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Homuncular Flexibility in Virtual Reality

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Immersive virtual reality allows people to inhabit avatar bodies that differ from their own, and this can produce significant psychological and physiological effects. The concept of homuncular flexibility (Lanier, 2006) proposes that users can learn to control bodies different from their own by changing the relationship between tracked and rendered motion. We examine the effects of remapping movements in the real world onto an avatar that moves in novel ways. In Experiment 1, participants moved their legs more than their arms in conditions where leg movements were more effective for the task. In Experiment 2, participants controlling 3-armed avatars learned to hit more targets than participants in 2-armed avatars. We discuss the implications of embodiment in novel bodies.

Keywords: Homuncular Flexibility, Avatars, Tool Use, Body Schema, Virtual Reality.

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What if you could become a bat—your arms acting as wings allowing you to fly through the night sky? The avatars that users inhabit in virtual reality (VR) make this possible. The control of such avatars was explored starting in the late 1980's by Jaron Lanier and his colleagues at VPL Research, who experienced a number of bizarre avatars in the course of developing virtual reality systems and prototyping avatars. These experiences motivated an informal study to see how far they could push the design of avatars that could still be controlled by users. For example, could people learn to control a lobster avatar that had many more limbs than its human user? A number of increasingly strange, but usable, nonhuman avatars were created and tested between approximately 1989 and 1999 (Lanier, 2006). These avatars, radically different from the human body, were controlled by mapping different degrees of freedom to

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the human user's body. Tracked movements that the user made in the physical world would be rendered as different movements of the avatar body. Thus, an eight-armed lobster could have each limb powered by the rotation of a wrist, the flex of an ankle, or some combination of the two.

Much previous research establishes that users can be brought to identify with avatars whose bodies differ from their own; for example, ones of a different age, race, or gender. Previous research on establishing presence in bodies that are not the user's own has prioritized realistic and biological appearing bodies. However, we also know that people are tool-users; and tool use can alter and perhaps extend the user's sense of his or her body. This may occur even when the tool is a simple extension like a stick, which Berti and Frassinetti (2000) propose "caused a remapping of far space as near space" (p. 1). Media are among the most powerful tools of the current era. Can how users are embodied in media—how their mediated bodies interact with the environment and provide feedback to the user—actually change their sense of not only their surroundings, but also their own bodies? Can users thus control bodies that do not match the normal human template when those are more effective for a particular task?

Because humans understand the world through embodied senses, investigating how people learn to control novel bodies through sensory feedback helps us to understand how people use normal bodies to perceive the world. As Biocca (1997) points out in his classic work "The Cyborg's Dilemma," technology that changes the appearance or affordances of the body also changes the self. While the way we perceive the world, including our own bodies, is mediated by our senses, we remain largely unaware of this process during daily life (Loomis, 1992). Mediated perception makes it apparent that we are influenced by the constraints and affordances of our senses, through which we experience the world and ourselves.

In the following pages, we describe how this reliance on sensory feedback, which allows us to understand not only our environments, but also our own bodies, provides us the flexibility to control novel bodies in mediated environments. We then describe two studies in which we investigated whether participants could learn to control novel bodies within a short time period. To do so, we designed tasks in which participants could be more successful in avatars that did not fit the normal human schema. In Experiment One, participants moved their legs more than their arms to hit targets when such a strategy caused their avatars to be more effective for the task. In Experiment Two, participants controlling three-armed avatars learned to hit more targets than participants in two-armed avatars.

Embodiment in the Physical World is Flexible

The term "homuncular flexibility" was chosen to describe the phenomenon of controlling avatars by using different degrees of freedom from the physical body. "Homuncular" refers to Penfield's "homunculus." As Penfield and Boldrey (1937) discovered during a series of experiments conducted during surgery, parts of the body with greater innervation were represented by more space in the primary motor cortex than body parts with less innervation. Although the scientific concept of the homunculus has since been revised (Barinaga, 1995) in general the homunculus refers to the idea of a map of the body in the brain.

Human embodiment is flexible. Injuries like amputation and stroke can change the sense of where bodies begin and end. For example, after amputation, cortical mapping may shift such that areas that previously innervated the hand may shift to other parts of the body (Roricht, Meyer, Niehaus, and Brandt, 1999). This cortical plasticity is hypothesized to be one source of phantom limb pain, the phenomenon in which an amputee continues to have sensation, sometimes very painful, perceived as originating in the absent limb long after the trauma has healed. Ramachandran and Rogers-Ramachandran (1996) proposed that "moving" a representation of one's phantom limb helped to remap the motor cortex and thus alleviate phantom limb pain. Patients were asked to place their uninjured limb in a box with a mirror in the midline and to position their head to look in the mirror so that moving their uninjured limb resulted in the illusion of two normally moving limbs. Thus, the cortical map which had been distorted due to the lack of real input from the missing limb could be restored by the visual input of a plausible limb in the location of the amputated limb. Mirror Visual Feedback (MVF) has also been used to treat pathologies similar to phantom limb pain, like complex regional pain syndrome (CRPS), in which patients suffer pain to an existing limb (Sato et. al., 2010). These treatments suggest that people can be led to alter their body schema by sensory input.

There is a long history of interfering with perception to alter a user's sense of his or her body. One method is that described in detail by Welch (1978), the use of prism glasses or similar methodologies to systematically distort participants' visual fields. A characteristic of this kind of experiment is that participants experience the perceptual rearrangement by moving the head or reaching for objects, and their behavior in compensating for the distortion is measured.

Other experiments have combined visual and tactile sensory feedback to alter participants' feelings of embodiment. For example, in "rubber hand illusion" studies (Botvinick & Cohen, 1997), participants saw a rubber hand on the table in front of them and observed it being stroked by a soft brush while feeling synchronous touch on their real hand hidden under the table. Participants gained a sense of ownership of the hand, such that they flinched when it was threatened. Ehrsson (2007) demonstrated similar effects for the entire body using first-person perspective and simultaneous touch. These feelings of ownership, or being present in the simulated body, provide clues to how a sense of presence may be created in an avatar body.

