# Effects of Likeness and Synchronicity on the Ownership Illusion over a Moving Virtual Robotic Arm and Hand

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## I. Abstract

In this study we investigated body ownership over a virtual hand and arm as a function of their visual appearance (likeness) and synchronicity of visuo-tactile stimulation with a virtual electric toothbrush and a vibrotactile glove. In all conditions, participants controlled the movement of arm and fingers, maintaining synchronicity in motor-proprioceptive-visual signals. While the effects of varying likeness and temporal synchronicity of visual and haptic stimuli on the ownership illusion have both been investigated individually before, their relative contribution is still unknown. We find that likeness should be complete: making only the hand robotic reduces the subjective ownership illusion to same level as that of a full robotic arm and hand. Visuo-tactile synchronicity is not a hard prerequisite for an ownership illusion to occur: a high degree of agency with congruent motor-proprioceptive-visual cues and an arm/hand layout similar to one's own body can be sufficiently strong to overrule incongruent visuo-tactile cues. This work is part of a larger study on the relative contribution of factors such as likeness, viewing mode, tactile stimulation and degree of agency on the body ownership illusion. The results may contribute to the enhancement of dexterous performance in remote telemanipulation tasks.

## II. Introduction

Ownership over a robotic or prosthetic hand can increase dexterous performance [1], [2], [3]. We are interested in exploring ownership as a mediating factor for task performance in telerobotics. Telerobotics [4] aims to replicate human manipulative skills and dexterity at a remote workplace over an arbitrary distance and at an arbitrary scale. Despite the increasing availability and capability envelope of autonomous systems, robots that are remotely controlled by humans still remain a key technology for operations in inaccessible areas (e.g. in space or undersea applications) or in complex, unpredictable or hazardous conditions with a high degree of uncertainty, such as minimally invasive surgery, search and rescue operations, disaster response or explosive ordnance disposal [5]. To improve performance and reduce workload, we follow a telepresence approach, referring to the phenomenon of behaving and feeling as if one is present in the virtual or remote world (e.g. [6]). We hypothesize that telepresence interfaces allow operators to intuitively employ their full psycho-motor capabilities for many tasks that would otherwise put heavy demands on their limited cognitive resources. This shift from the cognitive to the psycho-motor level is expected to reduce workload and increase performance and situational awareness [7], [8]. A telepresence approach goes beyond vision and audition and includes dexterous telemanipulation.

Ideally, telemanipulation should feel as natural and intuitive as possible. To afford a flawless and seamless operation, a telerobotic system should therefore be fully transparent, so that the user forgets about the fact that the operation is mediated. However, limitations of the human-machine interface, the communication channel and the robotic device can cause the control signals transferred via the multi-sensory (e.g. visual, auditory, haptic) feedback to the human operator to be delayed, out of sync, and of reduced quality and resolution compared to unmediated (direct) interaction [4]. This degraded interaction quality can reduce task performance, and/or increase the cognitive workload of the human operator, possibly resulting in the need for extensive training.

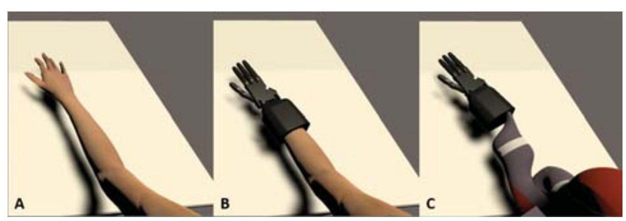


Fig. 1. The virtual arm models used: A) Human arm and hand (BlocBros Studio, Sweden) B) Human arm and robot hand (Shadow Hand-Lite, Shadow Robot Company, London, UK) C) Robot arm (LBR iiwa, KUKA Robotics, Augsburg, Germany) with a robot hand.

### A. *Factors influencing ownership over a robotic hand*

To investigate the mediating effect of ownership over a robotic hand on telemanipulation performance, we need to verify several underlying assumptions. The three most important ones are: (1) humans can incorporate non-bodily objects (tools) into their body schema (2) an ownership illusion can be evoked by mediated haptic and motor interaction and (3) an ownership illusion can be evoked by mediated viewing. Building upon the classic rubber hand illusion [9], numerous studies have investigated the key factors for an ownership illusion to occur. An important finding is that it is indeed possible to induce a strong sensation of ownership over

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extracorporeal objects such as fake limbs and robotic hands and arms, mannequins and virtual bodies and even empty volumes of space and invisible bodies (e.g., [10], [11], [12], [13]). However, there is still a vivid debate going on about the relative importance of for instance visuo-tactile synchronicity and visual-motor synchronicity (for a review see [14]), and in what way texture [15], size [16], orientation [17], continuity [18], and viewing mode (direct view, VR and AR: [19]) modulate the strength of the illusion. While there is an extensive body of literature on the effects of each of these single factors on the ownership illusion, their relative contribution when combined is still unknown. More specifically, the viewing modality (direct view, camera view, virtual or augmented reality), and the role of visual-motor-proprioceptive-tactile synchronicity has not been systematically investigated, the latter requiring active movement of hands and fingers.

