avatar Hand Size on Non-verbal Communication in Virtual Reality

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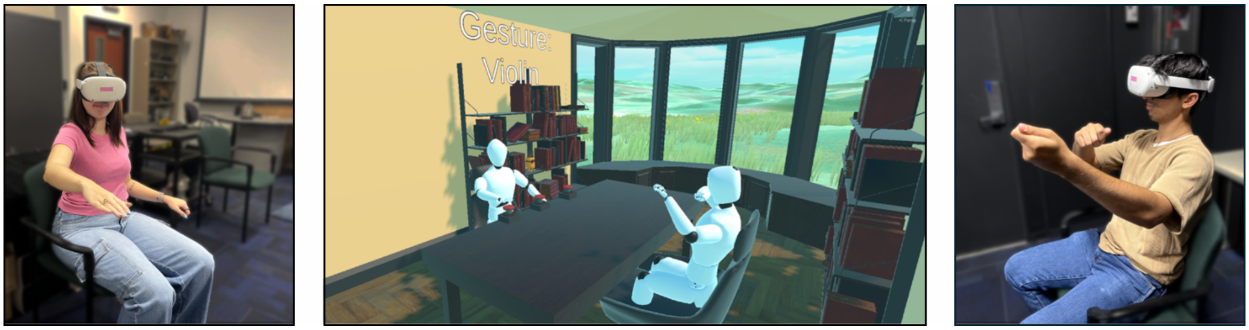

Fig. 1: Two users playing charades in VR. The user on the left is the guesser and the user on the right is the performer. Their respective avatars are shown in the center.

Abstract— Virtual reality (VR) has increasingly become a popular platform for socializing and collaborating remotely because it enables both verbal and nonverbal aspects of communication through the use of embodied avatars. However, such avatars are not typically adjusted to match the proportions of the user, leading to inaccuracies which might diminish experiences involving nonverbal communication. Therefore, in this paper, we investigated the impact that out-of-proportion avatar hands (relative to the user's hands) have on nonverbal communication and collaboration in VR. We designed an experiment based on the game "charades", wherein two users nonverbally interact with each other trying to communicate and guess words. In a within-subjects study with 72 participants (36 dyads), participants' avatar hands were scaled to be 25% smaller, the same size, and 25% larger than their own hands. We measured aspects related to task performance, avatar embodiment, communication satisfaction, workload, and user experience. We found that that changes in hand size of 25% did not significantly impact any of our measurements when looking at all participants. Interestingly, despite the relatively obvious change in size, less than half of the participants noticed this change. On further inspection, we uncovered significant effects in two of our workload measures when focusing only on the participants who noticed the changes. We conclude that the effects of changes in hand size may be modest for the type of task and hand size manipulations investigated in this work.

Index Terms—Virtual environments, communication, avatars, virtual reality, body proportions, embodiment

1 Introduction

Virtual reality (VR) has become an increasingly popular platform for socializing and remote collaboration. Applications such as VRChat, Horizon Worlds, and Rec Room enable users to socialize and play games in shared virtual environments and customize their appearance in the virtual world. Research suggests that communicating in VR might be an intuitive alternative to face-to-face conversation, with users exhibiting similar conversational patterns to real-life conversational scenarios [49].

Communication is complex and multi-modal, with many non-verbal cues such as facial expressions, body language, and gestures. When interacting in VR, users often embody and control an avatar that represents themselves in the virtual environment. Avatars are essential for elevating social and collaborative experiences in virtual reality. Avatars enable users to be co-located in a shared virtual space, which offers advantages over videoconferencing, allowing for a higher sense of co-presence [6] and enables indicative (deictic) gestures, such as pointing to an object of interest. Many aspects of avatars can affect user experience and perception [55], including the appearance [61] and animation [59]. Since most VR applications use one-size-fits-all avatars that are not proportional to each user, there might be limitations to using such avatars in conversational scenarios involving extensive nonverbal communication and gesturing. Therefore, we investigate whether altering the scale of avatar hands affects non-verbal communication and the perception of one's avatar.

Research emphasizes the importance of accurate finger motions for virtual characters and avatars [23]. Alterations to finger motion have been shown to affect the perceived personality of virtual characters [48] and the perception of an action being performed [22]. Moreover, diminished avatar hand animation may impact communication performance [3]. Therefore, it is crucial that users' intended actions are accurately mapped to their avatar. Hand tracking technology facilitates natural gesturing during avatar-mediated communication, and is now in popular VR devices such as the Meta Quest headsets and the Apple Vision Pro. However, avatars can vary widely in appearance, from highly realistic (e.g. Epic's "Metahumans"), to highly stylized (e.g.

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Meta's "Metaverse Avatars"), with variations in shape, size, color, and more. Most VR applications use relatively simple avatars that are one-size-fits-all, with customization mostly limited to visual features, such as hairstyle and clothing. Since the scale of an avatar's hands often does not match the size of the user's hands, the user's actions must be re-targeted to the avatar hand, which might result in inaccurate finger motion and diminish the quality of their gestures, and have negative consequences on non-verbal communication.

In this study, we investigate whether disproportionately scaled avatar hands (relative to the user's hand sizes) affect non-verbal communication and the perception of one's avatar. To this end, we designed an experiment in which two participants, each embodying featureless avatars, play charades in VR, while the scale of their virtual hands is manipulated. Charades requires one player to gesture certain words or phrases and the other player to guess, all without speaking to each other, and has been used in previous studies on communication in VR [3, 6, 17]. In our study, we vary only the scale of the avatar's hands, and measure participants' performance and concepts related to their communication experience and user experience.

2 Related Work

2.1 Communication in Virtual Reality

Technology has become essential for communicating with others in different locations, enabling a more globally connected world than ever before. With the increasing importance of remote connectivity, there is also a growing need for tools that facilitate remote communication and collaboration. Virtual Reality (VR) offers a promising channel for remote communication, facilitating both verbal and nonverbal interactions via embodied avatars in a shared virtual environment. Research shows that using avatars for communication results in high levels of social presence and is often preferred over communication without them [6]. One key advantage of avatars is that they enable nonverbal communication, particularly gestures, through the use of motion tracking. Hand gestures are critical components of nonverbal communication. They facilitate thought [16], improve collaboration, and help to convey information [4].

While videoconferencing applications, such as Zoom, are widely used, research indicates that VR offers advantages over videoconferencing for collaborative tasks. For instance, when comparing communication patterns between embodied VR and videoconferencing, Abdulla et al. [1] found evidence that nonverbal behavior using avatars was more effective in VR. Furthermore, social presence, a key measure of communication experiences in VR, is often found to be higher in VR. Greenwald et al. [17] compared face-to-face communication to VR by having participants perform charades and Pictionary, measuring social presence, workload (TLX), and system usability. Although their system did not support hand tracking, participants nevertheless reported high levels of social presence in the VR condition.

Previous research evaluating communication and collaboration in VR spans many aspects of the experience, from user perceptions about immersion to effects on remote collaboration. Our work expands on previous research by measuring user experience and effects on communication quality with a focus on hand motion and nonverbal communication during a two-party conversational task.

2.2 Avatar Appearance and Animation

Avatars offer countless ways to represent users in the virtual world. They can match the user closely, as with Apple's "Personas", or be heavily stylized and customized, such as the avatars in Horizon Worlds. The specific application may influence the style of avatar used [46], and technical limitations may limit the realism of avatars or the extent to which avatars can be customized. In the most popular VR social applications, avatars are limited and specific to that application, with limited customization, and unlikely to match the user's appearance or proportions.

Many characteristics of avatars can affect our perceptions of them [61], from their visual appearance and style [60] to their motion [22, 40, 48, 50]. Furthermore, just as we are adept at perceiving human motion [51], we are also highly sensitive to the motion of avatars and virtual humans [3, 22, 48].

The appearance of avatars can have wide-ranging effects on users' perceptions and preferences. For example, several studies suggest that moderately stylized avatars are preferred [40], while realistic self-avatars can result in higher perceived ownership [28]. When it comes to communication involving virtual humans, the appearance of avatars can affect aspects such as trustworthiness and appeal [6, 60]. Yoon et al. found no effect of avatar style (realistic vs. cartoon) on social presence [56].

In addition to the visual appearance of avatars and their overall motion, a range of qualities can be interpreted through hand movement alone. Gestures in particular play a significant role in communication [15]. Research suggests that this is true when communicating in VR as well, with evidence that an absence of finger motion can negatively affect the communication experience [3]. Other research indicates that very small errors in finger motion are perceptible and may impact the perceived actions being performed [22], and that altering gesture timing can affect the perceived personality of the agent [48]. Furthermore, the perceived personality of avatars can even be attributed to their hand motion [54]. These studies highlight the importance of detailed and accurate hand animation for virtual humans and avatars.

