Consciousness and Cognition 36 (2015) 75–86

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Body-ownership for actively operated non-corporeal objects

Ke Ma *, Bernhard Hommel

Leiden University, Institute for Psychological Research & Leiden Institute for Brain and Cognition, Leiden, The Netherlands

ARTICLE INFO

Article history:
Received 25 July 2014

Keywords:
Rubber hand illusion
Virtual hand illusion
Body ownership
Non-corporeal object
Sense of agency

ABSTRACT

Rubber-hand and virtual-hand illusions show that people can perceive body ownership for objects under suitable conditions. Bottom-up approaches assume that perceived ownership emerges from multisensory matching (e.g., between seen object and felt hand movements), whereas top-down approaches claim that novel body parts are integrated only if they resemble some part of a permanent internal body representation. We demonstrate that healthy adults perceive body ownership for a virtual balloon changing in size, and a virtual square changing in size or color, in synchrony with movements of their real hand. This finding is inconsistent with top-down approaches and amounts to an existence proof that non-corporeal events can be perceived as body parts if their changes are systematically related to one's actions. It also implies that previous studies with passive -stimulation techniques might have underestimated the plasticity of body representations and put too much emphasis on the resemblance between viewed object and real hand.

1. Introduction

One commonly has no problem telling one's own body from a tool or another person's body and experience one's body as constituting some kind of "me". This achievement is commonly ascribed to two (often not very well defined: De Vignemont, 2011) cognitive representations: an internal body image, which is considered a rather permanent representation of the body's configuration, and a body schema, a sensorimotor representation based on afferent and efferent information related to bodily movements. Interestingly, body representations are quite malleable. A striking example is the rubber hand illusion (RHI), showing that people perceive a rubber hand in front of them as their own if it is stroked synchronously with their real, unseen hand (Botvinick & Cohen, 1998). Similarly, people adopt ownership for a virtual hand if this hand moves in synchrony with their own physical hand—the virtual-hand illusion (VHI; e.g., Ma & Hommel, 2013; Perez-Marcos, Sanchez-Vives, & Slater, 2012; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008).

According to bottom-up approaches (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998), this is because synchronous stroking (or movement) leads to an intermodal match between the visual pattern created by stroking the rubber hand (or by moving the virtual hand) and the tactile pattern created by stroking (or the proprioceptive pattern created by moving) the real hand. As intermodal matching is considered the main criterion for telling one's own body parts from those of others, the artificial hand is integrated into one's body representation. Especially the VHI suggests that any controllable object or event can become part of one's body, provided that its movements are synchronized with self-generated re-afferent information (Short & Ward, 2009). Interestingly, this suggests that body ownership (the sense that a given object

* Corresponding author at: Leiden University, Institute for Psychological Research, Cognitive Psychology Unit, Wassenaarseweg 52, 2333 AK Leiden, The Netherlands.

E-mail address: k.ma@fsw.leidenuniv.nl (K. Ma).

http://dx.doi.org/10.1016/j.concog.2015.06.003

or event is part of one's body) and agency (the sense of control over a particular object or event) are more strongly related than commonly assumed. It is also of interest that a key variable for both ownership and agency, the temporal correlation between self-generated movement and environmental changes, has also been considered crucial for the acquisition of voluntary action (see Hommel, 2009).

However, the bottom-up approach has been challenged by authors claiming that body ownership emerges from the interaction between current multisensory input and internal models of the body (e.g., Tsakiris, 2010; Tsakiris, Schütz-Bosbach, & Gallagher, 2007). According to this idea, the eventual multisensory matching process is preceded by a comparison of the visual form of the viewed object with a stored, stable body representation and a comparison between some postural and anatomical features of the object with the current state of the body. For instance, Makin, Holmes, and Ehrsson (2008) and Ehrsson, Spence, and Passingham (2004) proposed a model, based on Maravita, Spence, and Driver (2003), that assumes that ownership emerges from multisensory signal matching (a bottom-up component) which however has to satisfy particular top-down constraints: the candidate effector should be placed in an anatomically plausible position and the multisensory bottom-up information needs to appear near to it. Tsakiris (2010) considered even this model as too parsimonious. According to his approach, synchronous multisensory input information is mediated by a full-fledged body model which contains anatomical, postural, and spatial information about the body, so that ownership illusions will only occur if the candidate effector fits with the model (e.g., Costantini & Haggard, 2007; Haans, IJsselsteijn, & de Kort, 2008; Lloyd, 2007; Tsakiris, 2010; Tsakiris, Carpenter, James, & Fotopoulou, 2010; Tsakiris & Haggard, 2005; Tsakiris et al., 2007).

Top-down approaches have been motivated by two arguments (for an overview, see Tsakiris, 2010). First, various studies show that the strength of the RHI depends on anatomical, postural and spatial constraints, especially the similarity between the to-be-integrated object (such as a rubber hand) and the compared/related body part (e.g., Graziano, Cooke, & Taylor, 2000; Haans et al., 2008; Holmes, Snijders, & Spence, 2006; Tsakiris & Haggard, 2005; Tsakiris et al., 2010). While these observations have been taken to support top-down approaches, they actually do not: Dissimilarities between novel object and actual body part are likely to reduce the degree of intersensory matching (the key factor of bottom-up approaches), which renders this factor theoretically nondiagnostic. The second argument for top-down approaches refers to the fact that there is no convincing demonstration of perceived body-ownership for non-corporeal objects. The only exception is Armel and Ramachandran's (2003) observation that synchronous stroking of a real hand and a table induced a kind of RHI. However, not only has this finding never been replicated, it also can be accounted for by ad-hoc generalization: the table condition was always run right after a rubber-hand condition, which was likely to induce transfer.

However, there are some indications that do not seem to fit with the assumption that ownership illusions require a tight fit between the candidate effector and the internal body model. For example, Longo, Schüür, Kammers, Tsakiris, and Haggard (2009) showed that differences in skin luminance and hand shape did not influence experience of the RHI. Along the same lines, Farmer, Tajadura-Jiménez, and Tsakiris (2012) found that the RHI can be induced with a hand of different skin color. Pavani and Zampini (2007) showed ownership effects for a rubber hand that is bigger, but not a smaller, than one's own hand. Schütz-Bosbach, Tausche, and Weiss (2009) reported that some (in)congruencies between the visual and tactile stimulation did not affect the RHI strength, similarly to the observations of White, Davies, Halleen, and Davies (2010). In all these studies, the visual form and anatomical properties of the rubber hand differed from those of the real hand to some extent, but the candidate effectors were still rubber hands—which arguably keeps considerable similarity to a real hand. However, Ehrsson et al. (2008) showed that amputees can experience rubber hand illusions, and Guterstam, Gentile, and Ehrsson (2013) observed that under multisensory integration conditions empty spaces can be embodied by healthy individuals. As the amputees no longer had a hand that could be similar to a rubber hand, and as empty space does not share any common visual form and anatomical properties with a real hand, these observations are difficult to explain from a top-down approach without additional assumptions (e.g., the imagination of a real hand).

