Effects of Virtual Arm Representations on Interaction in Virtual Environments

Tanh Quang Tran
Korea University
tqtanh@korea.ac.kr

HyunJu Shin
Samsung Electronics
hyunjushin@samsung.com

Wolfgang Stuerzlinger
Simon Fraser University
w.s@sfu.ca

JungHyun Han
Korea University
jhan@korea.ac.kr

ABSTRACT

Many techniques for visualization and interaction that potentially increase user performance have been studied in the growing field of virtual reality. However, the effects of virtual-arm representations on users' performance and perception in selection tasks have not been studied before. This paper presents the results of a user study of three different representations of the virtual arm: "hand only," "hand+forearm," and "whole arm" which includes the upper arm. In addition to the representations' effects on performance and perception in selection tasks, we investigate how the users' performance changes depending on whether collisions with objects are allowed or not. The relationship between the virtual-arm representations and the senses of agency and ownership are also explored. Overall, we found that the "whole arm" condition performed worst.

CCS CONCEPTS

• **Human-centered computing → User studies**; *Pointing*; *User centered design*; • **Computing methodologies → Perception**; **Virtual reality**;

KEYWORDS

3D Interaction, Virtual Reality, Virtual Arm, Selection Performance, Natural Hand Interaction

ACM Reference Format:
Tanh Quang Tran, HyunJu Shin, Wolfgang Stuerzlinger, and JungHyun Han. 2017. Effects of Virtual Arm Representations on Interaction in Virtual Environments. In *Proceedings of VRST '17*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3139131.3139149

1 INTRODUCTION

Virtual Reality (VR) is being used in a wide range of fields including education, entertainment, training, and simulation. Currently, the major driving force is the development of high-quality head-mounted displays (HMDs). On the other hand, much research has been aimed at providing efficient and accurate ways for users to interact with immersive virtual environments (IVEs), which has also contributed to the prosperity of VR.

An important class of interaction techniques is to use a *virtual arm*, which refers to the virtual representation of a user's real arm. This topic has been widely studied in VR, human-computer interaction, and psychology. Those studies showed that users are sensitive to the virtual-arm appearance. For example, people in IVEs often complained that their virtual arms did not have the same length as their real ones [Lugrin et al. 2015]. However, there has been no research on how the appearance of the virtual arm affects user's interaction in IVEs.

The human arm is comprised of hand, forearm, and upper arm. In our study, we use three different representations of the virtual arm: "hand only," "hand+forearm," and "whole arm" to investigate their effects on users' performance in selection tasks. The experiment is designed with multiple independent variables in addition to the virtual-arm representations, and we also investigate how the users' performance changes depending on whether collisions with objects are allowed or not.

This paper is organized as follows. Section 2 reviews related work. Section 3 presents the experiment design and procedure, and Section 4 presents the experiment results. Section 5 gives discussion on the analysis results, and Section 6 concludes the paper.

2 RELATED WORK

Virtual arms have been widely used and studied in the fields of VR and psychology. Kilteni et al. [Kilteni et al. 2012b] studied human perception of different arm lengths in IVEs. In their study, participants observed their virtual arms with different lengths relative to their real arms and reported their feelings. They found that changes in the body shape and size did not affect the users' perception of the presented multisensory and sensorimotor information. Yuan et al. [Yuan and Steed 2010] and Slater et al. [Slater et al. 2008] used virtual hands to study the rubber hand illusion [Botvinick and Cohen 1998] in IVEs. Other psychologists modified the shape of the virtual hand to study human perception when estimating different virtual object sizes [Linkenauger et al. 2013]. The representations of a virtual hand were also studied in relation to the sense of ownership [Lin and Jörg 2016] or with different types of threats [Argelaguet et al. 2016; Lugrin et al. 2015].

Virtual-hand representations have been studied as an effective tool for interacting with objects in IVEs. Poupyrev et al. [Poupyrev et al. 1996] presented a technique that permits users to extend their virtual hand to interact with and select objects at a far distance.

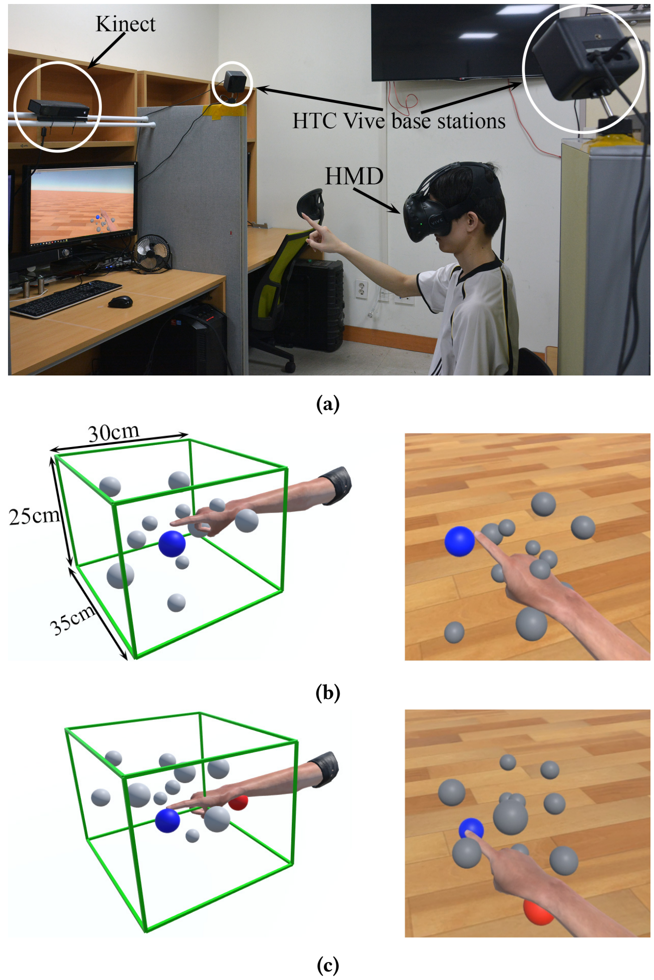
VRST '17, November 8–10, 2017, Gothenburg, Sweden

