The Effect of Hand Size and Interaction Modality on the Virtual Hand Illusion

Lorraine Lin* Clemson University
Aline Normoyle† Venturi Labs
Alexandra Adkins‡ Clemson University
Yu Sun§ Clemson University
Andrew Robb¶ Clemson University
Yuting Ye‖ Facebook Reality Labs
Massimiliano Di Luca** Facebook Reality Labs & University of Birmingham UK
Sophie Jörg†† Clemson University

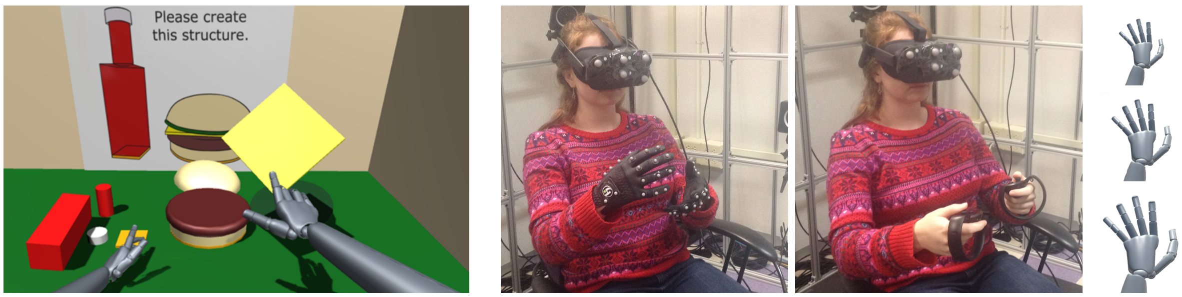


Figure 1: In our experiment, participants complete block stacking puzzles in virtual reality (left), controlling their avatar's hands either with tracked gloves (middle, left) or with touch controllers (middle, right). The avatar's hands are varied to fit the participant's hands in size or to be 25% larger or smaller (right).

Abstract

Most commercial virtual reality applications with self avatars provide users with a "one-size fits all" avatar. While the height of this body may be scaled to the user's height, other body proportions, such as limb length and hand size, are rarely customized to fit an individual user. Prior research has shown that mismatches between users' avatars and their actual bodies can affect size perception and feelings of body ownership. In this paper, we consider how concepts related to the virtual hand illusion, user experience, and task efficiency are influenced by variations between the size of a user's actual hand and their avatar's hand. We also consider how using a tracked controller or tracked gestures affect these concepts. We conducted a 2x3 within-subjects study (n=20), with two levels of input modality: using tracked finger motion vs. a hand-held controller (Glove vs. Controller), and three levels of hand scaling (Small, Fit, and Large). Participants completed 2 block-assembly trials for each condition (for a total of 12 trials). Time, mistakes, and a user experience survey were recorded for each trial.

Participants experienced stronger feelings of ownership and realism in the Glove condition. Efficiency was higher in the Controller condition and supported by play data of more time spent, blocks grabbed, and blocks dropped in the Glove condition. We did not find enough evidence for a change in agency and the intensity of the virtual hand illusion depending on hand size. Over half of the participants indicated preferring the Glove condition over the Controller condition, mentioning fun and efficiency as factors in their choices. Preferences on hand scaling were mixed but often attributed to efficiency. Participants liked the appearance of their virtual hand more while using the Fit instead of Large hands. Several interaction effects were observed between input modality and hand scaling, for example, for smaller hands, tracked hands evoked stronger feelings of ownership compared to using a controller. Our results show that the virtual hand illusion is stronger when participants are able to control a hand directly rather than with a hand-held device, and that the virtual reality task must first be considered to determine which modality and hand size are the most applicable.

Index Terms: Human-centered computing—Virtual reality Human-centered computing—Gestural input; Human-centered computing—Interaction design; Computing methodologies—Perception

1 Introduction

The cortical homunculus is the representation of the human body in the brain: it is a mapping of body locations to brain locations. Humans have a flexible representation of their bodies. They are able to control and feel ownership of avatars that do not resemble them. The ability to move and use discrepant bodies is a phenomenon termed homuncular flexibility [7] because it evidences the adaptability of the mental representation of the body in the brain. Experiments on homuncular flexibility such as giving subjects a controllable tail [24] or using arms to control legs [27] initially appear to have frivolous purposes, but they also open the important question of how to best tailor virtual reality bodies, user interfaces, and applications suited to medical, training, and educational fields to the limits (or lack of limits) in our minds.

The feeling that a body or body part belongs to oneself has been termed the body ownership illusion. Feeling that a rubber or otherwise fake hand belongs to oneself has been termed the rubber hand illusion, and the feeling of ownership for virtual hands is subsequently the virtual hand illusion. Body ownership illusions are similar to homuncular flexibility, but have a different neural basis. The brain can be easily tricked into feeling ownership over virtual

*e-mail: lorraine@clemson.edu
†e-mail: alinen@savvysine.com
‡e-mail: adkins4@clemson.edu
§e-mail: ysun3@g.clemson.edu
¶e-mail: arobb@clemson.edu
‖e-mail: yuting.ye@oculus.com
**e-mail: max.diluca@oculus.com
††e-mail: sjoerg@clemson.edu

limbs that do not belong to one's body [3]. Despite the extensive investigation on both the body ownership illusion and homuncular flexibility, there are still many questions that remain unanswered. For example, to what degree does a body part of unusual size influence perception and action? Lanier and colleagues at VPL Research pioneered some of the first informal studies on virtual worlds in which people could interact with each other [7]. He found through a bug that caused avatars' virtual hands to become gigantic, "like a web of flying skyscrapers," that people could learn quickly to control unusual bodies. This initial event was one inspiration for us to ask: with the simple change of relative hand size, what will people experience differently while completing tasks in a virtual environment? Most games or other applications with self avatars give users an unchangeable virtual body that does not correspond to each person's individual size. While previous studies have shown that experiencing the body ownership illusion with different sized body parts in virtual reality is possible, they do not take into account questions such as, do users have a preference for unaltered versus unusual sizes? Are discrepancies in body size disruptive to virtual experiences beyond influencing the ability to measure objects in comparison to the virtual body? Thus, we explore if it is important to adjust the avatar size to fit everyone, or acceptable to use a one-size-fits-all approach.