Recent research has considered factors that go beyond anatomical and postural factors and constraints by manipulating bottom-up factors, such as the kind of match between multisensory information about candidate effectors. Some studies have focused on active effectors in the kind of action they are involved in, which brings together aspects of body ownership and of agency (e.g., Hommel, in press; Hommel & Elsner, 2009; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005; Tsakiris, Prabhu, & Haggard, 2006; Tsakiris et al., 2007). In some modified RHI paradigms, researcher manipulated finger or palm movements (of real and rubber hand) to investigate the effect of visuomotor stimulation on illusion induction, which revealed the importance of visuomotor stimulation (or, more precisely, of the combination of self-produced visual, kinesthetic, and proprioceptive action feedback). Tsakiris et al. (2005) argued that efferent information (sense of agency) distinctively contributes to self-recognition (sense of ownership). In some experiments, RHI could be induced by finger or palm movements alone (e.g., Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2014), but this does not exclude the possibility of a mediation by a body model (see Dummer et al., 2009; Kalckert & Ehrsson, 2014; Tsakiris et al., 2005, 2006, 2007).

In contrast to the use of rubber hands, as common in RHI studies, virtual-reality techniques allow for relatively realistic visuomotor stimulation, which has been shown to produce reliable VHIs (Ma & Hommel, 2013; Perez-Marcos et al., 2012; Sanchez-Vives et al., 2010; Slater et al., 2008). In contrast to some action RHI studies (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2014; Tsakiris et al., 2006), in which visuomotor stimulation contributed equally to or less than visuotactile stimulation to the illusion, VHI studies (and even some RHI studies) have shown that visuomotor stimulation alone is sufficient to induce ownership illusions (Ma & Hommel, 2013; Sanchez-Vives et al., 2010). Kokkinara and Slater (2014) tested the two information sources against each other and found that visuomotor synchronicity contributes significantly more to ownership illusions than visuotactile synchronicity does. One possible interpretation of this finding is that a freely controllable virtual

hand provides more and more temporally extended multisensory information and thus a more extended database for bottom-up multisensory matching processes. This is consistent with Short and Ward's (2009) observation that visuomotor synchronous stimulation is sufficient to induce ownership for a wide variety of virtual controllable objects, including virtual hand and cones. However, in their work, the subjective ownership ratings for virtual cones was relatively low (3 on a 5-point scale), and the critical comparison was between controllable cones and uncontrollable hands, which is not consistent with most RHI/VHI studies.

Given the apparently great importance of visuomotor information for ownership illusions, we hypothesize that previous studies that used static objects, like rubber hands, might have systematically underestimated the contribution of bottom-up factors. If so, the use of virtual effectors, together with visuomotor manipulations, might allow participants to experience ownership for objects that do not look like a hand or other real effectors, that is, for non-corporeal objects. Given that the previous failures to demonstrate ownership illusions for non-corporeal objects were mostly obtained in traditional RHI paradigms, it remains to be seen whether a more dynamic manipulation in a VHI paradigm is equally unsuccessful. Accordingly, the aim of the present study was to provide, if possible, a demonstration of perceived body-ownership for non-corporeal objects—a finding that would not fit with the assumption of a crucial role of internal body models (Tsakiris, 2010). To allow for more reliable visuomotor stimulation, more flexibility in manipulating the artificial effector, and in order to avoid the rather distracting stroking procedure, we used the VHI as demonstrated by Slater et al. (2008) and Ma and Hommel (2013).

In our study, we designed two virtual non-corporal objects, a three-dimensional balloon and a two-dimensional square, that both did not bear any obvious visual and anatomical similarity to a real hand or any other human body part. These objects replaced the virtual hand in an otherwise standard VHI setup, so that participants could move their right hand to control the location, orientation, and size of the balloon (Experiment 1) and the location, orientation, and size or color of the square (Experiment 2). While the bottom-up approach to body ownership would suggest that synchronicity between people's own hand movements (with their unseen hand) and the growth or shrinkage of the balloon or of the square (or the changes of its color) creates perceived ownership of the event, the top-down approach would predict no perceived ownership for such non-corporeal objects, as they do not match any part of the participants' body images.

2. Experiment 1

Experiment 1 replicated the VHI-experiment of Ma and Hommel (2013), except that the virtual hand was replaced by a virtual balloon. Participants were exposed to a yellow balloon presented on a screen, the location, orientation, and size of which they could control by moving their right, unseen hand by means of a data glove. When participants moved and rotated their hand, the balloon would show the same movements and when participants opened and closed their hand, the balloon would grow bigger and smaller, respectively. These changes of the size of the balloon occurred either synchronously or asynchronously with movements of the real hand, with the assumption that synchronicity would induce more perceived ownership (and agency) than the asynchronous condition (Ma & Hommel, 2013). To further increase the convincingness of the experience (see Ma & Hommel, 2013), participants were also shown a virtual needle that either touched the virtual balloon (with its blunt or sharp end) or made it explode or not. As impact and threat of virtual effector have been found to induce affective reactivity in participants (Armel & Ramachandran, 2003; Ma & Hommel, 2013), we assessed skin conductance responses (SCR) in addition to the VHI questionnaire (an adapted version of the standard RHI questionnaire used by Botvinick & Cohen, 1998, and many others).

As the virtual balloon does not look like, and does not have the anatomical properties of, a real human hand or any other human effector, we considered it a non-corporeal object. Moreover, in contrast to most RHI/VHI studies (but similar to Short & Ward, 2009), the balloon was placed on the screen in a way that it looked 'disconnected' from the participant's body, which among other things increased the distance between viewed object and felt position (of the real hand). According to top-down approaches, and the model of Tsakiris (2010) in particular, these conditions should prevent participants from experiencing any ownership illusion for the virtual balloon. In contrast, bottom-up approaches would hold that the availability of synchronized/matched multisensory information should be sufficient to generate an ownership illusion.

2.1. Method

2.1.1. Participants

30 participants (7 male; mean age = 25 years, SD = 3.93 years, range 20–35) were recruited from Leiden University in exchange for course credit or pay. We used the department's standard advertisement system and accepted all volunteers registering in the first (and only) wave. Informed consent was obtained from all participants before the experiment. Participants were naive with respect to the RHI/VHI. The study was approved by the Leiden University Human research ethics committee.

2.1.2. Design

Participants underwent 8 conditions, in balanced order, which emerged from crossing three factors: (1) the size of the virtual balloon grew and shrunk either synchronously or asynchronously with the opening and closing of the participant's actual hand; (2) the virtual balloon was touched by a virtual needle's sharp or blunt end (as seen on the screen and felt [as vibration] in the palm of the hand); and (3) the contact of the needle made the balloon explode or not.

2.1.3. Experimental setup

The study was performed in a virtual reality environment (see Ma & Hommel, 2013). The setup consisted of a 3-DOF orientation tracker (InterSense), a data glove (Cyberglove), a cloth which is placed over the participant's right shoulder to cover the space between the virtual object and the participant, and a black box which participant put his right hand in to shield participants' hands from view, Biopac MP100 acquisition unit, AcqKnowledge software and remote transmitter for SCR recording, and virtual reality software (Vizard). The Cyberglove has six vibration stimulators attached, one on each finger and one on the palm; they are programmable to set the vibration time and strength. We designed a virtual balloon and imported the balloon, the tracker, and data glove modules into Vizard to establish data transfer between them. This allowed us to have the balloon being controlled by the participant's hand movement. Participants wore the data glove and tracker on their right and the SCR remote transmitter on their left hand, as in Ma and Hommel (2013). The instruments were shown in Fig. 1(A) and experimental setup is shown in Fig. 1(B).

