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ORIGINAL ARTICLE

Self-perception beyond the body: the role of past agency

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Abstract Technological progress provides us with an increasing variety of devices that now mediate what previously has been achieved by social face-to-face interaction. Here, we investigate whether this leads to the incorporation of such devices into representations of our body. Using explicit (body ownership questionnaire) and implicit (proprioceptive drift rate) measures together with a synchronous/asynchronous stroking technique, we show that people have an increased tendency to integrate non-corporeal objects into their body after synchronous stroking. Explicit measures of body ownership show that people had greater average scores in the synchronous condition as compared to the asynchronous condition for all objects that we tested (computer mouse, rubber hand, smart phone, and a wooden block). However, our implicit measure of body ownership showed a numerically larger proprioceptive drift for a rubber hand than for a computer mouse, numerically comparable ownership measures for a smart phone and a rubber hand, and a significantly stronger proprioceptive drift for a smart phone than for a wooden block. These findings suggest that direct, subjective measures and indirect, objective measures of body ownership are based on different kinds of information; the latter might be more sensitive to objects for which we recall past agency based on our history of personal experiences with these objects. Taken altogether, our observations support the idea that the perceived bodily self is rather flexible and is likely to emerge through multisensory integration and top-down expectations of agency.

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Introduction

How do we represent ourselves? The answer to this question has often been taken to depend on the time span under consideration: While the "narrative self" refers to those aspects that integrate the current experience with our history to maintain coherence, the "minimal self" refers to those aspects that we experience in the present situation (Gallagher, 2000). Authors differ with respect to the degree to which the minimal self is assumed to emerge from immediate experience, which is particularly obvious in recent accounts of the so-called "rubber-hand illusion" (RHI). When people are facing a fake hand that is stroked synchronously (but not asynchronously) with their own occluded hand (i.e., if there is a match of tactile and visual information), they experience the illusion that the fake hand becomes a part of their own body (Botvinick & Cohen, 1998). The concept of the RHI can even be applied to entire bodies (Lenggenhager, Tadi, Metzinger, & Blanke, 2007). While the exact mechanisms underlying this effect are not yet well understood, the available hypotheses fall into two categories. Some models attributed the RHI to the multisensory integration of bottom-up signals coming from vision and touch (Makin, Holmes, & Ehrsson, 2008), which would suggest that, in principle, any object could induce the perception of body ownership. In contrast, other models assume that body ownership arises through the interaction between the current multisensory input and a pre-existing internal body model (Tsakiris, 2010).

The main argument proponents of internal body models hold against bottom-up multisensory integration approaches is that the RHI has not been observed for non-corporeal, body-dissimilar objects, such as wooden blocks (Lenggenhager et al., 2007; Tsakiris, Carpenter, James, & Fotopoulou, 2010; Tsakiris & Haggard, 2005). However, recent studies have provided evidence for agency-induced increases of perceived ownership for non-corporeal objects (Ma & Hommel, 2013, 2015a, b). They show that people experience increased ownership when facing virtual balloons that vary in size, or virtual rectangles that vary in color synchronously with the receiver's own hand movements (Ma & Hommel, 2013, 2015a, b). This suggests that perceived ownership does not end at the skin but can extend to novel events, such as dynamic non-corporal objects, if they change systematically with one's own actions and can thus be considered as functional body extensions. In other words, what we perceive as our body is not (fully) determined by stored knowledge about body parts but may also comprise objects or events on which we exert agency.

The purpose of the present study was to investigate how far this principle can be extended. On the one hand, the dependence of the ownership illusion on the degree of control over the behavior of an object might suggest that ownership only extends to non-corporeal objects that currently move with our intentions and our body (*current agency*), as observed by Ma and Hommel (2015a). If so, the current lack of shared movement with our body should make the ownership illusion disappear. On the other hand, however, the mere memory of *past agency* (recalled agency) exerted on an object might be sufficient to create ownership illusions, if only some degree of multisensory (e.g., visual-tactile) synchrony is provided. The present study tested these possibilities by considering static non-corporal objects with different shapes and different past agency histories shared by the participant, that were either stroked synchronously or asynchronously with the participant's own hand.