2.3 Embodiment

The sense of embodiment over self-avatars is heavily studied, as it has implications for immersion and the overall virtual experience. The sense of embodiment (SoE) over one's avatar describes the perception that the avatar's body is one's own body [25]. The literature cites three components constituting the SoE: body ownership, self-location, and the sense of agency [25, 32]. Ownership refers to the feeling that the virtual body is one's own body. Location is the feeling that one's body and the virtual body are in the same place. Agency is the feeling that one has control over the virtual body.

Realistic avatar hand representation can result in higher levels of ownership [5], but ownership can be established over less realistic hands [53] and even non-corporeal objects [28, 35]. Motion fidelity (motion tracking) of self-avatars can affect interaction performance and sense of agency - IK-based solutions resulted in better interaction performance but some IK solutions can result in a lower sense of embodiment than motion capture [59]. The congruence between the input modality used and the corresponding avatar representation rendered has also been shown to affect interactions with respect to embodiment and performance.

Previous work has found that ownership can be influenced by avatar motion fidelity [57, 59], with agency driven by user control over the avatar [36]. Results from previous work indicate that the rendering style of one's avatar can impact the level of ownership and embodiment the user feels over the avatar during interaction tasks [5, 28, 63]. For example, realistic avatars have been found to result in higher perceived embodiment [5, 28, 35, 58]. Research also suggests that avatar motion fidelity might impact the ownership and agency during interaction tasks [59].

2.4 Avatar Size Manipulation

Researchers have investigated how anthropometric manipulations of self-avatars affect several aspects in virtual reality. Along these lines, it has been shown that alterations to one's avatar's eye-height, shoulder width, or foot size can affect perceptions of affordances like gap-passability and crossability [8, 11, 24, 39]. In general, humans are not all that good at estimating bodily proportions, but are rather good at estimating the size of objects using their bodily proportions as a reference [30].

With respect to arms and hands, scaling the size of users' hands via real-time video displayed on a monitor tends to result in the virtual hand illusion not emerging when the hands were scaled to be smaller [44]. The size of users' self-avatar hands can also influence the perception of the sizes and graspability of objects [29, 42, 43, 52]. In an experiment investigating the effect of scaled hand size on interaction performance and embodiment, Lin et al. [27] found that the size of the hand did not

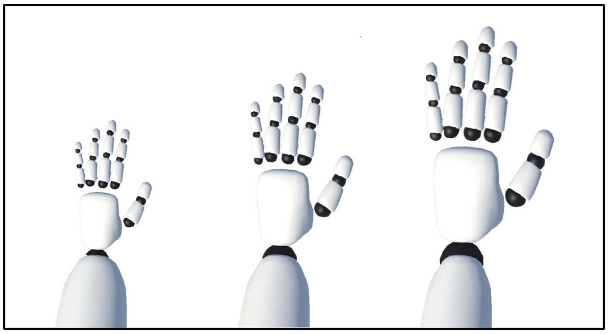

Fig. 2: The small (75%), fitted (100%), and large (125%) hand sizes used in our study.

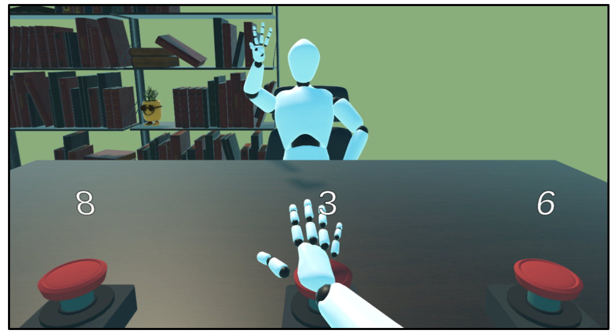

Fig. 3: Scene from the guesser's point of view during a trial.

significantly affect ownership or agency. When scaling the length of the avatar's arm, Kilteni et al. [26] reported that users experienced high levels of ownership over avatar arm-lengths scaled up to four times their real arm-lengths, but found that embodiment diminishes with increasing incongruity. While there has been extensive investigations into how the visual appearance of one's self-avatar affects self-avatar perceptions and virtual interactions, research into the influence of the size of one's self-avatar is comparatively sparse, particularly regarding communication. Therefore, we investigate the effects of self-avatar hand size manipulation within the context of communication.

3 Experiment

3.1 Task

For this experiment, a simple charades task was conceptualized wherein a dyad (two) of users would play a game of charades in the virtual world without verbal or auditory communication. The users were seated in front of each other in a virtual room with a virtual table separating them (Fig. 1). In each dyad, one user was randomly assigned the role of the performer and the other, the guesser. These roles were held throughout the course of the experiment. The performer was tasked with gesturing concepts/words using only their hands and the guesser would have to select the correct answer from one of three options laid out in front of them for each word/concept gestured. The experiment was divided into three blocks, one for each of the three levels of hand sizes investigated in this study (see Fig. 2). The hand size condition was the same for both participants in every block, meaning that at any point their hands would be either uniformly scaled by the same amount (75% or 125%) or by none at all (fitted). Each block consisted of twelve words/concepts that had to be guessed. Upon completing the charades task for these twelve words, both members of the dyad would answer a questionnaire measuring the constructs listed in Table 1. The completion of the questionnaire marked the end of the block. Before initiating the next block, both participants had to press a button confirming that they were ready to proceed, ensuring that each of them were ready before the next block commenced. This process was repeated until all three blocks of the experiment were completed. The order of the blocks was counterbalanced to control for potential order effects.

There were three categories of words/concepts namely easy, medium, and hard. Easy words were numbers between one and ten that could be gestured simply as one would by holding up their fingers. Words/concepts of medium difficulty were realized by making the three answer options distinguishable in terms of the gesturing commonly used to enact them. For example, a set of answer options containing "motorcycle", "car", and "plane" with the word to be gestured being "motorcycle" represented a word of medium difficulty. For words of hard difficulty, the answer options were less distinguishable from each other as in the case of a set of options containing "violin", "cello", and "guitar" with the word to be gestured being "violin". The classification of words into these three categories was performed based on pilot tests and semi-structured interviews with several participants to determine what options to provide for each word/concept category and which of them to preordain as the answer based on its distinguishability from the other options. The composition of word/concept-difficulties in each block was randomized by randomly choosing from a predefined list of 36 words equally represented by the three difficulty levels. This was accounted for in the analyses by ensuring that the average difficulty levels of the words/concepts across the blocks were not significantly different. A Shapiro-Wilk test of normality showed that difficulty (difficulty was 1=easy, 2=medium, 3=hard) was not significantly different from normal. A one-way ANOVA shows insignificant differences of average difficulty across hand size conditions ($F(2,105) = 1.289, p = 0.28$). While we considered using the same words/concepts across the three blocks, we refrained from doing so due to potential learning effects as a result of using the same words.

For each word/concept in a block, the performer was shown the word/concept to be gestured, and the guesser was provided three different options to submit as their answer, each marked by a separate button (see Fig. 3). The guesser would press the button denoting the option that they felt most closely represented the gestures being performed by the performer. Once the guesser confirmed their choice, visual feedback of whether their selection was correct or incorrect was provided through floating text above the performer. This feedback was only relayed to the guesser and not to the performer. This process continued until the remaining eleven words in that block were enacted and guessed by the dyad. Following this, the guesser would report how confident they were in their selection by pressing one of seven buttons displayed, which coincide with a 7-point Likert scale. The simulation was built such that the word/concept was only visible to the performer while the answer options were only visible to the guesser to ensure that the charades task was performed purely based on the gestures being performed using the performer's self-avatar hands without avenues for simulation-based exploits that members could make use of in attempts to game the system.

Prior to the experiment, each member of the dyad engaged in an embodiment phase. This phase, as routinely used in VR research on self-avatars [7, 9, 10, 33, 45], was used to promote and foster in users a sense of embodiment towards their self-avatars. Upon the commencement of this phase, users were provided with their self-avatars and could see themselves in a virtual mirror placed in front of them. Similar to Peck and Tutar's procedure [45], the embodiment phase required participants to perform a number of actions to achieve the desired sense of embodiment towards their self-avatar. Users were required to look around and move their self-avatars while looking into the virtual mirror, look down at their legs beneath their seats, and look in the up, down, and lateral directions. The users were also asked to perform actions and gestures like touching their fingertips, gesturing in front of their chests, and slowly moving their hands behind their heads, all while observing themselves in the virtual mirror. In addition to fostering a sense of embodiment to the avatar, performing these actions and gestures in the aforementioned locations gave participants a sense of the area in which their hands would be correctly tracked by the HMD and the areas beyond which hand-tracking would fail. This routine hence exposed participants to the bounds in which their hands could and could not be tracked for their self-avatars' movements, effectively serving as training for the upcoming experiment phase in which the charades game was played. This embodiment phase lasted for about five minutes after which each member of the dyad was prompted to press a "move on" button. When both members pressed their respective buttons, they were teleported to the virtual room in which the charades task was housed. On average, the embodiment phase and charades task blocks together took a dyad 25 minutes to complete.