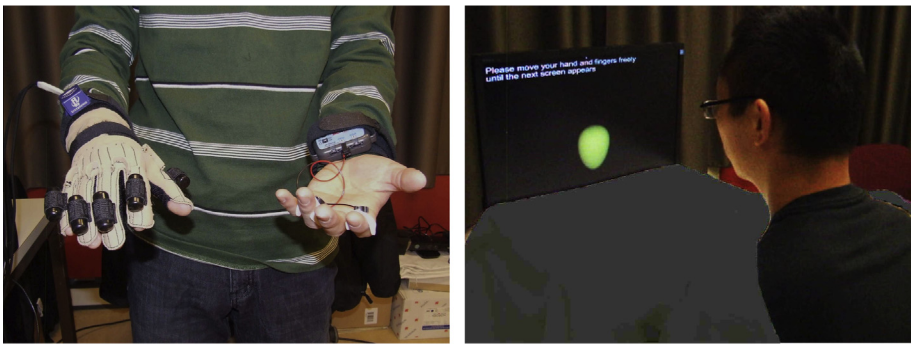
2.1.4. Procedure

Participants were seated in front of the black box with a computer monitor placed behind the other end of the black box, as shown in Fig. 1(B). They were asked to wear the glove, orientation tracker and SCR remote transmitter as shown in Fig. 1(A), then put their hands inside the box, and look at the monitor. At the beginning of each of the eight trials, they were to move their fingers for 10 s, which was necessary to initialize the system properly. Then the computer program generated a virtual balloon on the screen and the trial started. In each of the eight trials, participants were to open and close or rotate their right hand freely for 1 min—which allowed participants to explore the degree of control or agency over the shape of the balloon. After this phase of visuomotor stimulation, visuotactile stimulation was applied: A virtual needle appeared on the screen and took four seconds to move to contact the virtual balloon, which was associated with the onset of the palm vibration stimulator of the glove, and then took another four seconds to return to its original position. This procedure was repeated until 30 s were over. In the synchronous/balloon explosion trials, the orientation and size of the virtual balloon changed in synchrony with the participant's own hand orientation and opening and closing movement. The vibration again set in each time the needle contacted the balloon and the balloon exploded. In the asynchronous/balloon explosion trials, the size and orientation changes of the virtual balloon were delayed by 2 s with respect to the real hand movements, and vibration onset was delayed by 2 s with respect to the contact with the balloon and its explosion. After the illusion-induction phase of each condition participants were filled in the questionnaire.

2.1.5. Questionnaire

To assess the extent to which participants experienced the ownership illusion, we used an adapted version of the standard seven-item questionnaire (Botvinick & Cohen, 1998; Ma & Hommel, 2013; Slater et al., 2008). Each statement was rated by means of a 5-point (0–4) Likert scale, ranging from 0 for 'strongly disagree' to 4 for 'strongly agree'. While Q6 is the most direct ownership question, the remaining questions refer to implications or signs of ownership, like location-related similarity (Q1, Q3), visual similarity (Q4, Q7), intersensory interactions (Q5), and agency (Q2). Q1, Q3, Q5 and Q6 are usually supposed to be the core illusion questions (Guterstam et al., 2013; Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Sanchez-Vives et al., 2010; Slater et al., 2008). The statements were:

Q1. 'Sometimes I had the sensation that vibration I felt on my hand was on the same location where the virtual balloon on the screen was in contact with the virtual needle on the screen',
Q2. 'The movements of the virtual balloon on the screen were caused by me',
Q3. 'It sometimes seemed my own hand was located on the screen',



(A) (B)

Fig. 1. (A) Participants wore an orientation tracker and a data glove on their right hand, and SCR remote transmitter on their left hand; (B) setup of Experiment 1.

Q4. 'The virtual balloon on the screen began to resemble my own hand, in terms of shape, skin tone, freckles, or some other visual feature',
Q5. 'Sometimes it seemed as if what I was feeling was caused by the virtual needle that I was seeing on the screen',
Q6. 'Sometimes I felt as if the virtual balloon on the screen was my own hand or part of my body',
Q7. 'It seemed as if I might have a balloon-like hand besides my right and left hands'

2.1.6. Skin conductance response (SCR) measurements

We measured SCR during the entire experiment. SCR has been shown to be a reliable measurement of at least some aspects of illusory body ownership (Armel & Ramachandran, 2003; Ehrsson et al., 2008; Guterstam et al., 2013). Given that SCR reflects emotional arousal, it was expected to increase in response to the threat-inducing needle event to the degree that ownership for the threatened virtual object would be perceived (see Ma & Hommel, 2013).

We defined a latency onset window between 1 and 8 s after stimulus/event onset, namely when the virtual needle appeared and started to move toward the virtual balloon, with the skin conductivity before stimulus/event onset serving as baseline (see Armel & Ramachandran, 2003; Boucsein, 2011; Ehrsson et al., 2008; Figner & Murphy, 2010). We then calculated the magnitude of the event-induced SCR by subtracting baseline skin conductivity from the peak amplitude of the SCR during the analyzed time window, and took the log(magnitude + 1) per participant and condition.

2.2. Results

Responses to the seven items of the questionnaire and the SCR measures were analyzed by means of 2(synchronicity) × 2(needle's end) × 2(explosion) ANOVAs with all independent factors varying within participants. Table 1 provides an overview of the relevant design features, the presence or absence of the ownership illusion expressed as synchronicity effect for Q6, as well as the means for the aggregated illusion ratings (Q1, Q3, Q5 and Q6) and the most direct illusion rating (Q6) (see second column).

The seven ANOVAs of the questionnaire items revealed highly significant main effects of synchronicity for all items, $Fs(1,29) = 19.60–85.29$; $ps < .001$; $\eta p2s = 0.40–0.75$ (see Fig. 2(A) and Table 2). The only two remaining effects were an interaction of explosion and synchronicity for Q6, $F(1,29) = 7.07$, $p = .013$, $\eta p2 = 0.20$, indicating that participants felt more strongly that the screen object was part of their body if the balloon did not explode, and a main effect of explosion for Q7, $F(1,29) = 4.62$, $p = .040$, $\eta p2 = 0.14$, indicating that participants felt more strongly to own an extra balloon-like hand if the balloon did explode. An ANOVA of the event-induced SCRs revealed only a significant main effect of synchronicity, $F(1,29) = 4.26$, $p = .048$, $\eta p2 = 0.13$, showing more pronounced SCR with synchronicity (see Fig. 2(B)). To assess power, we calculated post hoc power values by means of G*power (Faul, Erdfelder, Buchner, & Lang, 2009), based on the sample size of Experiment 1. For questionnaires results, the power to detect a large-sized effect ($\eta p2 \geqslant .14$; Cohen, 1988) for the main effect of synchronicity, other main effects, and interactions was higher than .99. For SCR results, the power to detect a medium-sized effect ($\eta p2 \geqslant .13$; Cohen, 1988) for the main effect of synchronicity was higher than .99. Accordingly, we consider the size of our sample sufficient to detect the sought-for differences.

2.3. Discussion

The synchronicity effects in Experiment 1 provide evidence for perceived body-ownership for an actively controlled virtual balloon. As such an object does not bear any obvious similarity to a human hand or other human effectors, it was unlikely to be represented in the participants' body model. This demonstrates that synchronization-induced increases in perceived ownership do not require, and can thus not depend on processes that match external effector candidates against internal body representations, as top-down approaches suggest. A number of further observations are of interest:

Firstly, we obtained significant synchronicity effects for all the questionnaire items and not just the most direct illusion question Q6 or the core illusion questions. This is not consistent with some prior RHI/VHI studies, which often found reliable effects only for core questions. However, we note that the questionnaire that the present and these previous studies used was developed for static rubber hands, while we employed dynamic non-corporeal objects/events. It is thus possible that

Table 1
Overview of experimental factors (Hand Resemblance: whether the viewed object is similar to real hand; Connectedness: whether the viewed object is 'connected' to participants' body), illusion presence and ratings (aggregated illusion ratings for Q1, Q3, Q5 and Q6/most direct illusion item [Q6]) of the four studies: Experiment 1, Ma and Hommel (2013), Experiment 2 and the Control study.