In Experiment 1, we tested a rubber hand, which shared many anatomical features with the participant's own hand, against a computer mouse. Both a rubber hand and a computer mouse can be assumed to remind participants of their own hand- and mouse-related experiences, which, in the case of the mouse involved, shared movement of mouse and hand. Accordingly, both rubber hand and mouse were assumed to represent objects that the participant shared a history of agency with, even though there was no agency possible in the current situation.

If body part similarity would be essential to produce the RHI, the rubber hand, but not the computer mouse, should create an (or increase the) ownership illusion, operationalized as an increase of perceived ownership with synchronous as compared to asynchronous stroking of object and hand. In contrast, if past agency based on previous experience with the object would be sufficient, both objects should create ownership illusions. In Experiment 2, we extended the experimental rationale to a smart phone, that is, to a non-corporeal object people had an extended personal history of agency experiences with, but in a more indirect and personalized way than with a computer mouse. Finally, in Experiment 3, we compared the smart phone with a wooden block, with which participants did not share any personal agency history.

Experiment 1

This experiment sought to replicate the classical RHI in one condition and to extend this illusion, if possible, to a computer mouse in another condition. We assessed the tendency to integrate the objects into one's body scheme by means of two standard indicators of the RHI (Botvinick & Cohen, 1998; Tsakiris et al., 2010; Tsakiris & Haggard, 2005). First, as in almost all studies in the field, we assessed the tendency to agree (or disagree) to a series of statements in a body ownership questionnaire adapted from Botvinick and Cohen (1998). Second, as a more objective, but also more implicit measure, we assessed the tendency to perceive one's own unseen index finger as closer to the object after synchronous as compared to asynchronous stroking, the proprioceptive drift. To estimate this type of self-localization bias (Tsakiris & Haggard, 2005), we analyzed the differences between the perceived left index finger location before and after stroking. Past research has shown some, but not complete convergence of these two measures (Riemer, Bublatzky, Trojan, & Alpers, 2015; Rohde, Di Luca, & Ernst, 2011). While this can be considered problematic, in the sense that the theoretical relationship between the two remains opaque, it also shows that the two measures pick up different kinds of information, which for explorative studies as the present one seems useful.

The different approaches to body ownership differ in their predictions regarding the outcomes of this experiment. From an internal body model approach, one would expect that the rubber hand, but not the computer mouse would be perceived as a body part, which implies that neither subjective perception nor objective bias should increase with synchronous stroking for the computer mouse. From a multisensory integration approach, however, one might expect that both objects show a synchrony effect, as both should be able to become a perceived part of one's body in principle. However, it is also possible that non-corporeal objects are integrated only if their current behavior can be controlled (i.e., with current, but not with past agency). If so, our static mouse condition may not give rise to ownership perception. We tested these predictions by having participants (in different conditions) facing a rubber hand or a computer mouse that was stroked either synchronously or asynchronously with their own occluded left hand (see Fig. 1a).

Methods

Participants

Twenty right-handed adults (13 female; mean age 21.3; age range 18–30) all experienced in working with a computer mouse (range 6–18 years) participated. All had normal or corrected to-normal vision, were naive with regard to the hypotheses of the experiment, and received compensation for their participation. Participants gave their informed consent to participate in the study, which was conducted in accordance with the ethical standards laid down in the 1975 Declaration of Helsinki and with the ethical guidelines of the ethics committee of the University of Muenster.