Avatars Are Even More Flexible

Examples of studies that have used virtual reality to investigate embodiment include experiments similar to the prism adaptation experiments described above, conducted by Groen and Workhoven (1998) and the virtual rubber hand study conducted by IJsselsteijn, de Kort, and Haans (2006). Focusing on the effects of first-person perspective, other research has provided evidence that simply perceiving a virtual body from a first-person perspective can create a sense of identification with an avatar, or "body transfer" (Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). Such avatars may differ not only from users' own bodies, but from the normal human template. In Kilteni, Normand, Sanchez-Vives, and Slater's study (2012), participants inhabited avatars with arms ranging from normal to quadruple normal length. In addition to the first-person perspective, visuomotor synchrony and sensory feedback were also provided. Participants experienced ownership of the avatar arm and responded by flinching when the avatar hand was threatened. Similar feelings of ownership and similar responses to threat were evoked by an avatar with a tail controlled by hip movements, as demonstrated by Steptoe and colleagues (2013). A condition of visuomotor synchrony, in which participants could potentially learn to control the tail by swinging their hips, was compared to an asynchronous condition in which participants could not control the movements of the tail. In the synchronous condition, participants felt greater ownership and agency (compared to those in the asynchronous condition), and also responded with more anxiety to threats to the avatar tail. These results suggest that people can learn to identify with, and potentially control, bodies that differ radically from the normal human template.

Indeed, all experiments using avatars rely on altering the user's sense of embodiment to a greater or lesser extent. Experiments leveraging the Proteus effect, described by Yee and Bailenson (2007), show that people will unconsciously alter their behavior to conform to that of an avatar they inhabit. For example, participants were provided with avatar bodies independently rated as above or below average attractiveness, and were able to see themselves controlling these avatars in a virtual mirror. Participants with more attractive avatars then stood closer to conversational partners, and selected more attractive potential dating partners, than those who inhabited less attractive avatars. They had been affected by their experience of embodiment in that avatar.

Most experiments with avatars require users to take some action as the avatar, even if only moving their head to control first person perspective. However, the VR studies described above tend to emphasize body image, or the sense that the body belongs to the user, rather than body schema, or the ability to use a novel body to complete a task. (For a useful framework distinguishing between body morphology, body schema, and body image, see Haans & IJsselsteijn, 2012). It is important to examine how users learn to *use* novel avatar bodies, and how this use relates to feeling present in such bodies.

Being Versus Doing in a Novel Body

People have long been able to control the movement of avatars, for example in video games, by using key-presses or other abstracted movements. However, more naturalistic movements, defined as "the extent to which users of interactive technology perceive the interactivity to be predictable, logical, or in line with expectations" have been highlighted as unique (Skalski, Tamborini, Shelton, Buncher, & Lindmark, 2011) and control systems using body movements have been found as privileged in terms of promoting engagement (Bianchi-Berthouze, 2013). In addition, interfaces such as touchscreens and the Wii remote, which utilize gesture, and interfaces such as the Kinect, which rely solely on movements without requiring the user to hold a device or wear a marker, are becoming increasingly popular (Phillips, 2013). Thus, while users have demonstrated the ability to use nonanatomical control systems such as joysticks and gamepads to control avatars, it is important to investigate the extent to which users can use their bodies to control avatars or other self-representations, and the effects of such methods of control (Ratan, Santa Cruz, & Vorderer, 2007). Such investigations may also inform our understanding of human tool use, and how self-representation may be manipulated to affect body schema.

Virtual reality lends itself to dramatic explorations of the types of bodies that humans can learn to inhabit and control. In fact, current tracking systems are always imperfect, and the mediated nature of the sensory input is always detectable (i.e., there has yet to be built a VR system that rivals the human perceptual system in the physical world). Thus, even users inhabiting "normal" avatars meant to represent their own bodies are experiencing a kind of "homuncular flexibility" when they successfully operate in and identify with their avatars. This paper investigates how participants can become embodied in an avatar that has been designed to offer new affordances to complete a task. Thus we echo the suggestion of Clark (2007),"the body schema is a suite of neural settings that implicitly (and nonconsciously) define a body in terms of its capabilities for action." We propose that participants engaged in a physical task in a VR environment will use a novel avatar body configuration when doing so will enhance success. In two experiments, we altered the normal one-to-one relationship between actual movements of the physical body, and perceived movements of an avatar, to explore the limits of this adaptive ability.

Overview of Studies

In Study One, we predicted that, when provided feedback on task success, users will control avatar bodies in the way most conducive to task success, instead of moving in the way that is most similar to the way they navigate in the real world. We designed a world in which participants could pop balloons with any of their four limbs. Participants had 10 minutes to pop as many balloons as they could. The balloons appeared in random locations in front of their bodies and disappeared after 5 seconds. Participants were in one of three between-subjects conditions. In the Normal condition, the user's hands controlled the avatar hands, and the user's feet controlled the avatar feet, in a one-to-one relationship. In the Switched condition, users inhabited an avatar in which the user's hands controlled the avatar feet, and the user's feet controlled the avatar hands. In this condition, we predicted that users would use their feet more to control the avatar's hands, since that would allow users to pop more balloons. Finally, in the Extended condition, the user's hands controlled the avatar hands, and the user's feet controlled the avatar feet, but the feet movements were amplified such that the avatar legs would kick higher than the corresponding movement in real life, and the hand movements were constrained such that they could not move much above shoulder level. We again predicted that users would use their feet more to pop balloons, since this would allow them to reach more balloons more easily.

