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Evaluating Control Schemes for the Third Arm of an Avatar

Abstract

Recent research on immersive virtual environments has shown that users can not only inhabit and identify with novel avatars with novel body extensions, but also learn to control novel appendages in ways beneficial to the task at hand. But how different control schemas might affect task performance and body ownership with novel avatar appendages has yet to be explored. In this article, we discuss the design of control schemas based on the theory and practice of 3D interactions applied to novel avatar bodies. Using a within-subjects design, we compare the effects of controlling a third arm with three different control schemas (bimanual, unimanual, and head-control) on task performance, simulator sickness, presence, and user preference. Both the unimanual and the head-control were significantly faster, elicited significantly higher body ownership, and were preferred over the bimanual control schema. Participants felt that the bimanual control was significantly more difficult than the unimanual control, and elicited less appendage agency than the head-control. There were no differences in reported simulator sickness. We discuss the implications of these results for interface design.

1 Introduction

Avatars, the digital representations of users in a virtual environment, typically match the form and function of human beings (Bailenson & Blascovich, 2004). Subtle alterations to an avatar's appearance can affect the user's attitude and behavior positively and negatively (e.g., the Proteus effect, see Yee and Bailenson, 2007), and these effects transfer from the virtual to the real world (Peña, Hancock, & Merola, 2009; Steptoe, Steed, & Slater, 2013; Yee & Bailenson, 2007; Yee, Bailenson, & Ducheneaut, 2009). However, avatars do not have to conform to the normal human body template. In his article on homuncular flexibility, Lanier (2006) claimed that humans have the ability to take ownership of bodies with extra limbs and with a body as complex as an eight-armed lobster. In fact, research has shown humans have the capacity to inhabit and take ownership of novel avatar bodies (Steptoe et al., 2013; Won, Bailenson, Lee, & Lanier, 2015). Recent experiments have shown users accepting ownership and agency of six-digit virtual hands through tasks involving visuomotor and visuotactile synchronized control of the six-fingered hand (Hoyet, Argelaguet, Nicole, & Lécuyer, 2016).

Controlling novel avatar bodies may improve productivity and task performance; for example, participants learned to hit more targets with three-armed ava-

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tars than with two-armed avatars (Won et al., 2015). But improvements in task performance may not always correlate with an increase in the number of hands, as recent work by Kulu, Vasser, Zafra, and Aru (2016) with the "Human Octopus" phenomenon has suggested. In our current work, we explore the effects of controlling a novel avatar body using different control schemas, and how such schemas may relate to user experience and task performance. We define *control schema* as a direct spatial input method for controlling a body part or an appendage.

1.1 Designing Control Schemas for a Third Arm

Recent research in novel appendages has looked at controlling a third arm (Won et al., 2015) and human tails (Steptoe et al., 2013). But these studies focused on the ability to use and feel ownership for novel bodies, as opposed to studying the effects of different control schemas on these, or other novel appendages. Our current exploratory study compares different schemas for controlling two degrees of freedom (DOFs) in a long third arm to a human avatar body. Following Won et al. (2015), one end of the third arm was attached to the chest, allowing the other end to move up and down, right and left. This design provided two DOFs for controlling the third arm.

There are many possible control schemas for a novel appendage in VR. It can be controlled by a similar or dissimilar body part, where the similarity is based on the form factor (the geometry of the body). Similarity in form factor can leverage the existing muscle memory (McMahan, Bowman, Zielinksi, & Brady, 2012), which will be useful if the novel appendage has comparable freedom of movement, for example, controlling a leg with an arm or vice versa. For a related discussion on regular body schemas, see McMahan (2012). Conversely, it may follow that if the form factor of the controlling and controlled appendage differs significantly (e.g., controlling a tail), the control signals sent by the brain (based on the visual feedback of the controlled appendage) may not match those afforded by the controlling appendage (due to the differences in form factor). This is perhaps most apparent in the random asynchronous tail condition of Steptoe et al. (2013). VR and neuroscience researchers have recently started empirically exploring the effects of visuomotor synchronicity on body ownership and agency (Ehrsson, Spence, & Passingham, 2004; Kilteni, Maselli, Kording, & Slater, 2015; Petkova & Ehrsson, 2008).

If the main purpose of the novel body is task performance, the novel appendage needs to have the degrees of freedom (DOFs) necessary for the task, and in turn the controlling body parts will need to control those DOFs. The complexity of controlling the required DOFs is captured partly by McMahan's proposed transfer function symmetry (McMahan, 2012). Transfer function refers to the mappings between the input signals from tracked sensors to the interactions or control schemas designed in VR (Frohlich, Hochstrate, Kulik, & Huckauf, 2006). The minimum requirement for a valid transfer function is that the DOFs afforded by the tracking capabilities exceed the DOFs that need to be controlled, and the transfer function defines the rules of this control mapping.

In this study on novel avatar bodies, we measure objective task performance and also subjective user preference of different control schemas. We also explore whether different control schemas affect reported presence and simulator sickness (SS). First, we examine the existing research in 3D interaction design and evaluation. We then discuss how this research might apply to novel avatar bodies and appendage configurations, and finally describe our evaluation task, control schemas, and hypotheses.

1.2 3D Selection (as a 3D Interaction Subtask)

More than two decades of research in 3D user interfaces (3DUI) has identified four fundamental tasks in 3D interaction (3DI): selection, manipulation, navigation and system control (Bowman, Kruijff, LaViola, & Poupyrev, 2005). In this initial study exploring 3D interaction techniques with humanoid avatar bodies, we restricted our attention to just one of these four fundamental 3DI tasks, 3D selection.

1.3 Unimanual Control Schemas

"3D selection" in a virtual world is analogous to pointing and touching interactions in the real world, and is extensively studied in the 3DUI community, entirely as unimanual designs (a single hand of the user is used for the input). For egocentric (first-person perspective) interactions in head-tracked environments, selection techniques can be classified into virtual pointer and virtual hand-based metaphors (Poupyrev, Ichikawa, Weghorst, & Billinghurst, 1998).

The most basic pointer metaphor in a virtual world is ray-casting or ray-selection (Bolt, 1980), where a ray emanates from the end of our hand or pointing finger, and the first colliding or intersecting object is highlighted for selection. The most basic virtual hand metaphor involves representing the user's hand in the virtual space (Bowman et al., 2005). Similar to real-world interactions, people can generally select objects only in peripersonal space when using a virtual hand metaphor. However, the Go-go technique (Poupyrev, Billinghurst, Weghorst, & Ichikawa, 1996) allows selection outside the peripersonal space by elongating the virtual hand nonlinearly as it extends beyond the peripersonal space.

