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New frontiers in the rubber hand experiment: when a robotic hand becomes one's own

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Abstract The rubber hand illusion is an experimental paradigm in which participants consider a fake hand to be part of their body. This paradigm has been used in many domains of psychology (i.e., research on pain, body ownership, agency) and is of clinical importance. The classic rubber hand paradigm nevertheless suffers from limitations, such as the absence of active motion or the reliance on approximate measurements, which makes strict experimental conditions difficult to obtain. Here, we report on the development of a novel technology—a robotic, user- and computer-controllable hand—that addresses many of the limitations associated with the classic rubber hand paradigm. Because participants can actively control the robotic hand, the device affords higher realism and authenticity. Our robotic hand has a comparatively low cost and opens up novel and innovative methods. In order to validate the robotic hand, we have carried out three experiments. The first two studies were based on previous research using the rubber hand, while the third was specific to the robotic hand. We measured both sense of agency and ownership. Overall, results show that participants experienced a "robotic hand illusion" in the baseline conditions. Furthermore, we also replicated previous results about agency and ownership.

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Keywords Rubber hand illusion · Volition · Self-awareness · Sense of ownership · Sense of agency · Robotic hand

Introduction

In the rubber hand illusion (RHI), cognitive and sensorimotor systems categorize a fake hand as a part of the body. In the seminal study of Botvinick and Cohen (1998), participants look at a realistic rubber hand positioned in such a way that it appears connected to their body: The hand is placed in front of participants (e.g., on a table), at the same height as their real hand could be, and a piece of cloth is used to cover the region extending from the rubber hand's wrist to the participant's shoulder. The participants' real hand is typically positioned immediately under the table upon which the rubber hand lies. The experimenter then synchronously stimulates both the rubber hand and the participant's real hand (now hidden from view) by stroking each repetitively with a paintbrush. After a few minutes of such synchronous tactile and visual stimulation, participants report experiencing the (visible) rubber hand as their (concealed) own hand. Three measures of actual incorporation of the rubber hand in participants' body schema have been reported in the literature. They include (1) proprioceptive drift, a behavioral measurement whereby participants judge the location of their own real hand to be closer in space to the location of the rubber hand after RHI induction (Botvinick & Cohen, 1998); (2) objective physiological measures such as skin conductance (Armel & Ramachandran, 2003), skin temperature (Moseley et al., 2008), visuo-tactile perception (Aspell, Lenggenhager, & Blanke, 2009; Zopf, Savage, & Williams, 2010), heartbeat frequency (Tsakiris, Tajadura-Jiménez, & Costantini, 2011), and histamine reactivity (Barnsley et al., 2011), all of which show strong sensitivity to threatening stimuli (e.g., a hammer or knife) directed toward the rubber hand; and (3) subjective measures, such as questionnaires assessing both the sense of agency and ownership (Botvinick & Cohen, 1998).

A central question is how the illusion actually occurs. Botvinick and Cohen (1998) suggested that the RHI reflects an intermodal bottom-up interaction between vision, touch, and proprioception (i.e., one's own individual perception). The authors suggested that when participants see the tactile stimulation on the rubber hand, they appropriate this stimulation to their own hand. The result is mislocalization toward the fake hand (Tsakiris, 2010). Evidence for necessary bottom-up information in the RHI comes from studies where asynchronous stimulation (Botvinick & Cohen, 1998; Shimada, Fukuda, & Hiraki, 2009) and mismatches between the orientation and position of the fake hand (Costantini & Haggard, 2007; Erhsson, Spence, & Passingham, 2004; Tsakiris, Prabhu, & Haggard, 2005) cancel the RHI.

In addition, top-down information—that is, representation of the body structure—also has an impact on the RHI (Guterstam, Gentille, & Erhsson, 2013). Thus, the RHI fails to take place if noncorporeal objects replace the hand (e.g., Graziano, Cooke, & Taylor, 2000; Tsakiris & Haggard, 2005). However, if the object is hand-shaped, a strong RHI is measured (Haans, Ijsselstreijn, & de Kort, 2008). Furthermore, the RHI is abolished when the rubber hand is placed in an incongruent anatomical position (Costantini & Haggard, 2007)—for instance, when the rubber hand is in the half-space opposite to that occupied by the real hand (Tsakiris & Haggard, 2005) or when the fake hand is placed too far away from the real hand (Lloyd, 2007). Nevertheless, the latter argument is undermined through studies that showed that if the rubber hand is in a plausible anatomical position and positioned in the peripersonal space, the illusion occurs even if the posture of the rubber hand and the posture of the participant's hand are incongruent with each other (Ionta, Sforza, Funtao, & Blanke, 2013; Makin, Holmes, & Ehrsson, 2008; Makin, Holmes, & Zohary, 2007). To summarize, both top-down and bottom-up information are required to induce a strong RHI.