3.2 Study Design

To empirically evaluate how the size of virtual hands affects non-verbal communication in an avatar-mediated VR experience, we employed a within-participants design, manipulating the size of users' virtual hands across three experimental conditions: (1) Small hands (hands scaled to 75% of actual hands); (2) Fitted hands (hands scaled to actual hands); (3) Large hands (hands scaled to 125% of actual hands) (see Fig. 2), while keeping the participant's role consistent throughout the experiment. Since every dyad consisted of one guesser and one performer, the participant's role can be considered a between-subjects factor. The hand sizes were chosen based on previous work that altered hand scales by the same amounts [27], as well as the fact that for the average human hand (7.6 inches), these modifications would push the scaled hands below and above the 5th (7.0 inches) and 95th (8.1 inches) percentiles of human hand sizes, respectively [38]. The virtual hands are structured as a hierarchy of joints, where the wrist joint is the parent to all finger joints. To scale the hands, a uniform scaling transformation is applied to the wrist joint, ensuring that all finger joints are proportionally scaled along with it. This method preserves the relative proportions and movements of the fingers. For example, when a user performs a pinching gesture by bringing the thumb and any fingertip together, this action is reflected on the avatar regardless of scaling. The wrist position and orientation are also preserved. Users in each condition engaged in a charades task described in section 3.1 for a number of trials (words/concepts) over three blocks, one for each size of the virtual hands tested in the study. A Balanced Latin Square design was employed to counterbalance the order of the hand sizes tested. This design was chosen to control for potential order effects, ensuring that each hand size (small, fitted, and large) was presented in each ordinal position (first, second, third) an equal number of times across participants (dyads), thus minimizing the influence of learning or fatigue. Given three different hand sizes, this meant that every participant (every dyad) experienced one possible order (out of a total of 6 possible orders) of hand sizes. In each block, users worked together to complete twelve words/concepts thus accruing up to a total of 36 trials (each trial corresponds to one word/concept) across the entire experiment. These 36 words were equally divided into three categories of difficulty namely easy, medium, and hard (12 words in each). The order of these 36 words/concepts was randomized across all three blocks.

3.3 Measures

We recorded the number of correct guesses, the guessing duration and the wrist motions of the participants for our objective measures.

Number of Correct Guesses - We count the number of correct guesses (out of 12) as a measure for task performance. Each trial resulted in an outcome that was marked with either a success or a failure in correctly guessing the word/concept being gestured.

Completion time - In each trial, the total timespan from the start of the trial (when the word to gesture was shown) to the end of the trial (when an answer was selected) was recorded. The completion time is computed as the sum of the times for all trials for one hand size.

Motion - We collected participants' movement data and computed three measures: cumulative wrist translation, average wrist velocity, and the volume of the bounding box. The cumulative wrist translation reflects the total distance traveled by the hands during a trial (the timespan between displaying a new charade word and the guesser selecting an answer). The distance traveled by each hand was calculated as the sum of distances between consecutive wrist positions: $\sum_{f=1}^{F-1} ||wristPos_f - wristPos_{f-1}||$ for frame f with F being the number of frames in the trial. The left hand and right hand distances traveled were then added to obtain the cumulative wrist translation. The average wrist velocity over each phase was calculated by dividing the distance traveled by the length of the phase. The bounding box volume was calculated as the volume of the box containing the range of movement of the wrists for each phase.All distance units are in meters.

At the end of each phase corresponding to a hand size, subjective measures were collected with the questions listed in Table 1. The constructs measured were:

Ownership and Agency - We included two standard questions to evaluate ownership and three questions for agency based on Ma and Hommel [34] and Zhang and Hommel [62]. Each participant evaluated only their own hands and not their partner's.

Message Understanding and Communication Satisfaction - To assess how participants perceived the communication, we measure message understanding with questions from Harms & Biocca [18] and communication satisfaction based on Hecht's work [21].

Workload - We used the NASA TLX questionnaire [20] to assess users' perceived workload.

User Experience - We asked five additional questions to evaluate further aspects of the user experience. These questions investigated immersion, fun, realism, perceived efficiency, and perceived difficulty to perform the gestures [27, 28].

3.4 Research Question and Hypotheses

The overarching aim of this study was directed towards answering the following research question: **"How does the difference in virtual and physical hand size affect communication ability and perception?"** Furthermore, we were interested in understanding if differing virtual and physical hand sizes affect embodiment and user experience. We operationalized performance based on the measures described in Section 3.3 and developed the following hypotheses that reflect the work discussed in Section 2 and later on in this section.

H1: Fitted hands will be associated with faster completion times.
H2: Fitted hands will produce higher communication satisfaction.
H3: Fitted hands will result in higher levels of perceived embodiment.
H4: Fitted hands will produce the lowest perceived workloads.

It can be expected that having to gesture concepts with altered hand sizes is likely to increase the amount of time taken to communicate the concept. Previous work indicates the subtle alterations to finger movements are perceptible [22]. Scaling the avatar's hands affects the speed of the fingertips (e.g., larger sizes are associated with faster movements because more distance is covered in the same time). This alteration might be noticed by users, potentially eliciting compensatory movements that lead to unnaturalness. For these reasons, we expect that scaled hand sizes will lead to lower communication satisfaction.

Regarding ownership, a previous study on the effects of hand size suggests that ownership can be established over different hand sizes without significant differences for a puzzle assembly task [27]. However, other research suggests that hand size modulates ownership [44]. In general, it has been found that changes in the avatar can affect ownership. Therefore, we expect that fitted hand sizes will produce higher degrees of ownership in the task employed in this study given the increased concomitance between users' actual hand sizes and their virtual counterparts.

With respect to workload, altered hand sizes will require users to perform gestures accounting for the manipulation. For example, in the large hand condition, one does not have to bring the hands as close together for the fingers to overlap. With small hands, getting the avatar fingers to touch would require overlapping one's real fingers. Both alterations might require adjustments for certain gestures, requiring the user to factor in the hand size while gesturing. This is likely to result in increased perceived workload.

3.5 Participants

Given that this was a team-based communication study, two participants were required to be physically present and participate in the experiment at the same time. An apriori power analysis using G*Power revealed that for a study of three hand sizes manipulated within-subjects and

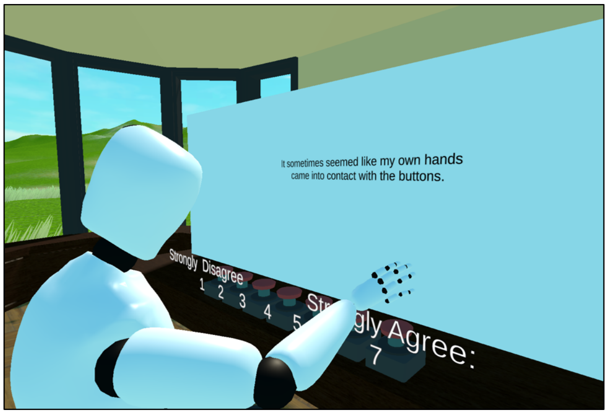

Fig. 4: Scene during the questionnaire phase of each block. Participants responded to each question displayed on a white dividing wall by pressing buttons laid out in front of them.

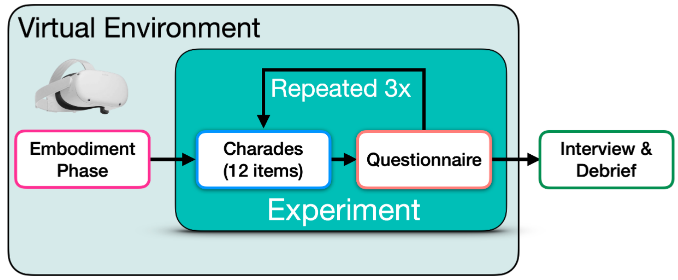

Fig. 5: Overview of the experimental procedure. Participants first embodied their avatar in an embodiment phase. They then played a game of charades and responded to our questionnaire at the end of the game. This process was repeated 3 times, once per hand size. Upon completion, they were interviewed and debriefed. Both the embodiment phase and experiment phase took place in VR.

two roles varying between-subjects, considering $\alpha = 0.05$, power ($1-\beta$) = 0.95, a medium effect size $f = 0.2$, correlation among repeated measures of 0.5, and assuming that sphericity is met, the estimated sample size was 66 (33 dyads). To ensure that all six possible orders of hand size configurations from the Balanced Latin square design were equally represented across all the participants of the study, we recruited 72 participants. In other words, 36 dyads engaged in the charades task across all three experimental conditions of virtual hand size. This led to a total of 1296 trials of charading for analysis on performance. Participant ages ranged from 18 to 40 years old (M = 21.54, SD = 3.83) with 48, 21, and 3 of them identifying as female, male, and non-conforming respectively. Additionally, ratings of charades-competence obtained on a 7-point Likert scale item phrased as "Do you know how to play the game Charades?" anchored from not at all to very well, indicated a mean score = 4.94 and SD = 1.69. All participants had normal or corrected-to-normal vision and normal upper body motor function. This research was performed under the oversight of Clemson University's Institutional Review Board.

