Virtual Grasping Feedback and the Virtual Hand Ownership

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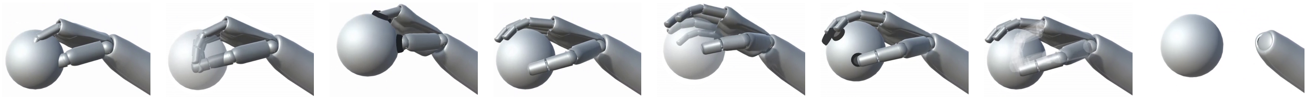

IH IHTR IHRA OH OHTR OHRA 2H DH

Figure 1: Grasping feedback techniques used in this study: Inner Hand (IH, displays the tracked hand), Inner Hand with Object Transparency (IHTR, object becomes transparent when grasped), Inner Hand with Reactive Affordance (IHRA, visualizations aiming at a more tactile feeling are added), Outer Hand (OH, virtual hand does not penetrate the object), Outer Hand with Object Transparency (OHTR) and Outer Hand with Reactive Affordance (OHRA), Two Hands (2H, visualizes the tracked hand and the outer hand), and Disappearing Hand (DH, virtual hand disappears during the grasp).

ABSTRACT

In this study, we analyze the performance, user preference, and sense of ownership for eight virtual grasping visualizations. Six are classified as either a tracked hand visualization or an outer hand visualization. The tracked hand visualizations are those that allow the virtual hand to enter the object being grasped, whereas the outer hand visualizations do not, thereby simulating a realistic interaction. One visualization is a compromise between the two, showing a primary virtual hand that stays outside the grasped object and a secondary hand that follows the users tracked hand into it. We use high fidelity marker-based hand tracking to control the virtual hands in real time. For each feedback technique, users repeatedly pick up a gray virtual ball, move it to a target position, and release it on the target. We found that the tracked hand visualizations result in better performance, however, the outer hand visualizations were preferred. We also found some evidence that ownership is stronger with the more realistic visualizations.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

virtual grasping, grasping feedback, virtual hand illusion, virtual reality, body ownership, virtual environments, virtual character

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1 INTRODUCTION

Immersive virtual reality (IVR) applications generally use a virtual hand metaphor for interaction because it most closely matches how we interact with objects in the real world. Many current virtual reality applications display limited, if any, virtual hand motion due to the limits of controllers (i.e. the Oculus Touch) and the high cost of high fidelity hand tracking hardware. As hand tracking hardware continues to advance, however, it becomes increasingly important to study visual feedback techniques for making it easier and more intuitive to interact with virtual environments using one's hands. One issue with using hand tracking for virtual grasping is finger object interpenetration, which reduces realism and can degrade the immersive experience [Prachyabrued and Borst 2012]. Additionally, knowing when an object is grasped without visual feedback is more difficult since there is no haptic feedback, such as the button on a controller or a physical object.

In this study, we focus on visual feedback for grasping. We use eight different visual feedback techniques for virtual grasping, shown in Figure 1, and examine the effect each technique has on grasp and release performance. Additionally, we examine the effect that each technique has on perceived ownership of the virtual hand. Participants are seated in front of a table in a virtual environment and perform a simple pick-and-place task, in which the users

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pick up and move a virtual ball to a target. As the task is repeated, the participants encounter two different virtual threats, which are used to test ownership over their virtual hand. Our study builds upon previous work by not only measuring task performance for different visual feedback techniques, but also examining the influence that they have on the virtual hand illusion. Furthermore, we use a novel hand tracking system that allows for real-time, highly precise hand tracking that is superior to systems used for previous studies.

2 RELATED WORK

Object selection and manipulation in virtual environments plays a significant role in the overall user experience. In IVR applications, high interaction fidelity, i.e. the degree to which real world interactions are reproduced [McMahan et al. 2012], is a goal that many researchers and designers aim for. There are a wide variety of techniques for interacting with objects in a virtual environment [Bowman and Hodges 1997; Poupyrev et al. 1997], and the best to use often depends on the specific application. In IVR, the most intuitive and commonly used methods are egocentric, meaning the user interacts with virtual objects from within the virtual environment [Poupyrev et al. 1998]. Though natural interaction techniques may not be the best to use for applications where high accuracy and performance are required, they do have benefits, such as intuitiveness and higher immersion [Bowman et al. 2012; Lin et al. 2019].

Some methods use hand tracking to simulate interactions in the real world and to provide a more intuitive and realistic interaction experience. Many of these methods strive for realism, using physically based methods for grasping [Borst and Indugula 2005; Zhao et al. 2013], a combination of physically based and data driven approaches [Liu 2008; Pollard and Zordan 2005], and even modeling skin deformations [Verschaar et al. 2018]. However, realistic physically based grasping currently suffers from drawbacks, such as not being able to generalize to every object due to use of synthesized motion data and the computational load of rigid body calculations. Furthermore, highly realistic rendering or grasping techniques without visual grasping feedback can result in visual-proprioceptive discrepancy [Prachyabrued and Borst 2013] and reduced grasping performance [Prachyabrued and Borst 2012; Prachyabrued and Borst 2014].