The relationship between agency and ownership has now been studied extensively (e.g. Gallagher, 2000; Tsakiris, Prabhu, & Haggard, 2006; Tsakiris, Schütz-Bosbach, & Gallagher, 2007). Several studies have shed light on the role of active movements in the RHI (e.g., Roessler & Eilan, 2003; Tsakiris & Haggard, 2003; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005; van den Bos & Jeannerod, 2002). Recently, some studies have incorporated an action-based paradigm into the classical RHI (Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2012; Riemer, Kleinböhl, Hölzl, & Trohan, 2013). For instance, instead of passively experiencing concurrent stroking, participants may be asked to repeatedly lift the index finger of their hand, which is placed in a box on the top of which the rubber hand lies. The participant's index finger is connected to the rubber hand's index finger, so that each movement of the participants' finger results in a corresponding movement of the rubber hand's index (e.g., Kalckert & Ehrsson, 2012). This *active* paradigm has been shown to elicit a much stronger RHI when compared with the classical rubber hand paradigm, presumably because participants experience themselves as agents of the rubber hand movement, rather than as passive witnesses. Accordingly, the action-based paradigm offers an attractive way to study the relation between agency and ownership.

Despite this abundance of positive and interesting results, the action-based RHI paradigm nevertheless suffers from limitations associated with the technical aspects of the experimental preparations and from often rudimentary methods. Well-controlled experimental conditions are difficult to obtain. For example, in some designs participants can move the fake index finger by means of a thin wooden rod attached to two plastic rings, which links the real hand and the fake hand (e.g., Kalckert & Ehrsson, 2012). If the experimenter wants to move the fake index finger (such as in a *passive* condition), a cord (or a string) and a pulley attached under the keyboard are required to copy the participant's finger movements. For asynchronous finger movements, the connection has to be severed, and the experimenter moves the fake hand manually and introduces a (necessarily very approximate) delay of 500 ms, as compared with the real hand movement.

To address such limitations and to sharpen the design of such studies, we here propose an improved version of the classic rubber hand in the form of a robotic hand coupled with a sensory glove, controlled by Arduino and MATLAB codes. Thus, the main goal of the present study was to develop a mechanical version of a human hand, together with other ancillary devices. We believe that this device will open new possibilities in the design of experimental paradigms, particularly because of the reproducible and low-cost characteristics of the robotic hand. We carried out three experiments based on previous studies to validate the use of the robotic hand: *active* versus *passive* movements in the first experiment, *synchronous* versus *asynchronous* movements in the second experiment, and *congruent* versus *incongruent* movements in the third experiment (see the video in the supplementary material). The three conditions (active, synchronous, and congruent) were similar and constituted *baseline* conditions. In the passive condition, the robotic hand moved without the intervention of the participant. In the asynchronous condition, a delay of 500 ms was introduced between the participant's movement and that of the robotic hand. In the incongruent condition, the participant moved with his/her index finger, and the robotic hand moved the little finger. Forty-two participants were recruited and then randomly assigned to one of the three experiments. The sample selection was made on the basis of previous studies (in action-based paradigms, the minimum sample size is generally about 40). To measure the strength of the illusion, participants indicated on a piece of graph paper where, according to them, their own hand was located (i.e., proprioceptive drift) and answered questions about both *sense of ownership* and *agency*. Previous studies have shown a positive correlation between ownership (i.e., scores at the questionnaire) and proprioceptive drift (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008), whereas other studies have demonstrated that these two measures are often dissociated (Holle, McLatchie, Maurer, & Ward, 2011; Rohde, Di Luca, & Ernst, 2011). In the present study, we chose to use both measures (i.e., proprioceptive drift and questionnaires) to richly document the illusion and to compare them. As was expected, we observed a "robotic hand illusion" in all baseline conditions. The major asset of the robotic hand is that it enables reproduction of specific experimental conditions. Delays and motion adaptation (e.g., movement of the middle finger instead of the ring finger) are all computer controlled, with a temporal precision that is impossible to achieve through manual control (i.e., in the asynchronous condition). In the Instruments section, we explain how the hand was designed and built. In the supplementary material, 3-D printer files and the assembling procedure, as well as Arduino and MATLAB codes, are available. Results are presented only in a summarized form, because they are not the major interest of this article. In the Discussion section, we review the advantages and limitations of the robotic hand.

Instruments

A robotic hand coupled with a sensory glove controlled by a microcontroller was used during the experiment. Robotic hands constitute an important research topic in robotics engineering because grasping and manipulation of a variety of objects by bionic hands are fundamental functionalities of various robotic systems and are used in different applications (Prattichizzo, Malvezzi, & Bicchi, 2010; Yoshibawa, 2010). For such tasks, the force that can be exerted by the fingers is important. Different designs of the hands have been developed over the past decades, both commercially (Townsend, 2000; Tuffield & Elias, 2003) and as research prototypes (Bicchi, 2000; Grebenstein et al., 2011; Melchiorri, Palli, Berselli, & Vassura, 2013). A major constraint is the limited physical size, relative to the required dexterity and strength. Usually, such robotic hands are very complex mechatronic devices with a very high cost (from 20 k€ to 100 k€), depending on the number of actuated joints. This lack of affordable hardware restricts testing with large user groups.

To address this important limitation, our robotic rubber hand is based on the Do-It-Yourself (DIY) mindset of the maker movement. The design is low-cost and open-access and includes easy-to-understand building instructions. This makes it possible for non-technically-skilled persons to manufacture the hand and use it in their experiments (Kuznetsov & Paulos, 2010). Due to the complexity and intricacy of the hand's design, classical manufacturing techniques are too expensive and would remain inaccessible. Thus, we used off-the-shelf components and accessible rapid prototyping and manufacturing techniques, with the aim that the experimental device can be built and further developed by a community of users. A complete overview of the hardware and implemented interfaces is depicted in Fig. 1.