In our study, we used a novel body that represents the selector as a virtual hand, but this virtual hand extends the user's peripersonal space, somewhat similar to the Go-go technique. However, because it is the third of three arms, a configuration that does not exist in nature, this third hand is not controlled in a one-to-one relationship with the user's hand, although it extends from the user's body. Thus, our study examines how control schemas that have previously been studied in the 3DUI community may apply in a novel avatar body.

So far, we looked at unimanual designs of control schemas. The next section looks at the implications of introducing bimanual control, and how manual labor can be divided between the user's hands.

1.4 Bimanual Control Schemas

Buxton and Myers (1986) ran one of the first comparison studies between bimanual and unimanual techniques using 2D mouse cursors. Their first experiment separated selection and positioning, and their second experiment separated navigation and selection into subtasks. In the bimanual design one hand handled each subtask, and in the unimanual design one hand handled both. Their first experiment demonstrated quick user adoption of the simultaneous use of two hands for the two subtasks, while the second experiment showed significantly higher performance with the bimanual technique, which they attributed to efficiency of hand motion. In bimanual interaction, the two hands can work in symmetry, or in asymmetry to each other, which we subsequently discuss separately.

1.5 Asymmetric Bimanual Interaction

Guiard (1987) proposed three postulates for asymmetric division of labor between our two hands: (a) the nondominant hand provides the frame of reference for the dominant hand, (b) the dominant hand works on a finer spatial and temporal scale, and (c) the nondominant hand leads, while the dominant hand follows. These postulates are widely accepted and replicated in several bimanual user studies (Balakrishnan & Kurtenbach, 1999; Cutler, Fröhlich, & Hanrahan, 1997; Hinckley, Pausch, Goble, & Kassell, 1994; Kabbash, Buxton, & Sellen, 1994).

1.6 Symmetric Bimanual Interaction

Kelso, Southard, and Goodman (1979) suggested that our brain produces simultaneity of action in bimanual tasks by organizing functional groups of muscles to act as a single unit, such as for the coordinated coupling between our two hands. Hauptmann (1989) reported user preference of symmetric bimanual gestures (like using a steering wheel) for scaling and rotations. Mapes and Moshell (1995) proposed symmetric bimanual techniques for scaling, rotating, and stretching in the Polyshop.

1.7 Comparing Bimanual to Unimanual Control Schemas

Research comparing two bimanual techniques with a unimanual technique showed that bimanual interactions can bring significant manual and cognitive benefit to the users (Leganchuk, Zhai, & Buxton, 1998). Manual integration of subtasks with two hands can lower the

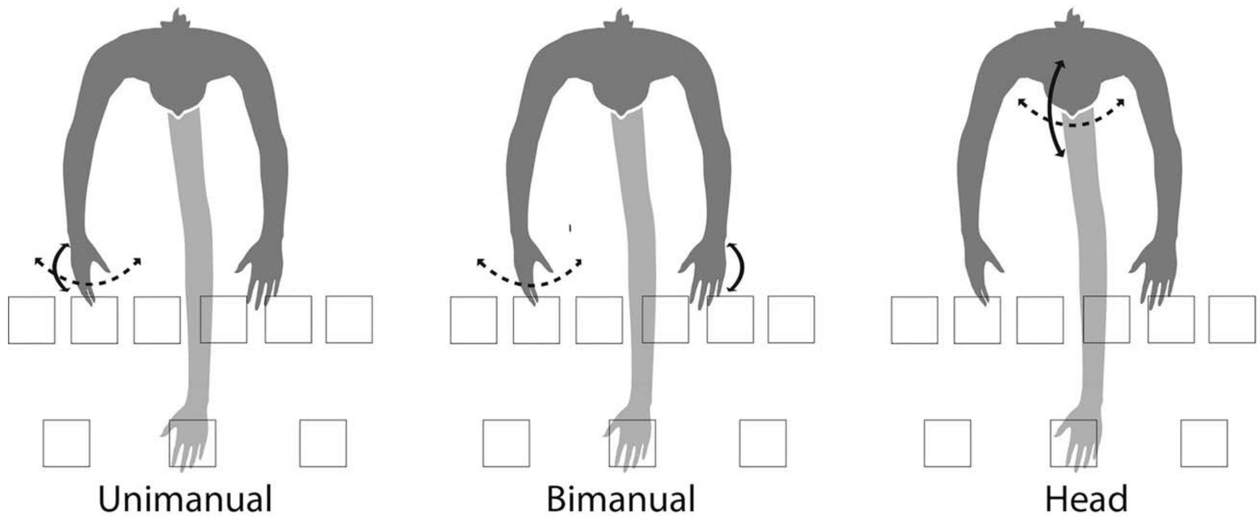

Figure 1. *A top-down view of our three control schemas. The dotted line of the controlling appendage maps to the third arm yaw (rotation about the vertical axis), while the solid line maps to the third arm pitch (rotation about the horizontal axis running from left to right).*

cost of task switching (Buxton & Myers, 1986), which could be the reason for the possible improvement at the cognitive level. For example, Owen, Kurtenbach, Fitzmaurice, Baudel, and Buxton (2005) reported that for a curve matching task, as the cognitive demands increase, bimanual technique provides greater performance benefits over unimanual technique. However, Balakrishnan and Hinckley (2000) showed that increasing difficulty of tasks, divided attention, and lack of visual integration all cause the brain to revert to a more sequential than parallel style of interaction, which might be a counterindication for bimanual control.

In our case, the unit of task is a singular 3D selection, which cannot be split between the two hands. Our design split the degrees of freedom of movement between the two hands in the bimanual interaction design, and compared this bimanual control to our unimanual design.

1.8 Head-Controlled Input Design

One of the first studies comparing head-controlled input to a mouse-based input was conducted by Radwin, Vanderheiden, and Lin (1990), for 2D movements of cursor on a computer display screen, to targets located along radial directions from the center. They found that mouse control was 63% faster than head-controlled input. In a follow-up study, the same group compared four control-display gain levels in a discrete target-acquisition task with a head-controlled 2D pointer, for a variety of target sizes and movement amplitudes (Lin, Radwin, & Vanderheiden, 1992). The results in their study conformed to Fitts' law (Fitts & Peterson, 1964), and they again found that the mouse control was always faster than the head-controlled pointer.