2.1 Visual Feedback for Grasping

Appropriate visual feedback for interaction in virtual environments can not only enhance the user experience but it can also affect the efficiency of completing certain tasks in a virtual environment [Argelaguet and Andújar 2013]. Lam et al. [2018] tested virtual grasping in a desktop environment and found that a grasping animation as visual feedback helped participants notice when an object is selected. Vosinakis and Koutsabasis [2018] tested the grasp and release performance of multiple visual feedback techniques in a desktop environment and in IVR. They found that bare hand grasping is performed best in IVR and that any form of visual feedback resulted in better grasping and release performance than none. Geiger et al. [2018] tested visual feedback for assisting users in gripping a virtual object in a specified way. The results were that for complex grip types, such as whole hand grasping, visual feedback significantly improved user performance.

Prachyabrued and Borst [2014] work in evaluating visual feedback for grasping is closest to ours. They evaluated the performance and subjective preference of eight different visual cues for finger interpenetration during manipulation. The techniques tested were called *Inner Hand* (IH), *Outer Hand* (OH), *See Through* (ST), *2-Hand* (2H), *Finger Color* (FC), *Object Color* (OC), *Arrow* (AR), and *Vibration* (VB). In IH, the virtual hand always follows the movements of the tracked hand. In OH, the virtual fingers are prevented from penetrating the virtual object. The 2H technique is considered a hybrid between IH and OH in that it keeps the primary virtual hand outside the object while a secondary virtual hand follows the tracked hand into the object. The FC, OC, AR, and VB techniques each give indirect feedback for interpenetration. The color of the fingers or object changes based on depth for FC and OC, respectively. In AR, arrows extend from the points of contact and change in length as a function of depth. In VB, the virtual fingers begin to vibrate as the tracked hand enters the virtual object. Participants used each technique to grasp a virtual ball and release it over a target. IH was found to be the best for performing the targeted ball drop accurately in contrast to OH, which was found to be the worst. 2H was notably a good compromise, as it generally resulted in better performance than the others. Visual appearance had a significant impact on the users preference, with OC and FC being the most preferred, followed by 2H, AR, ST, OH, IH, and VB.

Though it is well established that good visual feedback for virtual grasping is helpful in terms of interaction performance and user preference, it is important to consider the visual feedback from a presence and immersion standpoint. This is where virtual hand embodiment becomes a topic of interest. In contrast to Prachyabrued and Borst [2014], we measure not only the grasping performance for different visual feedback techniques, but also the effect that they have on ownership of the virtual hand.

2.2 Virtual Hand Embodiment

Virtual reality has allowed researchers to study the extent to which we can establish a sense of embodiment over virtual avatars. Kilteni et al. [2012a] define the sense of embodiment (SoE) as follows: *SoE toward a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body.* There are three components that contribute to SoE: body ownership, self-location, and the sense of agency [Kilteni et al. 2012a; Longo et al. 2008]. 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.

In an experiment by Botvinick and Cohen [1998], participants felt sensation in a rubber hand in front of them because it was being stroked with a brush at the same time as their unseen hand. Several studies have demonstrated that something analogous to this "Rubber Hand Illusion" can happen when the arm is hidden and visually replaced with an entirely virtual arm in a virtual setting. Slater et al. [2008] induced the *Virtual Arm Illusion* using tactile stimulation on the real hand and both synchronous and asynchronous virtual visual stimuli. The results were that synchronized visual and tactile stimuli result in significantly higher levels of ownership. Ma and Hommel [2013] subject the virtual hand to a threat, in which the virtual hand is cut with a knife, and an impact, where a ball hits the virtual hand. Though ownership was higher when the the user had synchronous control (the virtual hand followed the tracked hand accurately) over the virtual hand under the impact condition, asynchronous control (the virtual hand movement was delayed) had no effect on the users emotional investment in the threat condition.

Since accurate user control of the virtual hand has been correlated with ownership, researchers began investigating the relationship between the visual representation of the hand and ownership. Yuan and Steed [2010] tested two very different visual representations of the virtual hand: an abstract arrow and a realistic virtual hand. The users could control the movement of the virtual hand, and in some conditions, small distortions in tracking accuracy was introduced. Galvanic skin response data and participant responses showed that the sense of endangerment when there was a virtual threat was significantly higher for the realistic hand than for the abstract arrow. Kilteni et al. [2012b] extend the virtual arm, with results showing that users felt ownership over the virtual arm, even when extended up to three times the length of their real arm. Ma and Hommel [2015a] demonstrate that ownership can be established over non-corporeal objects, but only when there is minimal tracking error. To determine if agency or appearance has a stronger effect on ownership, Ma and Hommel [2015b] induced the *Virtual Hand Illusion* passively using a similar method to Slater et al. [2008], and actively, as done by Yuan and Steed [2010]. In each case, the virtual hand was represented as either a human hand or a rectangle and there were both synchronous and asynchronous conditions. They found that although the visual representation correlates with ownership, agency (associated with synchronous control of the hand) had a stronger effect. Furthermore, the asynchronous conditions significantly diminished the sense of ownership in both the active and passive conditions.