ACM ISBN 978-1-4503-5548-3/17/11…$15.00
https://doi.org/10.1145/3139131.3139149

In the guidelines for designing user-friendly IVEs, Bowman et al. [Hale and Stanney 2014] argued that a virtual hand is more natural for selection tasks than other methods, such as ray casting. Several surveys reviewed work on using a virtual hand as a 3D selection tool, including Argelaguet et al. [Argelaguet and Andujar 2013] and Jankowski et al. [Jankowski and Hachet 2013]. The relation between virtual hand representation and the senses of agency and ownership on interaction has been studied as well [Argelaguet et al. 2016]. Won et al. [Won et al. 2015] investigated the performance in target-hitting tasks between a hand and a virtual arm in three-arm avatars. These representations were in biological or mechanical appearance.

In many VR systems, the users' own bodies are not visible to them. Thus, representing a human body is critical to induce a sense of embodiment and to increase the sense of presence. For this, the virtual motion is synchronized with the real motion, which then enables the user to directly interact with the IVEs. Several works showed that the sense of ownership over a virtual hand could be induced through visuomotor correlations [Sanchez-Vives et al. 2010; Slater et al. 2009]. In addition, the relationship between the sense of embodiment and presence was studied and reviewed [Kilteni et al. 2012a], and the influence of visual representations on the sense of embodiment during interaction was investigated [Argelaguet et al. 2016]. The effects of various aspects of target appearance and highlights on user's performance have also been studied [Stuerzlinger and Teather 2014; Teather and Stuerzlinger 2014].

In spite of all these wide-ranging research efforts, no research can be found on the effects of different virtual-arm representations on users' performance and perception on selection tasks. The relationship between the virtual-arm representations and the senses of agency and ownership are also yet to be determined. This paper tackles those issues.



(a)

(b)

(c)

Figure 1: Experimental setup and interaction with objects. (a) Physical experimental setup with a participant wearing an HMD. (b) On the left is the third person's view of the interaction volume. On the right is the first person's view. The target object is highlighted in blue whereas the others are in gray. (c) If the participant collides with a non-target object, it turns red.

3 EXPERIMENT

Our experiment was conducted in a laboratory environment using a PC (Intel Core i7-6700 3.40GHz with 8GB RAM and nVidia GeForce GTX 980) and an HMD (HTC Vive). Users' motions were tracked through a Kinect, and the virtual environment was created and rendered with Unity3D. See Figure 1-(a).

3.1 Experiment Design

In our experiment, each participant wore an HMD and interacted with spherical objects contained in a 35cm×25cm×30cm virtual box. See Figure 1-(b). The box, termed *interaction volume*, was 35cm in front of the participant. All objects in the interaction volume were initially gray. Then, an object at a time was randomly designated as the *target* and highlighted in blue. The participant was instructed to touch the target using the tip of the dominant hand's index finger. If the participant successfully touched the target in 30 seconds ('success' case) or failed to do it ('fail' case), the target object turned into gray. Then, another object was designated as the target and highlighted in blue. The new target was always different from the previous one.

We used three different representations of the lifelike virtual arm: "hand only," "hand+forearm," and "whole arm," as shown in Figure 2. Our experiment adopted a multi-factorial 3×2×2×3 design based on three virtual-arm representations, two levels of *object density*, two levels of *object size*, and three types of *object movement*:

- The object density was determined by the number of sphere objects in the interaction volume, which was either six (low density) or twelve (high density).
- The object size was described by the sphere's diameter, which was either four centimeters (small) or six centimeters (large).
- All objects in the interaction volume were either static, jittered in randomized directions, or rotated around the vertical axis centered at the interaction volume. See Figure 3.

An additional independent variable was the *collision condition*. It divided the entire experiment into two blocks. In the first block

Figure 2: The virtual-arm representations: "hand only," "hand+forearm," and "whole arm" (from left to right). Kinect tracked the wrist and elbow joints of the participant. The virtual hand was attached to the wrist and was always aligned (parallel) to the line connecting the wrist and elbow.

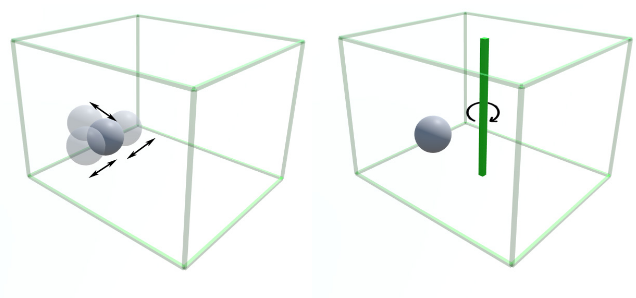


Figure 3: Object movement: 'jittering' on the left and 'rotating' on the right.

(Block I), the participants were allowed to collide with any object while approaching the target. In contrast, the participants were asked to avoid collisions in the second block (Block II). When a non-target object collided with the participant in Block II, its gray color turned into red, as illustrated in Figure 1-(c).

In both blocks of our experiment, the dependent variables were *selection time*, *hit error rate*, and *error distance*. Block II had an additional dependent variable, *contact error rate*.