However, for 3D interaction, head-controlled input has been used for controlling a robotic arm in laparoscopic surgery, the activation being controlled by a pedal (Finlay, 1996). A recent game popular in the Oculus Rift (Dumpy the Elephant) mapped the yaw, pitch, and roll of the human head to move an elephant's trunk in VR (Schrank, 2015). The wide acceptance of this game suggests that this mapping is easy to use without inducing much fatigue or motion sickness. This inspired us to design a simple mapping between the yaw and pitch of the head to the horizontal and vertical movement of our virtual third arm, respectively (see *Head* in Figure 1).

We are unaware of any formal evaluation study comparing head-controlled interaction for 3D selection to unimanual or bimanual designs. Thus, we selected head-controlled interaction as our third control schema for evaluation.

1.9 Hypotheses

The main goal of this study is to investigate how different control schemas for a novel appendage may affect task performance and presence in virtual reality. This work extends the study of Won and colleagues (2015), and further studies the third arm as a novel appendage. To the best of our knowledge, the effect of control schemas on task performance with novel appendages has not been empirically explored yet. Task, and its performance, can vary widely depending on the human appendage used and the purpose of the task. We choose to evaluate task performance for 3D selection, which has been identified as one of the four basic tasks in 3D interaction (Bowman et al., 2005).

Hypothesis 1. Task performance will vary between the control schemas.

We wanted to examine any differences in simulator sickness between the control schemas (Kennedy, Lane, Berbaum, & Lilienthal, 1993). We posit the following:

Hypothesis 2. Simulator sickness would not vary between the control schemas.

Finally we investigated how control schemas affected the user's sense of presence (Slater, 2003). The subjective feeling of presence can depend on a variety of factors. Two common types of presence measured in VR are body ownership, and environmental or spatial presence (Bailenson et al., 2005; Lee, 2004; Won, Bailenson, & Lanier, 2015). Body ownership, or self-presence (Ehrsson et al., 2004), is the psychological sense of ownership for the virtual self-avatar, and can be broken down into ownership of the virtual avatar's body (independent of its actions), and ownership of the avatar's actions through "appendage agency" (Steptoe et al., 2013).

Environmental or spatial presence is the feeling of being located in the surrounding virtual world (Lee, 2004; Won et al., 2015). Steptoe and colleagues (2013) reported differences in body ownership and appendage agency based on the synchronicity of the virtual tail, but did not measure effects on environmental presence. Barsalou (2008) notes that Gibsonian theorists discussing situated action focus on the close coupling of the action and the environment during task performance or goal achievement. Interaction with the surrounding environment might be important for feeling connected with that environment. In our case, the interaction of the participants with the virtual world was very limited, except for the task that involves interacting with a set of virtual boxes. So, we posit that the environmental presence may not vary between the conditions in our experiment.

Hypothesis 3. Both body ownership and appendage agency will vary between control schemas but environmental presence won't be significantly different according to condition.

2 Methods

Our experimental design used control schema as a within-subjects factor with three levels (three control schemas), and counterbalanced the orders of the control schemas. We chose hand and head as the two body parts for exploring control schemas for the third arm. Both of these offer at least two DOFs for control, and are both on the upper half of the body, which avoids any additional unexplored effects of comparing upper and lower body for control of novel appendages.

Our first control schema is head control. The human head has about 180° yaw (about the vertical axis), and about 180° pitch (about the horizontal axes passing through the two ears). Our second and third control schemas examine the effect of unimanual and bimanual controls. The effect of manual division of DOFs for a given task is unexplored. Thus, we compare controlling both the virtual third arm's DOFs with one hand (*unimanual*) to dividing the virtual third arm DOFs between the two hands *(bimanual*). Unimanual allows for more limbs to be controlled simultaneously, while bimanual allows distribution of the degrees of freedom between two hands in ways perhaps better suited for the task in hand. The unimanual control schema of the third hand can be tied to either the dominant or the nondominant hand; our study keeps the unimanual control of the third arm on the dominant hand (see *Unimanual* in Figure 1).

For bimanual control of the third hand, the DOFs can be divided between the two hands in two different