In this paper, we investigate the effects of (1) likeness (to what extent does the controlled arm/hand look like a human arm/hand) and (2) mediated visuo-tactile synchronicity in a setting in which the operator can actively control the virtual arm/hand while visual-motor-proprioceptive synchronicity is maintained. We expect (1) that body ownership effects occur for all levels of likeness but will decrease if the likeness becomes smaller, and (2) that visuo-tactile synchronicity will positively affect ownership, but that it is not necessary for ownership to occur as visual-motor-proprioceptive synchronicity is maintained in all conditions.

## III. METHOD

### A. Participants

Ten paid volunteers participated (four male, mean age 32.2 years SD 9.3, hand length between 15,5 cm and 18 cm). All participants had limited to no gaming or virtual reality experience. The study was approved by the TNO Internal Review Board. All participants received oral and written information about the experimental procedures and provided written informed consent.

Participants were invited using the following inclusion criteria: skin colour similar to the rubber hand (Caucasian), age 18-50 years, no glasses, right-handedness, and a maximum hand length of 20 cm. Exclusion criteria were exceptional sensitivity to motion sickness, gaming experience (in virtual reality more than once a month or generally more than 8 hours per week), and obvious properties by which the right arm or hand can be uniquely identified (e.g. prostheses, tattoos, scars).

### B. Apparatus

The VR worlds contained 3D models of a table, an arm, and an electric toothbrush. All three VR environments were modelled in a commercial game engine (Unity, Unity Technologies, San Francisco, USA) using standard VR software (SteamVR, Valve Corporation, Bellevue, USA) and displayed in a HTC Vive headset (HTC Vive, HTC Corporation, New Taipei City, Taiwan). The environments were calibrated to display the table at the same height as the real table in front of the participant. Participants' finger movements were tracked with a hand exoskeleton (Dexmo Hand Exoskeleton, Dexta Robotics, Shenzhen, PRC) [20] and their arm movements with a HTC Vive tracker connected to the ulnar side of the hand. Both measurements were updated with a 60Hz sample rate. These movements were mapped to the virtual hand and fingers (via the hand model provided by Dexta Robotics) and arm (via inverse kinematics (Limb IK, RootMotion, Tartu, Estonia)). In the virtual world, three different arm variants were used, with a varying degree of likeness to a human arm. Figure 1: (A) a human arm and hand, (B) human arm with a robot hand attached, and (C) a robot arm with a robot hand. The VR setup was calibrated to position the shoulder of the virtual arm on the shoulder of the participant based on the location of the worn HTC Vive headset.

Fig. 2. A participant in the setup, just before performing the pointing task.

We introduce a novel vibratory visuo-tactile stimulus. The visual part of the stimulus was realized with a floating model of an electronic toothbrush (Oral-B, Proctor & Gamble Corporation, Cincinnati, USA) controlled using a HTC Vive Controller. The vibrations were rendered with a vibrotactile glove (Elitac, Utrecht, NL) consisting of 16 vibration actuators (pancake motors), of which four (situated on the back of the proximal phalanges of the four fingers) were used. The vibrotactile glove stimulus was presented either manually by the experimenter (in asynchronous mode), or automated based on collisions between the VR model of the fingers and the toothbrush model (in synchronous mode). In the asynchronous treatments, the experimenter controlled the vibrotactile glove using a laptop keyboard, providing a stimulus that did not match the actual collisions. Earlier pilot experiments showed that when the asynchronous stimulus was automated, and a constant delay was introduced, participants would compensate by waiting for the stimulus to occur before breaking contact again.