- The selection time was the time between when a new target object was highlighted and when the participant successfully touched it.
- The hit error rate was the percentage of 'fail' cases.
- In a 'success' case, the distance between the target object's center and the finger tip's position was measured at the time of touching the object surface and was taken as the error distance. In a 'fail' case, the error distance was measured when 30 seconds passed [Bruder et al. 2013; Lubos et al. 2014].
- The contact error rate was the percentage of collisions between the non-target objects and the participant. It was measured only with the visible components of the virtual arm. For example, the collision between the objects and the upper arm was not considered for "hand only" and "hand+forearm" representations.

Table 1: Experimental procedure. The 1st, 2nd, and 3rd representations denote three virtual-arm representations in a counterbalanced order.

step	time (min)
instructions & informed consent	5
arm length measurement	5
training	10
break	5
experiment with the 1st virtual-arm representation	10
questionnaire	3
break	2
experiment with the 2nd virtual-arm representation	10
questionnaire	3
break	2
experiment with the 3rd virtual-arm representation	10
questionnaire	3

3.2 Participants and Procedure

We recruited twenty four students aged from 18 to 38 (M = 24.83, SD = 4.83). They had diverse majors including biology, linguistics, and computer science. Seven students had VR experiences, e.g., in wearing HMD, but the others did not. All participants were male and right-handed. They had normal or corrected to normal vision. Each participant was compensated with 10 USD for participation.

The steps of the experimental procedure are enumerated in Table 1 with the elapsed time on each step. After a brief explanation of the experiment, each participant signed the consent form and the lengths of his hand, forearm, and upper arm were measured such that the virtual arm was scaled to fit to the real arm. Then, the participants were trained on the task by using all three virtual-arm representations to touch target objects. After taking a break, they started the experiment with the three representations, which were presented in a counterbalanced order.

For each virtual-arm representation, we had 24 (2×2×3×2) combinations of 2 object densities, 2 object sizes, 3 object movements, and 2 collision conditions. For each combination, a participant was asked to perform eight trials for touching the target objects, i.e., a participant performed 192 (24×8) tasks with a single virtual-arm representation. The orders of object densities, object sizes, and object movements were randomized whereas the collision conditions, i.e., two blocks, were in a counterbalanced order.

On average, the experiment consumed about 10 minutes with a single virtual-arm representation. After completing the experiment with the first representation, the participant filled a questionnaire and took a break. In our study, the questionnaire was a modified version of the one used in [Argelaguet et al. 2016], and the modification was made based on the guidelines of [Kilteni et al. 2012a].

Table 2: Type III tests of one-way interaction for selection time.

effect	F-value	p-value
virtual-arm representation	$F(2, 40) = 23.42$	$p < .01$
object density	$F(1, 20) = 135.68$	$p < .01$
object size	$F(1, 20) = 223.58$	$p < .01$
object movement	$F(2, 40) = 38.57$	$p < .01$
collision condition	$F(1, 20) = 2434.80$	$p < .01$
representation order	$F(2, 18) = 0.01$	$p = .99$
block order	$F(1, 18) = 0.42$	$p = .53$

The same procedure was repeated for the other two representations. The total time consumed per participant was about 68 minutes.

3.3 Hypotheses

The goal of our experiment was to investigate the effects of different virtual-arm representations on the dependent variables. We made a few hypotheses. First, a smaller arm representation would lead to a faster selection time, i.e., "hand only" would be faster than "hand+forearm," which would be faster than "whole arm." Second, the longer arm would distract the participants more from the task of selecting the targets and therefore would result in a higher hit error rate. Third, the targets would be carefully touched by the participants with all virtual-arm representations. Fourth, the senses of agency and ownership would be the same for all representations. (The sense of agency refers to the feeling of being in control of the avatar [Argelaguet et al. 2016; Blanke and Metzinger 2009], and the sense of ownership refers to one's self-attribution of a body [Argelaguet et al. 2016; Gallagher 2000; Kilteni et al. 2012a].) Fifth, people would prefer "hand+forearm" to "hand only" and "whole arm" because "hand only" was less natural and realistic than "hand+forearm" but "whole arm" could be cumbersome, reducing the selection performance. In summary, our hypotheses are:

- **H1** The shortest selection time for "hand only"
- **H2** The longest selection time for "whole arm"
- **H3** The lowest hit error rate for "hand only"
- **H4** The highest hit error rate for "whole arm"
- **H5** The same error distance for all representations
- **H6** The same sense of agency for all representations
- **H7** The same sense of ownership for all representations
- **H8** Preference for "hand+forearm"

In Block II, where the participant was instructed to avoid colliding with non-target objects, we hypothesized that the simpler virtual-arm representation would lead to a lower contact error rate because the representation had fewer components to collide with the objects. (The components are hand, forearm, and upper arm.) We made two additional hypotheses for Block II:

- **H9** The lowest contact error rate for "hand only"
- **H10** The highest contact error rate for "whole arm"

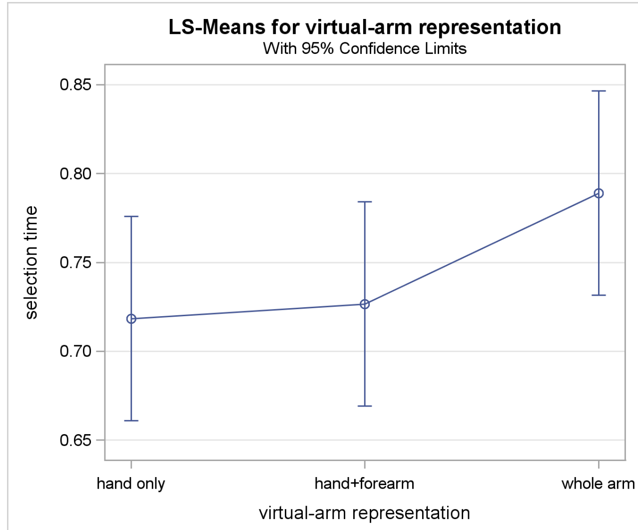


Figure 4: Estimated least squares means of selection time of virtual-arm representations.