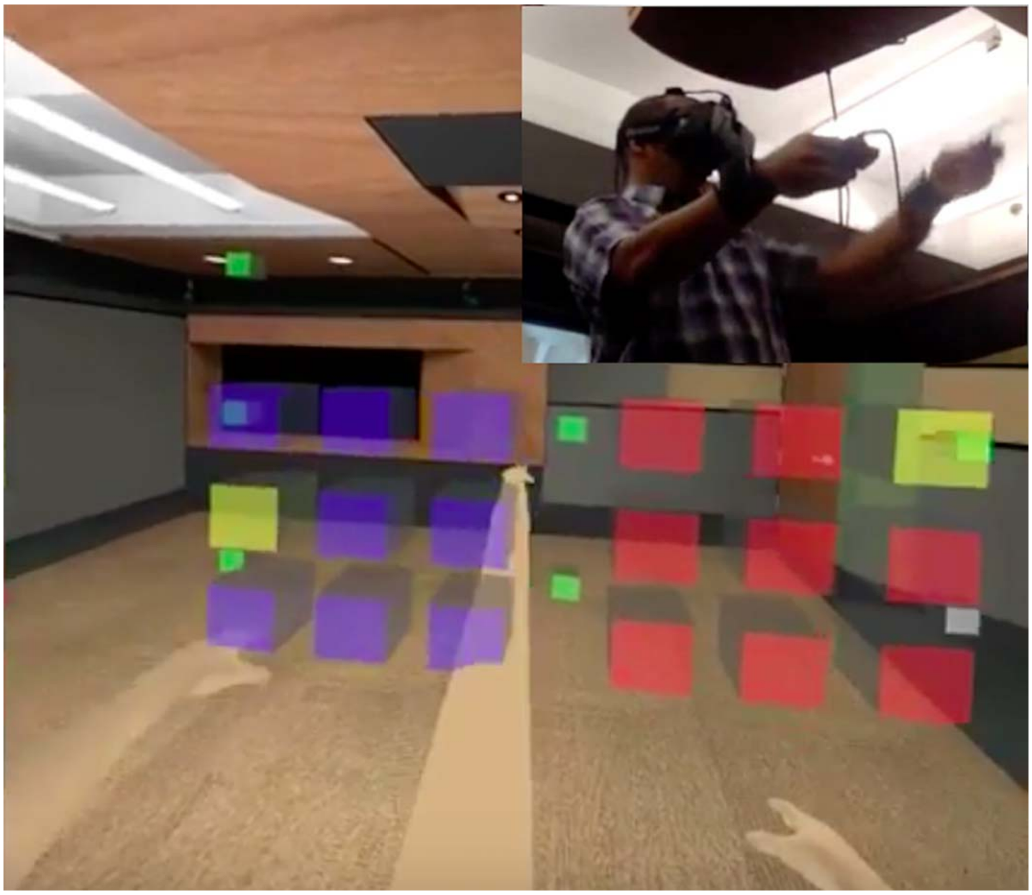

Figure 2. *A participant playing Touchcube using our setup.*

ways—the dominant hand can control the vertical movement and the nondominant hand can control the horizontal movement, or vice versa. The horizontal and the vertical movements of the third hand would seem more symmetric, than asymmetric, to each other, as they correspond in both spatial (in degrees of rotation) and temporal components (assuming the speed of rotation is similar). The perceived asymmetry may come from the fact that humans walk on the horizontal plane of the earth all the time, and have very little vertical movement, unless going up or down stairs. Consequently, horizontal movement might seem to be on a higher spatial scale of reference (the magnitude is determined by the sheer amount of space covered each day) than vertical movement. Whether any such perceived asymmetry exists, whether that leads to such spatial scale difference, and whether that really matters are all interesting research questions, and remain to be explored formally. Assuming they matter, based on Guiard's postulates (Guiard, 1987), the horizontal DOF (working on a possible higher spatial frame) was tied to the non-dominant hand and the vertical DOF to the dominant hand (see *Bimanual* in Figure 1). Differences in mobility of the controlling body part of the appendage play a key role in the task performance. For example, fingers are a lot more mobile and dexterous, and work on a lower spatial scale than our head. In our design, fingers control the bimanual and unimanual designs (see Figure 3).

2.1 Apparatus

We used an Oculus Rift DK2 (as shown in Figure 2), with a resolution of 960×1080 and a refresh rate of 75 frames per second per eye. A three-axis Oculus VR^{TM}

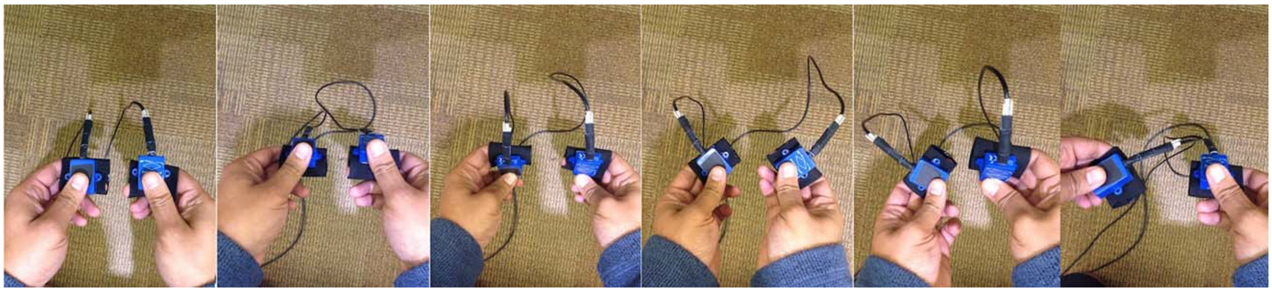

Figure 3. *The positions of the orientation trackers on the fingers, in various configurations, attached with custom Velcro^{TM} straps. (a) The initial default positions; (b) Both pitched down; (c) Both pitched up; (d) Both yaw'd; (e) Right pitched up, left yaw'd; (f) Right pitched down, left yaw'd.*

Sensor tracked three DOFs head orientation with an update rate of 1000 Hz and a 30-ms latency rate. An optical tracking system (Worldviz PPT E, update rate of 180 Hz with a 20-ms latency rate) provided three DOFs positional tracking for head and hands. Two Intersense InertiaCube4^{TM} (accuracy of 1° yaw, 0.25° pitch and roll at 200 Hz update rate; 2-ms latency) tracked three DOFs orientation of the hand gestures for the user interactions. Participants also received audio feedback when interacting with stimuli in the environment, provided by a 24-channel Ambisonic Auralizer Sound System from Worldviz. At each successful target hit of a cube, participants also received a small amount of haptic feedback through the floor of the room from low-frequency speakers. Worldviz's Vizard was used to generate the virtual world creating a true-to-scale virtual replica of the lab environment in which the experiment was performed (with the addition of the Touchcube game interface). Each participant had a first-person view of his or her body. Figure 2 shows the setup used by a participant.

2.2 Task Design

Before the task began, each participant received a few minutes of instruction and practice time on moving their avatars' limbs, guided by the researcher. Her normal left and right arm motions moved the avatar's arms. However, elbow and wrist movement were not rendered, so that the avatar arms remained straight. To maintain visual similarity with the third arm, inverse kinematics were not used to simulate the bending of the left and right arms. For the current exploratory study, we traded off the loss of presence related to the lack of elbow flexibility of the regular arms for a simpler design of control schemas.

Two Intersense inertial cube trackers with three DOFs (Intersense, 2015) were attached to Velcro^{TM} fitted straps on participants' index and middle fingers. They were instructed to hold the sensors between the index and the middle finger, and to control the sensors with the movement of their thumbs (see Figure 1). This arrangement allowed the most mobility of the trackers, while not confounding with the wrist movements, which would control the two regular arms. The straps were kept on during all three control schemas to avoid any confounds related to tethering. The positions of the orientation trackers on the two hands in the different yaw (rotations about the vertical axis) and pitch (rotations about the horizontal axis) configurations were as shown in Figure 3 (also, please check the supplementary video for more clarity: http://www.mitpressjournals.org/doi/suppl/10.1162/PRES_a_00251).

In the bimanual control schema, the participants moved the third hand horizontally with their nondominant hand, and vertically with their dominant hand. In the unimanual, both the vertical and the horizontal control of the third arm were from their dominant hand. In the head-control, the participants moved the third arm vertically and horizontally by bobbing their head up and down, and turning their head right and left, respectively.

In all the control schemas, the default position of the third arm was projecting outwards from the chest. The rotations from the hand or head to the third arm were mapped one-to-one in degrees. A movement of around 60° on either side of the start position, both along the pitch (about the horizontal axis) and along the yaw (about the vertical axis), was sufficient to cover the space containing all cubes in the Touchcube game—the corresponding movements with the hands or the head posed no restriction to the user.