	Virtual balloon (Experiment 1)	Virtual hand (extended) (taken from Ma & Hommel, 2013)	Virtual square (Experiment 2)	Virtual hand (above) (Control Study)
Hand Resemblance	No	Yes	No	Yes
Connectedness	No	Yes	Yes	Yes
Illusion	Yes	Yes	Yes	Yes
Ratings	2.05/1.39	2.67/2.20	2.80/2.16	2.81/2.31

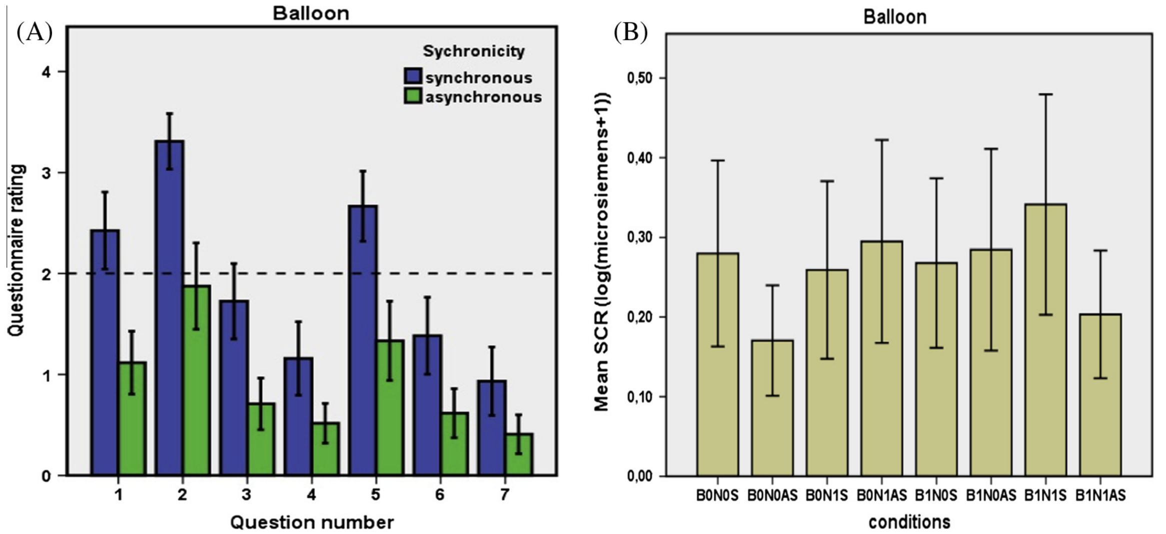


Fig. 2. Boxplots for (A) questionnaire ratings and (B) SCR results of Experiment 1. B0, B1, N0, N1, S, AS represent the same conditions as in Table 2.

Table 2
Experiment 1: Means and standard deviations (in brackets) for the questionnaire ratings. B0: Balloon not exploding; B1: Balloon exploding. N0: Needle's blunt end contacted the balloon; N1: Needle's sharp end contacted the balloon, S: Synchronous balloon movements; AS: Asynchronous balloon movements.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
B0-N0-S	2.43 (1.22)	3.32 (1.19)	1.80 (1.24)	1.07 (1.05)	2.60 (1.13)	1.37 (1.19)	0.90 (1.12)
B0-N0-AS	1.03 (1.19)	1.60 (1.67)	0.63 (0.85)	0.47 (0.73)	1.23 (1.30)	0.47 (0.73)	0.33 (0.66)
B0-N1-S	2.50 (1.28)	3.47 (0.90)	1.67 (1.15)	1.17 (1.12)	2.73 (1.11)	1.57 (1.33)	0.90 (1.12)
B0-N1-AS	0.97 (1.07)	2.07 (1.48)	0.67 (1.03)	0.50 (0.73)	1.13 (1.17)	0.53 (0.78)	0.20 (0.48)
B1-N0-S	2.30 (1.32)	3.13 (1.11)	1.60 (1.38)	1.13 (1.20)	2.47 (1.25)	1.27 (1.14)	0.97 (1.00)
B1-N0-AS	1.07 (0.98)	2.00 (1.44)	0.87 (1.01)	0.60 (0.85)	1.43 (1.48)	0.77 (0.86)	0.47 (0.82)
B1-N1-S	2.47 (1.20)	3.40 (0.77)	1.83 (1.34)	1.27 (1.11)	2.87 (1.20)	1.33 (1.12)	0.97 (1.00)
B1-N1-AS	1.40 (1.30)	1.83 (1.60)	0.67 (0.88)	0.50 (0.73)	1.53 (1.36)	0.70 (1.02)	0.63 (0.81)

the items of this questionnaire are not sufficiently specific to pick up ownership with more dynamic setups (and they indeed remain to be externally validated and psychometrically scrutinized), but it may also be that such dynamic setups produce more integrated percepts of ownership.

Secondly, we note that the explosion manipulation affected two items, one as a main effect and one in interaction with synchronicity. The fact that the two effects contradict each other to some degree (explosion increased the illusion of owning extra hands in one case and reduced the illusion of owning the balloon as ones' own hand in the other) makes these observations difficult to interpret. We speculate that two reasons might have been responsible. For one, the seeming contradiction may be taken as preliminary evidence for some, not yet fully understood role of affective factors in the perception of body ownership (see Ma & Hommel, 2013). For another, prior knowledge might have worked against the bottom-up bases of the illusion. While the synchronicity effect indicates that bottom-up information was effective in creating the illusion, resulting in the participants' perception of the virtual balloon as their own hand or other body part, prior knowledge might have suggested that one's own hand or body part does not explode through contact with a needle. If so, the balloon might have felt as one's own hand if it did not explode, but as an extra hand if the balloon did explode. In any case, none of these effects eliminated the general illusion, as ratings were still significantly increased in the synchronicity condition.

Thirdly, the mean direct ownership rating was relatively low (1.39), as was the mean for all illusion questions (aggregated illusion rating: 2.05 on the 0–4 rating scale; see Table 1). This means that participants were not very sure about whether the virtual balloon was or was not their hand or part of their body, a finding that is consistent with the equally low ratings for artificial objects reported by Short and Ward (2009). While these significant synchronicity effects show that some illusion was induced, it is interesting to consider possible reasons for the relatively low overall ratings. Equally low overall ratings (in the presence of significant synchronicity effects) were reported by Sforza, Bufalari, Haggard, and Aglioti (2010), who found an ownership illusion for other people's faces presented in front of the participants. This commonality might suggest that perceived connectedness between one's own body and the virtual extension plays a role. Neither was the other person's face connected to the bodies of the participants in the Sforza et al. study, nor were the virtual balloons connected to participants' real hands in our Experiment 1. Similarly, in the study of Short and Ward (2009), the virtual cones were not connected to participants' real hands. These observations suggest that the lack of connectedness might lead to a general drop of

ownership ratings. Indeed, the VHI has been shown to be highly dependent on the apparent connectedness between the virtual object and the participant's body (Perez-Marcos et al., 2012). Another possible reason for the rather low illusion ratings in Experiment 1 might have been the multisensory mismatch resulting from the considerable apparent distance between the real hand and the balloon. Hence, taken altogether, there are reasons to assume that the illusion obtained in Experiment 1 represents a rather conservative estimate.