The robotic hand was built on a 3-D printer with a common thermoplastic, acrylonitrile butadiene styrene (ABS), which combines the strength and rigidity of acrylonitrile and styrene polymers (see pp. 5–7 in the "RubberHandManual.pdf" for the assembling procedure and "RoboticHand_STL" for the printer in the supplementary material). The ABS 3-D printed parts are not as solid as metal computer numerical control milled parts, but because the hand is not physically loaded, ABS performs well in the target application (Davis, Tsagarakis, & Caldwell, 2008). The additive manufacturing

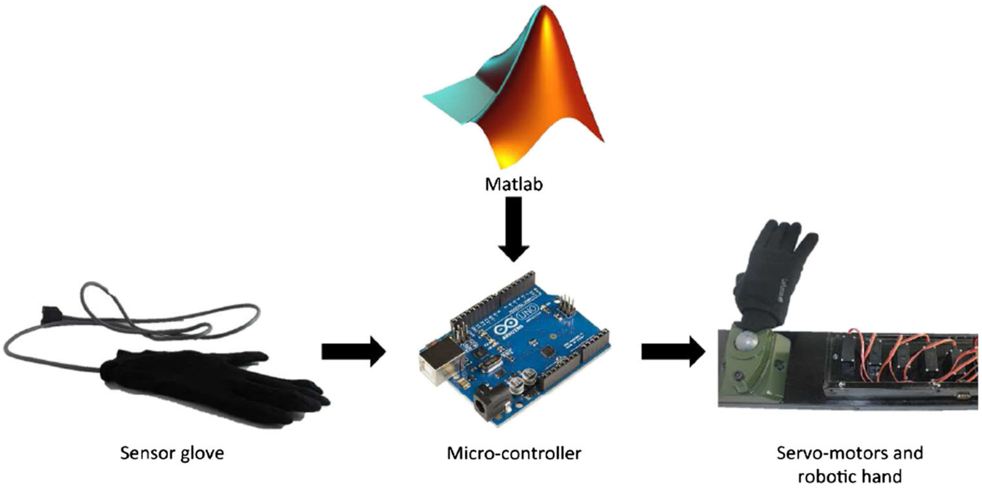

Fig. 1 Working principle of the robotic hand. Data are collected by the sensor glove and analyzed by the microcontroller (based on Arduino Uno). The program mode is selected by using MATLAB. The microcontroller then commands the servo-motors that actuate the fingers

machine produces parts by building them up in layers, printing each new layer on top of the last. As such, very complex parts can be produced with a very low cost. The resolution of the 3-D printing process dictates that no gap can be smaller than 0.17 mm, although other techniques may reach better resolution.

The robotic hand has five underactuated fingers. As in the human hand, where most of the muscles are situated in the forearm, in the robotic hand each finger has its own motor located in the forearm, with forces being transmitted to each of the fingers by tendons. The return springs are positioned within the finger. Each servomotor is fitted with a lever arm onto which the tendon is connected, converting the rotary motion of the motor into linear motion of the tendon. The wrist is, at the moment, not actuated but contains a passive joint so the mechatronic hand can also be positioned in different orientations, allowing the experimenter to match position of the participant's hand as well as possible.

To measure the bending of each of their fingers, participants wear a sensor glove. The glove is composed of flex sensors, the electrical resistance of which decreases when bent (see p. 9 in the "RubberHandManual.pdf"). Reading this electrical resistance with the microcontroller, it is possible to infer the bending of the participant's fingers.

Both the robotic hand and glove are controlled by an Arduino microcontroller, which is designed so that its sensors and motor signals can interface directly with it (see p. 12 and pp. 15–22 in the "RubberHandManual.pdf"). The microcontroller is commanded from an external PC running MATLAB so as to select the different operation modes, with high-level instructions transmitted over a USB cable (see p. 12 and pp. 22–23 in the "RubberHandManual.pdf"). This program allows flexible use of inputs from the glove to drive the robotic hand. The program further makes it possible (1) to record the motion both of the human and of the robotic hand with time stamps, (2) to introduce motion delays, (3) to select allowable robotic hand motions, and (4) to arbitrarily associate human and robotic finger motions. Many other adaptations are possible depending on the desired experimental task.

The parameters can be set over a graphical user interface. Energy is supplied via an external power source. By using standard off-the-shelf components such as hobby servomotors, instead of high-precision drive systems, the list of materials is cheap and can be readily purchased in local electronic shops.

The hardware was tested to ensure that it was sufficiently durable for the targeted experiments. The aim for the system is to distribute both the hardware and the software in an open manner, thus making it available for the broad research community. Currently, we are carrying out some design iterations in order to facilitate the manufacturing and improve robustness. Since this design is still under development, no final assembly instructions have been made available yet.

We now turn to the experimental results we obtained using the robotic hand in a typical RHI paradigm.

Experimental settings

Experiment 1

Method

Participants Fourteen right-handed participants took part in Experiment 1 (12 females; mean age: 19.21 years, *SD* = 2.547) and received course credit for their participation (1 credit for 20 min time). All participants gave their written informed consent prior to the experiment. The study was approved by the local ethical committee of the Faculty of Psychology of the Université libre de Bruxelles (ULB).

Procedure Prior to the experiment, participants were first invited to listen to verbal instructions. They sat at a table and placed their right hand on a shelf fixed under the table (see Fig. 2). The robotic hand was placed above the table, at the same height, as their real hand would be if it were laid out flat on the table. The distance between the real and the fake robotic hand was about 8 cm. The participants' arm and the box containing the motors of the robotic hand were hidden under a blanket, which covered the hand, wrist, and forearm up to the shoulder~~s~~.