In addition, technology is moving towards allowing new ways to interact with virtual environments. The default interface with virtual reality has been with controller and device inputs such as buttons and keyboards, but in recent years has extended to motion tracking body parts, allowing people to have the freedom of not physically holding a device while interacting. However, this is at the expense of haptic feedback. Current commercial virtual reality applications allow tracking of hands, but little research has been conducted on user preference for motion tracked body parts versus controller input. This is the motivation for our interaction modality condition: we would like to explore how people perceive their virtual hands if they can directly control them versus using game controllers.

As the modality and hand size could potentially influence each other, our study observes both variables at the same time. Both variables are relevant to the current development of virtual reality systems. We are interested in knowing more about how these conditions affect factors such as efficiency and fun. Thus, we conduct an experiment in a virtual environment with interactive puzzles to explore these questions (see Figure 1).

2 Related Work

2.1 Effect of Model Size on the Rubber Hand and Virtual Hand Illusions

Model appearance has been shown to influence the virtual hand illusion. While the virtual hand illusion can even be created with abstract shapes, human-like hands induce stronger feelings of ownership than non-anthropomorphic hands or abstract objects [14] [29] [1] [9]. For example, Schwind et al. found that participants felt like they owned human hands more than robot hands, robot hands more than cartoon hands, and cartoon hands more than abstract hands [23]. People also experience a high level of ownership when the hand model is controlled based on their motions. For example, they experience a higher level of ownership for a hand with six fingers when the extra finger is animated based on the tracking of the ring and pinky finger. [22]. Time spent inducing the rubber hand illusion increases its effect as well. Participants viewed a reflection of their left hand that was normal-sized, magnified, and minified while performing synchronized finger movements. They felt more strongly about ownership, agency, and location of the hand reflection for all reflection sizes after the finger movement task, as well as for the normal-sized reflection [25]. Stronger feelings of ownership does not always correlate to stronger feelings of agency, or the ability to control virtual body parts: Argelaguet et al. observed different hand realisms with direct control and found that the virtual human hand generated the strongest level of ownership, but the less realistic hands generated higher levels of agency [1]. If similarity to our own hands and control through our hands increase the virtual hand illusion, one could assume that a similarity in size and direct control are important factors.

The body-based scaling hypothesis proposes that the estimate of the size of virtual objects depends on the size of the virtual hands: the body is the metric for defining object size, so participants given a large hand underestimate object sizes, and participants given a small hand overestimate object sizes [10] [18]. In Haggard and Jundi's observation of the rubber hand illusion, after watching the stimulation of a large or small glove in synchrony with their own hand, participants were asked to hold cylinders and guess their weights. The large glove evoked a size-weight illusion in which the held cylinders were perceived to be smaller objects that weigh more [5]. Ogawa et al. observed how realism and hand size affect the perceived size of a held cube. They found that the cube appeared smaller for high, medium, and low avatar realism when the hand size was enlarged, but the cube's size was perceived smallest for the high realism avatar compared to the medium and low realism avatar [19]. Linkenauger et al. also found that objects are perceived to be smaller when a hand is magnified. However, hand sizes do not affect objects that are too big to be grasped, and thus are beyond the mechanism of judgement [11]. Pavani and Zampini found a constraint that the rubber hand illusion occurs when the fake hand is larger or similar in size to, but not smaller than participants' hands [20]. Additionally, the scale of surrounding objects or the environment can exert an effect on the perception of body size. People perceive virtual hands as larger and objects as smaller in virtual reality; but when interacting with objects, they tend to perceive the overall size of both depending on if they see the object or their hands first [17].

Context also affects perception of body size. Given a controllable child body instead of an adult body scaled down to the size of a child, participants overestimate object sizes more than in the small adult body and have faster reaction times on an implicit association test for child-like attributes [2].

2.2 Interaction Modalities in VR

Controllers and gestures have both been used as input devices for VR applications. Gesture-based interactions may create a more natural experience but are also frequently associated with diminished performance. McMahan et al. found that users reported that motion-based input as more fun in a racing video game, but that traditional controllers were easier to use. Motion-based input controls were also associated with diminished performance [15]. Moehring and Froehlich compared finger-based and controller-based ray casting in a CAVE and HMD. They found that users preferred finger-based interactions even though controllers had better performance. They also showed that adding visual and tactile feedback could improve the performance of the finger-based interactions [16]. Lin and Schulze compared grasping gestures for direct manipulation, magnetic grasping for remote manipulation, and interacting with objects via buttons in VR. Participants in a pilot study provided feedback that they felt the grasping was more natural, but that the button was more reliable [8]. Porter et al. explored users' behavior in a VR game that implements both direct, motion-based controls and indirect, button-based controls. They found that while users enjoyed motion-based controls more, both motion controls and buttons were frequently used side-by-side. This was attributed to a number of factors, including the physical cost of motion based controls, differences in the capabilities of the motion controls compared to the buttons, and uncertainty about the reliability of the motion controls [21].

Perceived naturalness, enjoyment, and efficiency can also be affected by the design of the interaction mechanics, especially when considering realistic interaction mechanics vs. more "magical" techniques. However, unlike the clear tradeoff between enjoyment and performance with gesture-based input vs. controller-based input, it is possible for less strictly realistic interaction mechanics to improve performance while also creating a more favorable user experience. For example, Eriksson evaluated the Go-Go technique (where a user's hand stretches out longer than their real arm) and a ray-casting technique for selection and manipulation. Both techniques performed at similar levels of efficiency, but Go-Go was rated as more satisfying, intuitive, and immersive, despite that it is less "natural" than ray-casting [4].