### C. Design

The experimental design consisted of two independent variables: likeness ('human arm and hand', 'human arm and robot hand', 'robot arm and hand') and visuo-haptic stimulus synchronicity (synchronous, asynchronous). All participants

TABLE I

STATEMENTS PRESENTED TO THE PARTICIPANTS AFTER EVERY CONDITION.

| | | |
|---|---|---|
| Ownership | 1 | I felt as if I was looking at my own hand |
| | 2 | I felt as if the rubber/robot hand was part of my body |
| | 3 | I felt as if the rubber/robot hand was my hand |
| Ownership control | 4 | It seemed as if I had more than one right hand |
| | 5 | It felt as if I no longer had a right hand, as if my right hand disappeared |
| | 6 | It felt as if my real hand was turning rubbery/robotic |
| Agency | 7 | The rubber/robot hand moved like I wanted it to, like it obeyed my will |
| | 8 | When I moved my finger, the rubber/robot hand moved in the same manner |
| | 9 | I felt as if I controlled the movements of the rubber hand |
| Agency control | 10 | It felt as if the rubber/robot hand was controlling my will |
| | 11 | It felt as if the rubber/robot hand was controlling my movements |
| | 12 | It seemed as if the rubber/robot hand had a will of its own |

performed all six conditions. After each condition, the proprioceptive drift was measured and a 12-item questionnaire on agency and ownership (Table I) was verbally graded by the participants on a 7-point Likert scale ranging from "strongly disagree" (-3) to "strongly agree" (+3) [21], [22]. The questionnaire contains items relating to the expected ownership and agency effects, and control items to rule out compliance, suggestibility and possible placebo effects. The questionnaire has been adapted to refer to a robot hand where applicable, and was translated to the participants' mother tongue (Dutch). The dependent variables were proprioceptive drift (proprioception of the right arm was measured before and after each treatment through a pointing task, the drift being the difference between the two) and the compound scores for ownership, agency and ownership control and agency control questions. Each of the dependent variables was analysed with a separate likeness (3) x synchronicity (2) repeated measures ANOVA and post-hoc tests were applied where appropriate. A one-sample t-test compared to '0' was performed to assess proprioceptive drift results. All statistical analyses were performed using SPSS (version 18, SPSS, Chicago, IL).

### D. Procedure

The participants underwent the six conditions as described above as part of a larger study distributed over four sessions on two distinct days. Each day contained two sessions with a 45 minute break in between, each session consisting of 7 conditions, which included the conditions described in this paper.

Participants were seated at a table, and after putting on the vibrotactile and tracking gloves, were asked to lay their right arm on an indicated position on the table. A VR headset showing an empty world was put on. Participants were then asked to indicate the position of their right hand with their left index finger on a proprioception measurement board (Figure 2) placed above the hand and arm. After returning their left arm to the resting position in their lap and removing the proprioception measurement board, they were presented with the VR scene containing the table and the right arm with the hand. The virtual right hand was initialized 25 cm to the left of the participants' real arm; this shift was maintained during tracking. This distance was based on the participants' head position, and was mechanically plausable. Participants were instructed to look at their virtual right hand, and were invited to move their right arm and fingers at will. While monitoring the movements on a computer screen, the experimenter held the electric toothbrush model 10 cm above the virtual hand and participants were instructed to lightly touch it with the top of their fingers.

After one minute, the participants were asked to return their right arm to the initial position, close their eyes, and to indicate the position of their right arm on the proprioception measurement board again. Finally, they verbally answered the 12 questionnaire items (Table I). The VR headset was removed and the participants were instructed to look at, move, and relax their arms for a short while. The procedure was repeated for the other conditions. The order of the conditions was unique per participant and balanced between sessions.

## IV. RESULTS

Table II presents the results on all five dependent variables. The 3x2 ANOVA on the proprioceptive drift and agency questions did not reveal significant effects. For the proprioceptive drift, we analysed whether the scores for the three levels of likeness differed significantly from 0. All three levels did: human arm and hand: $t(21) = 3.35 p = 0.003$, human arm/robot hand: $t(21) = 2.62, p = 0.016$ and the robot arm and hand: $t(19) = 2.19, p = 0.041$ (see Figure 4). The ANOVA on the ownership score showed a significant effect of likeness: $F(2, 18) = 7.84, p < 0.05$; see Figure 3. The post-hoc test revealed a significant difference between 'human arm and hand' and 'human arm and robot hand' ($p < 0.05$), and a trend between 'human arm and hand' and 'robot arm and hand' ($p < 0.09$). The ANOVAs on the control questions revealed no effects for the ownership control questions but a significant interaction between likeness and synchronicity for the agency control questions: $F(2, 18) = 5.87, p < 0.05$. However, the post-hoc test on this interaction revealed no significant differences between any of the six conditions.