Participants were first trained for 1 min to move their right index finger at a regular frequency of 1 Hz, prompted by brief sounds generated by the computer. Next, the experimental procedure was initiated with two conditions: *active* versus *passive*. Participants wore the glove sensor in each condition. In the active condition, participants were instructed to perform a movement with their index finger at a frequency of 1 Hz, although not always rhythmically; that is, participants were instructed that, at some point in time, they could vary the frequency, by performing, for instance, a double tapping. The robotic hand was programmed to execute the same index finger movement [changeData(0,100,9,1,9,9,9,9,arduino)]. In the passive condition, participants were instructed to relax their index and to attend only to the robotic hand (see the video in the supplementary material). The index of the robotic hand moved at a frequency of 1 Hz [changeData(0,70,9,8,9,9,9,9,arduino)]. During each condition, participants were instructed to look attentively at the robotic hand. The experimenter monitored whether the participants gaze was in the direction of the robotic hand during the experiment. Each condition was tested only once and lasted 3 min. The order of conditions was counterbalanced across participants. Immediately after the 3 min had elapsed, the experimenter instructed the participants to remove their hand from the box, so as to break the illusion, and to relax. The

Fig. 2 The setup used to induce the robotic hand illusion. The participant threaded the glove and put his/her hand on the tablet under the table. A blanket was placed under their wrist to heighten a little the participant's hand. A large blanket was then placed to cover the space between the robotic hand and the participant's arm. To measure the proprioceptive drift, a sheet of graph paper with a millimeter grid was placed on the left board on the table. Participants were instructed to close their eyes and to make a rapid and accurate pointing movement by touching the sheet

break lasted approximately 30–45 s. Proprioceptive drift was measured before each condition (i.e., baseline) and also at three moments during each condition (e.g., a first measurement was taken after 1 min of stimulation, the second after 2 min of stimulation, and the third at the end of the experiment). On each occasion, participants were instructed to close their eyes and to indicate, using their left hand, where they situated their own hand on the vertical axis. To this end, a sheet of graph paper with a millimeter grid was placed on the left vertical support of the table. Participants were instructed to close their eyes and to make a rapid and accurate pointing movement by touching the sheet. The experimenter then used a pen to mark the position corresponding to the top of the participants' finger on the sheet. The proprioceptive drift can then be measured by subtracting the position of the initial pointing (i.e., the baseline condition before the illusion takes place) from those of the subsequent pointings (i.e., during and at the end of the experiment). Positive scores indicate a perceptual drift toward the fake robotic hand, whereas negative or null scores indicate absence of the illusion.

At the end of each condition, participants answered an eight-statement questionnaire (see Table 1 for the English and French versions). This questionnaire was developed on the basis of previous studies (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2012) and was adapted for the robotic hand (i.e., the expression "rubber hand" was systematically replaced by "robotic hand"). Four statements measured the sense of ownership, and four statements measured the sense of agency. Participants reported their experience on a 7-point Likert-type scale ranging from −3 (*totally disagree*) to +3 (*totally agree*).

Table 1 The original (English version) of the questionnaire and the translated version (in French) that we used during the experiment

	English Version	French Version
	Ownership	
1	I felt as if I was looking my own hand	J'ai eu l'impression que j'étais en train de regarder ma propre main
2	I felt as if the robotic hand was part of my body	J'ai eu l'impression que la main robotique faisait partie de mon corps
3	It seemed as if I were sensing the movement of my finger in the location where the robotic finger moved	Il m'a semblé sentir le mouvement de mon doigt à l'endroit où la main robotique a bougé
4	I felt as if the robotic hand was my hand	J'ai eu l'impression que la main robotique était ma main
	Agency	
5	The robotic hand moved just like I wanted it to, as if it was obeying my will	La main robotique bougeait comme je le voulais, comme si elle obéissait à ma volonté
6	I felt as if I was controlling the movements of the robotic hand	J'ai eu l'impression que j'étais en train de contrôler les mouvements de la main robotique
7	I felt as if I was causing the movement I saw	J'ai eu l'impression que j'avais causé le mouvement que j'ai vu
8	Whenever I moved my finger I expected the robotic finger to move in the same way	N'importe où je bougeais mon doigt, je m'attendais à ce que le doigt robotique bouge dans la même direction

Note. The height statements were divided in two categories: four to assess ownership and four to assess agency

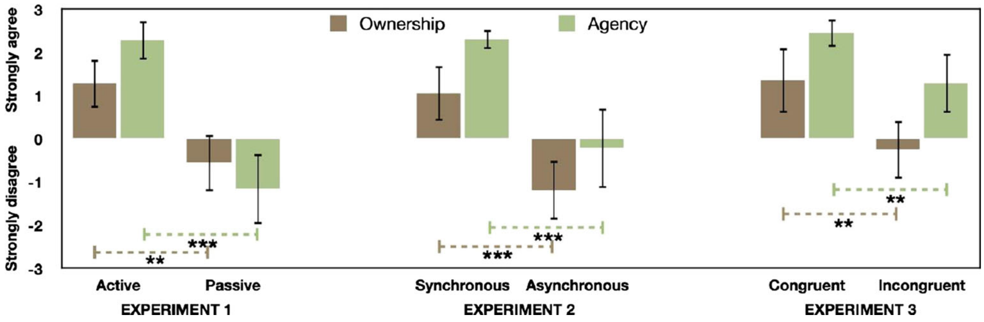

Fig. 3 Questionnaires were scored from −3 (*strongly disagree*) to +3 (*strongly agree*). Green columns represent the mean score of the four items assessing agency, and brown columns represent the mean score for ownership. All tests were two-tailed. ** indicates a significant difference of $p < .01$, and *** indicates a significant difference of $p < .001$ between conditions. Error bars refer to standard errors