In Study Two, we predicted that, when provided a novel avatar body that allows greater ability to complete a task, users would do better in that task using the novel avatar body, compared to using an avatar body that corresponds to normal human movement. We designed a world in which participants could hit target blocks at both near and far range. Participants completed the two within-subjects condition in a random order. In the ‘normal” condition they stepped forward and backward in space to hit the blocks in the near and far arrays. In the “third limb” condition, they hit the blocks in the most distant array by rotating their wrists to control the translation of a longer third arm that could reach the far array.

Experiment 1- Altering the Relationship Between Tracking and Rendering

In the first study, participants completed a task in virtual reality that allowed them to use their hands and feet to hit a series of floating targets (“balloons”) that appeared randomly in front of them. In order to examine whether our participants would be able to adjust to an avatar with a nonnatural relationship between tracked and rendered motions, we varied the affordances of the avatar, and the way in which that avatar was controlled by movement in the physical world. Participants controlled avatars of their own gender.

Our baseline was the Normal condition, in which the participants’ tracked arms and legs controlled the avatars’ limbs in a one-to-one relationship. We compared this condition to two “flexible” conditions, in both of which the use of participants’ physical legs controlled an area in VR comparable to their real-life arms. In the Switched Limb condition, participants’ physical legs powered their avatars’ arms, while their arms powered the avatars’ legs. The avatars’ arms and legs had the range these limbs normally have; thus, a kick near waist height in the physical world would allow the avatar’s arm to be raised over the head. In the Switched Range condition, participants’ physical arms controlled their avatar arms and their physical legs controlled their avatar legs. However, the ranges of the avatar limbs were reversed. In other words, the gain of participants’ leg movements was increased by a factor of 1.5, such that a moderate kick in the physical world gave the avatars’ legs great range in virtual reality. Conversely, the range of participants’ arms was decreased by .6, such that the avatar arms could not go much above shoulder level. The three conditions are illustrated in Figure 1 (top).

We predicted that participants would accommodate to the novel bodies by using their physical limbs to power the avatars in the ways that were most conducive to succeeding in the virtual task. In both the Switched and Extended conditions, the avatars could reach more balloons if the participants used their physical legs to pop balloons with their avatar’s hands or feet. On the other hand, in a normal human body people are accustomed to pop balloons near their midsection with their hands, because the hands can cover a greater area in front of the body.

> H1. Compared to the Normal condition, people will pop more balloons with their physical legs in the Switched and Extended conditions.

By comparing three conditions, we could also investigate whether one avatar configuration would be more productive. One possibility was that participants would not be able to adjust to either of the flexible conditions during the experiment, so that both scores would be lower than the control, Normal

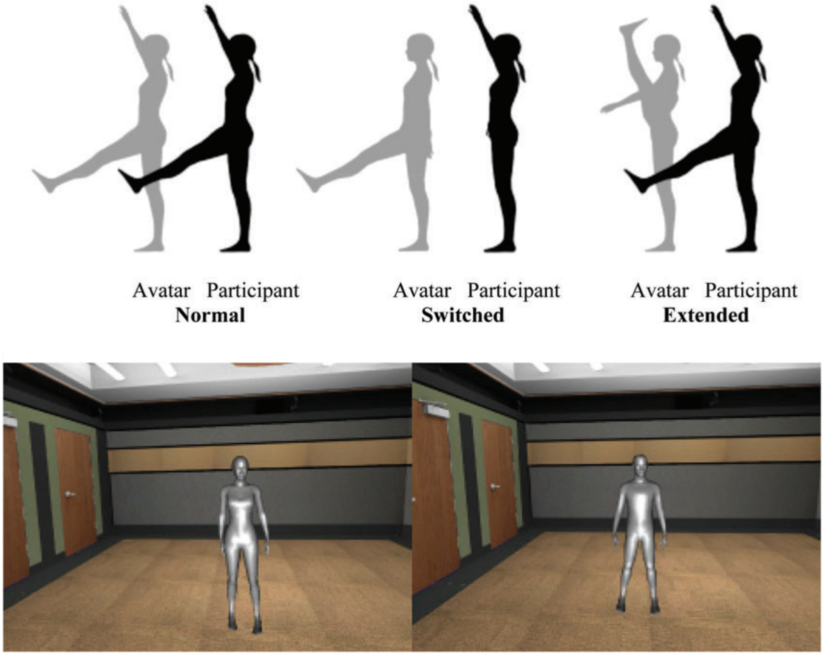

Figure 1 The top panel shows examples of the three conditions. In the Normal condition tracked motions and rendered motions are the same, while in the Switched and Extended range conditions the relationships between tracked and rendered movements were altered. The black figure represents the real-life tracked movements of the participants, and the gray figure represents the corresponding rendering of the avatar. Note that in the Normal condition, there is a one-to-one relationship between the amount that the participant's arms and legs move, and the amount that each corresponding avatar limb moves. In the Extended condition, the participant's leg movements have a gain of 1.5, so that a moderate kick in the physical world gave the avatars' legs great range in virtual reality. Conversely, the movements of participants' arms only move the avatar arms at .6 of their distance, such that the avatar arms could not go much above shoulder level. In the Switched condition, the participant's leg movements have a gain of 1.5, so that a moderate kick in the physical world gave the avatars' arms a similar range of motion to that they would have in the physical world. Conversely, the movements of participants' arms only move the avatar legs at .6 of their distance, such that the avatar legs could not go much above knee level. In the bottom panel the standardized female avatar is shown on the left, the standardized male avatar is shown on the right. The avatars are as seen in the virtual mirror from the participant's perspective.

condition. If participants were able to adjust, then we could examine which method of control was more successful. For example, the avatar appeared to move normally in the Switched condition (despite the unnatural control scheme). In contrast, in the Extended condition, the avatar's movements appeared bizarre but the correspondence between tracked and rendered motion was closer to that of the physical world.

> RQ1. Will there be a difference in total number of balloons popped (using arms and legs combined) between the three conditions?