To more thoroughly examine the effect of visual representation of the virtual hand on the level of ownership, Lin and Jörg [2016] tested a range of different hand representations. The virtual hand representations were realistic, toony (undetailed skin texture), very toony (cel shaded), zombie, robot, and a wooden block. The results were that some level of ownership occurs for all representations, however, ownership was stronger with the anthropomorphic representations and strongest with the realistic representation. Argelaguet et al. [2016] conducted a study to investigate the effect that virtual hand representation has on users' sense of agency and sense of ownership of the hand. They used three visual representations of the virtual hand: an abstract sphere, an iconic hand composed of simple shapes, and a highly realistic one. The users controlled the virtual hand and were tasked with moving a ball over visually dangerous virtual obstacles, including a flame, a spinning saw, and barbed wire. The results were that the realistic virtual hand elicited the strongest sense of ownership. For performance and agency, however, it was found that the abstract representations were superior. Though previous studies have demonstrated that agency and ownership are correlated, the reduced sense of agency over the realistic hand was not strong enough to affect ownership.

3 METHOD

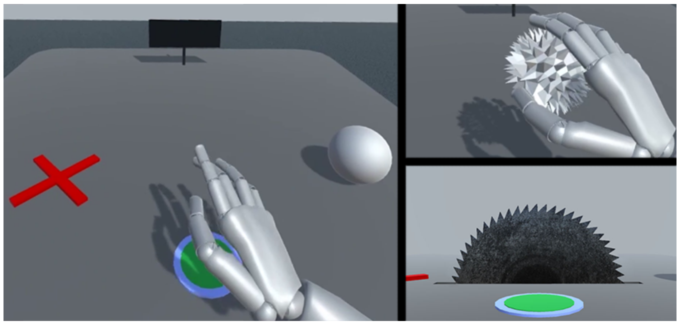

Figure 2: Virtual desk setup (left) and the virtual threats (right). The spiky ball is displayed twice at random during the second block. The spinning saw is displayed in the third block.

For this study, we created a simple virtual test room containing a desk, a chair, and a humanoid robot avatar using the Unity game engine. Participants are seated in front of a real table, and the robot avatar representing them is seated in front of the virtual desk. A virtual button is centered on the desk in front of the avatar with a virtual ball on one side of it, and a target (a red X) on the other side, as shown in Figure 2 (left). The participants perform a simple pick and place task in which they pick up the ball and move it to the target several times with each grasping feedback technique. While performing the task, two different virtual threats (Figure 2, right) occur at separate times.

3.1 Design

The experiment is conducted within subjects, with each participant performing the pick and place task with their dominant hand. The independent variables are the grasping visualization and the presence of a virtual threat. The dependent variables are grasp performance, release performance, level of ownership, and user preference. The experiment is counterbalanced by presenting the visual feedback conditions in random order.

3.2 Participants

We had 23 participants (11F, 12M) ages 18-60, with the median age group being 26-30.

The participants' experience with virtual reality and virtual characters ranged from no experience at all to very experienced. We obtained signed consent from all participants before the study and pre-screened each participant for cybersickness. After completing the study, participants were debriefed about their experience in the virtual environment and their encounter with the virtual threats. Participants received a $10 voucher for their time.

3.3 Apparatus

Our virtual reality setup consists of an Oculus Rift CV1 Head-Mounted-Display (HMD), 16 OptiTrack motion capture cameras mounted on support beams surrounding the user on four sides, and a small table in front of the user (Figure 3). We used real time

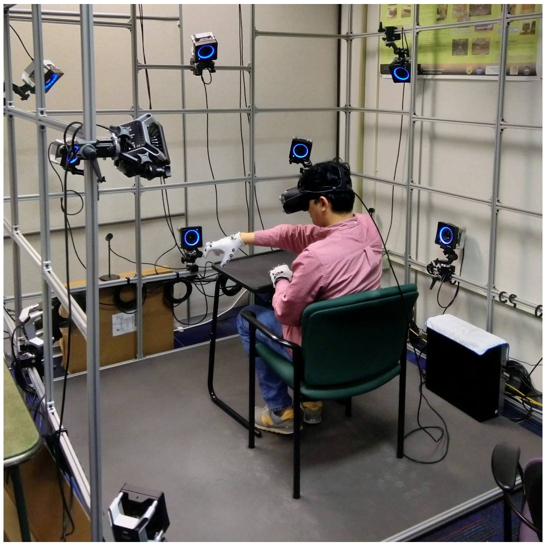

Figure 3: Motion capture system with 16 cameras.

marker based hand tracking [Han et al. 2018] with a dense marker set of 19 markers per hand. The markers are attached to six gloves of different sizes, and the system was pre-calibrated for use with each glove size. The system tracks hand motions at 120FPS, and the VR application runs at 90FPS.