Results

We first analyzed questionnaire scores on the sense of both agency and ownership (see Fig. 3). The data were tested for normality with a Shapiro–Wilk test in each experiment. Ownership score in both the active (Experiment 1) and the congruent (Experiment 3) conditions did not respect normality ($p < .05$). We computed the mean scores of the four items related to agency and ownership senses separately and then carried out a paired sample *t*-test to compare agency and ownership between each condition. We selected two measures for the proprioceptive drift. First, we calculated the difference between T_3 and T_0 for each of the two conditions and compared the two conditions by performing a one-sample *t*-test (see Fig. 4a). This procedure has been commonly reported in the literature. Additionally, we examined the progression of the proprioceptive drift as a function of time. We calculated the slope by computing the scores from T_0 (i.e., baseline) to T_3 (i.e., after the stimulation) in one unique value. A positive value indicates a positive slope, and inversely, a negative value indicates a negative slope. The data were tested for normality with a Shapiro–Wilk test in each experiment ($p > .05$). A one-sample *t*-test was performed to measure the difference from 0 (see Fig. 4b). Several authors reported that the drift continues to change during the duration of the stimulation (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005; Tsakiris, Hesse, Boy, Haggard, & Fink, 2007). On the basis of anecdotal observations in the pretest session, we noticed

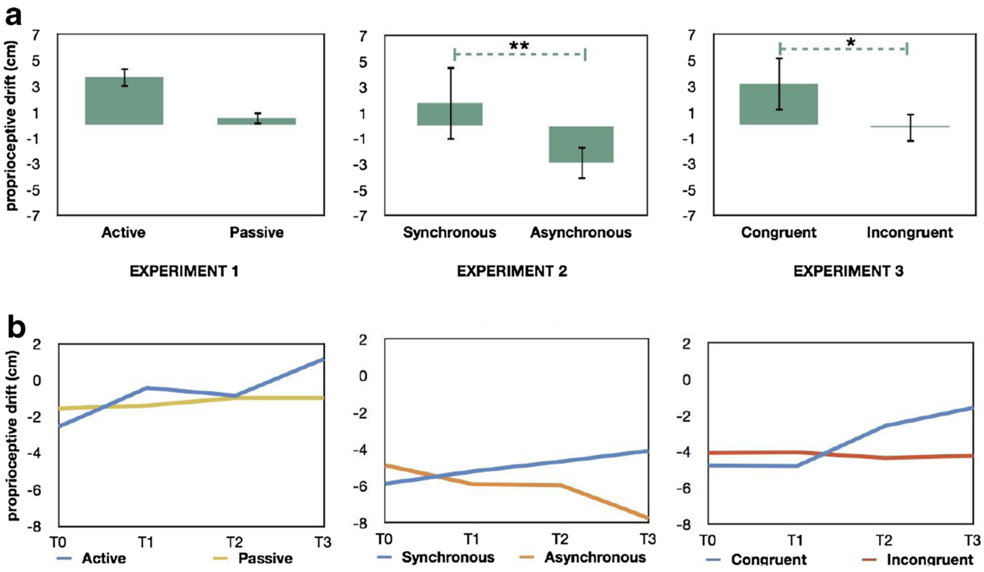

Fig. 4 **a** Each column represents the difference between T_0 (i.e., before the stimulation) and T_3 (i.e., after the stimulation). A significant positive value indicates that the participant reported that his/her own hand was closer of the robotic hand after the 3-min stimulation. Significant negative values or nonsignificant values indicate that the illusion had failed to take place. All tests were two-tailed. * indicates a significant difference of $p < .05$, and ** indicates a significant difference of $p < .01$ between conditions. Error bars refer to standard errors. **b** T_0 = the measure of the proprioceptive drift (PD) before the stimulation. T_1 and T_2 = measure of the PD after 1 and 2 min of stimulation, respectively. T_3 = the measure of the PD after the stimulation. The blue line represents the baseline conditions—respectively, the active condition in Experiment 1, the synchronous condition in Experiment 2, and the congruent condition in Experiment 3

that asking participants to express the drift measure before and at the end of the experiment can be strongly influenced by noise (i.e., some participants reported believing that they had pointed higher, whereas they had in fact pointed lower) and by participants' expectations (i.e., some participants reported having consciously chosen to press higher or lower in an attempt to second-guess the aim of the experiment). Consequently, we considered that reporting both measures was the better solution. The data were tested for normality with a Shapiro–Wilk test. Ownership scores in both the active and the congruent conditions statistical analyses were similar in Experiments 1, 2, and 3.

Questionnaires Results indicated that participants experienced a strong sense of both ownership (1.35, *SD* = 1.14) and agency (2.14, *SD* = 0.91) in the active condition. By contrast, in the passive condition, participants experienced neither a sense of agency (−0.73, *SD* = 1.63) nor a sense of ownership (−0.03, *SD* = 1.32). Paired sample *t*-tests indicated that agency and ownership diminished significantly in the passive condition, as compared with the active condition, $t(13) = 5.040$, $p < .001$, $\eta^2 = .661$, and $t(13) = 2.905$, $p < .02$, $\eta^2 = .393$.