3. Experiment 2

As pointed out, Experiment 1 provides evidence for ownership illusions for non-corporeal objects/events. However, even though the synchronicity effect was significant for all items, the overall level of the ratings for the location questions and the ownership question were rather low. We have discussed two possible reasons for that, namely, the (lack of) connectedness between real and candidate effector and spatial multisensory mismatch. According to this reasoning, increasing connectedness and reducing spatial mismatch should result in higher overall illusion ratings and, in particular, a higher ownership rating. We tested this possibility in Experiment 2, where we changed the setup so to maximize connectedness and minimize mismatch, as shown in Fig. 3.

3.1. Rationale and design

The experimental setup is shown in Fig. 3, with the screen being placed on the top of the box to avoid (considerable) multisensory mismatch. This setup also presented the virtual object in a way that it looked better connected to participants' bodies. A two-dimensional virtual square was used in Experiment 2 instead of the virtual balloon in Experiment 1. Similar to the controllability of the balloon, the location, orientation, and color or size of the square changed synchronously or asynchronously with the participant's hand movements. While we optimized the setup for connectedness and multisensory matching, we used this particular object to make it even less similar to real human effectors than the virtual balloon used in Experiment 1. For one, while the virtual balloon was as three-dimensional as the participant's real hand, the virtual square was two-dimensional. And, for another, while the size changes used in Experiment 1 and in the size condition of Experiment 2 bear some similarity to the opening and closing movement of the real hand (which also results in size changes of the real hand's shape), the color changes used in the color condition of Experiment 2 minimize this similarity. By comparing the results for the size and the color condition of Experiment 2, and by comparing the overall results of Experiment 2 to Experiment 1, these manipulations allowed us to assess the possible role of similarity between real hands and virtual objects.

3.2. Method

Twenty-two participants (5 males; mean age = 23 years, SD = 3.79 years, range 20–34) fulfilling the same criteria as in Experiment 1 were recruited. The study was approved by the Leiden University human research ethics committee. The participants experienced four conditions in balanced order, composed by combining two factors: (1) in addition to hand-controlled location changes, the square changed either in size or in color with the opening and closing of the participant's hand; and (2) the dimension changes of the virtual square were either synchronized or not synchronized with the movement of the participant's hand.

The experimental procedure of Experiment 2 was similar to Experiment 1. Participants wore the same instruments as shown in Fig. 1(A). They were seated in front of the screen and put their hands inside the box, and looked at the screen, as shown in Fig. 3, where a virtual square appeared. In each trial, the participants were to rotate, open and close their hands freely. In the synchronous size trials, opening the hand made the virtual square bigger while closing the hand made it smaller, and in synchronous color change trials, opening the hand made the square greener while closing it made it bluer. The

Fig. 3. Setup of Experiment 2 and Control study.

orientation of the virtual square changed synchronously with the orientation change of the real hand. This visuomotor phase lasted for 1 min. Then visuotactile stimulation was applied: a virtual ball appeared and took four seconds to move to contact the virtual square, which was again accompanied by vibration, and then took another four seconds to return to the original position. This procedure was repeated until 30 s were over. In asynchronous trials, the orientation and color/size change of the virtual square was delayed by 2 s with respect to the hand movements, and the vibration was delayed by 2 s with respect to the contact with the square.

After each condition, participants responded to the same seven questions as in Experiment 1, except that we replaced all references to the balloon by references to the square, and replaced all references to the virtual needle by references to the virtual ball. After the questionnaire and a short break, participants ran through the same procedure again, only that a threat phase was presented instead of the questionnaire. In the threat phase, we used the same virtual ball movement as in the synchronous condition. However, when the ball touched the square, the square broke into several pieces and participants received vibration at the palm of their hand. We measured SCR during the entire experiment, the SCR was computed almost the same way as in Experiment 1, except that the stimulus/event onset was defined as the time when the square broke.

3.3. Results

Table 1 provides an overview of the relevant design features, the presence or absence of the ownership illusion expressed as synchronicity effect for Q6, the mean of all illusion questions ratings, and the direct illusion question rating for Experiment 2. The most direct ownership illusion rating assessed by Q6 was 2.16 and the aggregated illusion rating (direct illusion and location questions) was 2.80 (see fourth column).

Responses to the seven items of the questionnaire and the SCR measures were analyzed by means of 2(synchronicity) $\times$ 2(changing dimension) ANOVAs with all independent factors varying within participants. The seven ANOVAs of the questionnaire items revealed highly significant main effects of synchronicity for all questionnaire items, $Fs(1,21) = 22.47$–84.23; $ps < .001$; $\eta p2s = 0.52$–0.80 (see Fig. 4(A) and Table 3), indicating that the illusion was created for all aspects we assessed. Moreover, there was an interaction between synchronicity and dimension for Q6, $F(1,21) = 4.59$, $p = .044$, $\eta p2 = 0.18$, showing that participants felt more strongly that the screen object was part of their body if the square changed in color than in size. The ANOVA of the event-induced SCRs produced only a significant main effect of synchronicity, $F(1,21) = 4.506$, $p = .046$, $\eta p2 = 0.177$, showing more pronounced SCR with synchronicity (see Fig. 4B). Power was calculated as in Experiment 1. For questionnaire results, the power to detect a large-sized effect ($\eta p2 \geqslant .18$) for the main effect of synchronicity and an interaction was higher than .99. For SCR, the power to detect a large-sized effect ($\eta p2 \geqslant .177$) for the main effect of synchronicity was higher than .99.

3.4. Discussion

Table 1 shows that ownership illusory ratings were higher for the virtual square in Experiment 2 than for the virtual balloon in Experiment 1; moreover, the rating for the direct illusion question Q6 was higher than the middle score. Together with the high ownership illusory ratings, the synchronicity effects in Experiment 2 clearly indicate that participants

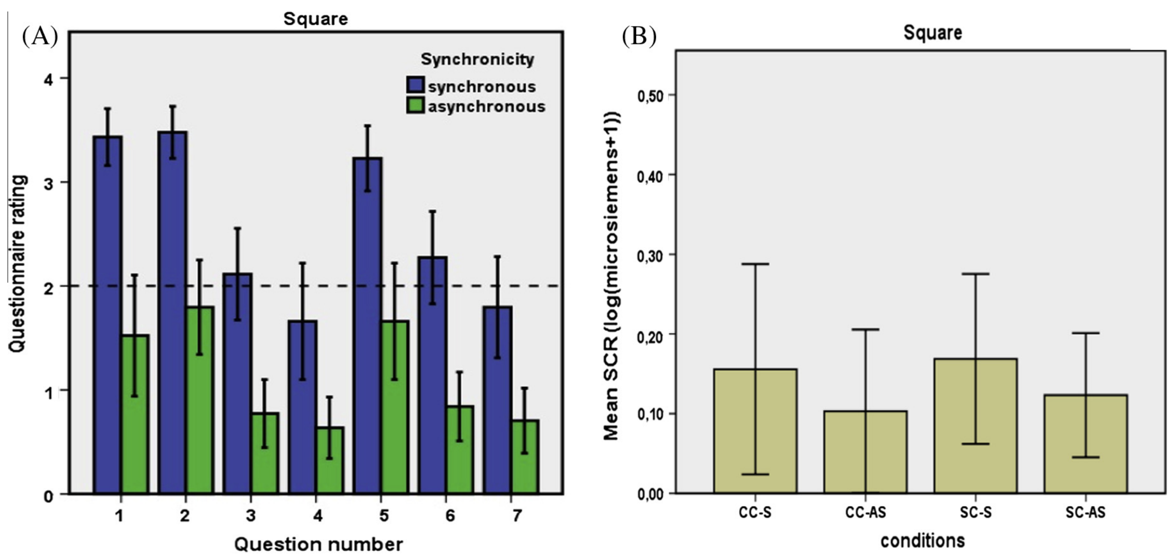


Fig. 4. Boxplots for (A) Questionnaire ratings and (B) SCR results of Experiment 2. CC, SC, S, AS represent same conditions as in Table 4.