3.4 Visualizations

We investigate eight different visualizations for virtual grasping, which we call *Inner Hand* (IH), *Inner Hand with Object Transparency* (IHTR), *Inner Hand with Reactive Affordance* (IHRA), *Outer Hand* (OH), *Outer Hand with Object Transparency* (OHTR), *Outer Hand with Reactive Affordance* (OHRA), *Two Hands* (2H), and *Disappearing Hand* (DH). Each of the visualizations are described and grouped as follows:

Tracked Hand Group:

1. *IH:* The virtual hand is always controlled by the user's tracked hand and can penetrate the virtual ball.
2. *IHTR:* Displays the Inner Hand and the virtual ball becomes semitransparent upon being grasped and opaque upon release.
3. *IHRA:* Displays the Inner Hand and a "dimple mesh" [1] is rendered at the projected contact points when the virtual hand is within a certain distance from the ball, and the dimple grows in size as the user tightens their grip.

Outer Hand Group:

1. *OH:* The virtual hand always remains outside of the virtual ball. That means that when the tracked hand penetrates the ball during a grasp, the displayed hand does not follow the users' motions.
2. *OHTR:* Same as IHTR, but the virtual hand remains outside of the virtual ball.
3. *OHRA:* Same as IHRA, but the virtual hand remains outside of the virtual ball.

Other:

1. *2H:* The primary virtual hand remains outside of the virtual ball (OH) and a secondary virtual hand corresponding to the tracked hand (IH) is displayed as the user grasps the ball.
2. *DH:* The virtual hand disappears once the ball is grasped and reappears when released.

We include these particular visualizations because of their use in previous work and in commercial VR applications. IH, OH, and 2H were used by Prachyabrued and Borst [2014] in their evaluation of visual feedback for grasping. IH was found to be best for performing the release task in their experiment, and OH was found to be among the worst, though it was preferred more than IH. 2H fell between IH and OH in terms of performance and preference, and thus is considered a good compromise between the two. The reactive affordance (IHRA and OHRA) visualizations render a black "dimple mesh" at the projected fingertip contact points when the hand is close to the ball and at the contact points when grasping. We think that this can help guide the user toward grasping the ball and that it may provide a more tactile feeling compared to the others. Additionally, IHRA and OHRA provide indirect feedback for hand-object interpenetration by changing the size and height of the dimple mesh based on the depth of the fingertip associated with it. The semitransparent visualizations (IHTR and OHTR) are included as simple, grasp specific feedbacks for both IH and OH. They are intended to show the user the state of the ball, i.e. whether or not it is being grasped. Vosinakis and Koutsabasis [Vosinakis and Koutsabasis 2018] showed that color feedback resulted in better grasping and release performance than no feedback. Occlusion could be a problem when using visual feedback for grasping, and as such, we include the disappearing hand (DH) visualization to keep the hand from occluding the ball when grasped and when placing on the target. The disappearing hand visualization is also used in some popular VR games [2].

3.5 Grasping Implementation

We use a heuristic algorithm for detecting when the user grasps and releases the ball. A grasp is registered when the tip of the thumb and at least two other fingertips have made contact with the ball, and a release is registered when no fingertips are touching the ball. To compute the outer hand, the ball is moved with the hand when the front of the hand collides with it. When grasping and releasing, the rotations for joints in the fingers are disabled or enabled based on whether or not the joint is contacting the ball.

3.6 Procedure

After agreeing to participate in the study, participants are fitted with a pair of gloves for motion tracking then seated in a chair in front of a small desk. The hand tracking system is set up for tracking of the glove size worn by each participant, then the tracking is tested. Once tracking is confirmed, participants put on and adjust the HMD (with the help of the investigator). Finally, the virtual

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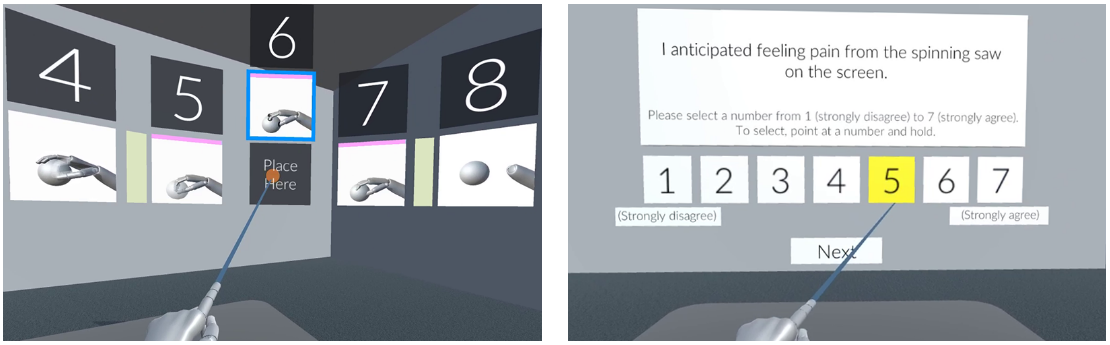
[1] http://blog.leapmotion.com/interaction-sprint-exploring-the-hand-object-boundary/

[2] https://owlchemylabs.com/games/
https://iexpectyoutodie.schellgames.com/



I anticipated feeling pain from the spinning saw on the screen.