TABLE II
RESULTS (MEANS AND STANDARD DEVIATIONS) OF THE EXPERIMENTS.

| Condition | Ownership | Ownership Control | Agency | Agency Control | Proprioceptive Drift [cm] |
|---|---|---|---|---|---|
| 1, synchronous | 0.50 ± 1.89 | -1.50 ± 1.10 | 0.97 ± 1.38 | -0.77 ± 1.47 | 2.70 ± 5.01 |
| 1, asynchronous | 0.57 ± 1.88 | -2.20 ± 0.80 | 1.30 ± 1.75 | -2.00 ± 0.98 | 5.15 ± 5.16 |
| 2, synchronous | -1.20 ± 1.79 | -1.80 ± 0.91 | -0.03 ± 1.82 | -1.50 ± 1.21 | 0.90 ± 3.81 |
| 2, asynchronous | -0.50 ± 1.65 | -1.90 ± 0.92 | 0.67 ± 1.54 | -1.47 ± 1.32 | 2.95 ± 3.18 |
| 3, synchronous | -0.83 ± 1.83 | -1.83 ± 1.06 | 1.07 ± 1.17 | -1.70 ± 1.25 | 1.55 ± 4.37 |
| 3, asynchronous | -0.90 ± 1.52 | -1.97 ± 0.85 | 0.63 ± 2.03 | -1.23 ± 1.56 | 2.00 ± 2.91 |

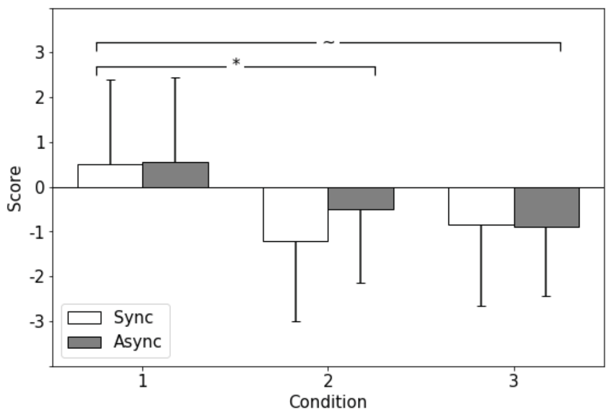


Fig. 3. Means and standard deviations of responses to the ownership questions (1-3). Condition 1 is human hand and arm, condition 2 is robot hand/human arm, condition 3 is robot hand and arm. N=10. $*: p < 0.05$, $\sim: p < 0.1$ between conditions.

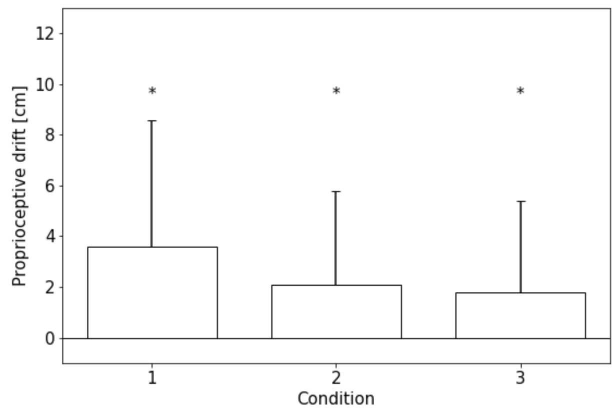


Fig. 4. The graph shows the means and standard deviations for the proprioceptive drift measurements in synchronous and asynchronous conditions combined. Condition 1 is human hand and arm, condition 2 is robot hand/human arm, condition 3 is robot hand and arm. $*$ indicates a significant ($p < 0.05$) difference from 0.

## V. DISCUSSION

In this experiment we investigated body ownership over a virtual hand and arm as function of their visual appearance (referred to as likeness) and synchronicity in visuo-tactile stimulation when the hand touches an electric toothbrush. In all conditions, participants had full control over the movement of the arm and fingers maintaining synchronicity in motor-proprioceptive-visual signals of the motions.

### A. Body ownership

We assessed body ownership through the standard questionnaire and through measuring the proprioceptive drift. We found a significant and substantial proprioceptive drift for all likeness conditions. On average the proprioceptive drift for the human hand and human arm condition was 3.6 cm which is in the range typically reported in the literature (e.g. [23], [24], [25]). The averages of our reported ownership scores vary between -1.20 and +0.57 and are within a similar range reported for (realistic) VR setups (e.g. [26], [27]). In addition, we found no effect or differences between conditions on the control questions, showing that participants were not led by for example compliance when answering the questionnaire. This indicates that our setup was able to evoke an illusion of body ownership and participants provided reliable ratings.

We should note though that the standard errors in both reported ownership and proprioceptive drift were large, indicating large differences between the participants. This may be related to the relative short interaction time of 60 seconds. Although this is enough to evoke for instance a rubber hand illusion (RHI), it is substantially lower than the time used in some other experiments where durations between 1 and 10 minutes are used (e.g. 5 minutes in [28]). A possible countermeasure would be to preselect the participants based on susceptibility to the physical RHI.