3 Experiment

3.1 Overview and Design

The goal of our experiment is to investigate the effects of hand model size and interaction modality on the virtual hand illusion. Ownership is the dependent variable that provides evidence of the virtual hand illusion. We furthermore explore the effects of hand model size and interaction modality on agency, realism, immersion, efficiency, performance, likability, fun, perceived size, and preference.

We observe how participants perceive virtual hands if the hand models are controlled directly by their own hands or with Oculus Touch controllers (Glove vs. Controller), and if the models are smaller than, fitted to, or larger than their hand (Small vs. Fit vs. Large). The interaction modalities are shown in the two center panels of Figure 1. To track the hands, we offer different sizes of motion capture gloves. The Fit hand size is created from the motion capture gloves that best fit each participant. In the Small and Large hand conditions, the virtual model is respectively 25% larger or smaller than the participants' glove fit. In the Glove condition, participants can pick up virtual blocks by grasping them. Their hand motions are tracked and displayed on the virtual hands. In the Controller condition, participants press buttons with their thumbs and index fingers to grasp blocks. The virtual hand model will imitate a corresponding pinch when the buttons are pressed.

Our study uses a 2x3 within-subjects design to observe all conditions in direct comparison. The independent variables are the interaction modality (Glove vs. Controller) and the virtual model hand size (Small vs. Fit vs. Large). The main dependent variable is ownership, which indicates the strength of the virtual hand illusion.

An overview of our study procedure is shown in Figure 2. The experiment consists first of a fitting room to adjust the avatar's size to participants, then of two sessions of interaction modality presented in randomized order. In each session, we allow participants to assemble two puzzles with each hand size condition, and after each condition we give the study questionnaire. We furthermore record gameplay data. The hand sizes are presented in randomized order. In addition, each puzzle is shown only once, and which puzzle has to be solved in which condition is also randomized. This results in a total of 6 conditions (2 interaction modalities x 3 hand sizes) and 12 trials since there are 2 puzzles for each condition. Afterwards, we ask participants about their experience to gather qualitative feedback.

Our hypotheses are:

- The virtual hand illusion is stronger for participants in the Glove condition.
- The virtual hand illusion is stronger for participants in the Fit hand condition.

3.2 Experimental Setup

Participants sit in a chair with a small table in front of them, surrounded by an OptiTrack motion capture system consisting of 16 cameras as illustrated in Figure 3. They view the virtual environment through an Oculus Rift head-mounted display (HMD).

Participants control a free robot model offered through Unity's 4.0 Mecanim Animation Tutorial.[1] The avatar is modified using Maya 2017 and Unity 5.6.1 to have resizable hands. We hide the avatar's head so that the participant can look down and see their virtual body without the head geometry obscuring it. The avatar hand has all the degrees of freedom for movement of the twenty finger joints, but does not perform subtler movements such as skin stretching and being able to flex the palm. The avatar is placed in a virtual room, which is a simple environment modeled using Maya 2017. Textures are created with Adobe Photoshop CC 2017 and PaintTool SAI. The scenes are built in Unity 5.6.1.

The experiment puzzles (see Figure 8) are created with blocks of a variety of shapes and sizes to simulate the potential diversity of objects people handle on a daily basis. When new puzzles are introduced, their blocks are randomly distributed in reachable space in front of the participants. Blocks turn semi-transparent when they are within reach of being picked up, and make a small noise when they are picked up. When a block comes into contact with another block it needs to be stacked on to progress the puzzle, the bottom block highlights in green; letting go of the held block then allows it to be snapped into place with a clicking noise. We also chose to not implement gravity so participants would not lose blocks easily, so if a block is let go of in mid-air, it stays in place until picked up again.

When a participant begins the virtual experiment, we first place them in a calibration area, where the avatar is adjusted to fit their body. We support resizing the torso, arms, palms, and fingers through the use of resizers, prismatic joints which can change the offset from their parent without distorting the avatar's skin (see Figure 4). The torso and arm sizes are estimated based on the participant's T-Pose while seated in the chair, and can be manually adjusted by the experimenter.

The hand sizes are determined by the glove size worn by the participant. The lengths from wrist to middle fingertips of the gloves range from 15cm to 21.5cm, and each glove is associated to a pre-saved avatar hand size. Figure 5 shows the ranges of available scales as well as how the hands change for each glove. Sizes are determined based on manual measurements taken from the gloves. Both the Glove and the Controller condition use the same hand models.

The avatar's upper body is animated based on the hand positions. The wrists follow the base of the hands using 2-link analytical inverse kinematics (IK) up to the avatar's shoulders. If the arms cannot reach the input positions, the torso leans to satisfy the reach.

We animate the hands using either tightly fitted gloves and an OptiTrack motion capture system or using Oculus Touch controllers. Each glove is tracked with 19 markers placed between the joints as seen in Figure 6. Participant hand poses are captured following Han et al.'s approach [6]. The resulting data, the first 3 joints of each finger along with global positions for each finger tip, is streamed to our virtual environment over a network connection. For the avatar's hands, the thumbs follow the finger tip using 3-link analytical IK. The avatar's fingers match the orientation of the streamed fingers.

We use marker positions of the HMD headset to align the motion-capture system with the Oculus system. To animate the hands with the touch controllers, we hard-code finger poses based on button presses. Pressing buttons under the thumbs makes the thumbs close, and pressing buttons under the index fingers makes the index fingers close. Pressing the buttons for the thumb and index fingers together creates the grasping pose that allows to pick up blocks.

To detect grasping and releasing hand gestures in the glove condition, we estimate the velocity between the index and thumb positions and test whether it is greater than a given threshold. This threshold is a function of the hand-size, so that the grasping experience is the same regardless of glove size. We use exponential smoothing so that small fluctuations in position do not trigger a grab or release. Both the Glove and Controller conditions allow users to drag blocks by simply pinching their index and thumb fingers together. In practice, participants use all fingers to grab.