4 RESULTS

The results of our experiment were analyzed with a Generalized Linear Mixed Model (GLMM) run by the GLIMMIX procedure in SAS®. Selection time was analyzed with a lognormal distribution and an identity link, whereas a Gaussian distribution and identity links were used for both error distance and contact error rate. We considered one- and two-way analyses of the independent variables. These interactions defined the fixed effects for the GLMM model whereas subjects were random effects. The target variables were selection time, error distance, and contact error rate. Their least squares means (LS-means) were estimated. We conducted Tukey-Kramer tests as post-hoc tests to compare differences of the LS-means of the fixed effects ($\alpha = 0.05$).

4.1 Selection Time

Virtual-arm representation, object density, object size, object movement, and collision condition had significant effects on the selection time ($p < .05$) whereas representation order and block order did not ($p > .05$), as shown in Table 2. The significant effects and differences found by the post-hoc tests are listed below.

4.1.1 Virtual-arm representation. The selection time with "hand only" ($M = 0.72$, $SE = 0.02$) was significantly shorter than that with "whole arm" ($M = 0.79$, $SE = 0.02$). The selection time with "hand+forearm" ($M = 0.73$, $SE = 0.02$) was also significantly shorter than that with "whole arm." See Figure 4.

4.1.2 Object density. The selection time with the low density ($M = 0.69$, $SE = 0.02$) was significantly shorter than that with the high density ($M = 0.80$, $SE = 0.02$).

4.1.3 Object size. Working with small objects ($M = 0.81$, $SE = 0.02$) took significantly longer time than working with large ones ($M = 0.68$, $SE = 0.02$).

Table 3: Type III tests of two-way interaction for selection time.

effect	F-Value	p-value
virtual-arm representation vs. object density	$F(2, 46) = 0.69$	$p = .51$
virtual-arm representation vs. object size	$F(2, 46) = 3.90$	$p < .05$
virtual-arm representation vs. object movement	$F(4, 92) = 2.61$	$p < .05$
virtual-arm representation vs. collision condition	$F(2, 46) = 6.24$	$p < .01$
virtual-arm representation vs. representation order	$F(4, 40) = 24.08$	$p < .01$
virtual-arm representation vs. block order	$F(2, 40) = 0.13$	$p = .88$

Table 4: Type III tests of one-way interaction for contact error rate with respect to hand.

effect	F-Value	p-value
virtual-arm representation	$F(2, 40) = 3.48$	$p < .05$
object density	$F(1, 20) = 303.98$	$p < .01$
object size	$F(1, 20) = 52.72$	$p < .01$
object movement	$F(2, 40) = 34.74$	$p < .01$
representation order	$F(2, 18) = 1.12$	$p = .35$
block order	$F(1, 18) = 2.97$	$p = .10$

4.1.4 Object movement. The subjects spent more time when the objects were rotating ($M = 0.80$, $SE = 0.02$) than when they were static ($M = 0.72$, $SE = 0.02$) or jittering ($M = 0.72$, $SE = 0.02$).

4.1.5 Collision condition. Collision between the subject and the non-target objects was allowed in Block I whereas it was not in Block II. The selection time in Block I ($M = 0.52$, $SE = 0.02$) was significantly shorter that that in Block II ($M = 0.97$, $SE = 0.02$).

The two-way analysis showed that there were interaction effects between virtual-arm representation and the independent variables of object size, object movement, collision condition, and representation order, as shown in Table 3.

4.1.6 Virtual-arm representation vs. object density. The two-way interaction effect between virtual-arm representation and object density was not significant, but "hand only" and "hand+forearm" had significantly shorter selection times than "whole arm" in both high and low densities.

4.1.7 Virtual-arm representation vs. object size. The representation of "hand+forearm" had a significantly shorter selection time than "whole arm" for both large ($M = 0.65$, $SE = 0.03$) and small ($M = 0.80$, $SE = 0.03$) objects. On the other hand, "hand only" had a significantly shorter selection time ($M = 0.77$, $SE = 0.03$) than "whole arm" ($M = 0.87$, $SE = 0.03$) for small objects.

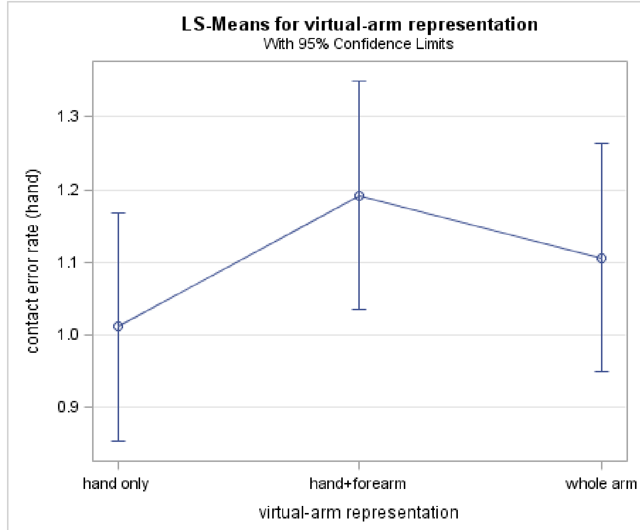


Figure 5: Estimated least squares means of contact error rate with respect to hand of virtual-arm representations.

4.1.8 Virtual-arm representation vs. object movement. For static and jittering objects, both "hand only" and "hand+forearm" took significantly shorter selection times than "whole arm."

4.1.9 Virtual-arm representation vs. collision condition. In Block I, "whole arm" ($M = 0.58$, $SE = 0.03$) had a significantly longer selection time than "hand only" ($M = 0.49$, $SE = 0.03$) and "hand+forearm" ($M = 0.48$, $SE = 0.03$). In Block II, no significant difference was found among the representations.