### B. Effect of likeness

We found a significant effect of likeness on the ownership questionnaires, but not on the proprioceptive drift. The human arm and hand resulted in higher embodiment scores than the human arm/robot hand and the robot arm and hand conditions. The latter two were not significantly different from each other. This confirms previous research comparing ownership effect for virtual hand illusions showing that the ownership illusion is stronger for a realistic hand compared a hand-like object with lower likeness such as a cat paw [29]. Similarly, likeness experiments using a head-mounted VR display and using agency as main stimulus report larger ownership over a realistic hand compared to an arrow [26], a sphere or a primitive hand [27], or a block, a zombie hand and a cartoon hand [30]. The latter publication, however, found no significant difference in reported ownership between a realistic hand and a robot hand. Contrary to our robot hand, that robot hand has five fingers and a very human anatomy however. Similar to our study, a previous study by Farmer *et al.* [31] also found an effect of likeness on the subjectively reported strength of the induced body-ownership illusion but no effect on proprioceptive drift.

The current results partly confirm our first hypothesis: "body ownership effects occur for all levels of likeness but will decrease if the likeness becomes smaller". Indeed, we found proprioceptive drift for all visual representations, and the subjective ownership scores were highest for the human arm and hand. However, the proprioceptive drift remains high with decreasing likeness and the ownership ratings do not decrease gradually, but rather abruptly. The high proprioceptive drift may be related to the amount of agency participants had over the arm and fingers. This high level of agency was independent of likeness and may have been the critical factor in proprioceptive drift. Regarding the ownership scores, we see that as soon as a single body part is replaced by a robot-like part, ownership scores already sharply decrease with no added effect of replacing additional parts.

### C. Effect of synchronicity

Our second hypothesis was that "visuo-tactile synchronicity will positively affect ownership, but that it is not necessary for ownership to occur as visual-motor-proprioceptive synchronicity is maintained in all conditions". To our surprise, we do not find an effect of visuo-tactile synchronicity at all. This means that visuo-tactile synchronicity is not a hard prerequisite for body ownership to occur, at least not if other cues are available such as the motor-proprioceptive-visual synchrony of arm and finger movements, or that our visuo-tactile stimulus was not adequate.

Vibrotactile stimuli for inducing the RHI have been validated previously [32], [33], [34]. However, (as far as we are aware) we are the first to combine a realistic VR model of a vibrating object with a vibro-tactile glove to present a realistic vibration stimulus in a VR setup. A remotely similar vibration stimulus was used by previously [35] using a vibrotactile glove that vibrated when a virtual balloon was popped by a virtual needle or a virtual ball touched a virtual square. We therefore consider our visuo-tactile stimulus as adequate and consider the data as supportive for the fact that visuo-tactile synchronicity is not a hard prerequisite for body ownership to occur.

Previous studies have also shown that visuo-tactile synchronicity is not required for the body ownership illusion to occur, although it can strengthen the illusion [36], [37]. When a fake body (part) is realistic and overlaps in space with the real body counterpart, a body ownership can even be induced in presence of asynchronous visuo-tactile stimulation [37].

Moreover, visuo-proprioceptive-motor correlations are very efficient in eliciting a body ownership illusion [38], [39], thanks to the rich information processing involved in the sensorimotor control loop. Synchronized movements of real and fake body parts can induce a body ownership illusion even in the absence of visuo-tactile stimulation (e.g. [40], [32], [41], [42], [43]). Using a virtual hand-arm model for visual stimulation in combination with vibrotactile feedback through a data-glove Padilla *et al.* [44] showed that synchronized movements in combination with self-inflicted tactile stimulation (through touching virtual objects) effectively induced a significant body ownership illusion. Visuomotor synchronicity effectively induced ownership over an extended-humanoid avatar in immersive VR [45]. In addition, visuomotor synchronicity between movements of real and virtual hands induced illusions of ownership, proprioceptive drift and agency of virtually presented hands [46], [42]). This is in line with our findings.

### D. Conclusions

- Likeness must be complete – partial robotic likeness reduces the ownership illusion to same level as a full robotic hand and arm, although the proprioceptive drift may be similar.
- Visuo-tactile synchronicity is not a hard prerequisite for an ownership illusion to occur: a high degree of agency with congruent motor-proprioceptive-visual cues and an arm/hand layout that is similar to one's own body in terms of location, orientation, size and likeness can be sufficiently strong to overrule incongruent visuo-tactile cues.

## ACKNOWLEDGMENT

We would like to thank our colleagues Kees van Teeffelen, Kaj Gijsbertse and Anja Langefeld for their help in respectively preparing, performing and analyzing these experiments.

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