3.6 Procedure

Upon arrival to the experimental setting, both participants (dyads) were asked to read and sign a consent form (informed consent) if they met the inclusion criteria (18 years or older, normal or corrected to normal vision, English-speaking, and having a full range of motion of arms and upper body). Participants were then separated, each following one experimenter to a different location. Upon separation, participants filled out a demographics questionnaire that included information about their backgrounds, experience with VR, and competence at charades. Following this, participants' interpupillary distances (IPD) were measured. The roles of guesser and performer were randomly assigned to the team members. Guessers were informed to take as much time as they needed and that their goal was to answer correctly. Each participant was also informed that there was no penalty for incorrect guesses. Each experimenter then detailed the task of the study based on the role to which they were assigned, further explaining the logistics involved with progressing through the three blocks of the experiment. These explanations included demonstrating how to perform gestures to interact with the HMD itself, such as the recentering command, as well as how to interact with the virtual environment, in particular with the buttons in the scene. Participants then donned the Oculus Quest 2 HMD (adjusted for their IPD) and familiarized themselves with the task and its mechanics. Participants then proceeded to perform the charades task in each block.

At the end of each block, participants filled out a questionnaire (Table 1) containing questions on embodiment, perceived communication effectiveness, workload, and user experience. Upon completion of all three blocks, participants removed the HMD. Each of the participants then proceeded to engage in a short semi-structured interview with the experimenter to discuss their experience in this study. The participants were asked what they thought the study was about, what strategies they used, whether they noticed any changes in between blocks, and whether their avatar changed at all between blocks. Finally, they were informed about the hand size modification and were asked if they felt that this affected anything in the study, such as communication or their sense of embodiment. They were then debriefed and compensated for their time. It took participants about 45 minutes to complete the entire experiment. An overview of the procedure is depicted in Fig. 5.

3.7 Apparatus

All participants wore a Meta Quest 2 HMD, which tracks the participants' hands using the native hand tracking system [41]. The experiment was implemented using Unity 2021.3.15f1 with XR Hands Package version 1.1.0 as well as the XR Interaction toolkit 2.3.3. The Mirror Networking for Unity package (version 79.0.1) managed the transmissions between a nearby desktop computer (the server) and the participants' HMDs over a WiFi 6 router. The simulation runs locally on each Quest 2 and simultaneously on the server. All data collection took place on the server, which received all inputs from each user. The server is a desktop PC with an Intel i7-7700K, 32GB of RAM, and an Nvidia GTX 1080 GPU.

3.8 Virtual Environment and Avatar

There were two virtual scenes used in this study, one for the embodiment phase and the other for the charades task. The environment for the embodiment phase was designed to be a small room with a mirror directly in front of where each participant sat. After both participants completed the embodiment phase (see Section 3.1), they each pressed a

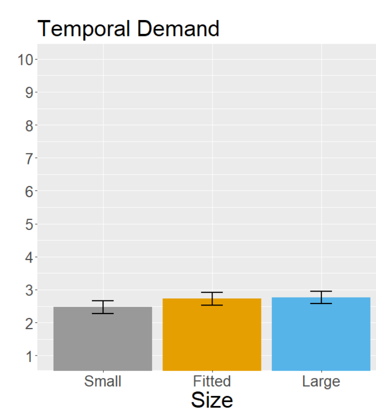

Fig. 6: There was a significant effect of hand size for temporal demand when looking at all participants (N = 72). Error bars show standard errors of the mean for each size.

Table 1: Questions shown to participants. All questions were answered on 7-point Likert scales except for NASA's Task Load Index, which was rated on a 10-point scale from Low to High, lower being better. Questions were shown to both participants, except for one question as indicated. The Statistic column shows the Friedman test results of Hand Size on each measure.

Measure	Question (RS = Reversed Scale)	Statistic	M (SD)
Ownership & Agency [34, 62]	O1: I felt as if the virtual hands were part of my body.	$\chi^2 = 0.473, p = 0.789$	5.67 (1.25)
	O2: It sometimes seemed like my own hands came, into contact with the buttons.		
	A1: I felt as if I could cause movements of the virtual hands.	$\chi^2 = 0.980, p = 0.613$	6.38 (0.85)
	A2: It felt as if I could control movements of the virtual hands.		
	A3: I felt as if the virtual hands moved just like I wanted them to, as if they were obeying my own will		
Message Under-standing [18]	My thoughts were clear to my partner.	$\chi^2 = 4.85, p = 0.0883$	5.27 (1.25)
	My partner's thoughts were clear to me.		
	It was easy to understand my partner.		
	Understanding my partner was difficult. (RS)		
	My partner had difficulty understanding me. (RS)		
Communi-cation Satisfaction [21]	The other person let me know that I was communicating effectively.	$\chi^2 = 0.765, p = 0.682$	2.71 (2.84)
	Nothing was accomplished. (RS)		
	I was very dissatisfied with the communication with my partner during the game. (RS)		
	I felt that during the game I was able to present myself as I wanted the other person to view me.		
	I did not enjoy communicating with my partner during the game. (RS)		
NASA's Task Load Index - 10pt Likert - [19]	How mentally demanding was the task?	$\chi^2 = 0.0306, p = 0.985$	3.15 (1.99)
	How physically demanding was the task?	$\chi^2 = 1.61, p = 0.447$	2.23 (1.79)
	How hurried or rushed was the pace of the task?	$\chi^2 = 7.21, p = 0.0271$	S: 2.47 (1.66) F: 2.72 (1.63) L: 2.76 (1.60)
	How successful were you in accomplishing what you were asked to do?	$\chi^2 = 1.07, p = 0.587$	7.88 (1.75)
	How hard did you have to work to accomplish your level of performance?	$\chi^2 = 0.349, p = 0.840$	3.70 (2.01)
	How insecure, discouraged, irritated, stressed, and annoyed were you?	$\chi^2 = 2.28, p = 0.32$	1.93 (1.39)
Realism [28]	I thought the virtual hands on the screen looked realistic.	$\chi^2 = 3.38, p = 0.185$	4.98 (1.60)
Immersion [28]	I was so immersed in the virtual environment, it seemed real.	$\chi^2 = 0.247, p = 0.884$	4.88 (1.47)
Fun [27]	I felt like using my virtual hands to communicate was fun.	$\chi^2 = 0.894, p = 0.640$	6.59 (0.72)
Perceived Efficiency [27]	I felt like I could very efficiently use my virtual hands to complete the task.	$\chi^2 = 0.659, p = 0.719$	5.86 (1.21)
Performer Perceived Difficulty	It felt easy to perform the gestures I intended to. (only asked performer)	$\chi^2 = 0.352, p = 0.839$	2.71 (2.84)

button that would spawn them into the environment where the charades task took place. This environment was designed to be a relatively simple game room containing a large table in the center, bookshelves, and a large window. Large interactable red buttons (see Fig. 4) were used to obtain inputs from the guesser on the charades task words/concepts that were enacted as well as inputs from both participants on questionnaire items.

The avatar that was chosen was a modified version of a robotic avatar sourced from the Unity asset store [14]. This avatar was chosen instead of a human-like avatar to prevent any possible influences on presence, ownership, eeriness, or implicit biases that could arise from choosing realistic human textures that are not matched ethnically or by gender, effects that prior work have demonstrated [31, 47]. The avatar resembles robotic avatars that have been used in previous work investigating virtual hand ownership with regard to avatar hand size [27] and grasping feedback [12, 13]. The avatar was modified to make the shoulder and hip width equivalent as well as making the color of the avatar white (increasing contrast with the background), towards realizing an avatar that was gender-neutral.

4 Results

We analyzed our results starting with the effect of hand size (small, fitted, or large) on our objective and subjective measures. We then aimed to get a better understanding of our findings by testing for significant effects of the role of the participant (performer or guesser) and by evaluating how many participants noticed the changes in hand size and how this influenced their responses.