Finally, we examined the concept of presence—the subjective experience of “being there”—as it relates to these novel bodies, to see if it was necessary for a person to consciously feel embodied, or present, in order to perform well in a virtual body. Presence is frequently divided into the interdependent categories of environmental (or spatial) presence, social presence, and self-presence (Lee, 2004; Ratan, 2012). In this experiment, only self and environmental presence were relevant as there were no other social actors in the scene. We based five self-presence questions on Ratan’s concept of “proto-self presence” or “using a virtual object as if it is an extension of the body” in order to investigate possible effects on self-presence of having a novel avatar body. In contrast, we did not expect to see differences in environmental presence since the environment remained the same across conditions. We adapted a second 5-item scale to measure environmental presence from Bailenson and colleagues (2004). See appendix.

RQ2. Will there be a difference in reported self-presence or environmental presence between the three conditions?

Methods and Materials

In this between-subjects design, participants were randomly assigned to one of three conditions: Normal (n=17, 6 males), Switched (n=17, 6 males), and Extended (n=19, 8 males). The 53 participants were undergraduate and graduate students from a midsized North American university. All received class credit for participation and gave informed consent. The experiment was approved by the university’s institutional review board.

Apparatus.

Each participant wore an nVisor SX111 head-mounted display (NVIS, Reston, VA) which provided stereoscopic images with a resolution of 2056 x 1024, a refresh rate of 60 frames per second per screen and a diagonal field of view of 111 degrees. The virtual environment was generated and programmed using Worldviz Vizard. An orientation sensor (Intersense3 Cube) tracked the pitch, yaw, and roll of the head, and an optical system (Worldviz PPTH) tracked an infrared marker for the X, Y, and Z position of the head. Similar trackers were worn on the two wrists, and the two ankles, as depicted in Figure 2. Elbow and knees were not tracked, and we chose not to implement inverse kinematics, so the avatars’ elbows and knees did not bend. In addition, we did not track rotation of either the hands or the feet (just translation). Participants were thus instructed to keep their arms and legs straight. Total latency for movements was 40 milliseconds. Head orientation was updated at 180 Hz and was recorded with an accuracy of 1° yaw and 0.25° pitch and roll. The five position trackers were updated at up to 175 Hz, capturing movement with an accuracy of .25 mm over a 3-cubic-meter volume. Participants also received spatialized audio feedback when interacting with stimuli in the environment, provided by a 24-channel Ambisonic Auralizer Sound System.

Procedure.

Participants were positioned in the center of the main lab room, which was 6.0 meters by 5.5 meters. Before the task began, participants received approximately 2 minutes of instruction on controlling their avatars’ limbs, lifting and rotating them in front of a virtual mirror. Avatar gender was matched to participant gender, and scaled to participant height, but were not otherwise customized. All avatars were silver-colored and undetailed. Figure 1 (bottom) shows both the female (left side) and male (right side) avatars as they were seen in the virtual mirror. At the end of the practice session, the virtual mirror was turned off, and participants were only able to see their avatar’s arms and legs from the first-person perspective. The balloon-popping task lasted ten minutes. A sequence of balloons was programmed to

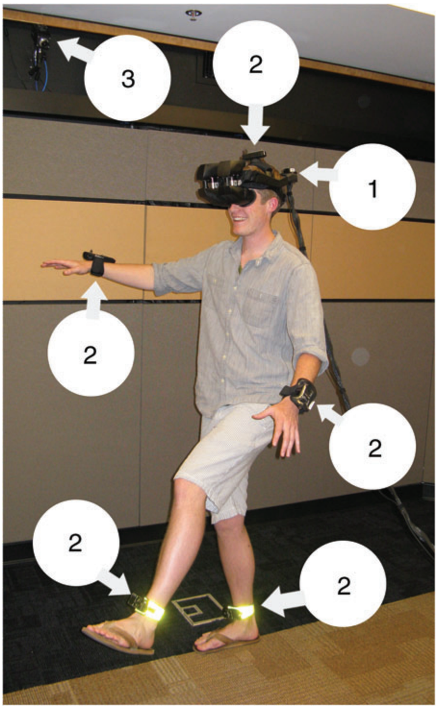

Figure 2 1. = intersense cube, tracking pitch, yaw and roll. 2 = trackers. 3= camera tracking position of infrared lights.

appear in the center of the room in front of the participant; they appeared randomly, in a 4-foot-wide plane scaled to the upper limits of the participant's reach. If a participant hit a balloon with a virtual hand or foot, audio feedback was provided in the form of a loud "pop." If a balloon were not popped within 5 seconds, it would disappear silently. After the balloon-popping task and removal of the HMD and tracking devices, participants completed a questionnaire on self- and environmental presence.

Measures.

During each trial, the time, location, and identification number of each balloon popped were automatically recorded, and the total number of balloon pops, by limb, was also automatically recorded. The range of balloons popped across participants was between 151 and 537, with a mean of 373.6 (*SD* = 86.0).

The 10 presence measures were (See appendix) averaged into two groups to provide an environmental measure and a self-presence measure for each condition. To increase reliability, we removed one item from the environmental presence questions, "To what extent did you feel that 'I felt like I could really touch the balloons in the virtual world'" which raised Cronbach's alpha to .74. The mean for the four averaged environmental presence measures was 3.3 (*SD* =.71). The mean for the five averaged self-presence measures (Cronbach's alpha .79) was 2.8 (*SD* =.71).