Table 3
Experiment 2: Means and standard deviations (in brackets) for the questionnaire ratings. CC: Square color changes, SC: Square size changes. S: Synchronous square changes, AS: Asynchronous square changes.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
CC-S	3.36 (1.00)	3.36 (0.73)	2.45 (1.26)	1.55 (1.22)	3.27 (0.70)	2.41 (1.22)	1.59 (1.26)
CC-AS	1.59 (1.62)	1.45 (1.14)	1.00 (1.27)	0.55 (0.74)	1.59 (1.50)	0.73 (0.83)	0.55 (0.67)
SC-S	3.50 (0.67)	3.55 (0.86)	2.32 (1.21)	1.55 (1.26)	3.18 (0.85)	1.91 (1.19)	1.86 (1.17)
SC-AS	1.68 (1.52)	1.91 (1.41)	1.14 (1.32)	0.68 (0.89)	1.95 (1.40)	0.95 (0.84)	0.86 (1.04)

perceived the actively operated virtual square as an extension of their own body. This pattern also supports our hypothesis that connectedness and minimal multisensory mismatch contribute to a high degree of perceived ownership.

The illusion again affected all questions, which confirms our previous observations that the standard RHI/VHI questionnaire is less specific (or the underlying processes are more integrated) with virtual, dynamic manipulations than it is for static rubber hands. The illusion was not any stronger for the size condition, which arguably captured more aspects of the real-hand movements that controlled the size of the virtual object, than for the color condition. In fact, the significant interaction for Q6 indicates that the main ownership question was more sensitive to the color manipulation than to the size manipulation. This shows that the similarity between real hand and virtual object, including their dynamics, do not seem to play a relevant role in inducing ownership illusions above and beyond basic spatiotemporal intersensory matching.

Another interesting observation was that the SCR level was lower in Experiment 2 than in Experiment 1. Along the lines of Ma and Hommel (2013), this is likely to reflect the impression that a ball hitting a virtual square (as used in Experiment 2) is perceived to be less threatening and less related to the real hand than a needle pricking into a virtual balloon (as used in Experiment 1). Hence, this observation provides convergent evidence that affective factors play a role in the perception of body ownership.

Taken together, the findings confirm our observation from Experiment 1 in showing that participants are likely to perceive ownership for a virtual object the shape or color of which they can directly control.

4. Control study

In the two experiments, we showed that participants can perceive non-corporeal objects as part of their own body, especially when the non-corporeal object was presented with optimized connectedness and multisensory matching. But one may argue that, despite the relatively high direct illusion item rating for the virtual square in Experiment 2, the absolute rating is still lower than in some previous studies that were using virtual hands (e.g., Kammers et al., 2009; Slater et al., 2008). To explore this issue, we considered the data from a previous study from our lab and ran a control study to collect ratings of corporeal objects (i.e., virtual hands) within the same virtual environment and experimental setup.

To allow for a direct comparison between the non-corporeal condition of the present Experiment 1 with a corporeal-effector condition, we compared our findings to data from a previous study. In this study, we replicated the VHI with virtual objects that looked like real human hands, as reported by Slater et al. (2008), and had the virtual hands threatened by a cutting knife (instead of the pricking injection needle that we used in the present Experiment 1). That is, apart from the particular kind of threat and the use of virtual hands rather than other virtual objects, the experimental conditions were identical. This study (reported and further described in Ma & Hommel, 2013) tested 18 participants and used a virtual display that seemed to extend the participant's own invisible hand into virtual space. Synchronicity manipulation and questionnaire were as in the present study (see Table 1, third column). As Table 1 shows, the ratings in Ma and Hommel (2013) were as high as in the present Experiment 2 but higher than in the present Experiment 1.

Given that the setup of Ma and Hommel (2013) was different from the setup used in the present Experiment 2—which minimized the multisensory mismatch—we ran a further control study to see whether a corporeal version of Experiment 2 would produce higher ownership ratings than our non-corporeal version. To do so, we replace the square by a virtual human hand that seemed connected to the participant's shoulder, and was located above the real hand, with the otherwise identical setup as in Experiment 2 (shown in Fig. 3). The experimental procedure was the same as in Experiment 2 with a virtual ball touching the virtual hand. All questionnaire items were the same as Experiment 2, except that we replaced references to the square by references to the virtual hand. We tested 24 participants (6 males; mean age = 23 years, SD = 3.87 years, range 20–34) who fulfilled the same criteria as in Experiment 1 and 2 were recruited. The study was approved by the Leiden University human research ethics committee.

The seven ANOVAs of the questionnaire items ratings revealed highly significant main effects of synchronicity for all items except Q7, $Fs(1,23) = 6.94–28.37$; $ps < .015$; $\eta p2s = 0.23–0.55$ (see Fig. 5 and Table 4). The power to detect a large-sized effect ($\eta p2 \geqslant .23$) for the main effect of synchronicity was higher than .99. The direct ownership rating assessed by Q6 was 2.31 and the aggregated illusion rating (direct illusion and location questions) was 2.81 (see Table 1, fifth column).

As Table 1 shows, with the optimized multisensory matching in the Control study, the illusion ratings did not differ from the ratings of Ma and Hommel (2013). This result is consistent with previous RHI/VHI studies (e.g., Ehrsson et al., 2008; Kammers et al., 2009; Ma & Hommel, 2013; Slater et al., 2008; Tsakiris & Haggard, 2005), in which a rubber/virtual hand induced the illusion successfully in different positions near the real hand. The fact that it does not matter much whether

the virtual hand seems to extend from or is located above the real hand suggests that the spatial distances within the range of our manipulations do not affect the degree of multisensory mismatch in our virtual environment. This provides indirect evidence for the possibility that connectedness (which was optimal in the Control study and in Ma & Hommel, 2013) plays a role.

Even more importantly, the ratings were comparable for Experiment 2 and the two virtual hand studies, which does not provide any evidence that synchronicity-induced ownership illusions are any more convincing for corporeal than for non-corporeal virtual objects. Moreover, our findings suggest that perceived connectedness between real hand and virtual object is not necessary for the ownership illusion as such, even though it increases the overall level of the ownership experience.