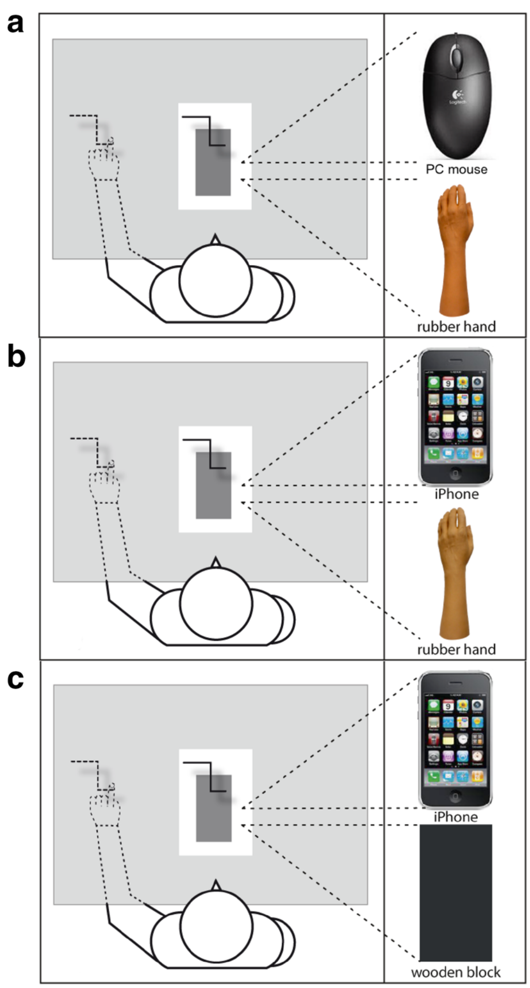

Fig. 1 Experimental setting: **a** A computer mouse or a rubber hand in Experiment 1, **b** an iPhone or a rubber hand in Experiment 2, and **c** an iPhone or a wooden block in Experiment 3 were placed in the participants' body-midline and were stimulated synchronously or asynchronously with the participants' occluded left index finger

Stimuli and apparatus

On the table in front of the participant was a box that prevented the participant's hand from view. The rubber hand/computer mouse (standard computer mouse: Logitech Optical Mouse PS/2) was placed under the surface of a board, so that it could be made visible by opening the board. The participant's left index finger was stroked on its top from knuckle to fingertip and back by means of a computer-controlled robot arm with a paintbrush attached, while the midline of the object was stroked synchronously or asynchronously by another, identical device (Tsakiris et al., 2010). This allowed the precise control of onset, direction, speed and stroking duration of both devices independently. The distance between the paintbrush over participants' index finger and the paintbrush over the rubber hand/computer mouse was 23 cm. A ruler was placed on the surface of the board to verbally indicate the perceived position of participant's left index finger.

Task and procedure

Each participant worked through four experimental blocks, which were composed by combining the two objects (rubber hand/computer mouse) and the two stroking conditions (synchronous/asynchronous). Block order was counterbalanced across participants. Each block started with a baseline measurement of the participant's felt index finger position (Botvinick & Cohen, 1998). During this measurement, the object was made invisible and there was no tactile stimulation. Participants saw a ruler placed on the surface and verbally indicated the perceived position of their left index finger (Tsakiris & Haggard, 2005). Then the ruler was removed, the object was made visible, and 1 min of (synchronous or asynchronous) stroking was delivered. Thereafter, the object was made invisible and participants again indicated the perceived location of their left index finger. Here, the ruler was presented with a different offset to avoid carry-over effects from the previous response. The object was made visible, finger and object were stimulated, and the perceived finger position was localized three more times to complete the block. At the end of each block, participants rated their agreement on a visual analog scale (10 cm) ranging from totally disagree (score 0) to totally agree (score 10) to a series of eight statements (Q1–Q8) related to *body ownership* (Q1–Q3), *perceived position* of one's own hand (Q4) or the object (Q7), the *experience of tactile stimulation* (Q5) and the *experience of body resemblance* (Q8) as adapted from Botvinick and Cohen (Botvinick & Cohen, 1998). The classification of the different items to underlying components of the RHI is based on the factors that have been proposed on the basis of a principal component analysis of 27 questions related to the subjective experience of the illusion performed by Longo, Schuur, Kammers, Tsakiris, and Haggard (2008). Q6 cannot easily be attributed to one of these components. We refer to this component as *body transformation*, as it is related to the feeling that one's own hand turns into the object.

Q1: It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand/computer mouse touched.
Q2: It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand/computer mouse.
Q3: I felt as if the rubber hand/computer mouse were my hand.
Q4: It felt as if my hand were drifting towards the rubber hand/computer mouse.
Q5: It seemed as if the touch I was feeling came from somewhere between my own hand and rubber hand/computer mouse.
Q6: It felt as if my hand was turning into the rubber hand/computer mouse.
Q7: It appeared as if the rubber hand/computer mouse were drifting towards my hand.
Q8: It felt as if the rubber hand/computer mouse began to resemble my own hand, in terms of shape, color or other features.

Each block was followed by a break of 5 min outside the laboratory to avoid carry-over effects to the next block. The procedure of the following blocks was the same as in the first block except the type of stroking, which was always different from that in the previous block. The object, however, was held constant and changes after the second block.