4.1 Objective Measures

Our objective performance measures were the number of correct guesses, completion time, and our motion metrics (cumulative wrist movements, average wrist velocity, and bounding box volume). For the first two measures, we had data points for each pair of participants while the motion data involved each participant producing data individually.

We tested the objective measures data for normality using the Shapiro-Wilk test and found that they significantly differed from normality. Therefore, we used Friedman tests to evaluate the effect of hand size. We found no significant effect of hand size on the number of correct guesses ($\chi^2(2) = 0.621$, $p = 0.732$) nor on completion time ($\chi^2(2) = 1.06$, $p = 0.589$) or on the three motion metrics of cumulative wrist movement ($\chi^2(2) = 2.78$, $p = 0.249$), average wrist velocity ($\chi^2(2) = 3.53$, $p = 0.171$), and bounding box volume ($\chi^2(2) = 0.583$, $p = 0.747$).

4.2 Subjective Measures

We also evaluated the effect of hand size on our subjective metrics shown in Table 1. Following the way the original questionnaires were analyzed, we averaged the two responses for ownership to obtain a single value for ownership. We followed the same procedure for agency, message understanding, and communication satisfaction. Shapiro-Wilk

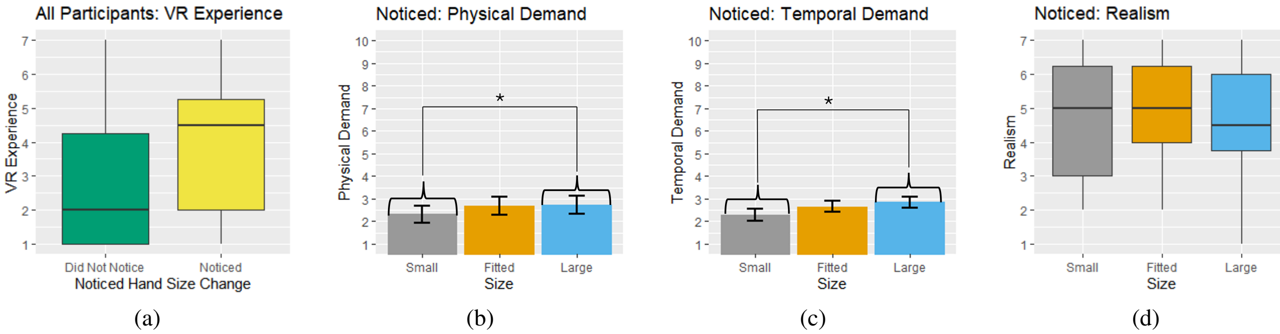

Fig. 7: (a) The self reported VR experience of all participants grouped by those who did not notice the manipulation and those who noticed. The difference was not significant ($p = 0.0893$); (b) There was a significant effect of Physical Demand when only considering the ratings from participants who noticed the hand size changes. The post hoc test shows that Physical Demand is perceived to be significantly higher for the Large than for Small hands ($p = 0.047$). (c) Effect of Temporal Demand for participants who noticed the changes. The Temporal Demand is higher with Large than Small ($p = 0.049$). (d) The ratings of Realism by participants who noticed the manipulation. The effect was significant, however, the post hoc did not show any significant differences.

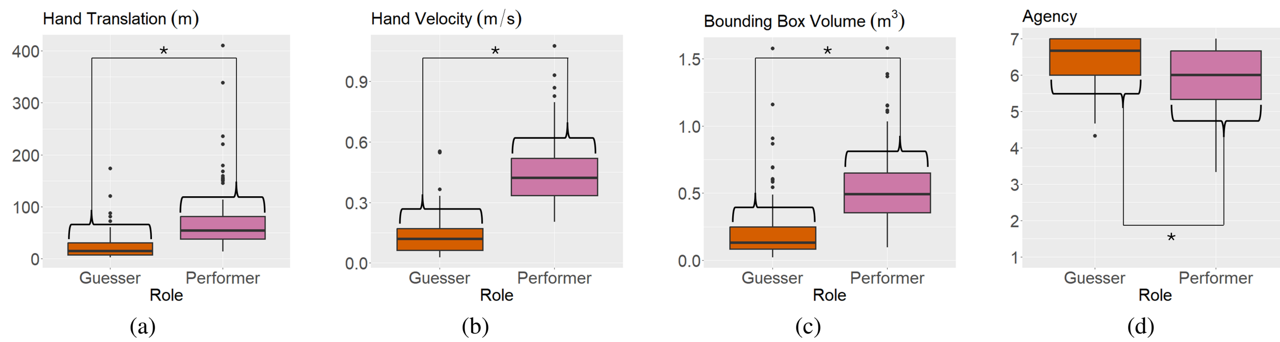

Fig. 8: (a) Effect of role on the wrist translation calculated using motion data from participants. The performers' hands covered more distance on average than the guessers' hands. (b) Effect of role on the wrist velocity calculated using motion data from participants. The performers' hand motions were faster on average than the guessers' hand motions. (c) Effect of role on the bounding box volume calculated using motion data from participants. The performers' hands covered a larger spatial volume than those of the guessers. (d) Effect of role on agency. The guessers perceived agency to be higher than the performers.

tests for normality showed that most of our response data for our subjective metrics significantly differed from normality. We therefore evaluated our results using Friedman tests for the effect of hand size. Additionally, we used pairwise Wilcoxon tests with Bonferroni corrected p-values for post hoc testing. There were no significant differences based on hand size for all of our questions except for one. The statistics are reported in Table 1.

We found a main effect of hand size for temporal demand ($\chi^2(2) = 7.21, p = 0.0271$), which is based on the question "How hurried or rushed was the pace of the task?", see Fig. 6. The post hoc test only indicates a trend that the temporal demand for the small hands tends to be lower than for the large hands ($p = 0.074$).

4.3 Influence of Participant Role

To better understand which factors influenced the participants' motions and perception, we evaluated whether the role of the participant (performer or guesser) affected our measures. For these analyses, we averaged participants' motion data and questionnaire responses across hand size and performed Mann-Whitney U tests.

We expected the performer to move more than the guesser as motion is needed to play charades when conveying the concepts. Unsurprisingly, we found significant differences between performers and guessers for our three motion measures: wrist translation ($W = 135$, $p = 3.11e^{-10}$), average wrist velocity ($W = 36$, $p = 4.48e^{-16}$), and the volume of the bounding box ($W = 133$, $p = 2.54e^{-10}$). The plots for each motion measure are shown in Fig. 8. Each of these measures was significantly higher for the performers than the guessers.

For our subjective measures, we found significant differences between roles for agency ($W = 908$, $p = 0.004$), message understanding ($W = 900$, $p = 0.005$), Perceived Efficiency ($W = 902$, $p = 0.004$), and for three items from the NASA TLX: Mental Demand ($W = 459$, $p = 0.033$), Performance ($W = 995$, $p = 9.081e^{-5}$), and Effort ($W = 434.5$, $p = 0.016$).

Agency was higher for the guesser ($M = 6.43$, $SD = 0.624$) than the performer ($M = 5.92$, $SD = 0.806$), see Fig. 8d. Message understanding was higher for the guesser ($M = 5.67$, $SD = 0.821$) than the performer ($M = 5.004$, $SD = 0.910$). The perceived efficiency was higher for the guesser ($M = 6.19$, $SD = 0.907$) than the performer ($M = 5.53$, $SD = 1.11$). The Mental Demand was higher for the performer ($M = 3.54$, $SD = 1.77$) than the guesser ($M = 2.76$, $SD = 1.69$). The Performance was higher for the guesser ($M = 8.48$, $SD = 0.971$) than the performer ($M = 7.27$, $SD = 1.38$). The Effort was higher for the performer ($M = 4.15$, $SD = 1.53$) than the guesser ($M = 3.25$, $SD = 1.78$).

4.4 Noticing Hand Size Changes, VR Experience

As described in the procedure (Section 3.6) we conducted semi-structured interviews at the end of the experiments. One goal of these interviews was to ascertain whether the hand size manipulation was noticeable. We consider the participant as having noticed the manipulation if they indicated at any point that the avatar's hands changed. We were surprised to see that despite the relatively large changes, only 44% of the participants noticed the differences in hand size between the three parts of the experiment. We report the detailed results in Table 2.