4.1.10 Virtual-arm representation vs. representation order. The two-way interaction effect between virtual-arm representation and representation order was significant. However, we did not observe any significant difference of each virtual-arm representation between representation orders.

4.2 Hit Error Rate and Error Distance

In the entire experiment, the hit error rate was zero, i.e., we observed no 'fail' cases. Section 5.2 discusses this in more detail. On the other hand, the error distance was significantly affected by object size ($F(1, 20) = 10585.0$, $p < .01$) and collision condition ($F(1, 20) = 13.28$, $p < .01$) but was not affected by the other independent variables.

4.2.1 Object size. It is obvious that a smaller target would have the shorter error distance, and the post-hoc test showed that the error distance with smaller object size was indeed significantly shorter.

4.2.2 Collision condition. The post-hoc test showed that the error distance in Block I was significantly less than that in Block II.

The results of two-way analysis between virtual-arm representation and the other independent variables showed that there was no significant interaction effect with respect to error distance.

Table 5: Type III tests of two-way interaction for contact error rate with respect to hand.

effect	F-Value	p-value
virtual-arm representation vs. object density	$F(2, 46) = 0.88$	$p = .42$
virtual-arm representation vs. object size	$F(2, 46) = 2.97$	$p = .06$
virtual-arm representation vs. object movement	$F(4, 92) = 0.75$	$p = .56$
virtual-arm representation vs. representation order	$F(4, 40) = 7.34$	$p < .01$
virtual-arm representation vs. block order	$F(2, 40) = 0.76$	$p = .48$

Table 6: Type III tests of one-way interaction for contact error rate with respect to forearm.

effect	F-Value	p-value
virtual arm representation	$F(2, 40) = 110.33$	$p < .01$
object density	$F(1, 20) = 47.04$	$p < .01$
object size	$F(1, 20) = 1.38$	$p = .25$
object movement	$F(2, 40) = 5.32$	$p < .01$
representation order	$F(2, 18) = 0.11$	$p = .90$
block order	$F(1, 18) = 0.41$	$p = .53$

4.3 Contact Error Rate

A contact error was committed by the hand and forearm components, but we never observed a contact error involving the upper arm.

4.3.1 Contact error with hand. Virtual-arm representation, object density, object size, and object movement had significant effects on the contact error rate with respect to hand ($p < .05$) whereas representation order and block order did not ($p > .05$), as shown in Table 4. The significant effects and differences found by the post-hoc tests are listed below.

Virtual-arm representation. The contact error rate for "hand only" ($M = 1.01$, $SE = 0.08$) was significantly lower than that for "hand+forearm" ($M = 1.19$, $SE = 0.08$, $p = .03$). Estimated LS-means of contact error rate with respect to hand of virtual-arm representations are shown in Figure 5.

Object density. In the low density condition, the subjects committed significantly fewer contact errors ($M = 0.61$, $SE = 0.07$) than with high density ($M = 1.59$, $SE = 0.07$).

Object size. Selecting small targets ($M = 1.31$, $SE = 0.07$) had a significantly higher contact error rate than selecting large ones ($M = 0.90$, $SE = 0.07$). The reason is that smaller objects were harder to select especially when they were occluded by moving non-target objects.

Object movement. Selecting rotating objects had significantly lower contact error rate ($M = 0.83$, $SE = 0.08$) than selecting jittering objects ($M = 1.40$, $SE = 0.08$) or static objects ($M = 1.07$, $SE = 0.08$). On the other hand, the contact error rate for jittering objects was significantly higher than that for static objects.

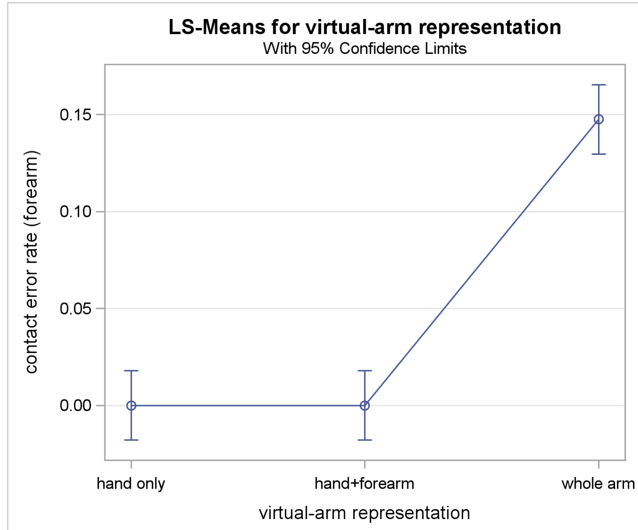


Figure 6: Estimated least squares means of contact error rate with respect to forearm of virtual-arm representations.

The two-way analysis between virtual-arm representation and the other independent variables showed that representation order had a significant effect on the contact error rate. See Table 5.

Virtual-arm representation vs. object size. The two-way interaction effect between virtual-arm representation and object size was not significant. However, we observed that, when selecting small target objects, "hand only" ($M = 1.13$, $SE = 0.09$) had a significantly lower contact error rate than "hand+forearm" ($M = 1.48$, $SE = 0.09$). In contrast, there was no significant difference in the contact error rate between "hand only" and "whole arm" for selecting large and small target objects. This was also the case between "hand+forearm" and "whole arm."

Virtual-arm representation vs. representation order. There was a significant effect in the two-way interaction between virtual-arm representation and representation order. In contrast, we did not find any significant difference of each virtual-arm representation between representation orders.