2.3 Procedure

On arrival, each participant was introduced to the lab, the study, and the hardware used. She read and signed an informed consent informing her about her rights during the study. She then filled out a background questionnaire. She was then briefed about the first control schema in her counterbalanced group and practiced the Touchcube game for 20 seconds. Then she played the game for three more minutes.

To begin the task, participants touched a blue cube, which expanded to present three stationary arrays; two located approximately 0.8 meters from the participant, and the other approximately 0.5 meters farther out. The position of the arrays was scaled to participant height, but the length of the third arm remained constant at 1.36 meters. The array on the participant's left was blue, the array on the right was red, and the most distant array was green (see Figure 2). In each trial, one target cube in each of the three arrays was randomly assigned to be white. To complete the trial, all three targets had to be hit, but could be hit in any order. When a participant successfully touched a target cube, a tone sounded, and that target cube turned yellow. Once all three targets had been touched, a second tone sounded, and a new random set of targets lit up. The unit task to perform in the Touchcube game was touching the cubes, which is a 3D selection task. The Touchcube game consisted of as many trials as the participant could complete in three minutes.

During the game, the positions and orientations of her tracked limbs were recorded, as well as the time each cube was hit. The experimenter paused the game if there were any equipment malfunctions. The software ignored the paused time from the recorded time for our performance measure, but did not increase the overall Touchcube playing time per control schema above three minutes to avoid fatigue. She filled out the post-condition survey measuring simulator sickness (SS) (Kennedy et al., 1993), presence, and control schema preference. She repeated the process for the two other control schemas according to her ordered group. Her final post-condition survey was also followed by a few additional post-experiment questions (see Appendix A). The experimenter then conducted a short free-form post-experiment interview to answer any questions or concerns.

2.4 Participants

We recruited 31 volunteers that were either paid $15 or received course credit for their participation. One participant was dropped due to technical difficulties. This left 30 participants (13 males) aged from 18 to 59 years old (average age 24.2), and 28 were right-handed. Participants were distributed randomly in the six ordered groups (five participants per group). Six of them had contacts and nine had glasses. All participants signed informed consent, and the Institutional Review Board approved all aspects of the experiment.

2.5 Measures

We assessed novel avatar control schemas in four ways: task success (time), SS, presence, and user preference (the means and standard deviations of these measures are in Appendix B).

2.5.1 Time. The system logged one point every time a participant touched all three of the lit cubes in the Touchcube game. To ensure that they were not penalized for any loss of time related to technical difficulties, we calculated the lowest score obtained by all the participants (43), and computed the time difference between subsequent scores leading up to that score. This gave us a repeated-measure time metric, in seconds.

2.5.2 Simulator Sickness. After the virtual reality game, participants self-reported their SS on a standard questionnaire (Kennedy et al., 1993). The SS self-report questionnaire had 16 separate measures, each on a four-point (zero to three) scale, where three means "a lot" and zero means "none at all." The SS metric examined if any of the control schemas triggered significantly more SS than the others.

2.5.3 Presence. Participants filled out a presence questionnaire after every SS questionnaire. The presence measures were grouped in three categories of body ownership or self-presence, appendage agency, and environmental or spatial presence, which has been the focus of recent research (Steptoe et al., 2013; Won et al., 2015). We normalized the presence measures by dividing the response to the first body ownership question by seven, and the remaining responses by five, which are the number of choices in each of those scales (see Appendix A). We adapted the ownership and agency measures from the human tail experiment conducted by Steptoe et al. (2013), and further incorporated one ownership and five environmental presence questions from Won et al. (2015). The factors of each of these categories are shown in the Appendix A. Each of these is on a five-point scale, ranging from "not at all" to "very strongly," except for the first body-ownership question, which had seven Venn diagrams showing varying degrees of overlap. We reverse-coded the third appendage agency question ("The third hand seemed to be moving around on its own"), so that a lower agreement to this statement would imply higher appendage agency.

2.5.4 User Preference. After each presence questionnaire, the participants reported their liking, ease level, and physical comfort for each control schema on a five-point, three-question post-condition questionnaire. The five-point Likert scale ranged from "not at all" to "a lot," the ease of use scale ranged from "very difficult" to "very easy" (reverse-coded), and the comfort scale ranged from "very uncomfortable" to "very comfortable." The final post-experiment questionnaire had three questions noting their preferred control schema while playing the Touchcube, in general, and finally capturing any final comments, suggestions, or concerns that they had.

3 Results

We conducted data analysis using the statistical package R (2015). We used linear mixed-effects regression (lmer) as our preferred method to account for random error between participants (including participant as a random factor in the models), and to take into account within-subjects correlations for repeated-measure designs (Baayen, Davidson, & Bates, 2008). Mixed-effects regression modeling also allowed for pairwise comparison of the levels of independent variables (using contrast coding), to minimize problems related to multiple comparisons in post-hoc analyses.

For each of our dependent measures, a linear mixed effect regression model was fitted using lmerTest (Kuznetsova, Brockhoff, & Christensen, 2013), with the two fixed factors as control schema (three levels within-subjects independent variable) and ordered groups (order of the control schema presented to subject; a six levels between-subjects variable). A significant effect of the ordered group (*group* from now on) as fixed factor would indicate that the counterbalancing may not have worked (MacKenzie, 2012). Using participants as a random effect accounted for the random variability between subjects. Deviation coding of the contrasts allowed for pairwise comparison of the different levels of the fixed factors in lmerTest.

At times during the Touchcube gameplay, some trials experienced technical difficulties related to hand-tracking, which caused a delay that froze the virtual arm movements of the avatar. The experimenter could see this issue immediately, as it was shown on a front-projected display wall that showed the first-person view of each participant. In such cases, the experimenter promptly paused the Touchcube gameplay using a key-press on a wireless keyboard, and informed the participant that the gameplay was paused. The "pause" kept everything visually the same for the participants as the initial start of the treatment, including the first-person head-tracked view of the avatar body, the virtual lab-room environment and the positions of the cubes in 3D space as seen by the participants. However, the one exception was that during the pause, the cubes no longer changed color and touch sound did not initiate. After the experimenter promptly verified that things were back to normal, the game was resumed, and the participants were verbally informed that they could continue their gameplay. This happened during 40 out of the 90 control schema runs (from 30 participants), for 16 bimanual runs, 15 head-control runs, and 9 unimanual runs.