Please select a number from 1 (strongly disagree) to 7 (strongly agree).
To select, point at a number and hold.

(a) (b)

Figure 4: (a) User interface for ranking in VR. The selected visualization (middle with blue outline) and the adjacent ones play a video of the same interaction under their respective visualization condition. The user can also point at one of the other images to play the video for that visualization. (b) VR questionnaire.

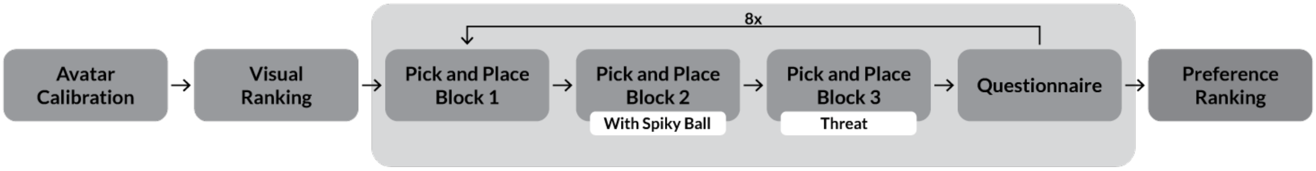


Figure 5: Experimental procedure of our study.

avatar is calibrated such that the arm span and height of the avatar closely match those of the participant.

After calibration, the participants are asked to rank the different grasping feedback techniques in order of visual appeal (Figure 4 (a)). Once they are finished ranking, a virtual ball appears on the desk and the participants can practice grasping and releasing it. After indicating that they feel comfortable with grasping and releasing, a practice trial is started in which each of the eight visualizations is used once. Each participant performs the experimental task with their dominant hand and completes the experiment in 35 to 60 minutes.

The main experimental task, referred to as "the pick-and-place task", is performed as follows: First, the participant presses a green button on the virtual table, triggering a stopwatch. The ball can not be moved until the participant has pressed the button. After pressing the button, the participant picks up the ball then moves it to the target. Once the ball makes contact with the target, the target turns white and the virtual button becomes red. After releasing the ball on the target, the participant presses the button again to stop the timer. After two seconds, the scene resets, and the procedure is repeated until the third block for each grasping visualization is over. The participants were instructed to perform the task as efficiently as they could.

The experiment is divided into eight sessions, one per grasping visualization, and each session is divided into three blocks. During the first block, the pick and place task is done ten times with the smooth version of the ball. The second block is similar to the first block, though this time the spiky ball replaces the smooth ball for two randomly selected trials of the ten. In the third block, a spinning saw appears between the ball position and the target position, and the pick and place task is done once more with the smooth ball. The appearance of the ball and the type of grasping visualization do not affect how a grasp or release is detected.

After the third block, a virtual questionnaire is presented, and participants can choose their response for each question by pointing and holding over the number that most closely matches how they feel for that statement (see Figure 4 (b)). After the questionnaire, the trial for the next hand visualization begins. Once the eighth and final session is complete, along with the questionnaire following it, the participants rank the visualizations in order of overall preference using the same procedure used for ranking based on appearance. Refer to Figure 5 for a visual summary of the procedure.

3.7 Hypotheses

Based on previous related work, we came up with four hypotheses to test:

- **H1:** Visualizations in the tracked hand group will result in better performance than those in the outer hand group.
- **H2:** Visualizations with grasping feedback will result in better performance than the base condition in each group.
- **H3:** The tracked hand group will result in higher levels of ownership than the outer hand group due to a stronger sense of agency (the virtual hand always reflects the tracked hand).
- **H4:** Visualizations in the outer hand group will be preferred.

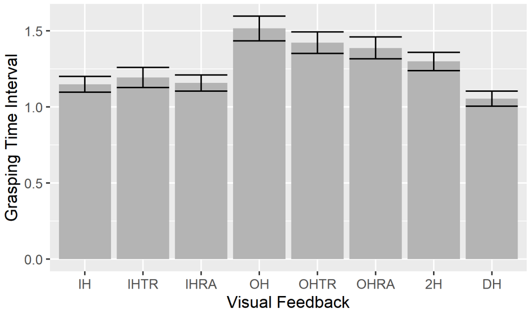


Figure 6: Grasping performance: Time includes reaching for ball and moving it. We found significant differences with $p < 0.05$ between the following conditions: DH / IH / IHRA < 2H / OH; DH < OHRA / OHTR; and IHTR < OH. We furthermore found that the time interval for the grasping in the outer hand conditions is significantly longer than for the conditions displaying the tracked hand.