[1] https://www.youtube.com/watch?v=Xx21y9eJq1U

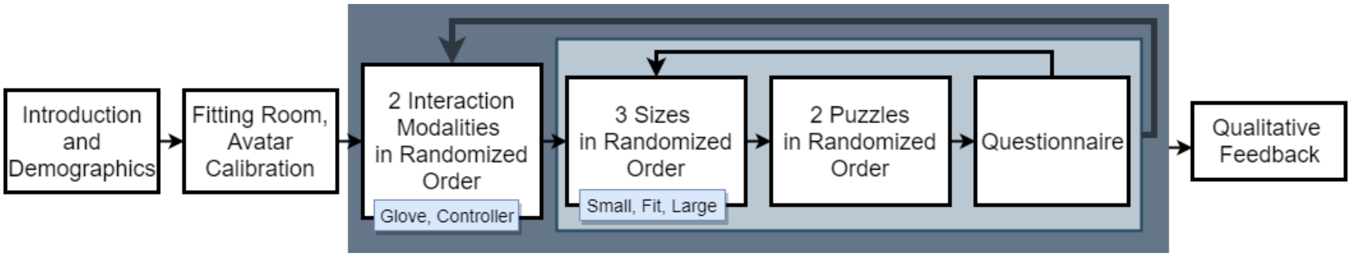


Figure 2: Overview of our study procedure. Participants begin with an introduction and demographic questionnaire. In VR, the avatar is calibrated to fit their body. For the experiment, participants complete each of 12 puzzles using either the glove or touch interface and with either small, fit, or large sized hands. At the end, we ask participants for qualitative feedback.

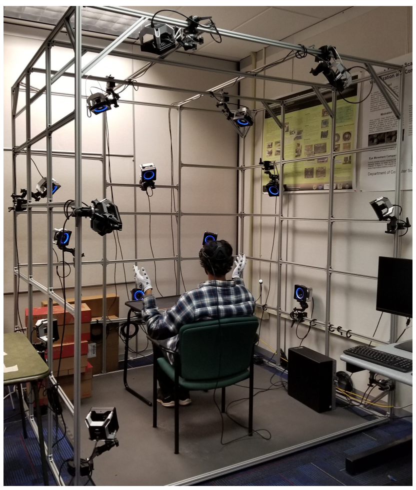


Figure 3: Experimental setup. Participants sit in the middle of a motion capture system at a small table. The placement of the cameras is optimized for capturing the small markers on each glove.

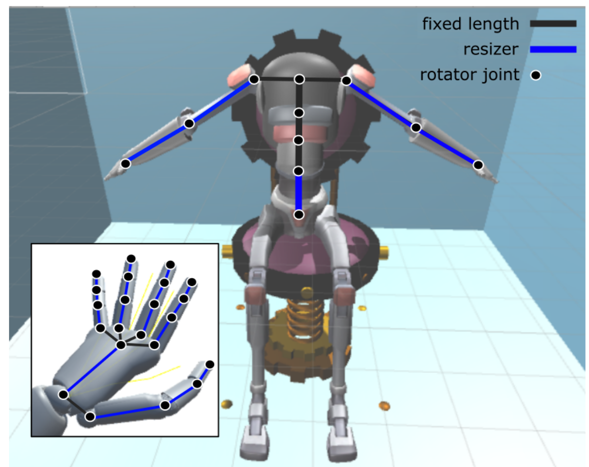


Figure 4: Virtual character in our fitting room. We use resizers, shown in blue, to change the size of the avatar's arms, torso, and hands to match the participants without distorting the skin. Rotational joints, shown as circles, are used to change the pose.

3.3 Participants

Twenty participants (12 male, 8 female; ages between 18 and 40) volunteered for our study. Participants consisted mainly of undergraduate and graduate students recruited from Clemson University. Nineteen of our participants were right-handed and one was left-handed. One participant wore our size 2 gloves, four wore size 3, three wore size 4, nine wore size 5, and three wore size 6. We obtained informed consent from all participants before the study following the guidelines set by our Institutional Review Board. Participants received a $5 voucher for their time.

3.4 Procedure

After filling out an initial demographic questionnaire, participants put on motion capture gloves in their size and are seated in the motion capture system.

Wearing the Oculus Rift places participants in the virtual fitting room. Participants are asked to hold out their arms in a T-pose for the motion capture gloves to track and scale the avatar's arm length to theirs, then place their arms in their lap for scaling the avatar torso to their height. Then, the main experiment scene is started.

Participants are asked to take as much time as needed to become comfortable with the virtual environment, a small room with a table and a box. Then, they play through a tutorial stage with three simple puzzles and a background image with instructions as seen in Figure 7. Participants learn how to use their hands to move blocks, stack blocks, and assemble structures. Each completed puzzle lowers into the ground and a new puzzle rises to take its place. Once the tutorial stage is completed, participants are asked to let the researchers know when they are ready for the main puzzles.

The main puzzles (see Figure 8) take place in the same box as the tutorial puzzles. After every two puzzles, the questionnaire appears in place of the puzzle instructions and participants read their answers aloud for the researcher to record. After the questionnaire, the next puzzle rises and the avatar switches to the next hand size condition.

Halfway through the main puzzles, participants are given a break as they switch from using one interaction modality to complete the remaining six puzzles with the other interaction modality. After completing all puzzles, participants are asked to remove the headset for a post-study interview. Replies are scribed for qualitative feedback.