5. General discussion

In two experiments, we showed that people are more likely to perceive a virtual balloon or a square as part of their body if they have direct, immediate control over spatiotemporal and appearance-related features of these objects. Body ownership was accompanied by significantly stronger affective "care" about the respective object, as indicated in the increases in SCR—a pattern that has also been claimed to indicate ownership (Armel & Ramachandran, 2003). Taken altogether, our findings amount to an existence proof that non-corporeal objects can be perceived as parts of one's own body, which provides strong evidence against the idea that perceived body-ownership relies on pre-existing, temporally stable body models (Tsakiris, 2010). This challenges the speculation that body representations integrate novel parts only to the degree that there is a functional reason for that part to be integrated (Tsakiris et al., 2007) and provides strong support for bottom-up approaches to self-representation (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998).

Our findings also show that the integration of temporally and spatially congruent multisensory signals is sufficient to induce the body ownership illusion, even when visual information directly contradicts the presence of a physical limb at the location of the perceived illusory hand or effector. However, we also found that the ownership illusion is more convincing if real and virtual effectors seem to be close and connected. This suggests that self-perception is modulated by Gestalt laws, as known from object perception, where connectedness (as captured by the laws of proximity and the law of continuity) is a central cue for perceived unity (i.e., belongingness to the same object or event; e.g., Sternberg, 2003). Hence, the process of perceiving oneself may not be special but rely on the same principles as perceiving objects and non-personal events (Hommel, 2013; Hommel, Colzato, & van den Wildenberg, 2009)—including Gestalt laws. In the following, we discuss a number of theoretical and practical implications of our findings.

An obvious theoretical implication of our findings is that similarity between one's body parts and a novel candidate effector is unlikely to be a necessary requirement for ownership perception. Tsakiris (2010) has suggested that an object will be perceived as a body part if, and only if, it meets three criteria: (1) the visual appearance of the object matches internal knowledge about of the shape of human body parts; (2) the postural and anatomical state of the object matches that of a real effector (that is hidden from view); and (3) seen stimuli (about the object) and felt stimuli (about one's real effector) match. In the present study, the third criterion was fully met, but neither did the balloon or the square look similar to any of our participants' body parts nor did the balloon's or square's postural and anatomical state match that of a real effector. This implies that the first and second criterion are unlikely to be absolutely critical for inducing illusory ownership. If so, our findings are

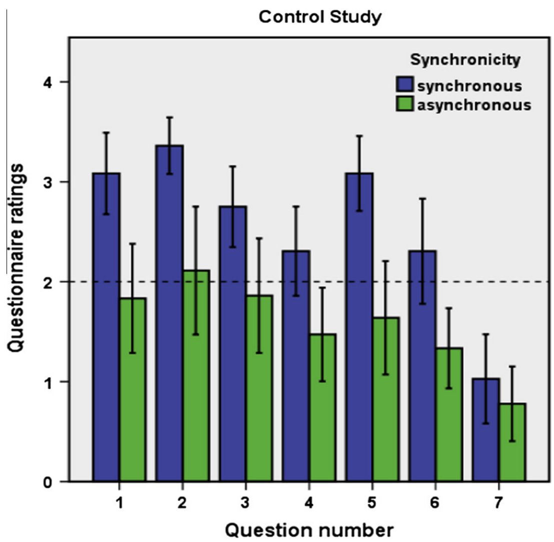


Fig. 5. Boxplots for questionnaire ratings of Control study.

Table 4
Control study: Means and standard deviations (in brackets) for the questionnaire ratings.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Synchronous	3.08 (1.00)	3.36 (0.69)	2.75 (0.99)	2.31 (1.09)	3.08 (0.92)	2.31 (1.29)	1.03 (1.09)
Asynchronous	1.83 (1.34)	2.11 (1.57)	1.86 (1.40)	1.47 (1.15)	1.64 (1.39)	1.33 (0.98)	0.78 (0.92)

more consistent with a (however very relaxed and stripped) version of the model proposed by Makin et al. (2008), with the only remaining constraint that virtual object and body are perceived to be connected.

Another interesting finding of our study that may be of either methodological or theoretical relevance is that we found comparable synchronicity effects for almost all questionnaire items. On the one hand, this might indicate that the questionnaire taken from traditional RHI studies does not work quite as well for non-corporeal virtual objects. On the other hand, however, this may be more than a methodological observation. It is possible that static manipulations systematically underestimate the impact of synchronicity manipulations on all self-perception aspects but the most direct ownership question. More dynamic manipulations may make more perceptual dimensions perceivable or salient, which then leads to measurable synchronicity effects on all items relating to any aspect of self-perception. In other words, the broader, less selective effects we consistently observed may represent the more realistic pattern. This possibility would fit the idea that ownership and agency may be more closely related than hitherto assumed (cf., Short & Ward, 2009).

It is interesting to note that our finding of a rather close relationship between ownership and agency does not seem to fit with recent observations of Kalckert and Ehrsson (2014). They compared three versions of the classical rubber-hand setup: a standard version in which the experimenter stroked both the rubber hand and the real hand; a passive movement condition in which the experimenter moved a finger of the rubber hand and a finger of the real hand; and an active movement condition in which the participant him or herself moved a finger of the real hand and thereby induced a movement of the corresponding rubber-hand finger. The findings did not provide evidence for the difference between these three conditions, and so the authors concluded that these conditions are comparable. Given that the active-movement condition can be considered to induce more agency (which is indeed what the authors observed), the failure to find more pronounced ownership does not seem to fit with our results. The fact that Kalckert and Ehrsson (2014) manipulated agency within a rubber-hand setup while we manipulated agency within a virtual-hand setup makes direct comparisons difficult, and null effects are difficult to interpret as well. However, we note that the agency-inducing condition in the Kalckert and Ehrsson study was unlikely to increase the amount of cross-modal stimulation—it just brought the time point of stimulation under the control of the participant. In contrast, our setup strongly boosted the number of data points available for cross-modal comparison in the agency condition. This can be taken to support the speculation that it is not the experience of agency that matters for ownership but the amount of bottom-up information that is available for cross-modal matching operations. In other words, it seems that it is not the experience of agency but objective agency and its information-generating potential that play the decisive role.

While our findings do not support claims of a necessary role of top-down factors in the experience of body ownership, they do leave space for a possible compensatory or additive role in ownership perception. The very fact that people accept immobile rubber hands as body parts may suggest that body-part resemblance can compensate for controllability. This would fit the considerations of Short and Ward (2009), who assume that a wide variety of virtual objects can be incorporated if their actions are predictable and in accordance with the intentions of the agent. In the absence of control, other factors, such as visual appearance, other anatomical and postural properties, may become more important.

More generally speaking, perceived ownership might arise from a rather broad integration of both top-down and bottom-up factors, much like it has been considered for judgments of agency (Synofzik, Vosgerau, & Newen, 2008). Indeed, in real life neither ownership nor agency issues are particularly common, so that evolutionary pressure to create dedicated mechanisms to explicitly judge ownership or agency must have been low. If so, people that are forced to make such judgments are likely to "grab" any information they can get hold on, so that the use of multiple sources of information and stimulation seems to make a lot of sense.

Taken altogether, our findings challenge strict top-down models that require a match between external objects and some internal body representation for illusory ownership to occur. Rather, people seem to be relatively liberal in accepting all sorts of objects to become part of their body, if they can control relevant features and the behavior of these objects, and in particular if the objects seem physically connected to their body. In other words, people perceive as their body everything that expresses their intentions, including things within reach that move "as they wish". Given the emphasis of the ideomotor approach to action control on self-generated action effects (Hommel, 2009), this suggests that ideomotor mechanisms play an important role in the generation of self-representations (Hommel, 2013).