The total playing time was not increased during the pause to avoid fatiguing participants, or confounding our SS measure. However, we do not have any data on the effect of the pauses on SS, except for the participants' response to our post-control-schema SS questionnaire (Kennedy et al., 1993). In addition, the pauses and the instructions from the experimenter might have affected the presence of the participants in our study (lowered absolute values, or confounded the relative presence between control schemas). However, both presence and simulator sickness were secondary measures in this study, as the primary focus of the experiment was to examine the effects of control schema on task performance and user preference. Thus we wish to present the presence and simulator sickness results as potentially affected by the pause but still interesting.

We used time as our objective performance metric instead of score, which allowed us to overcome any effects related to the pauses.

3.1 Time

Table 1 provides the means and standard deviations of the time the participants took to touch each set of three lit cubes in the Touchcube game, with the three control schemas.

We ran a mixed-effects regression on the time metric, with the control schema and group as fixed factors, and the repeated measure index as a within-subjects factor, nested within the participant (i.e., ID as the random factor). There was no main effect of group, which suggests that the counterbalancing may have worked (MacKenzie, 2012). Table 2 provides the statistics for the linear mixed-effects model fitting on the time metric, showing a pairwise comparison of the control schemas. Both the head-control and the unimanual schemas were significantly faster than the bimanual control schema. The head control was close to significantly faster ($p = 0.05$) than the unimanual schema.

3.2 Simulator Sickness

Table 3 gives the means and the standard deviations for the SS measures across the three control schemas.

Table 1. *Means and Standard Deviations for the Time Metric*

Control Schema	Average time (in seconds)	Standard Deviation (in seconds)
Bimanual	4.16	1.82
Head-control	3.36	1.32
Unimanual	3.66	1.53

We ran a mixed-effects regression on SS, with control schema and group as fixed factors, and participant as a random factor. We found no main effect of the control schemas, suggesting that participants did not experience significantly different levels of SS. Bimanual control elicited the highest amount of SS among all the three schemas. Table 4 shows the statistics related to pairwise comparison of the SS induced by the control schemas. There was no significant main effect of group as a fixed factor for the self-reported SS, which suggests that the counterbalancing may have worked for this metric (MacKenzie, 2012).

3.3 Presence

The means, standard deviations, and reliability of the body ownership measures for the three control schemas are shown in Table 5. Tables 6 and 7 give the means, the standard deviations, and the reliability of the appendage agency and the environmental presence, respectively, for the three control schemas.

We ran mixed-effects regression on each of body ownership, appendage agency, and environmental presence, with control schema and group as the fixed factors, and participant as the random factor. None of these three regression models showed a main effect of group, suggesting that the counterbalancing may have worked for our presence measures (MacKenzie, 2012).

Participants reported significantly higher body ownership or self-presence with each of the unimanual and head-control, than with the bimanual control (see Table 8). The environmental (or spatial) presence ratings showed no main effects of control schema. The pairwise comparisons between the control schemas are in Table 9

Table 2. *Linear Mixed-Effects Regression Results for the Time Metric (Sample Size = 3870)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	9.24	3786	0.34	< 0.001
Bimanual vs. Unimanual	7.26	3786	0.34	< 0.001
Head-control vs. Unimanual	−1.97	3786	0.34	0.05

Table 3. *Means and Standard Deviations for the Simulator Sickness across the Control Schemas*

Control Schema	Average score (range: 0–2437.88)	Standard Deviation
Bimanual	281.32	348.71
Head-control	237.31	225.96
Unimanual	257.06	323.12

for the appendage agency and in Table 10 for the environmental presence. Participants reported significantly higher appendage agency with the head-control than with the bimanual control schema (see Table 9).

3.4 Liking, Difficulty, Physical Discomfort, and Preference

Table 11 shows the means and standard deviations for the self-reported measures in the post-condition questionnaire, for the three control schemas.

We ran mixed-effects regression on each of liking, ease, and physical comfort, with control schema and group as the fixed factors, and participant as a random factor. Tables 12, 13, and 14 give the statistics for the linear mixed-effects model fitting on the self-reported liking, ease, and physical discomfort, respectively, from the post-condition questionnaire. There was no significant main effect of group as a fixed factor in any of these models, suggesting that counterbalancing may have worked for the user preference metrics (MacKenzie, 2012).

The participants' liking and physical comfort levels did not significantly vary between the control schemas. However, the participants reported that the bimanual control was significantly more difficult than the unimanual control (see Table 13).

Table 15 shows the user reported preference of the three control schemas. They showed a strong preference for both the head-control and the unimanual control schemas, both for playing the Touchcube game and in general.

4 Discussion

Revisiting our hypotheses in light of the results, we find that task performance in 3D selection was significantly improved with both unimanual and head-control, over bimanual control (see Tables 1 and 2). Further, the performance improvement from unimanual to head-control was statistically close to significant ($p = 0.05$; see Table 2). This supports our hypothesis H1. McMahan (2012) posits that the dimensional symmetry, contributing to the fidelity of interaction, can play a role in objective task performance. We believe our hypothesis H1 supports that theory partly (the *integration* part of dimensional symmetry), as the main difference between the bimanual control, and both the unimanual and head-control, is the integration of the two DOFs for the third arm in a single controlling appendage (head-control and unimanual), or not (bimanual).

Further, the experimenter observed for several participants that with the unimanual control, when the selection cube was at the corner of the far (green) array, the participants moved their dominant hand forward, while the third arm movement was actually affected by the head-movement. In the unimanual control, the 2DOF orientation (pitch about the horizontal axis and yaw about the vertical axis) of the third-arm was controlled by the Intersense cube held in the dominant hand, while its 3DOF position was mapped to the head position of the user. During the head-control, this came naturally, as all the 5DOFs for position and orientation

Table 4. *Linear Mixed-Effects Regression Results for Self-Reported Simulator Sickness (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	−0.93	48	0.88	0.36
Bimanual vs. Unimanual	−0.3	48	0.88	0.76
Head-control vs. Unimanual	0.62	48	0.88	0.54

Table 5. *Means, Standard Deviations, and Reliability for the Body Ownership Measures across the Control Schemas*

Control Schema	Mean (range: 0–1)	Standard Deviation	Reliability (Cronbach's alpha)
Bimanual	0.55	0.21	0.92
Head-control	0.62	0.20	0.91
Unimanual	0.63	0.21	0.91

Table 6. *Means, Standard Deviations, and Reliability for the Appendage Agency Measures across the Control Schemas*

Control Schema	Mean (range: 0–1)	Standard Deviation	Reliability (Cronbach's alpha)
Bimanual	0.72	0.10	0.96
Head-control	0.81	0.10	0.98
Unimanual	0.82	0.11	0.98