3.5 Questionnaire

Table 1 shows our study questionnaire given after participants experience each condition by playing two puzzles. The dependent variables are measured by asking participants to rate statements testing ownership and implications or signs of ownership. We furthermore ask questions about agency, realism, immersion, efficiency, and likablility. Statements from the standard Botvinick and Cohen 9-question survey [3] altered for the virtual hand illusion by Ma and Hommel [12] [13] [14], Yuan and Steed [28], Zhang and Hommel [29], Argelaguet et al. [1], and Lin and Jörg [9] have been adapted for this experiment. For each statement, participants choose a rating on a seven-point Likert scale ranging from 1 for "strongly disagree" to 7 for "strongly agree." The one exception from the Lik-

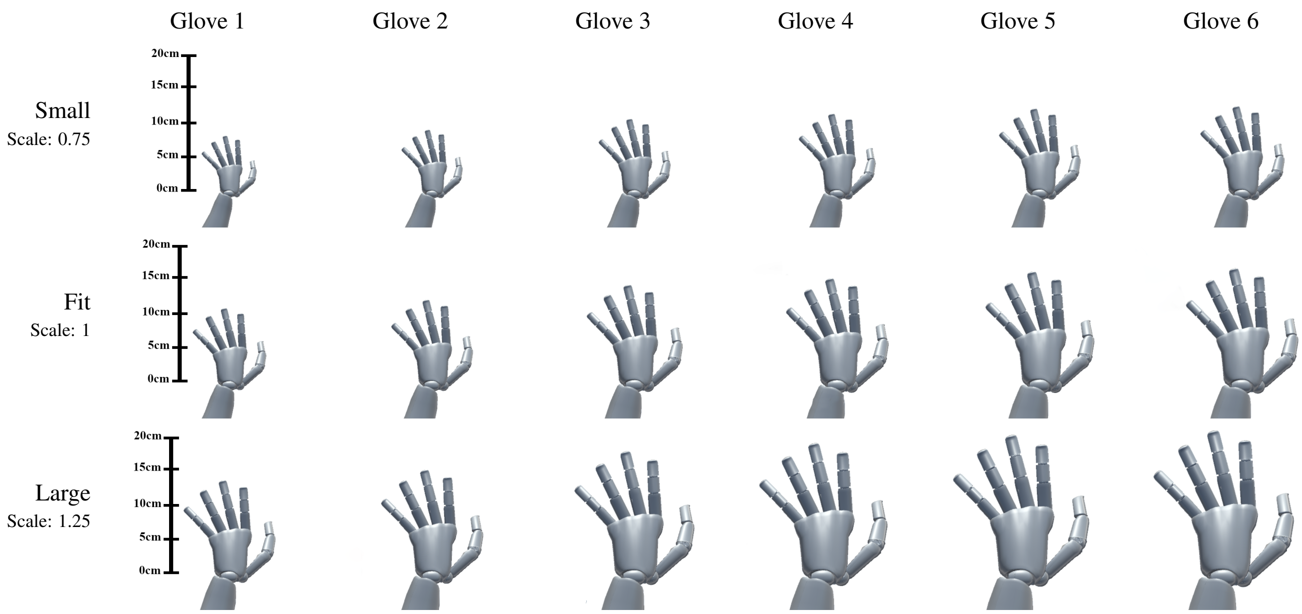


Figure 5: Experiment hand model displayed as a function of the motion capture glove worn by the participant (Figure 6). The scale 1 hand corresponding to glove 4 matches the model sent to our system. All other glove sizes are scaled relative to glove 4 based on the average finger lengths of each glove size (measured manually). The hand displayed in the Fit condition corresponds to the participant's glove size. The hand displayed in the Small condition is 75% of the fit glove size. The hand displayed in the Large condition corresponds to 125% of the fit glove size.

Figure 6: The motion capture gloves used in our study. Each glove has 19 markers, with finger markers being placed between joints. In the Glove condition, we receive global wrist positions and orientation along with the poses of fingers.

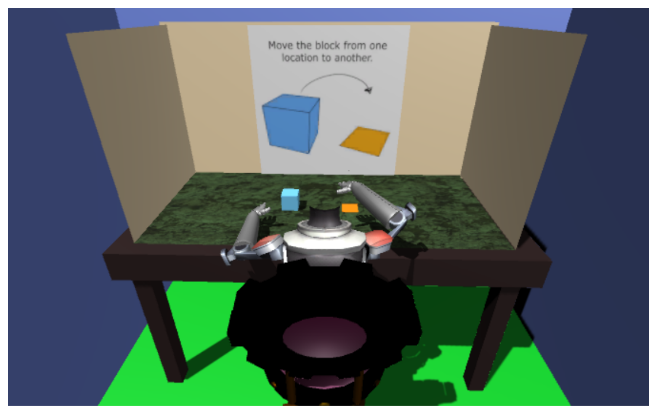


Figure 7: Avatar and environment in one of the tutorial puzzles.

ert scale format is the last question on the list, in which participants report their virtual hand size from 0 to 200 percent of their real one. Statement order is randomized in the study.

4 Results

4.1 Questionnaire

We conducted the aligned rank transform procedure [26] followed by a 2x3 two-way repeated measures ANOVA on the questionnaire results with the modality (Glove vs. Controller) and hand size (Small vs. Fit vs. Large) as the within-subjects factors. Mauchly's test of sphericity was conducted. For questionnaire statements that did not pass Mauchly's test, we applied a Greenhouse-Geisser correction on the data. Main and interaction effects were found for several of our questionnaire items (see Table 1 for an overview as well as Figures 9, 10, and 11. Error bars represent the standard errors of the mean in all graphs.)

Ownership. We found an interaction effect for ownership statement **O1.** "I felt as if the virtual hands were part of my own body" with $F(2,38) = 3.8$ and $p = 0.031$. Pairwise comparisons with LSD corrections showed that ownership was rated higher in the Glove condition ($M = 4.8$, $SE = 0.452$) than in the Controller condition ($M = 3.7$, $SE = 0.357$) with the Small hands, whereas there was no difference between the conditions with the Fit or Large hands (see Figure 9 (a)). No effects were found for separately analyzing the ownership questions:

- **O2.** "It sometimes seemed my own hands were located on the screen."
- **O3.** "It sometimes seemed my own hands were coming into contact with the virtual objects."