As the proportion of participants who noticed the changes was smaller than expected, we hypothesized that participants without VR experience maybe did not mention changes in hand size as they did not

Table 2: Number of participants who noticed the changes in hand size. Some participants only noticed the hands being smaller than their own, others only noticed the hands being larger. Some participants mentioned the changes without being asked if they noticed something, others only after we specifically asked if they noticed any changes of the avatar's hands (after prompting)

Category	Total	Performers	Guessers
Noticed total	32 (44%)	15 (41.7%)	17 (47.3%)
Noticed small	21 (29.2%)	9 (25%)	12 (33.4%)
Noticed large	21 (29.2%)	9 (25%)	12(33.4%)
Before prompting	22 (30.6%)	10 (27.8%)	12 (33.4%)
After prompting	10 (27.8%)	5 (13.9%)	5 (13.9%)

know what to expect in a virtual environments due to a lack of experience with VR. If that were the case, noticing the hand size changes would need to be correlated with VR experience.

We therefore analyzed whether participants noticing the manipulation could be predicted by their experience with VR. To do so, we fit a logistic regression model with VR experience as the predictor and Noticing as the response. The change in deviance when VR experience was added to the null model was 2.89 (1 df), resulting in a residual deviance of 96.04. The chi-square test for VR experience produced a p value of 0.0893, which suggests a trend toward significance. Fig. 7a visualizes the VR experience ratings for participants who noticed ($M = 3.81$, $SD = 2.01$, $MED = 4.5$) and who did not notice ($M = 3.00$, $SD = 1.01$, $MED = 2$).

Finally, we were wondering if our measurements would be affected for a subgroup of the participants. We hence conducted exploratory analyses to examine whether hand size affected our measures when only looking at participants who noticed the manipulation or those who were more experienced. For VR experience, we consider participants as experienced who self-reported scores between 4 and 7 (inclusive) in response to the prompt "How experienced would you rate yourself with virtual reality (VR)?", with 1 indicating not at all experienced and 7 indicating very experienced.

For the group of participants who noticed the hand size changes (N=32), we found a significant effect of hand size on Physical Demand ($\chi^2(2) = 6.22$, $p = 0.0446$, see Fig. 7b) and Temporal Demand ($\chi^2(2) = 7.89$, $p = 0.0193$, see Fig. 7c). Post hocs show a higher Physical Demand for Large than for Small hands ($p = 0.047$) and higher Temporal Demand for Large than for Small hands($p = 0.049$). There was also a significant main effect of hand size on Realism ($\chi^2(2) = 7.01$, $p = 0.0300$, see Fig. 7d), but the post hoc only indicated a trend with Large being higher than Fitted ($p = 0.063$).

The were no significant effects of hand size for the group of participants who rated themselves high (4-7 on a scale from 1 to 7) in terms of VR experience (N = 30) for any of the responses.

5 Discussion

The results from our experiment seem to indicate that self-avatar hand sizes have a modest influence on non-verbal communication experiences in virtual reality. We found no significant main effects of hand size on our objective measures of completion time, number of correct guesses, and motion-related metrics. Additionally, our measures on ownership, agency, message understanding, communication satisfaction, and those related to user experience remained relatively unaffected by the manipulations. Collectively, this meant that we did not obtain support for any of the hypotheses listed in Section 3.4. We found a main effect of hand size on Temporal Demand ("How hurried or rushed was the pace of the task?"), with no significant post hoc test and only indications that the small hand size could have led to less perceived temporal demand than the large hand size. Surprisingly, over half of our participants did not notice the changes in hand size even though these alterations seemed rather obvious when paid attention to. Interestingly, while previous research has shown that the type of size-changes we investigated are perceptible [27], they were not noticeable and did not have any major effects on communication in our experiment. Based on these results, we assume that the task may play a major role in dictating whether or not hand sizes matter. For example, research has shown that hand-size manipulations can affect the performance of tasks that involve perceptual judgments on affordances and object-sizes [29,37,43]. However, it appears that the same need not hold true for tasks like charades which purely involve non-verbal communication.

There could be several explanations as to why there were no strong effects of hand size manipulations on our non-verbal communication task. First, our task involved a game and was designed to be an enjoyable experience as one could expect from a virtual reality experience. We indeed observed that participants enjoyed the task, which was also reflected in the high levels of fun reported by users (rated with a mean of 6.59 on a scale from 1 to 7 across conditions). Participants may have prioritized performing well on the charades game task, driving them to focus more on thinking about how to gesture certain words to the other person rather than on their virtual hands, as indicated by several participants in their interviews. Second, our task, while engaging, was also relatively easy: on average, participants answered 10.3 questions correctly out of 12. Moreover, participants' self-reported ratings of charades-competence indicated that they were rather proficient at this task (rated with an average of 4.94 on a scale from 1 to 7). It is hence possible that we obtained ceiling effects because users that are already competent in such tasks may be relatively unaffected by such manipulations. However, it cannot be claimed that such hand size alterations would have similar negligible effects for users in general. Perhaps a more challenging task would have resulted in more noticeable differences in the measures obtained. Third, users embodied an abstracted robotic avatar that can be considered unrealistic or non-lifelike. The willingness to suspend disbelief might be larger for such avatars, increasing the tolerance for virtual hands that do not veridically match users' actual hands. Perhaps a tailored and more realistic avatar would have led to a lower tolerance for the scaled hands, producing stronger effects on the aspects investigated in this work. An additional explanation pertains to the method in which the hands were scaled. Uniform scaling of the hands need not necessarily affect one's ability to perform certain gestures since the movement mapping is still retained (e.g. pinching the thumb and fingertip together on the same hand was reflected on the avatar hand regardless of size). The same cannot be said of hand-scaling realized by altering the proportions of the fingers because this would directly impact and alter how users would have to gesticulate to communicate the same concept. It may be that scaling hands using other methods can differentially affect communication in VR, an avenue that warrants further investigation.

Although we found effects on certain measures when specifically focusing on users that noticed the hand size manipulation, one has to be skeptical about whether or not such differences would matter in practice. For example, when analyzing Temporal Demand with only participants who noticed the differences, the mean was 2.28 for the small hands and 2.84 for the large hands. We computed an effect size of 0.19, which is considered very small. Results were similar for Physical Demand, with means 2.31 for small and 2.72 for large hands with an even smaller effect size of 0.09. These differences are statistically significant but might be negligible in practice.

While the significant effects we found for participant roles were not surprising, they give us confirmation and sometimes additional information on our experiment. The higher motion values for the performer showed that the charader indeed moved more than the guesser, as one would expect. In general, the task was more challenging for the performer (higher mental demand and required effort), and the guesser felt more successful (higher success in accomplishing the task, higher perceived message understanding and efficiency). Interestingly, there was a difference in agency which was higher for the guesser. While participants were aware of and instructed to stay within the tracking area, it is possible that performers encountered more tracking inaccuracies as a consequence of their gestural motions covering larger volumes with greater velocities. This being said, both groups rated agency as very high (6.43 on average for guessers and 5.92 for performers on a scale from 1 to 7), indicating that tracking was relatively accurate overall.

Notwithstanding the minimal impact of the hand size manipulations on our measures, there could be other aspects that are influenced by such manipulations. For example, Adkins et al. [3] found that subtle changes in hand motions can affect the perception of a character in a similar communication task. We, however, did not investigate how the guesser and performer perceived each other but focused on the efficacy of non-verbal communication and the perceived extent of avatar-embodiment. Further research is necessary to determine if hand size changes affect the way a conversational partner is perceived.

6 Limitations

In this study, users were placed in a virtual environment with other objects in the scene such as books, bookcases, and a table (see Fig. 3). Although these objects may have affected participants' perception of the virtual scene as well as their body parts, we believe that our findings are still valid because the sizes of these objects remained consistent throughout all blocks of the experiment. While these objects could have acted as size-references, allowing the user to notice the manipulations, our post-study interviews revealed that the majority of participants were not aware of the hand size manipulations. Moreover, none of those who were aware mentioned using these objects as size references. Nonetheless, it would be interesting if future studies investigated how other environmental cues might affect one's perceptions of their hand sizes and non-verbal communication in virtual reality experiences. Another limitation of this work is that our participant sample was not fully gender balanced. We attempted to randomize the roles of participants that volunteered to participate in our study, but did not ensure equal representation amongst genders. Future research could investigate if there are gender-related effects on non-verbal communication in virtual reality experiences. Finally, we chose to represent the users with a robotic avatar which can be argued to be limited in generalizability or ecological validity. This design decision was motivated based on attempts to reduce possibilities of misrepresenting users with avatars or virtual hands that are not visually matched to their race, gender, or other features (e.g., age, proportions, hairiness, etc.). Future work could address this limitation by designing each user's avatar to more accurately represent them.

7 Conclusion and Future Work

In this study, we investigated the effect of avatar hand size in a communicative task on measures related to task performance, embodiment, perceived communication effectiveness, workload, and user experience. We found that there were nearly no significant effects in our measures when looking at all participants. Less than half of our participants even noticed the changes. When focusing only on participants who noticed the changes in hand size, we found significant differences in NASA's Task Load Index measures Physical Demand and Temporal Demand. However, even these differences are so small that one wonders if they are worth taking into account when designing VR experiences.