Proprioceptive drift With respect to drift size, a positive proprioceptive drift was present in the active condition ($T_3 - T_0 =$ 3.7 cm, *SD* = 5.74), whereas there was no proprioceptive drift in the passive condition ($T_3 - T_0 = 0.57$ cm, *SD* = 3.82). Paired sample *t*-tests indicated that the difference between the two was not significant, $t(13) = 1.743$, $p > .1$.

With respect to drift progression, a one-sample *t*-test indicated that the slope in the active condition was significantly different from 0, $t(13) = 2.156$, $p = .05$, but not in the passive condition, $p > .1$, indicating that participants had reported that their real hand was higher (i.e., closer to the robotic hand) only in the active condition.

Experiment 2

Method

Participants Fourteen participants took part in Experiment 2, (14 females; mean age: 20.36 years, *SD* = 2.790) and received credit course for their participation (1 credit for 20 min time). Thirteen were right-handed. All participants gave their written informed consent prior to the experiment. The study was approved by the local ethical committee of the Faculty of Psychology of the ULB.

Procedure The procedure was identical to that in Experiment 1, except for the inclusion of two experimental conditions: *synchronous* versus *asynchronous*. The synchronous condition was similar to the active condition in Experiment 1: The index of the robotic (fake) hand moved at the same time as the index of the participants' (real) hand. In the asynchronous condition, we introduced a delay of 500 ms between the index movement of the robotic hand and the index movement of the participants' hand [changeData(50,100,9,1,9,9,9,9,arduino)].

Results

Questionnaires Results indicated that participants had experienced a strong sense of both ownership (1.05, *SD* = 1.28) and agency (2.30, *SD* = 0.46) in the synchronous condition. As was expected, in the asynchronous condition, participants experienced a sense of neither agency (mean = −0.21, *SD* = 1.86) nor ownership (mean = −1.19, SD = 1.36). Paired sample *t*-tests indicated that agency and ownership decreased significantly in the asynchronous condition, as compared with the synchronous condition, $t(13) = 5.169$, $p < .001$, $\eta^2 = .672$, and $t(13) = 4.494$, $p = .001$, $\eta^2 = .608$, respectively.

Proprioceptive drift With respect to drift size, a positive proprioceptive drift was present in the synchronous condition ($T_3 - T_0 = 1.77$ cm, *SD* = 4.11), whereas there was no proprioceptive drift in the asynchronous condition ($T_3 - T_0 =$ −2.87 cm, *SD* = 2.28). Paired sample *t*-tests indicated that the difference between the two was significant, $t(13) = 3.433$, $p < .005$, $\eta^2 = .475$.

With respect to drift progression, one-sample *t*-tests indicated that the slope in the synchronous condition was not significantly different from 0, $p > .1$, but that the slope in the asynchronous condition was significantly lower than 0, $t(13) = -3.999$, $p = .002$, indicating a repulsion in the asynchronous condition.

Experiment 3

Method

Participants Fourteen participants took part in Experiment 3 (13 females; mean age: 19.64 years, *SD* = 1.646) and received credit course for their participation (1 credit for 20 min time). Eleven were right-handed. All participants gave their written informed consent prior to the experiment. The study was approved by the local ethical committee of the Faculty of Psychology of the ULB.

Procedure The procedure was identical to that in Experiments 1 and 2, except for the inclusion of two experimental conditions: *congruent* versus *incongruent*. The congruent condition was similar to both the active and synchronous conditions. In the incongruent condition, participants moved their index finger, which now resulted in movement in the little finger of the robotic hand [changeData(0,100,9,9,9,9,9,1,arduino)].

Results

Questionnaires Results indicated that participants experienced a strong sense of both ownership (1.36, *SD* = 1.52) and agency (2.45, *SD* = 0.64) in the congruent condition. As was expected, in the incongruent condition, participants experienced a sense of agency (mean = 1.28, *SD* = 1.38) but not ownership (mean = −0.25, *SD* = 1.36). A paired sample *t*-test indicated that ownership decreased significantly in the incongruent condition, as compared with the congruent condition, $t(13) = 3.487$, $p < .005$, $\eta^2 = .483$. A paired sample *t*-test indicated that agency also diminished significantly in the incongruent condition, as compared with the congruent condition, $t(13) = 3.167$, $p < .01$, $\eta^2 = .435$, suggesting that even if agency stayed high in the incongruent condition, the reduced sense of ownership could equally influence the sense of agency.

Proprioceptive drift With respect to drift size, a positive proprioceptive drift was present in the congruent condition ($T_3 - T_0 = 3.7$ cm, *SD* = 5.68), whereas no proprioceptive drift was present in the incongruent condition ($T_3 - T_0 = -0.156$ cm, *SD* = 2.58). A paired sample *t*-test indicated that the difference between the two was significant, $t(13) = 2.163$, $p = .05$, $\eta^2 = .264$.

With respect to drift progression, one sample *t*-tests indicated that the slope in the congruent condition was significantly higher than 0, $t(13) = 2.325$, $p < .05$, but not the slope in the incongruent condition, p > .1, indicating that participants felt their own hand to be closer to the robotic hand only in the congruent condition.