4.3.2 Contact error with forearm. As subjects could not see their forearm in the "hand only" condition, all contact errors with respect to the forearm were observed in either the "hand+forearm" or "whole arm" conditions. The analysis results showed that virtual-arm representation, object density, and object movement had significant effects on the contact error rate whereas representation order and block order did not, as presented in Table 6. The significant effects and differences found by the post-hoc tests are listed below.

Virtual-arm representation. The representation of "whole arm" ($M = 0.15$, $SE = 0.01$) had significantly higher contact error rate than "hand+forearm." Estimated LS-means of contact error rate

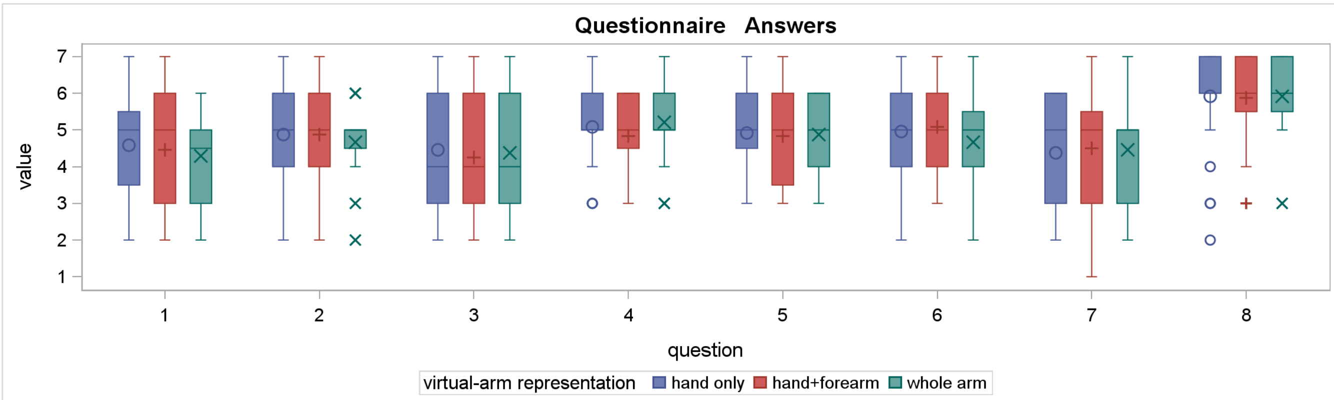


Figure 7: Means and standard deviations per question. See Table 8 for the questions.

Table 7: Type III tests of two-way interaction for contact error rate with respect to forearm.

effect	F-Value	p-value
virtual-arm representation vs. object density	$F(2, 46) = 47.04$	$p < .01$
virtual-arm representation vs. object size	$F(2, 46) = 1.38$	$p = .26$
virtual-arm representation vs. object movement	$F(4, 92) = 5.32$	$p < .01$
virtual-arm representation vs. representation order	$F(4, 40) = 0.17$	$p = .95$
virtual-arm representation vs. block order	$F(2, 40) = 0.65$	$p = .53$

with respect to forearm of virtual-arm representations are shown in Figure 6.

Object density. The low density had a significantly lower contact error rate ($M = 0.02$, $SE = 0.01$) than the high density ($M = 0.08$, $SE = 0.01$).

Object movement. The contact error rate for jittering objects ($M = 0.07$, $SE = 0.01$) was significantly higher than those for static objects ($M = 0.04$, $SE = 0.01$) and rotating objects ($M = 0.03$, $SE = 0.01$).

The two-way analysis showed that there were interaction effects between virtual-arm representation and the independent variables of object density and object movement, as presented in Table 7.

Object density. The representation of “hand+forearm” had a significantly lower contact error rate than “whole arm” in both low and high densities.

Object movement. The representation of “hand+forearm” had a significantly lower contact error rate than “whole arm” for all types of object movement.

4.3.3 Relation between selection time and contact error rate. We analyzed the relationship between selection time and contact error rate (of both hand and forearm) using Spearman's rank-order correlation. The analysis result showed that there was a monotonic association between them. We found a weak negative linear relationship between selection time and contact error rate of hand ($r_s = .23$, $p < .01$) and only a very weak relationship between selection time and contact error rate of forearm ($r_s = .07$, $p < .05$). Thus, there was a weak correlation between selection time and contact error rate of both hand and forearm.

4.4 Questionnaire

As presented in Section 3.2, the subject filled a questionnaire after completing the experiment with each virtual-arm representation. The questionnaire was designed to investigate subjects' opinions about the appropriateness, effectiveness, senses of agency and ownership, and so on for each representation, as well as the experience of motion sickness during the experiment. The questionnaire responses for all virtual-arm representations were analyzed using Friedman tests. The results are given in Table 8 and Figure 7.

The analysis results of the first and second questions showed that there was no significant difference in appropriateness and effectiveness among the virtual-arm representations. Similarly, the analysis result of the third question indicated that subjects perceived the same degree of experimental difficulty for all virtual-arm representations. The fourth and fifth questions were related with the sense of agency whereas the sixth and seventh were related with the sense of ownership. We found that there was no significant difference in both senses among the representations. The analysis result of the final question showed that subjects did not experience serious levels of motion sickness when performing the experiment.

5 DISCUSSION

This section discusses the analysis results of the experiment data and questionnaire answers. The first four subsections discuss selection time, hit error rate and error distance, user's perception, and contact error rate in order. Then, the final subsection presents the limitations of our study.

Table 8: Chi-squared (χ^2) and p-values for each question.