Results

We performed a 2 × 2 factorial MANOVA (Q1–Q8, *Pillai's* trace) and univariate ANOVAs using each individual item (Q1–Q8) as response variables with Object (rubber hand, computer mouse) and Synchrony (synchronous, asynchronous) between seen and felt stroking as within-subject variables. The latter served to separately assess the presence of the RHI (Q1–Q3), the experience of perceived position (Q4 and Q7), the experience of tactile stimulation (Q5), the experience of body transformation (Q6) and the experience of body resemblance (Q8) during the experiment. To analyze proprioceptive drift during the experiment, we performed a 2 × 2 factorial ANOVA with Object (rubber hand, computer mouse) and visuo-tactile Synchrony (synchronous, asynchronous) as within-subject variables.

Questionnaire

We obtained a significant main effect of Synchrony, $F(8, 12) = 5.68$, $p = 0.004$, partial $\eta^2 = 0.79$. As shown in Fig. 2a, synchronous stroking increased the body ownership scores as compared to asynchronous stroking in all statements assessing the presence of the RHI (Q1–Q3: $F\text{s} > 24.38$, $p\text{s} < 0.001$). The questions measuring the experience of perceived hand/object position and the experience of tactile stimulation showed no Synchrony effect (Q4, Q5, Q7: $F\text{s} < 2.85$, $p\text{s} > 0.107$). Perceived body transformation (Q6) showed higher scores after synchronous than after asynchronous stroking, $F(1, 19) = 13.07$, $p = 0.002$, partial $\eta^2 = 0.41$. Body resemblance was also experienced as stronger after synchronous as compared to asynchronous stroking (Q8: $F(1, 19) = 11.71$, $p = 0.003$, partial $\eta^2 = 0.38$). There was no significant interaction of Synchrony and Object, $F(8, 12) = 0.85$, $p = 0.577$, which was also true for questions Q1–Q7 ($F\text{s} < 1.59$, $p\text{s} > 0.222$). Only Q8 tended to approach an interaction effect, $F(1, 19) = 3.32$, $p = 0.084$, partial $\eta^2 = 0.15$, indicating a tendency of a larger stroking effect for the rubber hand as for the computer mouse with respect to body resemblance. A main effect of object was present, $F(8, 12) = 4.91$, $p = 0.007$, partial $\eta^2 = 0.76$, reflecting higher scores for the rubber hand than for the computer mouse, which was based on the questions Q1, Q3, Q6, Q7 and Q8 ($F\text{s} > 5.49$, $p\text{s} < 0.031$). Because the questionnaire data are subjective, the different intervals of the visual analog scale may not have the same meaning for participants. We therefore also calculated a non-parametric Friedman test on each item of the questionnaire separately for the computer mouse and the rubber hand to verify our results. This analysis showed a reliable synchrony effect for the computer mouse and the rubber hand in all three ownership items.[1]

[1] For the computer mouse, the Friedman test of the questionnaire data showed significantly increased ratings after synchronous than asynchronous stroking for body ownership items Q1 ($\chi^2(1) = 15.21$, $p < 0.001$), Q2 ($\chi^2(1) = 15.21$, $p < 0.001$) and Q3 ($\chi^2(1) = 4.77$, $p = 0.029$). We found no synchrony effect in Q4 and Q7 ($\chi^2\text{s}(1) < 0.23$, $p\text{s} > 0.63$). For Q6 ($\chi^2(1) = 5.40$, $p = 0.020$) and Q8 ($\chi^2(1) = 11.27$, $p = 0.001$) synchronous as compared to asynchronous stroking significantly increased the ratings, while a similar pattern was found for Q5 that, however, did not reach the significance level ($\chi^2(1) = 3.27$, $p = 0.071$). For the rubber hand, we found a significant increase after synchronous than asynchronous stroking in all body ownership items Q1 ($\chi^2(1) = 10.89$, $p = 0.001$), Q2 ($\chi^2(1) = 7.20$, $p = 0.007$), and Q3 ($\chi^2(1) = 9.80$, $p = 0.002$). Q4, Q5 and Q7 showed no significant effect of Synchrony ($\chi^2\text{s}(1) < 2.01$, $p\text{s} > 0.15$), while there were marginally increased ratings after synchronous than asynchronous stroking in Q6 that, however, did not reach the standard significance level ($\chi^2(1) = 3.56$, $p = 0.059$) and Q8 ($\chi^2(1) = 3.20$, $p = 0.074$).