When analyzing the three ownership statements together, we found a main effect of modality where the Glove condition generates a higher level of ownership than the Controller condition (see Figure 9 (b)). Cronbach's alpha for the three ownership statements was 0.943.

Agency. No effects were found for analyzing the agency statements separately and together:

Table 1: Questionnaire results for our study.

Questionnaire Item	Concept	F-test, p-value	Mean and Standard Error (M, SE)	Results
O. Three ownership statements averaged	Ownership	Main effect of Modality: $F(1,19) = 7.22$, $p = 0.015$	Glove $(4.5, 0.328)$ Controller $(3.8, 0.326)$	Controller < Glove
A. Three agency statements averaged	Agency		Overall average $(5.3, 0.310)$	
Q1. I thought the virtual hands on the screen looked realistic.	Realism	Main effect of Modality: $F(1,19) = 8.01$, $p = 0.011$	Glove $(4.0, 0.382)$ Controller $(3.3, 0.362)$	Controller < Glove
		Main effect of Size: $F(2,38) = 3.83$, $p = 0.030$	Small $(3.9, 0.404)$ Fit $(3.7, 0.327)$ Large $(3.3, 0.370)$	
Q2. I was so immersed in the virtual reality, it seemed real.	Immersion		Overall average $(4.6, 0.385)$	
Q3. I felt like I could very efficiently use my virtual hands to interact with the environment.	Efficiency	Main effect of Modality: $F(1,19) = 6.46$, $p = 0.020$	Glove $(4.6, 0.320)$ Controller $(5.2, 0.291)$	Glove < Controller
Q4. I liked the physical appearance of my virtual hands.	Likability	Main effect of Size: $F(1.37, 26.1) = 5.61$, $p = 0.018$	Small $(4.5, 0.334)$ Fit $(4.6, 0.292)$ Large $(3.9, 0.366)$	Large < Fit
Q5. I felt like using my virtual hands to interact with the environment was fun.	Fun	Main effect of Size: $F(2,38) = 3.38$, $p = 0.044$	Small $(5.7, 0.333)$ Fit $(5.9, 0.306)$ Large $(5.5, 0.352)$	
Q6. What size were your virtual hands?	Perceived size	Main effect of Modality: $F(1,19) = 6.15$, $p = 0.023$	Glove $(123, 6.5)$ Controller $(135.4, 6.8)$	Glove < Controller
		Main effect of Size: $F(1.27, 24.1) = 120.7$, $p < 0.001$	Small $(89.8, 4.5)$ Fit $(124.1, 5.0)$ Large $(173.8, 11.1)$	Small < Fit < Large
Duration	Play Data	Main effect of Modality: $F(1,19) = 17.12$, $p < 0.001$	Glove $(185.6, 10.5)$ Controller $(144.2, 11.1)$	Controller < Glove
		Interaction effect Size x Modality: $F(2,38) = 7.09$, $p = 0.002$	Glove Small $(206.1, 19.5)$ Glove Fit $(173.6, 19.5)$ Glove Large $(177.0, 12.0)$ Controller Small $(137.4, 13.8)$ Controller Fit $(178.5, 18.784)$ Controller Large $(166.6, 7.9)$	Controller Small, Controller Large < Glove Small, Glove Large; Controller Small, Controller Large < Controller Fit
Number of Grabs	Play Data	Main effect of Modality: $F(1,19) = 56.71$, $p < 0.001$	Glove $(67.9, 3.86)$ Controller $(40.0, 1.69)$	Controller < Glove
		Interaction effect Size x Modality: $F(2,38) = 6.26$, $p = 0.004$	Glove Small $(74.7, 6.55)$ Glove Fit $(63.05, 5.6)$ Glove Large $(66.1, 4.4)$ Controller Small $(35.0, 2.4)$ Controller Fit $(44.4, 2.8)$ Controller Large $(40.7, 2.7)$	Controller Small < Controller Fit
Number of Drops	Play Data	Main effect of Modality: $F(1,19) = 8.93$, $p = 0.008$	Glove $(24.7, 0.585)$ Controller $(22.4, 0.375)$	Controller < Glove

- **A1.** "I felt as if I could cause movements of the virtual hands."
- **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."

Cronbach's alpha for the three agency statements was 0.938.

Realism Participants felt like the virtual hands looked more realistic in the Glove condition. Analysis of the realism statement Q1 revealed a main effect of modality where participants rated the Glove condition higher than the Controller condition (see Figure 10 (a)). We also found a main effect of size, but pairwise comparisons did not reveal any significant difference.

Efficiency. We found a main effect of modality for the efficiency statement Q3. The Controller condition was perceived as more efficient than the Glove condition (see Figure 10 (b)).

Likability. Analysis of likability statement Q4 revealed a main effect of size. Participants liked the Fit hand more than the Large hand (see Figure 10 (c)).

Fun. We found a main effect of size, but pairwise comparisons did not reveal any significant difference between sizes.

Perceived size. For size statement Q6 we found a main effect of modality where participants rated hands in the Controller condition as larger than in the Glove condition (see Figure 10 (d)). Participants were able to differentiate between the hand models as shown by the main effect of size with all differences being significant. Participants overestimated the size of their hands in virtual reality.

4.2 Play Data

To give us further insights into participants' behavior, we analyzed the play duration, number of times blocks were grabbed, and number of times blocks were dropped using the same methods as for the questionnaire. The number of drops does not include successful block placements. Our analysis showed a main effect of duration in modality (see Figure 11 (a)). Participants spent more time in the Glove condition than in the Controller condition. An interaction effect showed that participants spent more time in the Glove condition with the Small and Large hands than in the Controller condition with the Small and Large hands. In addition, in the Controller condition, participants spent more time with the Fit hands than the Small or Large hands.