Results and Discussion

Table 1 reports the means and standard deviations of the total number of balloons popped as well as the percentage of balloons popped using participants' physical legs. In order to compare leg use across

Table 1 Experiment 1: Means of balloons popped by each limb by condition (SD in parentheses)

Condition	Balloons popped by hands	Balloons popped by feet	Total balloons popped	Percentage of balloons popped by feet
Normal (n 17)	273.71 (42.60)	113.59 (49.84)	387.29 (77.02)	28.45 (7.14)
Switched (n 17)	175.94 (68.15)	142.65 (68.69)	318.59 (91.44)	44.77 (18.44)
Extended (n 19)	166.00 (78.29)	241.25(91.20)	407.25 (66.34)	58.27 (19.58)

conditions, we used a general linear model with condition as a between-subjects variable and percentage of balloons popped by feet as the dependent variable. As illustrated in Table 1, Hypothesis 1 was confirmed, showing a main effect of condition on the percentage of balloons popped by participants' feet ($F\ (2, 51) = 14.13$, $p < 0.001$, $\eta p^2 = .36$). Participants used their feet a higher percentage of the time in the switched and extended conditions than in the normal condition, supporting the hypothesis that they had changed their behavior according to condition. Post hoc tests using Tukey's LSD indicated all conditions were different from each another at an alpha level of .05.

We next ran a general linear model with condition as a between-subjects variable and total balloons popped overall as the dependent variable. There was a main effect of condition ($F\ (2, 51) = 6.1$, $p = 0.004$, $\eta p^2 = .20$) such that fewer balloons were popped in the Switched condition than in either the Normal or Extended conditions. Post hoc tests using Tukey's LSD indicated the Switched condition was significantly different from the Extended condition and the Normal condition ($p < .05$), popping fewer balloons. However, Normal and Extended conditions did not differ significantly from each other ($p = .73$). Hence, in regards to Research Question 1: participants in the Extended condition completed the task as well as participants in the Normal condition, but the performance of participants in the Switched condition was impaired.

Self-presence and environmental presence questionnaires were administered after participants were removed from the HMD and adjusted for reliability as described in Measures. To increase reliability, we removed one item from the environmental presence questions, "To what extent did you feel that 'I felt like I could really touch the balloons in the virtual world'" which raised Cronbach's alpha to .74. The mean for the four averaged environmental presence measures was 3.3 ($SD = .71$). No significant difference was found between conditions for self-presence ($F(2,51) =. 86$ $p = .43$, $\eta p^2 = .03$), or for environmental presence ($F(2,50 = .01$, $p = .99$, $\eta p2 = .001$).

Our findings in Experiment 1 demonstrated that participants were able to adapt to "flexible" conditions in less than 10 minutes, changing the way they moved their bodies in the physical world to adapt to novel avatar bodies. However, the experimental design did not allow us to examine whether participants could do *better* in a nonhuman body, compared to a typical one. Participants could only pop balloons with one leg, since they had to stand on the other. In addition, while the relationship between tracked and rendered motion was altered in both the Switched and Extended conditions, the avatar body was the same size and shape as a normal human body. In our next experiment we investigated a more radical departure from the normal.

Experiment 2: Adaptation to an Additive Body Schema

To answer the question of whether participants could perform better in a modality that differs from the normal human configuration, we designed a task in which we could compare each participant's performance using a normal configuration to his or her performance using an enhanced avatar with three upper limbs.

We created a task in which all participants needed to touch three target cubes in three arrays. Two of the arrays were at normal arm's-length. The third was about one meter in front of the participant. There were two experimental conditions. In the Normal condition, participants could reach the targets in the front two arrays with their avatars' right and left hands, but had to take a step forward to hit a target in the more distant array with one of their two arms. In the Third Limb condition, participants could reach the targets in the front two arrays with their avatars' right and left hands, as in the normal condition, but also controlled a longer third limb, which allowed them to hit the most distant target array without having to step forward. Thus, participants should surpass their performance in the Normal condition using this appendage.

> H2. We predicted a main effect of condition, such that participants could hit more targets using the enhanced avatar with the third limb than they could using the normal avatar.
>
> We also examined time, asking how fast participants could adapt to an additive body schema.
>
> H3. We predicted an interaction between condition and the linear effect of time, such that the advantage for the third limb (compared to the normal avatar) would emerge toward the end of the session, as people learned to accommodate to the new avatar body.

Methods and Materials

Experiment 2 had a within-subjects design in which participants were randomly assigned to begin with one of two conditions. Nine participated in the "Normal" condition first and 11 participated in the "Third-Limb" condition first. All participants gave informed consent and received class credit for participation, and the study was approved by the institutional IRB. The 20 participants (10 female, 10 male) were undergraduate and graduate students from a midsized university in the United States. Each participant was matched by gender to either a male or female avatar, scaled to their height, similar to those described in Experiment 1.

Apparatus.

All apparatus was the same as described, with the following exception. In the Third Limb condition, position of participants' physical arms controlled the position of their avatars' arms, using the optical trackers attached to the wrists, as described above. However, participants also controlled a third, longer limb that extended from the middle of their chests by rotating their wrists. Rotation was tracked using two extra Intersense orientation trackers (in addition to the one attached to the HMD for head orientation) on each hand, such that rotation of the participant's right hand moved the third limb up and down on the X axis, while rotation of the left hand moved the third limb back and forth on the Y axis (see Figure 3, top). This method was chosen so that the third limb's movement was orthogonal to the translation of the left and right arms.

Procedure.

Participants were again positioned near the center of the main lab room. Before the task began, participants received approximately 2 minutes of instruction on moving their avatars' limbs, lifting and rotating them in front of a virtual mirror. At the end of the practice session, the virtual mirror was turned off, and as before, participants were only able to see their avatar's arms and legs when they entered their field of view (Figure 3, bottom left).