	Question (Worst is 1, and the best is 7.)	Chi-square	p-value
1	How did you feel about the appropriateness of the virtual arm?	$\chi^2(2)$ = .61	p = .74
2	How did you feel about the effectiveness of the virtual arm for the selection task?	$\chi^2(2)$ = 1.00	p = .61
3	How did you feel about the experiment? Was it hard or easy? (The hardest is 1, and the easiest is 7.)	$\chi^2(2)$ = 1.77	p = .41
4	Did you feel that you controlled the movement of the virtual arm?	$\chi^2(2)$ = 2.92	p = .23
5	Did you feel that the virtual arm was reacted as you desired?	$\chi^2(2)$ = .15	p = .93
6	Did you feel that the virtual arm was a part of your body?	$\chi^2(2)$ = .3.45	p = .18
7	Did you feel that the virtual arm was not out of your control when it was not reacting properly?	$\chi^2(2)$ = 1.00	p = .61
8	Did you experience motion sickness when you performed the experiment?	$\chi^2(2)$ = .20	p = .91

5.1 Selection Time

Our analysis showed that "whole arm" had a significantly longer selection time than "hand only" and "hand+forearm." This supports hypothesis **H2** (The longest selection time for "whole arm") presented in Section 3.3. However, there was no significant difference in selection time between "hand only" and "hand+forearm," and therefore hypothesis **H1** (The shortest selection time for "hand only") is only partially supported.

The two-way analysis showed that, when selecting static or jittering objects, "hand only" and "hand+forearm" took significantly less than "whole arm." This supports **H2**, but **H1** is only partially supported. Worse still, both **H1** and **H2** are not supported when selecting rotating objects.

On the other hand, "whole arm" took significantly more time than the other representations for both small and large objects. This supports **H2**, but **H1** is only partially supported.

Similarly, in Block I, **H2** is supported, but **H1** is partially supported. In contrast, **H1** and **H2** are not supported at all in Block II.

In general, "hand only" and "hand+forearm" outperformed "whole arm." Consequently, either of them can be used to support faster selection. However, choosing a specific representation would make no difference in selection time if the application involves rotating objects or if collisions need to be avoided.

5.2 Hit Error Rate and Error Distance

In the entire experiment, we observed no 'fail' case, i.e., the hit error rate was zero, disproving hypotheses **H3** (The lowest hit error rate for "hand only") and **H4** (The highest hit error rate for "whole arm"). The generous time limit of 30 seconds was set to accommodate the 'rotating' object movement in Block II, where it would be hard for the subjects to touch the targets without colliding with the other objects. If the time limit were reduced, we might observe differences among the different virtual-arm representations. This should be investigated in the future.

Our observations in the experiment confirmed that subjects could accurately select the target objects, and the analysis results showed that there was no significant difference in error distance among the virtual-arm representations. Thus, hypothesis **H5** (The same error distance for all representations) is supported.

5.3 User's Perception

The answers to questions 4 through 7 listed in Table 8 are used to evaluate hypotheses **H6** (The same sense of agency for all representations) and **H7** (The same sense of ownership for all representations). The analysis results showed that the senses of agency and ownership were not different among the virtual-arm representations, i.e., subjects perceived the representations in a similar manner even though some components of the arm were invisible. These support both **H6** and **H7**. On the other hand, the analysis results for questions 1 and 2 showed that there was no significant difference in the appropriateness and effectiveness of three representations. This disproves hypothesis **H8** (Preference for "hand+forearm"). Simply put, any of the conditions "hand only," "hand+forearm," and "whole arm" could be used in a virtual environment from the viewpoint of user's perception.

5.4 Contact Error Rate

As presented in Section 4.3, the contact error was only for collisions committed by the hand and forearm. Regarding the contact error rate with the hand, we found that "hand only" had a significantly lower rate than "hand+forearm," but there was no significant difference between "hand only" and "whole arm" and also between "hand+forearm" and "whole arm." These results only partially support both **H9** (The lowest contact error rate for "hand only") and **H10** (The highest contact error rate for "whole arm").

Regarding the contact error rate with the forearm, we found that "whole arm" had a significantly higher error than "hand+forearm." Thus, **H10** is supported.

Contact error rate depends on virtual-arm representation. Simply put, "hand only" could be considered as the best representation in virtual environments for reducing collision with non-target objects. The second choice would be "hand+forearm."

5.5 Limitations

Our experiment had some limitations. First of all, the user's arm skeleton was not always correctly tracked by the Kinect. Once in a while, spurious joints appeared in the virtual arm, which might in turn have affected the selection time. Whenever this problem happened, the experiment was paused, the skeleton posture was corrected, and then the experiment was resumed.

Learning effects could also have affected our experiment. These might have occurred due to representation order and block order. When a subject performed the task first with "hand only," for example, the performance in selection time seemed to lead to an increase for the next condition with "hand+forearm." We believe that more training could reduce this problem. Yet, the counter-balancing seems to have worked overall as we did not observe an effect for condition order.

6 CONCLUSION

In this paper, we presented the results of a selection experiment made with three different representations of the virtual arm: "hand only," "hand+forearm," and "whole arm" which includes the upper arm. We studied the effects of virtual-arm representations on users' performance and perception on selection tasks, how the users' performance changes depending on whether collisions with objects are allowed or not, and the relationship between the virtual-arm representations and the senses of agency and ownership. The results showed that "hand only" and "hand+forearm" were faster than "whole arm" but there was no significant difference among the representations in terms of accuracy and the senses of agency and ownership.

We believe our research result can be applied in various applications where multiple virtual representations of a user's body need to be considered. An obvious example is the virtual-leg representation in the context of kicking applications. On the other hand, we plan to investigate the impact of different virtual-arm representations on other interaction tasks such as grasping, writing, and gestures, for which we need hand tracking devices, such as Leap Motion.