Table 7. *Means, Standard Deviations, and Reliability for the Environmental Presence Measures across the Control Schemas*

Control Schema	Mean (range: 0–1)	Standard Deviation	Reliability (Cronbach's alpha)
Bimanual	0.64	0.17	0.90
Head-control	0.68	0.17	0.92
Unimanual	0.64	0.20	0.94

Table 8. *Linear Mixed-Effect Regression Results for Body-Ownership (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	−2.53	48	0.91	0.02
Bimanual vs. Unimanual	−2.90	48	0.91	< 0.01
Head-control vs. Unimanual	−0.37	48	0.91	0.72

Table 9. *Linear Mixed-Effects Regression Results for Appendage Agency (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	−3.00	48	0.71	< 0.01
Bimanual vs. Unimanual	−1.67	48	0.71	0.10
Head-control vs. Unimanual	1.33	48	0.71	0.19

Table 10. *Linear Mixed-Effects Regression Results for Environmental Presence (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	−1.57	48	0.93	0.12
Bimanual vs. Unimanual	−0.59	48	0.93	0.56
Head-control vs. Unimanual	0.98	48	0.93	0.33

Table 11. *Means (Range: 0–1) and Standard Deviation for the Post-Condition Measures*

Control schema	Liking		Ease (not difficult)		Physical comfort	
Bimanual	0.65	0.27	0.57	0.17	0.65	0.18
Head-control	0.79	0.18	0.79	0.15	0.73	0.16
Unimanual	0.80	0.23	0.81	0.14	0.70	0.20

Table 12. *Linear Mixed-Effects Regression Results for the Self-Reported Liking (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	0.00	48	0.75	1.00
Bimanual vs. Unimanual	−0.41	48	0.75	0.69
Head-control vs. Unimanual	−0.41	48	0.75	0.69

Table 13. *Linear Mixed-Effects Regression Results for the Self-Reported Ease (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	−1.01	48	0.71	0.32
Bimanual vs. Unimanual	−2.52	48	0.71	0.02
Head-control vs. Unimanual	−1.51	48	0.71	0.14

Table 14. *Linear Mixed-Effects Regression Results for Self-Reported Physical Comfort (Sample Size = 90)*

Contrasts	t	DF	r^2 (effect size)	p
Bimanual vs. Head-control	0.54	48	0.76	0.60
Bimanual vs. Unimanual	0.54	48	0.76	0.60
Head-control vs. Unimanual	0.00	48	0.76	1.00

Table 15. *User Preference for the Three Control Schemas for Playing Touchcube, and in General*

Control Schema	Preferred for Touchcube	Preferred in general
Bimanual	1	2
Unimanual	14	13
Head-control	15	15

were controlled by the head. While this shows that they probably treated the third-arm as an extension of, or a tool attached to, their dominant hand in the unimanual control, the division of the DOFs for position and orientation lowered the task performance with the unimanual compared with the head-control ($p = 0.05$), as with the head-control there was a match between the 3DOF movement of the controlling (head) and the controlled (third-arm) appendages.

Hypothesis H2 was also supported as the SS of the participants did not vary between the control schemas (see Table 4). Previous research into the factors of VR system fidelity causing SS has provided evidence for latency (Meehan, Razzaque, Whitton, & Brooks, 2003), as well as field of view and field of regard (Lin, Duh, Parker, Abi-Rached, & Furness, 2002) as the main contributors to simulator sickness. Others have identified translation geometry (Dorado & Figueroa, 2014), and various factors of the fidelity of interaction (Chance, Gaunet, Beall, & Loomis, 1998) as causing simulator sickness. More recent research into factors affecting simulator sickness has identified the lack of the outline of nose in VR as an important trigger (Whittinghill, 2015), which could be related to the type of visual reference point users have. SS was not the main dependent variable in our study, and consequently, we did not vary any of the factors with a hope to see a difference in SS. Rather, SS would have served as a covariant in our analysis, if its effects were significant (as task performance could potentially be lowered due to SS). Knowing SS did not vary between the conditions improves the robustness of our findings.

Our results support our hypothesis H3, as both body ownership and appendage agency varied significantly between the control schemas; however, environmental presence did not. Both body ownership and appendage agency increased from bimanual to unimanual control, which indicates that the unimanual elicited significantly higher presence in the novel avatar body than with the bimanual control schema. Body ownership also increased significantly from bimanual to head-control, but without any significant change in the appendage agency. These indicate that the head-control also elicited higher presence in the novel avatar body than bimanual control; however, the reported increase was less than that with unimanual control.

These results together show that among the three control schemas we tested, unimanual control appears to elicit the strongest level of presence with a novel body equipped with a third arm, followed by head-control. The task performance and presence results also coincide with participants' subjective ratings of preference of the control schemas. The participants rated unimanual control significantly less difficult than bimanual. This rating is consistent with the other three metrics (task success, sickness, and presence), in which unimanual schema was either the best of three or better than at least the bimanual schema.

4.1 Reasons to Study Control Schemas for Novel Appendages

There are multiple reasons to study and embody nonhuman avatars. For example, embodying a virtual cow or a coral leads to greater connectedness to nature, providing implications on eliciting pro-environmental behaviors (Ahn et al., 2016). Embodying and controlling novel body configurations can trigger cognition grounded in novel bodily states (Barsalou, 2008) and will allow us to test theories of situated action (Gibson, 1979) by inhabiting various environments in novel avatar bodies.

Varying the type of body users control can alter their perceptions of the virtual environment; for example, the amount of space objects take up (Banakou, Groten, & Slater, 2013) can potentially impact performance. Natural mappings of interfaces can increase presence within and enjoyment of a virtual interaction (Skalski, Tamborini, Shelton, Buncher, & Lindmark, 2010). In addition, the ease with which people move their bodies influences how they make decisions and choose between various options (Casasanto, 2011). For example, Casasanto's experiments (2009) showed that we implicitly associate positive valence (honesty, happiness, intelligence) with the side of space in which we act more fluently with our dominant hand.