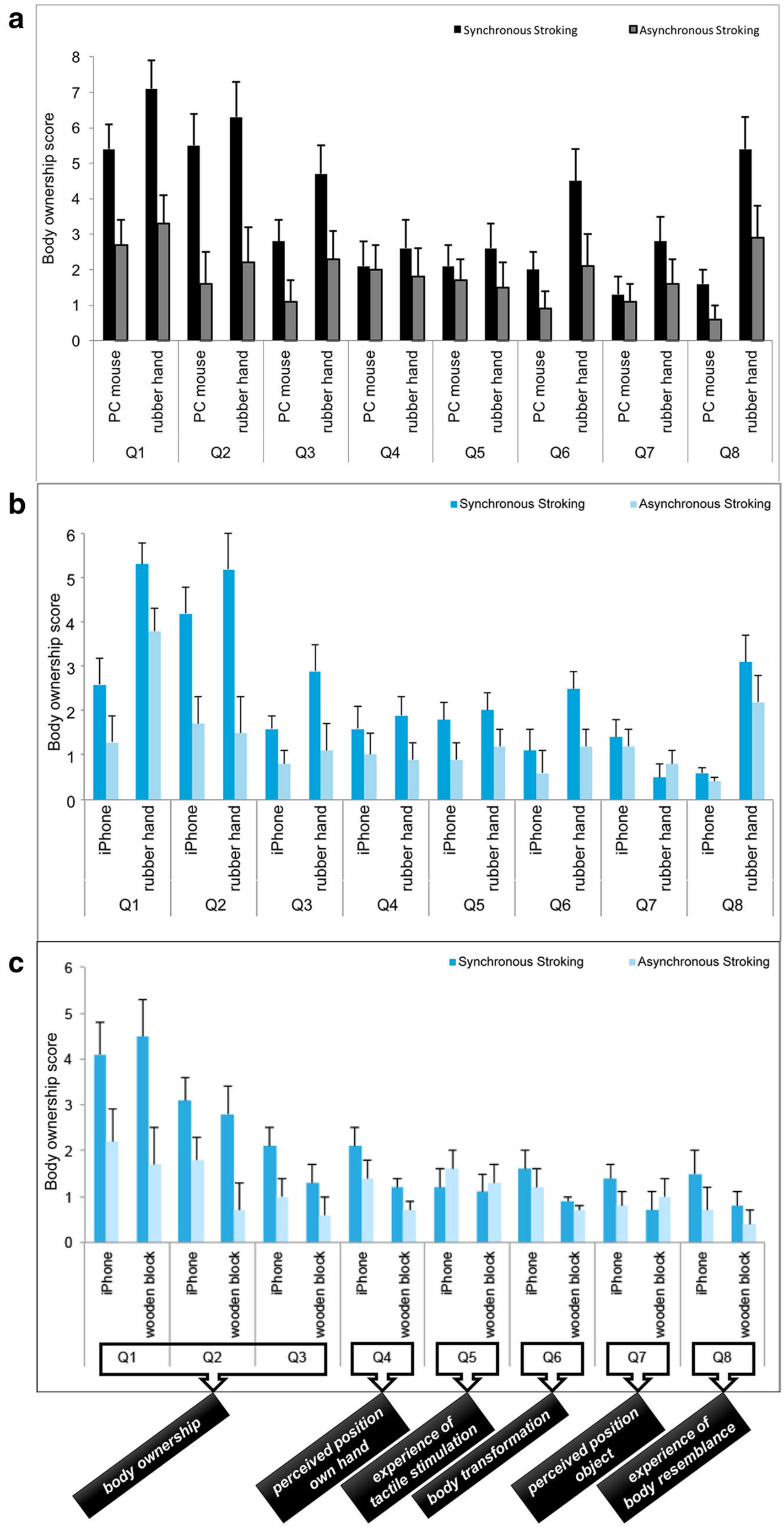

Fig. 2 Body ownership score (mean) of the "body ownership questionnaire" (Q1–Q8) as adapted from (Botvinick & Cohen, 1998) and their related underlying components (*black boxes*). Synchronous stroking induced a stronger illusion of body ownership as compared to asynchronous stroking for **a** the computer mouse and the rubber hand in Experiment 1, **b** the iPhone and the rubber hand in Experiment 2, and **c** the iPhone and the wooden block in Experiment 3. *Error bars* depict the standard errors of paired difference scores SE_{PD} (Pfister & Janczyk, 2013), calculated for each question and object condition