Each target-hitting task lasted 5 minutes. Participants were presented with three stationary arrays (Figure 3, bottom right). One target cube in each of the three arrays was white; participants were

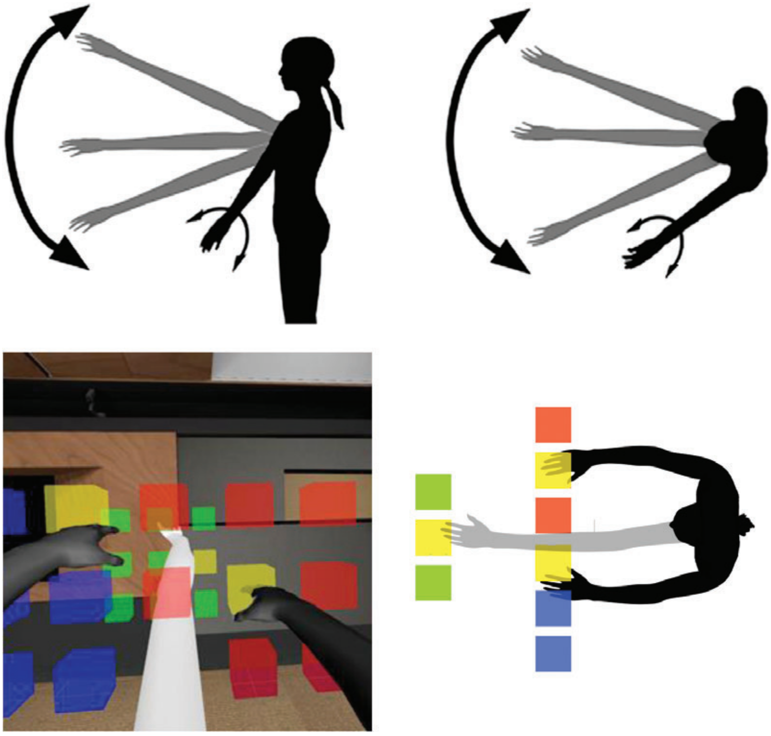

Figure 3 The top panel shows the control system for the “third limb” condition. The black figure represents the real life tracked movements of the participants, and the gray figure represents the corresponding rendering of the avatar. As can be seen, rotation of the participant’s right hand resulted in the third, “avatar” limb moving up and down in the X axis, while rotation of the participant’s left hand resulted in the third limb moving back and forth in the Y axis. In the bottom panel, the left side shows a participant’s POV during the target-hitting task. In this example, the white “third limb” is visible, as well as the two silver avatar arms. The right side of the bottom panel shows a schematic of the three arrays of cubes that appeared in front of each participant. The blue array appeared on participants’ left, the red array on participants’ right, and the green array was approximately 18’ beyond the first two arrays. The target in each array initially appeared as white, and turned yellow after it was successfully hit. When all three target cubes in each array had been hit, participants heard a second tone and a new set of targets appeared.

instructed to hit the white cube in each array with a hand. Targets could be hit in any order, and when a participant successfully hit a target cube, a tone sounded, and that target cube turned from white to yellow. Once all three targets had been hit, a second tone sounded, and a new set of targets lit up.

In the normal condition, participants had to move forward one step to hit the target cubes in the third array. In the third-limb condition, they reached it while standing still by rotating their wrists to use the third limb. The third limb could only hit targets in the back array, while the other two limbs could hit targets in any of the three arrays.

After the target-hitting task, the HMD and the rotation-tracking devices (if in the third-limb condition) were removed, the wrist-tracking devices were turned off, and participants completed a brief questionnaire on self and environmental presence in another room. Participants then re-entered the main lab room and repeated the target-hitting task in the other condition, completing a second questionnaire at the end of the experiment.

Measures.

During each of the 5-minute sessions, we recorded each time that a trial was completed (a trial was considered to be completed when a participant hit all three targets), and defined the dependent variable “Score” as the total number of trials completed. Participants scored between 31 and 106 completed sets per session, with a mean of 62.8 ($SD = 19.0$). In addition, we created an independent variable called “Time” by segmenting the session into ten 30-second chunks.

The 10 presence measures were (See appendix) again averaged into two groups. The mean for the five averaged environmental presence measures (Cronbach’s alpha .83) was 3.21 ($SD = .75$). To increase reliability, we removed one item from the self-presence questions, “To what extent did you feel that ‘I was in the avatar’s body.’” The mean for the remaining four averaged self-presence measures (Cronbach’s alpha .81) was 2.38 ($SD = .60$).

Results

We used a general linear model, with condition and time as repeated measures factors, condition “Order” (either normal first or third limb first) as a between subjects factor, and score as the dependent variable. H2 was supported, with a significant main effect of condition ($F(1,18) = 4.36$, $p = .05$, $\eta p^2 = .20$) on score, such that participants completed more trials using the avatar with a third limb than the normal avatar. H3 was also supported; there was a significant interaction between condition and the linear component of time ($F(1,18) = 12.52$, $p = 0.002$, $\eta p^2 = .41$). As shown in Figure 4, participants were initially slow to hit the targets using the third limb but improved over time at a rate higher than the normal condition. Both conditions showed a significant main effect of Time on Score, as skill at the task increased; ($F(1,18) = 47.78$, $p < 0.001$, $\eta p^2 = .73$). However, a t-test showed no significant difference between conditions at Time 1 (.5 seconds, $t = 1.29$, $p = 0.21$) or Time 2 (1 minute, $t = 1.20$, $p = 0.24$).

There was no significant main effect of condition order on score ($F(1,18) = 1.62$, $p = .69$, $\eta p^2 = .01$), or any significant interaction of condition order and condition ($F(1,18) = 1.72$, $p = .21$, $\eta p^2 = .09$), or of condition, time, and order effects ($F(1,18) = .68$, $p = .42$, $\eta p^2 = .04$).

As in the first experiment, self-presence and environmental presence questionnaires were administered post-task and adjusted for reliability, and no significant effects of condition on either presence measure were found (self-presence $F(1,18) = 2.65$, $p = 0.15$, $\eta p^2 = .12$; environmental presence ($F(1,18) = .67$, $p = 0.43$, $\eta p^2 = .03$)). While one should not draw conclusions from a null result, the lack of significant differences in this condition was somewhat surprising given that the avatar with the long third limb looked radically different from the avatar in the normal condition. The fact that neither avatar looked particularly realistic or personal (both being a silver gray and low detail) may partially account for the lack of difference. However, this may also highlight differences between using an avatar body as a tool, and feeling of a sense of ownership of that avatar body.