4 RESULTS

4.1 Performance

Our evaluation of performance is based on the time required for grasping and the time required for releasing the ball. We measure performance using data from the first block of the pick and place task in each visualization condition.

Grasping Performance: To measure the full action of grasping starting before the grasp until after the user realizes that the grasp was successful, which might include multiple grasp attempts, we define a spherical grasping area with the ball at its center and a radius of 25cm. The radius of the ball is 5.48cm. We measure the time interval between when the base of the palm of the virtual hand enters the grasping area until it leaves it. The data is first filtered to remove outliers in completion time ($\pm 2\sigma$), since in some instances the motion tracking might have stopped responding. Ninety-five percent of the data is retained after filtering.

A one-way ANOVA, with Greenhouse-Geisser sphericity corrections, was performed with grasping performance as the dependent variable and grasping feedback as the independent variable. A statistically significant effect of visual feedback condition on grasping performance was found, with $F(7, 154) = 3.67, p < 0.05$. Post-hoc Tukey test on a linear model with Bonferroni correction indicates statistically significant differences in performance between several conditions, see Figure 6. Grouping the tracked hand conditions and outer hand conditions as independent variables for an ANOVA yielded statistically significant differences in grasping performance with $F(1, 22) = 6.74, p < 0.05$. The tracked hand conditions outperformed the outer hand conditions leading to shorter grasping times.

Based on the results of the post-hoc test and confirmed by comparing the tracked hand conditions to the outer hand conditions, we can see that outer hand methods are inferior in terms of grasping performance to their inner hand counterparts. Interestingly, OHRA and IHRA do not yield statistically significant differences in grasping performance. This may be due to the users adjusting how they grasped the ball based on the reactive affordance. Indeed, several participants reported that they adjusted how they picked up the ball based on the projected contact points calculated by OHRA.

We also compared the visualizations that have grasping feedback (IHTR, OHTR, 2H, DH) to those without it (IH, OH). There were no significant differences in grasping performance between visualizations with feedback specifically for grasp start and end (IHTR, OHTR, 2H, DH) and those without it (IH, OH, IHRA, OHRA).

Release Performance: We define a spherical release area with the ball at its center and a radius of 25cm. Release performance is gauged using two measures: release time and placement accuracy. Release time is the time interval from when the ball contacts the target to when the center of the virtual hand exits the release area. Placement accuracy is the horizontal distance between the ball and the target after release.

For release time, there were no statistically significant results between each condition nor between the tracked hand and outer hand group (Figure 7 (c)).

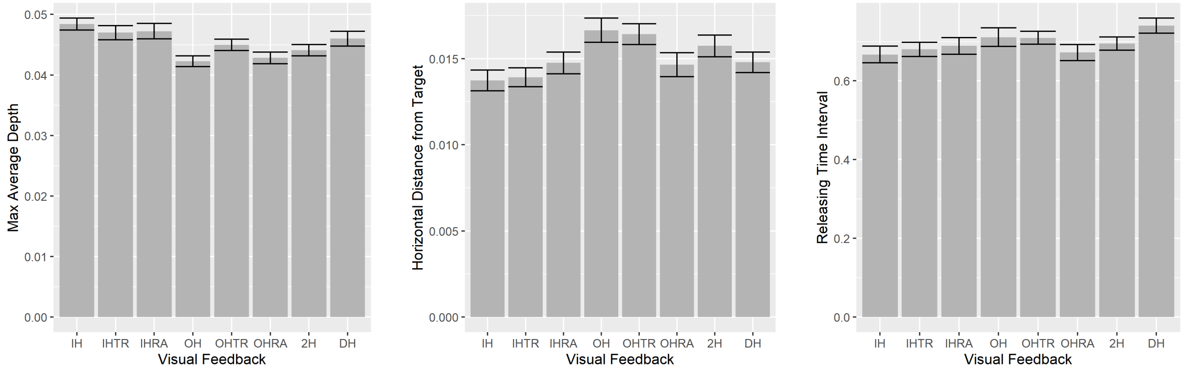
Though no statistically significant differences were found between all conditions for placement accuracy, the general trend ($p = 0.1$) follows our hypothesis that tracked hand conditions tend to outperform outer hand conditions. This trend is shown in Figure 7 (b), with IH resulting in the lowest displacement, and OH resulting in the highest. Again, OHRA is a notable exception, resulting in a slightly higher placement accuracy than its tracked hand counterpart, IHRA.