We found a main effect in modality where participants grabbed blocks more often in the Glove condition than in the Controller condition. There was also an interaction effect in the Controller

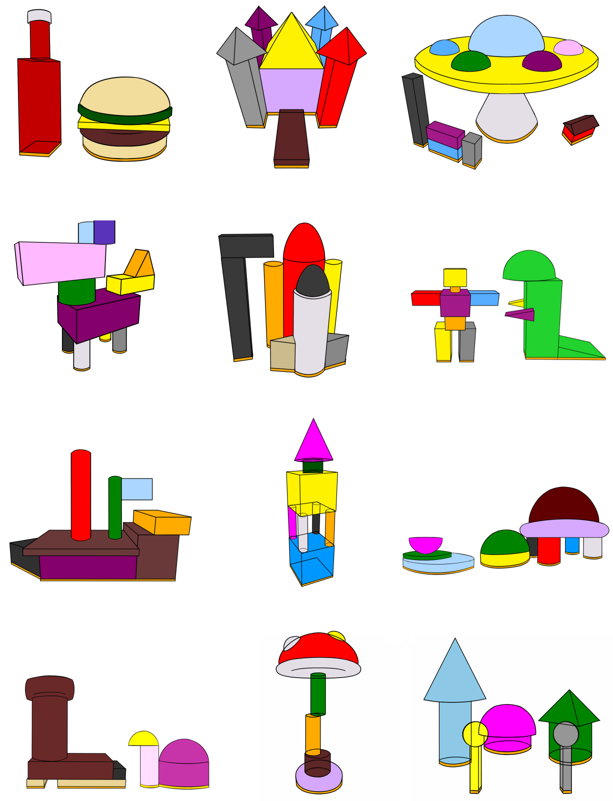


Figure 8: The 12 main puzzles in our study. The number of blocks ranges from 7 to 13 per puzzle.

condition where participants grabbed blocks more in the Fit than the Small condition. Finally, there was a main effect of modality where participants dropped blocks more in the Glove than in the Controller condition.

Participant move trajectories were recorded as well. Figure 12 illustrates the difference in movement between the Glove and Controller condition in a participant's trajectory visualization.

4.3 Qualitative Findings

We asked participants in our post-study interview if they experienced dizziness or disorientation during or after the study. We also debriefed them on the independent variables and asked if they had a preference for modality and hand size.

One participant felt "a little [disorientation]" while wearing the headset and another participant's head physically hurt from wearing it, but all 20 participants reported that they did not experience dizziness or disorientation after taking off the headset.

Eight participants preferred the Fit hand size, citing reasons such as "they seemed to work best," and "it felt more like it was part of my body." Four participants preferred Fit or Small hands. One participant preferred the Small hands "for more precise movements." Three participants preferred Large hands as they were "easier to manipulate the objects with," and "the funnest." Two participants preferred the Fit and Large hands, "the smaller one might be the one I had more trouble with," "I didn't like the small ones." The Large hands were also reported as "unrealistic, it [looks] too big to me," "most difficult [size] to work with," and "it felt like a kid's version of the game." One participant said they preferred hand size based on the size of the block they were moving, preferring the Small hands for "better dexterity" and reporting the Large hands as "floppy" but preferred for more "macro applications (bigger blocks)." One participant reported not noticing the Small hands, saying they would prefer a smaller hand size if we had made one for the study.

Thirteen participants preferred the Glove condition, citing reasons such as the gloves were "easier to control," "it felt more realistic," "more immersive," "more fun," "more comfortable," "I prefer the gloves since I was able to move all of my fingers and it looked just like my own hands," and "with the gloves it felt much more physical, like I was building with my hands than versus the controllers," and "I felt like I was [going to] drop the controllers because I had to keep thinking 'I'm using controllers, I can't let go of these."' Four participants who preferred the Glove condition reported that they felt the Controller condition had better feedback. Six reported preferring the controllers because "it was more precise when I was picking things up," "more responsive," "the gloves were more immersive, but the controllers seemed to work better," "with the gloves there wasn't any real feedback." One controller-preferring participant would prefer the gloves if they "worked like my real hands." One participant had no preference for modality.

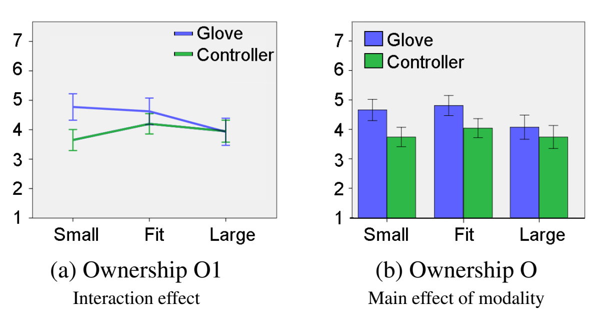


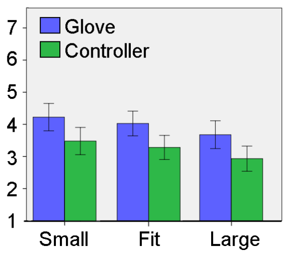
Figure 9: Significant results for ownership statement O1 and all ownership statements averaged.

5 Discussion

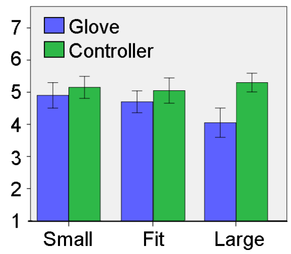
We confirmed our hypothesis that being able to directly control virtual hands rather than use a controller induces a stronger level of virtual hand ownership and thus increases the virtual hand illusion. It is noteworthy that, in contrast to Argelaguet et al. [1], we did not find that agency is stronger for hands less similar to participants'. Although there were no differences for agency among our conditions, like Lin and Jörg [9], we found that participants generally had high ratings for feeling like they could control the hands. Being able to move the hands may have been enough to generate similar feelings of agency among our models. Since grasping was the only task and buttons were assigned to the controllers to mimic a grasp, our button implementation may have been convincing enough to place the controllers on a similar agency level with the gloves as well.