General Discussion

In Experiment 1, we found that participants changed the way they moved in real life within 10 minutes—using their legs more than they did in a control condition—in order to use their avatar body most effectively to pop virtual balloons. In Experiment 2, we found that, when compared to

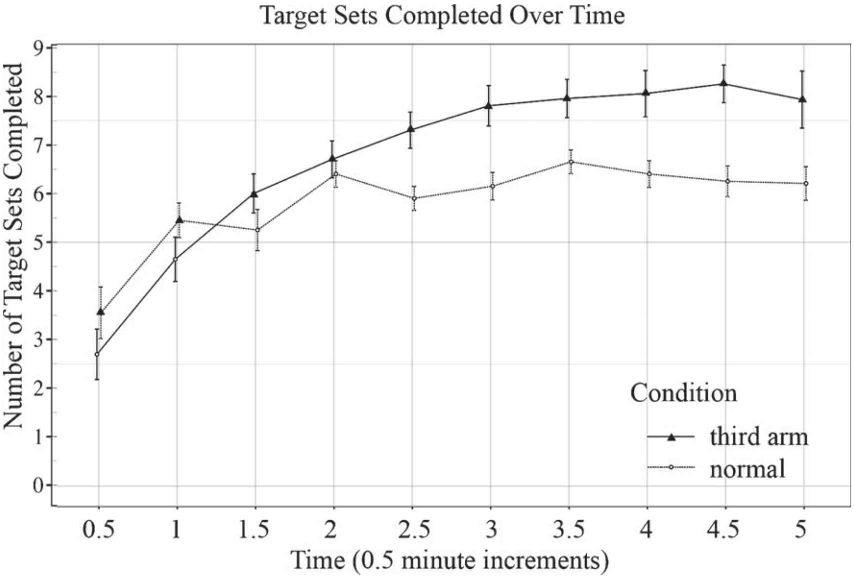

Figure 4 Each shape indicates the mean score of sets of targets that were completed in each .5 minute increment. The line marked by circles represents the mean scores of participants in the third-limb conditions, while the line marked by triangles represents the mean scores of participants in the normal condition. Error bars represent one standard error.

performance in a "normal" avatar body (with the ability to step forward, and two avatar arms that were controlled by the participant's two physical arms), participants could hit more targets using an avatar with three upper limbs, which allowed greater reach with less physical movement. This was true even though motions mapped from the participants' tracked movements were rendered in a different modality (rotation of the wrist moved the avatar's third limb in arcs corresponding to pitch and yaw). Use of more intuitive mappings might enable even faster adaptation and greater success. These initial experiments confirmed that people could rapidly learn to use a novel body and succeed in that body compared to a more "normal" configuration, even when the body schema differs radically from that of the user's own body.

Limitations

Presence measures in both experiments did not reveal a significant difference between conditions. This is somewhat surprising, considering the bizarre appearance of the three-limbed avatar in particular. One possibility, since the presence scores were low overall, is that none of the conditions engendered a greater feeling of ownership since the neutral, silver gray avatar design we used for all participants did not look particularly realistic. Also, since elbow and knee joints were not tracked, the avatar's movement in the Normal conditions was also not completely realistic. While we cannot argue from this null result, the lack of huge differences in self-presence between conditions is encouraging for those who seek to implement nonhuman avatars.

An alternative explanation is based on earlier work involving constructs of presence (Haans & Ijsselsteijn, 2012; Ratan, 2012). This work implies that controlling a novel avatar to complete a task, or altering body schema, is a qualitatively different construct from that of body transfer—altering body image, or the feeling that the body of the avatar belongs to the user. This relates to the definition, by Lombard and colleagues (2000) of presence as “the perceptual illusion of non-mediation.” When the participant is fluently using the avatar body as a tool, they may be immersed in the task, and thus less aware of—perceiving less consciously—their virtual surroundings. Thus, the most relevant analogy to the sense of being embodied in the avatar in these experiments may not be the sensation of “being” the avatar, but the ability to fluently *control* the avatar, which may not be captured by the presence questions in our survey. Referencing the avatar’s body may thus have been misleading. Comparing presence in virtual reality to other media is also useful. A study looking at novels found changes in the sensorimotor cortex of readers who identified with the protagonist in the novel (Berns, Blaine, Prietula, & Pye, 2013). Although this medium is quite removed from immersive virtual reality, it is still relevant because it demonstrates that embodiment may be a factor in even nonimmersive media.

Another issue is that when comparing the performance of participants in the normal and third-limb conditions, no statistically significant difference in success was found at time zero. However, any difference in difficulty may have been masked by the initial adjustment to virtual reality and the environment in which the task was to be completed.

Future Directions

Our results demonstrate that people are able to rapidly learn to control novel avatars when provided with sufficient feedback. However, important questions remain. First, what affordances are required for people to use a novel body to effectively interact with the environment? While virtual environments necessarily provide only a fraction of the sensory richness of the real world, the virtual environment in which we conducted these experiments provided feedback in several modalities. Participants received both audio and stereo visual feedback at very high resolution, but people may be capable of adapting to much sparser environments over time.

Second, how should the self and its extensions be represented in mediated environments? Avatars in this study were loosely based on the human body, but this may not be necessary, and may even be a handicap. Biological realism, which has been shown to be important in establishing a sense of ownership (Maselli & Slater, 2013; Tsakiris, Carpenter, James, & Fotopoulou, 2010), may aid in user identification with an avatar, and thus task success. Alternatively, it may be confusing because such realism may reinforce the user’s desire to move as he or she would in the physical world. Whether appendages should appear to extend directly from the body—rather than float or be detached, which has been shown to be important in work on tool incorporation (Pegna et al., 2001; Longo & Lourenco, 2006)—is another question to be investigated.