4.2 Ownership

In the second block of the experiment, we measure the time taken between pressing the start button and the first successful grasp attempt. The data is analyzed using a linear mixed effects model with ball type (smooth or spiky) and visualization as the independent variables and the subject treated as the random factor. There was an overall significant effect of ball type on the time to grasp ($p < 0.05$), with the spiky ball resulting in longer times for all grasping feedback conditions except for 2H, where it slightly decreased (Figure 8). Though the presence of the spiky ball increased the grasping time overall, OHTR was the only visualization where the time taken to grasp the ball was significantly higher with the spiky ball ($p < 0.05$).

For the third block, the overall completion time is used. There were no significant effects of grasping feedback on completion time. This is most likely due to users becoming used to the presence of the saw over the experiment, resulting in quicker completion times after each exposure. Using a linear mixed model to check for effects of feedback on the mean difference in completion time between block 1 and block 3 showed no significant changes in completion time. This is likely due to the large variance between subjects in completion time and due to a single measure per feedback condition per subject.

Seven ownership and two agency questions were presented after completion of the third block for each grasping feedback condition. Each question and the mean responses are shown in Table 1. The Friedman rank test was used to test for effects of grasping feedback on responses per question. If significant effects were found,



(a) (b) (c)

Figure 7: (a) The maximum average fingertip depth while grasping. (b) Placement accuracy: horizontal distance of the ball from the target. (c) Release time, includes reaching the target and moving away from the ball after releasing it.

Table 1: Questionnaire items grouped by concept with the means ($\bar{x}$) and standard deviations (σ) of the responses for DH, OH, and all visualizations. The statements resulting in significant differences in response based on visualization have gray backgrounds.

Concept	Statement	DH ($\bar{x}$, σ)	OH ($\bar{x}$, σ)	All ($\bar{x}$, σ)
Ownership	I felt as if the virtual hands were part of my body.	4.17, 1.67	5.22, 1.48	5.07, 1.49
	It sometimes seemed like my own hands came into contact with the virtual object.	3.91, 1.76	4.83, 1.47	4.55, 1.52
	I thought that the virtual hands could be harmed by a virtual danger.	3.04, 1.92	3.78, 2.17	3.67, 2.23
	I felt that my real body was endangered during the experiment.	2.13, 1.14	3.00, 1.95	2.61, 1.83
	I felt that my real hand was endangered during the experiment.	2.22, 1.28	3.13, 2.07	2.66, 1.90
	I anticipated feeling pain from the spinning saw on the screen.	2.65, 1.85	3.78, 2.15	3.17, 2.00
	I tried to avoid the virtual saw while performing the task.	4.30, 2.38	5.09, 2.47	4.69, 2.41
Agency	I felt as if I can control movements of the virtual hands.	5.00, 1.65	5.39, 1.37	5.33, 1.48
	I felt as if the virtual hands moved just like I wanted them to, as if they were obeying my will.	4.91, 1.56	5.00, 1.45	5.06, 1.49

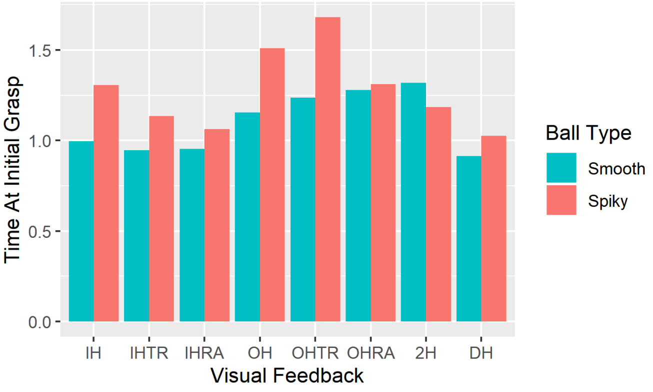


Figure 8: The mean time taken to grasp the ball.

a post-hoc pairwise Wilcoxon test with Benjamini-Hochberg adjusted p-values was used. A significant effect of visualization on response was found ($p < 0.05$) for the first, fourth, and sixth ownership questions in Table 1. The post-hoc test did not show any significant differences between pairs of visualizations, however, DH consistently resulted in lower responses than OH. No statistically significant differences between the outer hand and tracked hand groups were found for the the ownership statements, though the outer hand group resulted in slightly higher responses.

A one-way repeated measures ANOVA on the averaged responses to the ownership questions showed significant effects of grasping visualization on response ($F(7, 154) = 2.38, p < 0.05$). The post-hoc paired Wilcoxon test showed that only the responses to DH and OH were significantly different.

There were no significant differences in responses to the two agency questions, suggesting that users felt an equally strong sense of control over the virtual hands for each condition. This goes against our hypothesis that the visualizations in the tracked hand group will result in a reduced sense of agency and thus reduced ownership.