There were multiple main effects of modality showing differences in areas beyond ownership. Though we did not change the robot model throughout the study, participants thought the hands looked more realistic in the Glove condition, which could be attributed to the fact that they were able to move individual fingers in that condition, thus creating more natural-looking hand motions. Our play data supported participants' perceived efficiency for the Controller Condition over the Glove Condition. One reason for these findings might be in the tracking and grasp detection. While our motion capture system was well calibrated and our thresholds for grasp detection were carefully adjusted, grasp detection is still less reliable than a button press [8]. Users might also feel more in control when having haptic feedback in the form of a button.

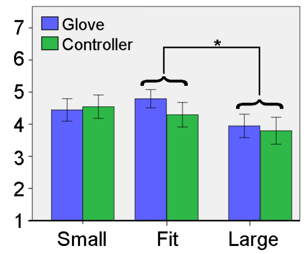
In contrast to Wittkopf et al. [25]'s findings, we could not confirm our hypothesis that having a hand size similar to one's own induces a stronger virtual hand illusion. Like Ogawa et al. [17], we observed that participants overestimate virtual hand size. Participants also per-



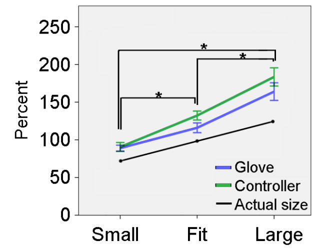
(a) Realism Q1
Main effect of modality
Main effect of size



(b) Efficiency Q3
Main effect of modality

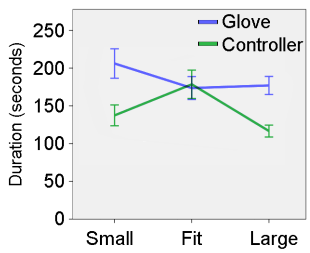


(c) Likability Q4
Main effect of size

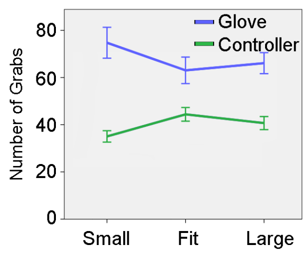


(d) Perceived size Q6
Main effect of modality
Main effect of size

Figure 10: Significant results for statements Q1-Q6.



(a) Duration
Main effect of modality
Interaction effect



(b) Grabs
Main effect of modality
Interaction effect

Figure 11: Significant results for the play data. The main effect of modality for Drops is not represented. The averages are for two puzzles as we had two puzzles in each condition.

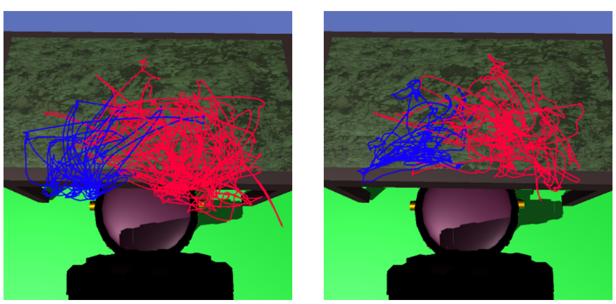


Figure 12: A participant's trajectory visualization in the Glove condition (left) and in the Controller condition (right). In both conditions, this participant used their right hand more than their left. They also moved their hands more in the Glove condition.

ceived hands as being larger in the Controller condition. They could have been able to judge the body part better in the Glove condition because they were directly controlling it [11]. Several participants were observed playing with the finger movements throughout the study in the Glove condition. Being able to look at and control individual finger movements could have made participants more self conscious, and thus better at judging their hand sizes.

Finally, we did not find any consistent differences due to interaction modality or hand size for some of our statements, most interestingly Q2 and Q5, which are related to immersion and fun. Our puzzles may have been entertaining enough to create a fun and immersive experience independent of the interaction or hand model. Different effects could also have balanced each other out. For example, a higher feeling of ownership could increase fun and immersion in the glove condition, whereas a less efficient control of the grasping might reduce them.

6 Conclusion and Future Work

We found multiple main effects of modality, showing that being able to directly manipulate the environment with gloves increases feelings of ownership, accuracy in judging virtual hand size, and the perception of realism for the virtual model. Interestingly, participants preferred the Glove condition, despite the Controller condition resulting in better task performance.

Ownership, agency, realism, immersion, fun, and task efficiency were not directly affected by hand size in our study. However, the physical appearance of the virtual hands was preferred for the Fit hands over the Large hands.

In summary, the choice of the interaction modality should depend on the application: if realism and the intensity of the virtual hand illusion are important, we recommend using gloves; if task efficiency is the main focus, controllers should be used. An accurate hand size can be used to increase how much users like the appearance of their virtual hands. However, our results do not support any main effect of hand size on the virtual hand illusion or task efficiency. Finally, it seems that an interesting application might be fun and immerse players in any of the presented conditions.

Our experiment examines the effects of two interaction models and three hand sizes. There are several limitations of our setup which could be fruitful grounds for future work. For example, our interaction model does not integrate physics simulation. Specifically, blocks were allowed to intersect and did not react to gravity, so the movement of blocks is not consistent with the real world. Our study also focused on interacting with objects in a range of sizes likely to be handled in reality. A future study could observe if results for our conditions, especially hand sizes, differ when the same puzzles are scaled at smaller or larger sizes.

Furthermore, the avatar's shape and motion differs slightly from the participant's. The avatar hand shape and motion are both retargeted from a more faithful representation of the users hand. For example, the fingers of the avatar are aligned in a straight line across the palm with even spacing between them and the palm is rigid. A more realistic hand model could influence our observations.

Finally, future work could investigate further ways to combine efficiency with realism. Haptic feedback could be added to gloves or grasp detection could be improved by examining user intent.

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