ACKNOWLEDGMENTS

This research was supported by Next-Generation Information Computing Development Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT (NRF-2017M3C4A7066316)

REFERENCES

Ferran Argelaguet and Carlos Andujar. 2013. A survey of 3D object selection techniques for virtual environments. *Computers & Graphics* 37, 3 (2013), 121–136. https://doi.org/10.1016/j.cag.2012.12.003

Ferran Argelaguet, Ludovic Hoyet, Michaël Trico, and Anatole Lécuyer. 2016. The Role of Interaction in Virtual Embodiment: Effects of the Virtual Hand Representation. In *2016 IEEE Virtual Reality (VR)*. 3–10. https://doi.org/10.1109/VR.2016.7504682

Olaf Blanke and Thomas Metzinger. 2009. Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences* 13, 1 (2009), 7–13. https://doi.org/10.1016/j.tics.2008.10.003

Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (February 1998), 756–756. https://doi.org/10.1038/35784

Gerd Bruder, Frank Steinicke, and Wolfgang Stürzlinger. 2013. Effects of Visual Conflicts on 3D Selection Task Performance in Stereoscopic Display Environments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. 115–118. https://doi.org/10.1109/3DUI.2013.6550207

Shaun Gallagher. 2000. Philosophical conceptions of the self: implications for cognitive science. *Trends in Cognitive Sciences* 4, 1 (2000), 14–21. https://doi.org/10.1016/S1364-6613(99)01417-5

Kelly S. Hale and Kay M. Stanney. 2014. *Handbook of Virtual Environments: Design, Implementation, and Applications* (2nd ed.). CRC Press, Inc., Boca Raton, FL, USA.

Jacek Jankowski and Martin Hachet. 2013. A Survey of Interaction Techniques for Interactive 3D Environments. In *Eurographics 2013 - State of the Art Reports*, M. Sbert and L. Szirmay-Kalos (Eds.). The Eurographics Association. https://doi.org/10.2312/conf/EG2013/stars/065-093

Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012a. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments* 21, 4 (2012), 373–387. https://doi.org/10.1162/PRES_a_00124 arXiv:http://dx.doi.org/10.1162/PRES_a_00124

Konstantina Kilteni, Jean-Marie Normand, Maria V. Sanchez-Vives, and Mel Slater. 2012b. Extending Body Space in Immersive Virtual Reality: A Very Long Arm Illusion. *PLOS ONE* 7, 7 (July 2012), 1–15. https://doi.org/10.1371/journal.pone.0040867

Lorraine Lin and Sophie Jörg. 2016. Need a Hand?: How Appearance Affects the Virtual Hand Illusion. In *Proceedings of the ACM Symposium on Applied Perception (SAP '16)*. ACM, New York, NY, USA, 69–76. https://doi.org/10.1145/2931002.2931006

Sally A. Linkenauger, Markus Leyrer, Heinrich H. Bülthoff, and Betty J. Mohler. 2013. 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 (July 2013). https://doi.org/10.1371/journal.pone.0068594

Paul Lubos, Gerd Bruder, and Frank Steinicke. 2014. Analysis of Direct Selection in Head-Mounted Display Environments. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 11–18. https://doi.org/10.1109/3DUI.2014.6798834

Jean L. Lugrin, J. Latt, and Marc E. Latoschik. 2015. Anthropomorphism and Illusion of Virtual Body Ownership. In *Proceedings of the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments (ICAT - EGVE '15)*. Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, 1–8. https://doi.org/10.2312/egve.20151303

Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The Go-go Interaction Technique: Non-linear Mapping for Direct Manipulation in VR. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology (UIST '96)*. ACM, New York, NY, USA, 79–80. https://doi.org/10.1145/237091.237102

Maria V. Sanchez-Vives, Bernhard Spanlang, Antonio Frisoli, Massimo Bergamasco, and Mel Slater. 2010. Virtual Hand Illusion Induced by Visuomotor Correlations. *PLOS ONE* 5, 4 (April 2010), 1–6. https://doi.org/10.1371/journal.pone.0010381

Mel Slater, Daniel Perez Marcos, Henrik Ehrsson, and Maria V. Sanchez-Vives. 2008. Towards a Digital Body: The Virtual Arm Illusion. *Frontiers in Human Neuroscience* 2 (2008), 6. https://doi.org/10.3389/neuro.09.006.2008

Mel Slater, Daniel Perez-Marcos, H. Henrik Ehrsson, and Maria V. Sanchez-Vives. 2009. Inducing Illusory Ownership of a Virtual Body. *Front Neurosci* 3, 2 (15 September 2009), 214–220. https://doi.org/10.3389/neuro.01.029.2009 20011144[pmid].

Wolfgang Stuerzlinger and Robert J. Teather. 2014. Considerations for Targets in 3D Pointing Experiments. In *Proceedings of HCI Korea (HCIK '15)*. Hanbit Media, Inc., South Korea, 162–168. http://dl.acm.org/citation.cfm?id=2729485.2729510

Robert J. Teather and Wolfgang Stuerzlinger. 2014. Visual Aids in 3D Point Selection Experiments. In *Proceedings of the 2Nd ACM Symposium on Spatial User Interaction (SUI '14)*. ACM, New York, NY, USA, 127–136. https://doi.org/10.1145/2659766.2659770

Andrea Stevenson Won, Jeremy N. Bailenson, and Jaron Lanier. 2015. Appearance and Task Success in Novel Avatars. *Presence: Teleoperators and Virtual Environments* 24, 4 (2015), 335–346. https://doi.org/10.1162/PRES_a_00238 arXiv:https://doi.org/10.1162/PRES_a_00238

Ye Yuan and Anthony Steed. 2010. Is the Rubber Hand Illusion Induced by Immersive Virtual Reality?. In *Proceedings of the 2010 IEEE Virtual Reality Conference (VR '10)*. IEEE Computer Society, Washington, DC, USA, 95–102. https://doi.org/10.1109/VR.2010.5444807