A third issue is that every instance of modification alters the natural affordances and constraints of the body. For example, adding a longer third limb to a humanoid avatar, as in Experiment Two, makes the targets of such a limb appear smaller, but the distance also makes it possible for the user to keep a larger array in his or her field of view. This, of course, is not only true for bodies intentionally created to be novel, but for all avatars that offer up a perceptibly mediated version of the body. Thus, the effects of “necessary” transformations, which occur simply because the body has more degrees of freedom than can be tracked with technology, should perhaps be considered separately from the effects of “strategic” transformations that are qualitatively different from the human body (e.g., having a third arm).

Fourth, how far can we push these adaptations? Can people learn to control eight limbs, or kilometer-long arms, as Lanier demonstrated anecdotally decades ago? What kind of avatar bodies will participants willingly inhabit, in the short or long term? And what kind of avatar bodies will inspire people to extra effort? This paper describes instances of *ipsimodal remapping*, or changes within a single channel of interaction, in this case, physical movement. However, other transformations are possible.

S*ensory substitution* creates a remapping between two different sensory modalities. For example, tracked visual information may be rendered as tactile stimuli, or auditory signals may be rendered visually (Bach-y-Rita & W Kercel, 2003). Another organizational scheme is *para-synthetic expression*, or a remapping of tracked input of which the interactant may not be aware (such as psychological arousal or heart rate) as easily observable renderings (Janssen, Bailenson, Ijsselsteijn, & Westerink, 2010).

Most importantly, what are the effects of "flexible" mapping on non-physical tasks? If we allow people to control their media environment by mapping more degrees of freedom from their physical bodies, do we reduce or increase the effects of multi-tasking and distraction? If people are having mediated experiences in more embodied ways, how does this affect their interactions with others? How users with such extended capabilities may interact with each other is an important question for computer-mediated communication. Much research has established that gestures, facial expressions, tone of voice, and other nonverbal behaviors impact moods, thoughts, intentions and desires, often very rapidly (Burgoon, Guerrero & Floyd, 2010; Ambady & Rosenthal, 1993). Although the affordances differ, nonverbal communication also impacts these processes in mediated environments, even those with very sparse cues (Walther, 2007). The investigation of how humans look for cues from mediated representation has led to extensive research on the effects of avatar representation and behavior in these interactions (Nowak & Rauh, 2005; Bente, Eschenburg, & Krämer, 2007; Bailenson, Yee, Merget, & Schroeder, 2006). How will users understand interactions in such novel bodies? As major social media corporations invest in VR technology, the question of how users' senses of self are affected by the way they interact with virtual environments becomes ever more important.

Embracing the concept of homuncular flexibility may allow greater control of space in mediated environments, allow users to organize information more efficiently, and use more of their body to navigate virtual worlds. The augmented abilities provided by VR and augmented reality interfaces are sometimes thought of in terms of external entities and affordances that can assist the user (Broll, Shafer, Hollerer, & Bowman, 2001). However, a better metaphor might be that of the user herself becoming a more powerful entity, in a rich and responsive environment.

Leveraging these opportunities will require further investigation of the phenomenon of self-representation in mediated environments. The notion of homuncular flexibility is one that has been percolating for decades (see Lanier, 2006, for a brief discussion), but recent technological advancements are bringing the construct to the forefront of research that examines computer science, neuroscience, psychology, and biology through media. As technology continues to push the boundaries of how humans may be embodied in virtual reality, we gain opportunities to learn how we understand our bodies through action and experience.

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Appendix 1

Experiment 1

Questions: 1. Not at all 2. Slightly 3. Moderately 4. Strongly 5. Very strongly)	Normal Condition		Switched Condition		Extended Condition	
To what extent did you feel that …	Mean	SD	Mean	SD	Mean	SD
If something happened to the avatar, it was happening to me.	3.00	0.94	2.71	0.77	2.95	0.78
The avatar's body was my own body.	2.88	0.93	2.44	1.09	2.84	0.96
I was in the avatar's body.	2.71	0.92	2.88	1.11	3.17	0.97
The avatar was an extension of me.	3.24	0.75	2.71	0.92	3.11	1.10
The avatar was me.	2.65	1.06	2.24	1.03	2.11	0.99
I was really inside the virtual lab	3.24	0.97	3.41	1.00	3.53	0.90
I felt surrounded by the virtual lab	3.41	0.87	3.53	1.07	3.32	1.00
I really visited the virtual lab	3.41	1.12	3.41	0.87	3.53	1.07
The virtual lab seemed like the real world.	2.88	0.78	2.70	1.03	2.74	0.87
I felt like I could really touch the balloons in the virtual lab.	2.71	0.85	2.66	1.29	2.79	0.98

Experiment 2

Questions: (1.Not at all 2. Slightly 3. Moderately 4. Strongly 5. Very strongly)	Normal Condition		Third Limb Condition	
To what extent did you feel that …	Mean	SD	Mean	SD
If something happened to the avatar, it was happening to me.	2.95	0.94	2.95	1.05
The avatar's body was my own body.	3.05	0.89	2.85	0.99
I was in the avatar's body.	2.94	0.96	2.90	0.97
The avatar was an extension of me.	3.50	1.10	3.25	1.33
The avatar was me.	2.40	1.05	2.15	1.04
I was really inside the virtual lab	3.75	0.79	3.55	0.94
I felt surrounded by the virtual lab	3.55	0.94	3.45	1.10
I really visited the virtual lab	3.50	0.95	3.25	1.21
The virtual lab seemed like the real world.	2.55	1.28	2.59	1.34
I felt like I could really touch the cubes in the virtual lab.	3.30	0.98	3.40	1.04