4.3 Preference

Appearance ranking is done at the beginning, before the participants have experienced each condition, and preference ranking is done at the end. While ranking overall preference, participants were allowed to interact with the ball using the selected visualization. In general, users preferred the visualizations in the outer

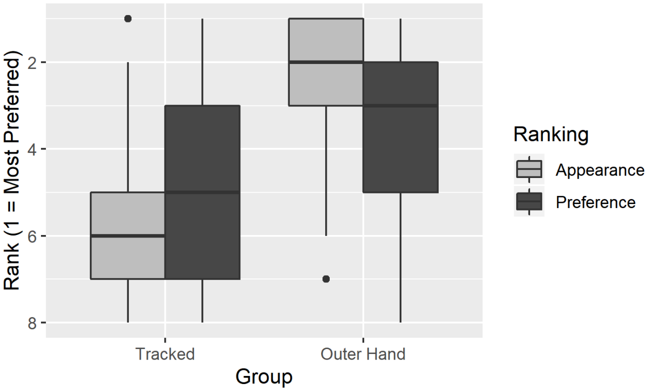


Figure 9: Boxplot of the appearance and preference rankings for each visualization group.

Table 2: Median rank assigned to each visualization before and after the experiment (lower is better).

Visualization	Appearance	Preference
IH	6	6
IHTR	5	4
IHRA	5	5
OH	2	2
OHTR	2	4
OHRA	3	3
2H	4	4
DH	8	8

hand group (OH, OHTR, OHRA) over those in the inner hand group (IH, IHTR, IHRA), as hypothesized. DH was consistently among the least preferred in both preference measures, with some participants reporting that it was "jarring", though a few ranked it higher after using it. Although the rankings for the two groups were more uniform in the appearance ranking (Figure 9), they did not change significantly after the participants used each visualization, suggesting a preference for natural looking interactions despite the performance penalty. The median rankings for each visualization are shown in Table 2.

5 DISCUSSION AND LIMITATIONS

As hypothesized, we found that the visualizations in the tracked hand group resulted in better grasping performance than those in the outer hand group, though release performance was similar for both. Better grasping performance with the tracked hand conditions is most likely the result of fewer constraints on how a grasping motion can be performed since the virtual hand does not have to remain outside of the ball. Therefore, the ball does not have to move to accommodate this constraint when the fingers contact it. Notwithstanding, the 2H visualization resulted in better grasping performance than the outer hand visualizations, which can be attributed to the secondary hand piercing the ball, thus providing a clear sign that the ball is being gripped. This result partially agrees with that of Prachyabrued and Borst [2014], where they found that the 2H technique resulted in better release performance than OH. No statistically significant results were found for placement accuracy, likely due to there being no explicit instructions to center the ball on the target.

As for ownership, the time to grasp the ball was longer when the spiky ball was present, indicating hesitation to pick up the ball. This result is similar to the results in [Argelaguet et al. 2016], where the barbed wire and flame resulted in longer task completion times. However, hesitation could be due to an elevated sense of endangerment, though other factors cannot be ruled out. Other factors may include surprise (though we expect that this effect diminishes after repeated exposure), conditioning from games to avoid dangerous virtual obstacles, or changes in motion planning for grasping. Based on the questionnaire responses, we did not find any significant differences in ownership between the two groups. Users felt a strong sense of agency over the virtual hand with each of the visualizations, most likely due to the high fidelity hand tracking used. Thus, we could not confirm our hypothesis that outer hand visualizations will diminish the sense of ownership due to a reduced sense of agency.

User preference was found to align with our hypothesis that the visualizations in the outer hand group will be preferred. Initially, the participants ranked the visualizations based only on how they looked by watching videos of the same interaction occurring with each feedback. The difference in ranking between the tracked hand grouped and the outer hand group was most stark in this ranking, as shown in Figure 9. After completing the experiment, participants ranked the visualizations based on overall preference. The outer hand group was still ranked higher than the tracked hand group, even though the performance of the tracked hand group was better than that of the outer hand group. This suggests that users prefer more realistic interactions.

Based on these results, we recommend OHTR if the priority is user preference and ownership. In general, we would recommend against using DH for applications that make use of hand tracking, since it can be distracting to the user and it was preferred less than the others. If performance is essential, any of the tracked hand visualizations are good, though IHRA may be preferred because it provides additional feedback.

Limitations to this experiment include the repetitive task and within subjects design, which led to weaker responses to the questionnaire and increasing familiarity with the virtual threats. Other limitations include the relative ease of the task being done and the use of a sphere as the only object to grasp. The preference rankings may change more if the task were more difficult to perform or if the object were more complex. Though previous studies have indicated that ownership can be established over unrealistic virtual hands and even non-corporeal objects, the use of the robot avatar in this study could have reduced the overall sense of danger from the threats.

6 CONCLUSION

We tested the performance of eight visual feedback techniques for virtual grasping and also tested how they affected the users’ sense of ownership. Differences in ownership were, in general, not significant perhaps due to a high sense of agency for all the conditions.

Those that prevent the hand from entering the ball were preferred over those that did not, even though grasping performance was not as good.

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