Relation between agency and ownership An additional statistical analysis was performed to look at the relation between agency and ownership. To improve statistical power, three baseline groups (active condition in Experiment 1, synchronous condition in Experiment 2, and congruent condition in Experiment 3) were computed, and the Pearson correlation between agency scores and ownership scores was analyzed. Results indicated a significant positive correlation, $r = .477$, $p = .034$, which suggest that each depends on the other (see Fig. 5).

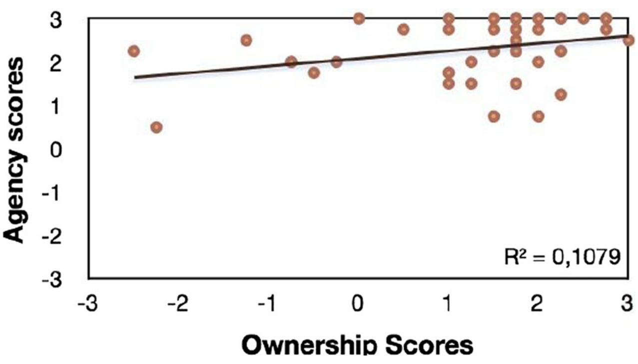

Fig. 5 Correlation between agency scores and ownership scores

Relation between proprioceptive drift, agency and ownership In addition, correlations between proprioceptive drift, agency, and ownership were performed. The sample was composed by the three samples of the baseline conditions. Results indicated no significant correlation between ownership scores and proprioceptive drift, $r = .256$, $p > .1$, or between agency scores and proprioceptive drift, $r = -.063$, $p > .6$. Results on these correlations indicate that the proprioceptive drift constitutes an independent measure of embodiment when compared with the questionnaires.

Discussion

In the present study, we showed that the robotic hand induces both a sense of *ownership* and a sense of *agency*. Indeed, we observed high scores on both dimensions, as well as a positive proprioceptive drift in all three baseline conditions.

Similar to previous studies, we found that proprioceptive drift increased in parallel to the length of the experiment (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005 (revisited); Tsakiris, Hesse, et al., 2007). On the basis of the hypothesis that the proprioceptive drift reflects the degree of embodiment, the present result could suggest a progressive embodiment of the robotic hand through a learning process.

Furthermore, we replicated the results observed in other studies assessing agency and ownership in action-based paradigms (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012). Indeed, we observed that the asynchronous condition (i.e., in which a delay of 500 ms was introduced between the participant's movement and the robotic hand movement) eliminated the sense of both agency and ownership. Furthermore, the incongruent condition (i.e., in which the robotic hand *little* finger moved after participants had moved their *index* finger) eliminated the sense of ownership, but not agency. In the passive condition, we expected to observe an elimination of the sense of agency, while the sense of ownership would remain intact. Although results confirmed the former, the sense of ownership was diminished. Two possible explanations could account for these results.

First, in the passive condition, participants were instructed to relax their index finger and to look attentively at the moving index finger of the robotic hand. These instructions could have, simultaneously, induced a paradoxical feeling of both an incongruent and a congruent sensation—that is, the fake (robotic) index finger moved, while the participants' finger stayed immobile. A possible solution would be to place a computer-controlled servomotor on the participant's finger to induce a movement without the intervention of the experimenter.

A second explanation concerns the relationship between agency and ownership itself. From one perspective, agency and ownership are related, meaning that the former strongly depends on the latter (i.e., the *additive model*). Conversely, it may also be that agency and ownership are two separate components or processes (i.e., the *independent model*). Tsakiris, Longo, and Haggard (2010) showed different cerebral activity for the sense of agency, when compared with the sense of ownership, which suggests two different and independent systems. However, analysis on the questionnaires revealed that both agency and ownership were related, supporting the additive model. The results we observed in the baseline conditions offer support for the additive model, with a positive correlation between agency and ownership scores at the questionnaire.

Concerning the relation between proprioceptive drift and ownership or agency, the present results indicate no significant correlations between each, which suggests that these two measures are independent. This conclusion is consistent with some previous studies (e.g., Rohde et al., 2011), but not with others (e.g., Longo et al., 2008). The sensitivity of the questionnaires used to assess ownership could account for these differences.

As was previously mentioned, whereas some studies found that an incongruent anatomical position eliminates the RHI, others have instead concluded that the RHI can persist in this incongruent condition (1) if the rubber hand is positioned in a plausible anatomical perspective and (2) if the hand is positioned in the peripersonal space (see Makin et al., 2008, for a review). In our study, although the incongruent condition replicated the Makin et al. (2008) criteria, no signs of embodiment were observed. However, the mentioned criteria have only been applied with the classical rubber hand paradigm—that is, a static fake hand (Costantini & Haggard, 2007; Ionta et al., 2013). Consequently, one could conclude that the sense of agency and sensorimotor information in our study failed to produce the same perception of incongruency as that found in the Ionta et al. and the Constantini and Haggard studies. Further studies could, for instance, assess the boundaries of the incongruent condition by comparing the action-based paradigm versus the classical paradigm.

To summarize, the present results replicate action-based paradigms using a robotic hand instead of a rubber hand. In the following section, we first consider the advantages of using a robotic hand and will overview the limitations of this technology. Finally, we propose possible improvements for future research.