These effects of avatar embodiment indicate a need to better understand the underlying mechanism and ability to use different control schemas for novel appendages. If task performance varies based on control schemas, it is important to further investigate whether and which of these factors contribute towards it. The existing research on controlling novel avatars has been sparse, most likely due to the high costs involved in earlier body tracking capabilities. However, with the advent of inexpensive virtual reality (VR) systems that are capable of tracking both head and hand movement, the opportunities to experience embodiment in novel ways has suddenly increased. Thus, it is important to ask how novel avatars or body parts (appendages) should be controlled. Understanding if and how the control schemas affect our sense of presence in the virtual world will allow us to better design ways to inhabit and use novel avatar bodies. Better interactivity with novel avatars will help further research in embodiment, and empathy (Gallagher, 2005; Won, Haans, IJsselsteijn, & Bailenson, 2014).

4.2 Implications for Design

Based on the results from this preliminary study, we have some recommendations for designers of third-arm control schemas for better performance in 3D selection tasks. Unimanual control of the third arm appears to have the best combination of ratings across all our metrics (task performance, presence, and user preference) followed by head-control. Bimanual design should be considered only if the other control schemas are infeasible (e.g., controlling a third arm in a laparoscopic surgery), as it appears to have the lowest ratings across the four metrics in our study. Since the bimanual control differed from the other control schemas on the splitting of the DOFs between two hands, preserving the DOFs for control in a single controlling appendage might be better than splitting them in more than one controlling appendages, for 3D selection task performance, presence, and user preference.

4.3 Future Work

Our design methodology provides guidance on how to design control schemas for novel extensions to the human body. The results provide insights on which designs may work better for task performance in 3D selection. Future work can design and evaluate other kinds of control schemas, for other novel body extensions, and for other kinds of tasks, including 3D manipulation and path following (Bowman et al., 2005).

The design of our bimanual control schema looked very briefly into approaches of symmetric and asymmetric division of labor between the human hands. The existing kinematic chain theory for asymmetric division of labor is for two hands (Guiard, 1987), as division of labor between three hands has not been explored yet. If the kinematic chain theory can be extended to three arms, in the hierarchy of hands providing frames of references to each other (if such a hierarchy exists), a third arm can come above the nondominant hand, between the two hands, or below the dominant hand. The hierarchy of human hands (above two) in manual labor is a big research question by itself, which can be explored in future studies with control schemas for more than two hands.

Bowman et al. (2012) define naturalism or interaction fidelity as "the objective degree with which the actions (characterized by movements, forces, or body parts in use) used for a task in the user interface correspond to the actions used for that task in the real world." They also argue that naturalness in the interaction could be beneficial or detrimental depending on the task in focus. Recent theoretical work has identified biomechanical and control symmetry as two important factors for gauging how natural a control schema is (McMahan, 2012). This paper is a first step towards understanding how these factors affect presence and task performance in novel bodies, and how these factors can inform the design of control schema in different novel body configurations. Understanding how presence and task performance affect each other, and their connection to body image and body schema, as recently proposed by theorists, might help to explore the effects of embodiment on cognition (Gallagher, 2005).

Prior research has shown that when handling more than one task, splitting the tasks between the two hands might be useful for reducing the cognitive load (Leganchuk et al., 1998; Owen et al., 2005). In our bimanual design, we split the DOFs for controlling an appendage between two hands, for a single task of 3D selection with the third hand. A future study can perhaps vary DOFs and tasks independently, and evaluate the interaction between them for cognitive load, task performance, and presence.

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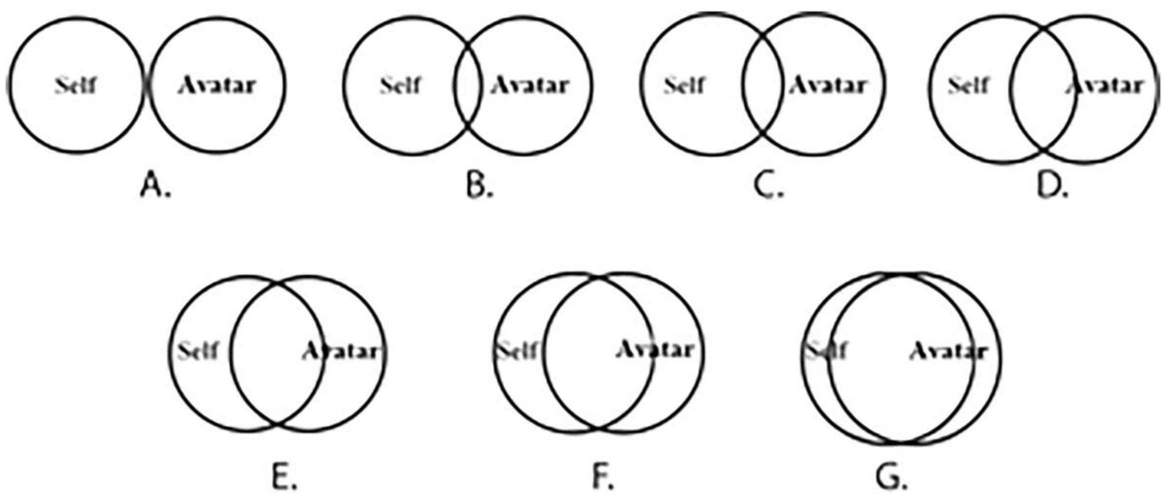
Appendix A

Body ownership or self-presence measures:

1. Please indicate which image best corresponds to the relationship between you and your avatar.

The following questions had five responses: a. Not at all; b. Slightly; c. Moderately; d. Strongly; e. Very strongly.



2. I felt as if the body of the avatar I saw in the game was my body
3. I felt as if the third hand was a part of the body I saw in the game
4. At times during the game, I imagined that I had a real third hand
5. I considered the third hand to be as much part of the body as the other arms and legs were

Appendage agency measures:

1. Not considering the third arm, the movements of the body seemed to be my movements
2. I could easily move the third hand to where I wanted
3. The third hand seemed to be moving around on its own
4. I learned how to control the third hand more accurately as the game went on
5. There were times in the game that moving the third hand came naturally to me

Environmental or spatial presence measures:

1. I felt I was really inside the virtual lab
2. I felt surrounded by the virtual lab
3. I felt I really visited the virtual lab
4. The virtual lab seemed like the real world to me
5. I felt like I could really touch the cubes in the virtual lab

Appendix B

Table 16. *The Overall Means and Standard Deviations of the Measures in This Study*

Measure		Mean	Standard Deviation
Time		3.73	1.61
Simulator sickness		258.56	301.01
	Body ownership or self-presence	0.60	0.21
Presence	Appendage agency	0.78	0.11
	Environmental or spatial presence	0.65	0.18
User preference	Liking	0.74	0.24
	Ease	0.72	0.19
	Physical comfort	0.69	0.18