Overall, our results show that there is tolerance for differences between the avatar's hand sizes and the user's hand sizes in virtual scenarios similar to our study. We conclude that, at least in an entertaining communication task such as ours, a one size fits all approach for hand sizes can likely be taken without any large negative effects. While there was some evidence that the experience might be affected for a subgroup of participants, further study is needed to support and understand such effects. Of course, there might be other tasks, such as precise manipulation tasks, that require more accurate avatar hand sizes. We leave that question for future work to find out.

In summary, despite our thoroughly designed and conducted experiment and our in-depth analysis, our results remain limited. Still, conducting this type of experiment is important as we as a community currently have the opportunity to develop and influence the standards that will be used in future VR technologies. In future work, we wish to investigate how our findings are affected by using anthropomorphically realistic virtual hands. We further wish to ascertain if these results hold when altering the virtual hands in other ways like scaling the individual fingers, removing/adding fingers, and adjusting the geometry of the hand, to name a few. Lastly, the research community may benefit from pursuing investigations that pose questions such as: How do avatar size manipulations affect conversational and verbal communication? Would users notice the hand size alterations in a mixed reality scenario where they can see their real hands? Would hand size alterations affect collaborative tasks that involve interacting with virtual objects, such as the collaborative survival task employed by Adkins et al. [2]? Obtaining answers to these kinds of questions will help determine how to better design virtual experiences in the years to come.

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References

[1] A. Abdullah, J. Kolkmeier, V. Lo, and M. Neff. Videoconference and Embodied VR: Communication Patterns Across Task and Medium. *Proceedings of the ACM on Human-Computer Interaction*, 5(CSCW2):453:1–453:29, Oct. 2021. doi: 10.1145/3479597 2

[2] A. Adkins, R. Canales, and S. Jörg. Hands or controllers? How input devices and audio impact collaborative virtual reality. In *Proceedings of the 30th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–12, 2024. doi: 10.1145/3641825.3687718 9

[3] A. Adkins, A. Normoyle, L. Lin, Y. Sun, Y. Ye, M. Di Luca, and S. Jörg. How important are detailed hand motions for communication for a virtual character through the lens of charades? *ACM Trans. Graph.*, 42(3):27:1–27:16, 2023. doi: 10.1145/3578575 1, 2, 9

[4] M. W. Alibali, S. Kita, and A. J. Young. Gesture and the process of speech production: We think, therefore we gesture. *Language and Cognitive Processes*, 15(6):593–613, Dec. 2000. doi: 10.1080/016909600750040571 2

[5] F. Argelaguet, L. Hoyet, M. Trico, and A. Lecuyer. The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *2016 IEEE Virtual Reality*, pp. 3–10, Mar. 2016. doi: 10.1109/VR.2016.7504682 2

[6] S. Aseeri and V. Interrante. The Influence of Avatar Representation on Interpersonal Communication in Virtual Social Environments. *IEEE Transactions on Visualization and Computer Graphics*, 27(5):2608–2617, May 2021. doi: 10.1109/TVCG.2021.3067783 1, 2

[7] D. Banakou, S. Kishore, and M. Slater. Virtually being Einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in psychology*, p. 917, 2018. 3

[8] 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)*, pp. 519–528. IEEE, 2020. 2

[9] A. Bhargava, R. Venkatakrishnan, R. Venkatakrishnan, K. Lucaites, H. Solini, A. C. Robb, C. C. Pagano, and S. V. Babu. Can I squeeze through? Effects of self-avatars and calibration in a person-plus-virtual-object system on perceived lateral passability in VR. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2348–2357, 2023. 3

[10] A. Bhargava, R. Venkatakrishnan, R. Venkatakrishnan, H. Solini, K. Lucaites, A. C. Robb, C. C. Pagano, and S. V. Babu. Did I hit the door? Effects of self-avatars and calibration in a person-plus-virtual-object system on perceived frontal passability in VR. *IEEE Transactions on Visualization and Computer Graphics*, 28(12):4198–4210, 2021. 3

[11] A. Bhargava, R. Venkatakrishnan, R. Venkatakrishnan, H. Solini, K. Lucaites, A. C. Robb, C. C. Pagano, and S. V. Babu. Empirically evaluating the effects of eye height and self-avatars on dynamic passability affordances in virtual reality. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 308–317, 2023. 2

[12] R. Canales and S. Jörg. Performance is not everything: Audio feedback preferred over visual feedback for grasping task in virtual reality. In *Proceedings of the 13th ACM SIGGRAPH Conference on Motion, Interaction and Games*, pp. 1–6, 2020. 6

[13] R. Canales, A. Normoyle, Y. Sun, Y. Ye, M. D. Luca, and S. Jörg. Virtual grasping feedback and virtual hand ownership. In *ACM Symposium on Applied Perception 2019*, SAP '19, article no. 4, 9 pages, pp. 4:1–4:9, 2019. doi: 10.1145/3343036.3343132 6

[14] B. Y. Games. Banana man | 3d humanoids, 2022. https://assetstore.unity.com/packages/3d/characters/humanoids/banana-man-196830. 6

[15] S. Goldin-Meadow. The role of gesture in communication and thinking. *Trends in Cognitive Sciences*, 3(11):419–429, Nov. 1999. doi: 10.1016/S1364-6613(99)01397-2 2

[16] S. Goldin-Meadow. *Hearing Gesture: How Our Hands Help Us Think*. Harvard University Press, Oct. 2005. 2

[17] S. W. Greenwald, Z. Wang, M. Funk, and P. Maes. Investigating social presence and communication with embodied avatars in room-scale virtual reality. In *Immersive Learning Research Network: Third International Conference, iLRN 2017, Coimbra, Portugal, June 26–29, 2017. Proceedings 3*, pp. 75–90. Springer, 2017. 2

[18] C. Harms and F. Biocca. Internal consistency and reliability of the networked minds measure of social presence. In *Seventh annual international workshop: Presence*, vol. 2004. Universidad Politecnica de Valencia Valencia, 2004. 4, 6

[19] D. Harris, M. Wilson, and S. Vine. Development and validation of a simulation workload measure: The simulation task load index (SIM-TLX). *Virtual Real.*, 24(4):557–566, 10 pages, dec 2020. doi: 10.1007/s10055-019-00422-9 6

[20] S. G. Hart and L. E. Staveland. Development of NASA-TLX (task load index): Results of empirical and theoretical research. In *Advances in psychology*, vol. 52, pp. 139–183. Elsevier, 1988. 4

[21] M. L. Hecht. The conceptualization and measurement of interpersonal communication satisfaction. *Human Communication Research*, 4(3):253–264, 1978. doi: 10.1111/j.1468-2958.1978.tb00614.x 4, 6

[22] S. Jörg, J. Hodgins, and C. O'Sullivan. The perception of finger motions. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, APGV '10, 5 pages, p. 129–133, 2010. doi: 10.1145/1836248.1836273 1, 2, 4

[23] S. Jörg, Y. Ye, F. Mueller, M. Neff, and V. Zordan. Virtual hands in VR: Motion capture, synthesis, and perception. In *SIGGRAPH Asia 2020 Courses*, pp. 1–32. ACM, Virtual Event, Nov. 2020. doi: 10.1145/3415263.3419155 1

[24] E. Jun, J. K. Stefanucci, S. H. Creem-Regehr, M. N. Geuss, and W. B. Thompson. Big foot: Using the size of a virtual foot to scale gap width. *ACM Transactions on Applied Perception (TAP)*, 12(4):1–12, 2015. 2

[25] K. Kilteni, R. Groten, and M. Slater. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, Nov. 2012. doi: 10.1162/PRES_a_00124 2

[26] K. Kilteni, J.-M. Normand, M. V. Sanchez-Vives, and M. Slater. Extending body space in immersive virtual reality: A very long arm illusion. *PloS ONE*, 7:1–15, July 2012. doi: 10.1371/journal.pone.0040876 3

[27] L. Lin, A. Adkins, Y. Sun, A. Robb, Y. Ye, M. Di Luca, and S. Jörg. The effect of hand size and interaction modality on the virtual hand illusion. In *2019 IEEE Virtual Reality Conference*, 2019. 2, 4, 6, 8

[28] L. Lin and S. Jörg. Need a hand? How appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '16, pp. 69–76, 2016. doi: 10.1145/2931002.2931006 2, 4, 6

[29] S. A. Linkenauger, M. Leyrer, H. H. Bülthoff, and B. J. Mohler. Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PloS one*, 8(7):e68594, 2013. 2, 8