Advantages of the robotic hand

The major advantage of using a robotic hand is the possibility of achieving better-controlled experimental conditions. Through MATLAB coding, a computerized supervision of initial experimental conditions allows one to control the hand entirely. A single line of code controls the movement of each finger, implementing different settings, such as the delay, the frequency of movements, and so forth. Furthermore, through computerized control (i.e., MATLAB coding), very few modifications are actually mandatory to develop complex combinations (e.g., asynchronous incongruent condition) of different experimental designs (i.e., intra- and intersubject) and consequent analysis. In addition, the use of a robotic hand represents a more realistic replication of the human hand in both movement and anatomy, instead of the more rudimentary material used up to now. Moreover, given the fact that the robotic hand is fully independent from the participants' own movement (i.e., no physical or mechanical connection between participant's hand and the robotic hand model), a new generation of experiments can be imagined. For instance, one could apply the robotic hand to a vast array of psychology experiments, such as mental chronometry (i.e., reaction times latencies). Specifically, one could place a keyboard below both the real and fake hands to study in which measure the sense of agency is modulated by the degree of embodiment by combining the robotic hand with the intentional binding effect (i.e., Haggard, Clark, & Kalogeras, 2002).

A second advantage of the robotic hand is its polyvalence. For example, this is the only study that reports the incongruent condition via an interdigit substitution. Specifically, in our study, we asked participants to indicate where they situated their own hand for the proprioceptive drift, without differentiating the index or the little finger position. Nevertheless, we could expect that the proprioceptive drift should be different across the congruent and the incongruent conditions, for the little finger and the index finger. This represents a possibility to study finger representation. Another possibility is to use the entire hand. Indeed, in action-based paradigms, only one finger is (can be) moved. It would be interesting to observe to what extent the entire hand contributes to the sense of agency and ownership when compared with a single finger. Finally, the robotic hand is capable of performing both flexion and extension, which allows a more realistic human hand movement replication.

A third advantage concerns the decrease in experimenter bias. In psychology, experimenter bias is a well-known concern, since it leads to unexpected (or expected) results (e.g., Barber & Silver, 1968; Doyen, Klein, Pichon, & Cleeremans, 2012; Rosenthal & Lawson, 1964; Rosenthal, Persinger, & Fode, 1962; Troffer & Tart, 1964). In general terms, the less the experimenter interacts with the participants, the more bias is avoided. In the classic RHI, notably in action-based paradigms, interactions between experimenter and participant are part of the current procedure. Therefore, an advantage of the robotic hand is the possibility of decreasing this interaction due to the fact that the robotic hand is entirely controlled by the computer.

Limitations of the robotic hand

In its current form, the robotic hand cannot replicate all possible human finger movements. For example, if the participant has his/her own hand pressed on the table and moves the finger upward, the hand will not move likewise, because the finger of the robotic hand can only move downward. Additionally, it is possible that participants in the present study perceived a slight rebounding at the end of the (robotic) hand movement (see Video in the supplementary material), which could represent an inconsistency. This limitation stems from the hand's design, and one possibility would be to conceive a different model that permits both upward and downward movements. However, these inconsistencies don't seem to affect the illusion, thereby suggesting flexibility of the mechanisms of embodiment.

A second point concerns the delay between participant's hand movement and the robotic movement. The strength of the illusion critically depends on the duration of the delays between actual movements and copied movements. In our study, the delay was about 10 ms, which represents the minimum possible requirement to send a command from the glove to the robotic hand. This minimal delay implies the use of powerful and fast servomotors, and it comes with a price. Specifically, the higher the frequency of the movement (i.e., velocity and acceleration) is, the higher the sound resulting from the servomotor is. Thus, when participants perform a movement, they also hear the mechanical sounds produced by the servomotors that drive the movements of the robotic hand. Every finger movement is thus accompanied by a sound, which produces a congruency between sound and movement. A pilot study where servomotor noise was canceled (i.e., by asking participants to wear isolating headphones) was conducted, and results suggested that sound does not influence results. Nevertheless, further investigation is required in this matter.

Conclusions

The classic rubber hand paradigm is often used in psychology, particularly in the study of embodiment and body ownership (see Ramakonar, Franz, & Lind, 2011, for a review). Overall, more strict and novel experimental conditions will be possible through a versatile robotic platform, allowing one to conceive new and more sophisticated studies in these fields. Although we were particularly interested in the senses of ownership and agency, and their relationship to a robotic hand, the present material is also important for clinical research—specifically, orthotics. Indeed, the RHI has clinical implications for the study of body scheme integration by amputee patients who received prosthesis members (e.g., Ehrsson et al.., 2008; Ramakonar, Franz, & Lind, 2011). Psychologists and engineers are now working together with health care professionals on the RHI, as well as the rubber leg illusion (e.g., Aldhous, 2009; Beckerle et al., 2012; Christ, Beckerle, et al., 2012; Ramakonar et al., 2011). Several robotic prostheses have already been developed (e.g., Cherelle, Grosu, Matthys, Vanderborght, & Lefeber, 2013; Geeroms, Flyyn, Jimenez-Fabian, Vanderborght, & Lefeber, 2013; Hochberg et al., 2012), and the field is in constant progress. Specifically, the study of the interaction between patient's will and their robotic (prostheses) member through a brain–computer interface is of particular importance (e.g., Allison, Wolpaw, & Wolpaw, 2007; Haselager, 2013). By combining robotic advancements and an interdisciplinary research approach, our study represents a new example of computing technologies applied to the field of psychology.

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