Acknowledgments

This research was supported by a post-graduate scholarship of the China Scholarschip Council to K.M. and an infrastructure grant of the Netherlands Research Organization (NWO) to B.H. We would like to thank an anonymous reviewer for detailed assessments. Figs. 1 and 3 show the first author with his permission.

References

Armel, K. C., & Ramachandran, V. S. (2003). Projecting sensations to external objects: Evidence from skin conductance response. *Proceedings of the Royal Society of London, Series B: Biological Sciences, 270*(1523), 1499–1506. http://dx.doi.org/10.1098/rspb.2003.2364.

Botvinick, M., & Cohen, J. (1998). Rubber hands' feel' touch that eyes see. *Nature, 391*(6669). http://dx.doi.org/10.1038/35784. 756-756.

Boucsein, W. (2011). *Electrodermal activity*. Heidelberg: Springer.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Costantini, M., & Haggard, P. (2007). The rubber hand illusion: Sensitivity and reference frame for body ownership. *Consciousness & Cognition, 16*, 229–240.

De Vignemont, F. (2011). Embodiment, ownership and disownership. *Consciousness and Cognition, 20*(1), 82–93.

Dummer, T., Picot-Annand, A., Neal, T., & Moore, C. (2009). Movement and the rubber hand illusion. *Perception, 38*(2), 271–280.

Ehrsson, H. H., Rosén, B., Stockselius, A., Ragnö, C., Köhler, P., & Lundborg, G. (2008). Upper limb amputees can be induced to experience a rubber hand as their own. *Brain, 131*(12), 3443–3452.

Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science, 305*(5685), 875–877.

Farmer, H., Tajadura-Jiménez, A., & Tsakiris, M. (2012). Beyond the colour of my skin: How skin colour affects the sense of body-ownership. *Consciousness and Cognition, 21*(3), 1242–1256.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160.

Figner, B., & Murphy, R. O. (2010). Using skin conductance in judgment and decision making research. In *A handbook of process tracing methods for decision research: A critical review and user's guide* (pp. 163–184).

Graziano, M. S., Cooke, D. F., & Taylor, C. S. (2000). Coding the location of the arm by sight. *Science, 290*, 1782–1786.

Guterstam, A., Gentile, G., & Ehrsson, H. H. (2013). The invisible hand illusion: Multisensory integration leads to the embodiment of a discrete volume of empty space. *Journal of Cognitive Neuroscience, 25*(7), 1078–1099.

Haans, A., IJsselsteijn, W. A., & de Kort, Y. A. (2008). The effect of similarities in skin texture and hand shape on perceived ownership of a fake limb. *Body Image, 5*(4), 389–394.

Holmes, N. P., Snijders, H. J., & Spence, C. (2006). Reaching with alien limbs: Visual exposure to prosthetic hands in a mirror biases proprioception without accompanying illusions of ownership. *Perception and Psychophysics, 68*, 685–701.

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research, 73*, 512–526.

Hommel, B. (in press). Action control and the sense of agency. In B. Eitam & P. Haggard (Eds.), *Human agency: Functions and mechanisms.* New York: Oxford University Press.

Hommel, B., Colzato, L. S., & van den Wildenberg, W. P. M. (2009). How social are task representations? *Psychological Science, 20*, 794–798.

Hommel, B., & Elsner, B. (2009). Acquisition, representation, and control of action. *Oxford Handbook of Human Action*, 371–398.

Hommel, B. (2013). Ideomotor action control: On the perceptual grounding of voluntary actions and agents. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action science: Foundations of an emerging discipline* (pp. 113–136). Cambridge, MA: MIT Press.

Kalckert, A., & Ehrsson, H. H. (2014). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition, 26*, 117–132.

Kammers, M. P., de Vignemont, F., Verhagen, L., & Dijkerman, H. C. (2009). The rubber hand illusion in action. *Neuropsychologia, 47*, 204–211.

Kokkinara, E., & Slater, M. (2014). Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception, 43*(1), 43–58.

Lloyd, D. M. (2007). Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition, 64*(1), 104–109.

Longo, M. R., Schüür, F., Kammers, M. P., Tsakiris, M., & Haggard, P. (2009). Self awareness and the body image. *Acta Psychologica, 132*(2), 166–172.

Ma, K., & Hommel, B. (2013). The virtual-hand illusion: Effects of impact and threat on perceived ownership and affective resonance. *Frontiers in Psychology, 4*, 604. http://dx.doi.org/10.3389/fpsyg.2013.00604.

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. *Behavioural Brain Research, 191*(1), 1–10.

Maravita, A., Spence, C., & Driver, J. (2003). Multisensory integration and the body schema: Close to hand and within reach. *Current Biology, 13*, R531–R539.

Pavani, F., & Zampini, M. (2007). The role of hand size in the fake-hand illusion paradigm. *Perception, 36*(10), 1547.

Perez-Marcos, D., Sanchez-Vives, M. V., & Slater, M. (2012). Is my hand connected to my body? The impact of body continuity and arm alignment on the virtual hand illusion. *Cognitive Neurodynamics, 6*(4), 295–305.

Sanchez-Vives, M. V., Spanlang, B., Frisoli, A., Bergamasco, M., & Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. *PLoS ONE, 5*(4), e10381. http://dx.doi.org/10.1371/journal.pone.0010381.

Schütz-Bosbach, S., Tausche, P., & Weiss, C. (2009). Roughness perception during the rubber hand illusion. *Brain and Cognition, 70*(1), 136–144.

Sforza, A., Bufalari, I., Haggard, P., & Aglioti, S. M. (2010). My face in yours: Visuo-tactile facial stimulation influences sense of identity. *Social Neuroscience, 5*(2), 148–162.

Short, F., & Ward, R. (2009). Virtual limbs and body space: Critical features for the distinction between body space and near-body space. *Journal of Experimental Psychology: Human Perception and Performance, 35*, 1092–1103.

Slater, M., Perez-Marcos, D., Ehrsson, H. H., & Sanchez-Vives, M. V. (2008). Towards a digital body: The virtual arm illusion. *Frontiers in Human Neuroscience, 2*, 6. http://dx.doi.org/10.3389/neuro.09.006.2008.

Sternberg, R. (2003). *Cognitive psychology* (3rd ed.). Thomson Wadsworth.

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition, 17*, 219–239.

Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia, 48*, 703–712.

Tsakiris, M., Carpenter, L., James, D., & Fotopoulou, A. (2010). Hands only illusion: Multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research, 204*(3), 343–352.

Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: Visuotactile integration and self-attribution. *Journal of Experimental Psychology: Human Perception & Performance, 31*, 80–91.

Tsakiris, M., Haggard, P., Franck, N., Mainy, N., & Sirigu, A. (2005). A specific role for efferent information in self-recognition. *Cognition, 96*(3), 215–231.

Tsakiris, M., Prabhu, G., & Haggard, P. (2006). Having a body versus moving your body: How agency structures body-ownership. *Consciousness and Cognition, 15*(2), 423–432.

Tsakiris, M., Schütz-Bosbach, S., & Gallagher, S. (2007). On agency and body-ownership: Phenomenological and neurocognitive reflections. *Consciousness and Cognition, 16*, 645–660.

White, R. C., Davies, A. M. A., Halleen, T. J., & Davies, M. (2010). Tactile expectations and the perception of self-touch: An investigation using the rubber hand paradigm. *Consciousness and Cognition, 19*(2), 505–519.