[30] S. A. Linkenauger, H. Y. Wong, M. Geuss, J. K. Stefanucci, K. C. McCulloch, H. H. Bülthoff, B. J. Mohler, and D. R. Proffitt. The perceptual homunculus: The perception of the relative proportions of the human body. *Journal of Experimental Psychology: General*, 144(1):103–113, 2015. 2

[31] M. Lira, J. H. Egito, P. A. Dall'Agnol, D. M. Amodio, Ó. F. Gonçalves, and P. S. Boggio. The influence of skin colour on the experience of ownership in the rubber hand illusion. *Scientific Reports*, 7(1):15745, 2017. 6

[32] M. Longo, F. Schüür, M. P M Kammers, M. Tsakiris, and P. Haggard. What is embodiment? A psychometric approach. *Cognition*, 107:978–98, July 2008. doi: 10.1016/j.cognition.2007.12.004 2

[33] S. Lopez, Y. Yang, K. Beltran, S. J. Kim, J. Cruz Hernandez, C. Simran, B. Yang, and B. F. Yuksel. Investigating implicit gender bias and embodiment of white males in virtual reality with full body visuomotor synchrony. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2019. 3

[34] K. Ma and B. Hommel. The virtual-hand illusion: Effects of impact and threat on perceived ownership and affective resonance. *Frontiers in psychology*, 4:604, 2013. 4, 6

[35] K. Ma and B. Hommel. Body-ownership for actively operated non-corporeal objects. *Consciousness and Cognition*, 36:75 – 86, June 2015. doi: 10.1016/j.concog.2015.06.003 2

[36] K. Ma and B. Hommel. The role of agency for perceived ownership in the virtual hand illusion. *Consciousness and Cognition*, 36:277 – 288, July 2015. doi: 10.1016/j.concog.2015.07.008 2

[37] B. F. Marino, N. Stucchi, E. Nava, P. Haggard, and A. Maravita. Distorting the visual size of the hand affects hand pre-shaping during grasping. *Experimental brain research*, 202:499–505, 2010. 8

[38] J. T. McConville, C. E. Clauser, T. D. Churchill, J. Cuzzi, and I. Kaleps. Anthropometric relationships of body and body segment moments of inertia. Technical report, Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, 1980. 4

[39] M. K. McCracken, H. C. Finney, S. Yang, B. Bodenheimer, S. H. Creem-Regehr, and J. K. Stefanucci. Big feet for little people: Scaling gap affordance judgments of children and adults with virtual feet. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 249–258. IEEE, 2024. 2

[40] R. McDonnell, M. Breidt, and H. H. Bülthoff. Render me real? Investigating the effect of render style on the perception of animated virtual humans. *ACM Transactions on Graphics (TOG)*, 31(4):1–11, 2012. 2

[41] Meta Quest Blog. Introducing Hand Tracking on Oculus Quest—Bringing Your Real Hands into VR. https://www.ocu lus.com/blog/introducing-hand-tracking-on-oculus-quest-bringing-your-real-hands-into-vr/, Sept. 2019. Accessed on 2021-06-14. 5

[42] N. Ogawa, T. Narumi, and M. Hirose. Object size perception in immersive virtual reality: Avatar realism affects the way we perceive. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 647–648, 2018. 2

[43] N. Ogawa, T. Narumi, and M. Hirose. Virtual hand realism affects object size perception in body-based scaling. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 519–528, 2019. 2, 8

[44] F. Pavani and M. Zampini. The role of hand size in the fake-hand illusion paradigm. *Perception*, 36(10):1547–1554, 2007. 2, 4

[45] T. C. Peck and A. Tutar. The impact of a self-avatar, hand collocation, and hand proximity on embodiment and stroop interference. *IEEE Transactions on Visualization and Computer Graphics*, 26(5):1964–1971, 2020. 3

[46] L. Ring, D. Utami, and T. Bickmore. The right agent for the job? The effects of agent visual appearance on task domain. In *Intelligent Virtual Agents: 14th International Conference, IVA 2014, Boston, MA, USA, August 27-29, 2014. Proceedings 14*, pp. 374–384. Springer, 2014. 2

[47] V. Schwind, P. Knierim, C. Tasci, P. Franczak, N. Haas, and N. Henze. "These are not my hands!" Effect of gender on the perception of avatar hands in virtual reality. In *Proceedings of the 2017 CHI conference on human factors in computing systems*, pp. 1577–1582, 2017. 6

[48] H. J. Smith and M. Neff. Understanding the impact of animated gesture performance on personality perceptions. *ACM Trans. Graph.*, 36(4), article no. 49, 12 pages, Jul 2017. doi: 10.1145/3072959.3073697 1, 2

[49] H. J. Smith and M. Neff. Communication behavior in embodied virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–12. ACM, Montreal QC, Canada, Apr. 2018. doi: 10.1145/3173574.3173863 1

[50] S. Thomas, Y. Ferstl, R. McDonnell, and C. Ennis. Investigating how speech and animation realism influence the perceived personality of virtual characters and agents. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 11–20, March 2022. doi: 10.1109/VR51125.2022.00018 2

[51] J. Thompson. Biological motion perception. In R. R. Hoffman, P. A. Hancock, M. W. Scerbo, R. Parasuraman, and J. L. Szalma, eds., *The Cambridge Handbook of Applied Perception Research*, Cambridge Handbooks in Psychology, chap. 21, pp. 427—442. Cambridge University Press, 2015. 2

[52] B. van der Hoort, A. Guterstam, and H. H. Ehrsson. Being Barbie: The size of one's own body determines the perceived size of the world. *PLOS ONE*, 6(5):1–10, 05 2011. doi: 10.1371/journal.pone.0020195 2

[53] R. Venkatakrishnan, R. Venkatakrishnan, B. Raveendranath, C. C. Pagano, A. C. Robb, W.-C. Lin, and S. V. Babu. How virtual hand representations affect the perceptions of dynamic affordances in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2258–2268, May 2023. doi: 10.1109/TVCG.2023.3247041 2

[54] Y. Wang, J. E. F. Tree, M. Walker, and M. Neff. Assessing the impact of hand motion on virtual character personality. *ACM Trans. Appl. Percept.*, 13(2), article no. 9, 23 pages, mar 2016. doi: 10.1145/2874357 2

[55] F. Weidner, G. Boettcher, S. A. Arboleda, C. Diao, L. Sinani, C. Kunert, C. Gerhardt, W. Broll, and A. Raake. A systematic review on the visualization of avatars and agents in AR & VR displayed using head-mounted displays. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2596–2606, 2023. doi: 10.1109/TVCG.2023.3247072 1

[56] B. Yoon, H.-i. Kim, G. A. Lee, M. Billinghurst, and W. Woo. The effect of avatar appearance on social presence in an augmented reality remote collaboration. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 547–556, March 2019. doi: 10.1109/VR.2019.8797719 2

[57] C. You, R. Venkatakrishnan, R. Venkatakrishnan, Z. Han, B. Lok, and T. Peck. A sense of urgency on the sense of agency: Challenges in evaluating agency and embodiment in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 2024. 2

[58] Y. Yuan and A. Steed. Is the rubber hand illusion induced by immersive virtual reality? In *Proceedings of the 2010 IEEE Virtual Reality Conference*, VR '10, 8 pages, pp. 95–102, 2010. doi: 10.1109/VR.2010.5444807 2

[59] H. Yun, J. L. Ponton, C. Andujar, and N. Pelechano. Animation fidelity in self-avatars: Impact on user performance and sense of agency. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 286–296, March 2023. doi: 10.1109/VR55154.2023.00044 1, 2

[60] E. Zell, C. Aliaga, A. Jarabo, K. Zibrek, D. Gutierrez, R. McDonnell, and M. Botsch. To stylize or not to stylize? the effect of shape and material stylization on the perception of computer-generated faces. *ACM Transactions on Graphics (TOG)*, 34(6):1–12, 2015. 2

[61] E. Zell, K. Zibrek, and R. McDonnell. Perception of virtual characters. In *ACM SIGGRAPH 2019 Courses*, SIGGRAPH '19, article no. 21, 17 pages, 2019. doi: 10.1145/3305366.3328101 1, 2

[62] J. Zhang and B. Hommel. Body ownership and response to threat. *Psychological research*, 80:1020–1029, 2016. 4, 6

[63] J. Zhang, M. Huang, L. Zhao, R. Yang, H.-N. Liang, J. Han, L. Wang, and W. Sun. Influence of hand representation design on presence and embodiment in virtual environment. In *2020 13th International Symposium on Computational Intelligence and Design (ISCID)*, pp. 364–367. IEEE, 2020. 2