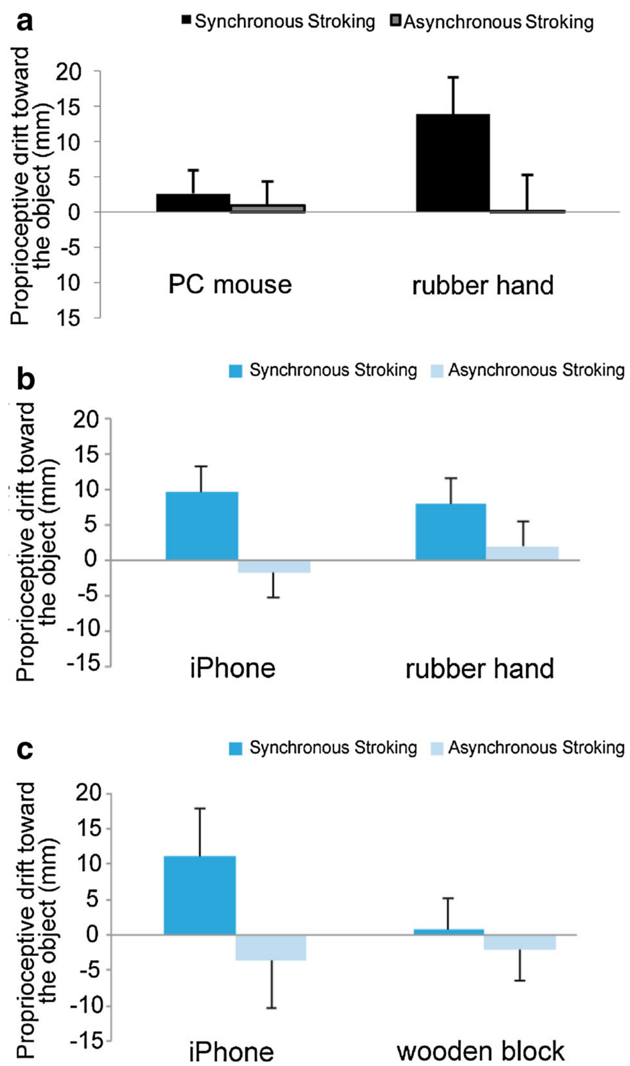

Fig. 3 Proprioceptive drift rate under synchronous and asynchronous stroking for **a** a computer mouse and a rubber hand in Experiment 1, **b** an iPhone and a rubber hand in Experiment 2, and **c** an iPhone and a wooden block in Experiment 3. Synchronous, but not asynchronous stroking produced a significant proprioceptive drift of **a** the left hand localization towards the rubber hand, while no drift was observed towards the computer mouse, **b** towards the iPhone and towards the rubber hand, and **c** towards the iPhone, while no drift was observed towards the wooden block. *Error bars* depict the standard errors of paired difference scores SE_{PD} (Pfister & Janczyk, 2013), calculated for each object condition

Proprioceptive drift

The analysis revealed a significant main effect of Synchrony, $F(1, 19) = 5.82$, $p = 0.026$, partial $\eta^2 = 0.23$, indicating an overall larger proprioceptive drift after synchronous than after asynchronous stroking (Fig. 3a). However, the proprioceptive drift tended to be numerically larger for the rubber hand (14 mm, $p = 0.016$, two tailed) than for the computer mouse (2 mm, $p = 0.633$, two tailed). The interaction of Synchrony and Object did, however, not reach the standard significance level, $F(1, 19) = 4.06$, $p = 0.058$, partial $\eta^2 = 0.18$. There was no significant main effect of object, $F(1, 19) = 2.01$, $p = 0.172$.

Discussion

Unsurprisingly, we were able to replicate the well-established RHI (i.e., the synchrony-induced increase in perceived ownership), demonstrating that our experimental setup was suited to produce the generic ownership illusion. More interestingly, however, the subjective ownership illusion did not vary with the kind of object and was equally pronounced for the rubber hand and the computer mouse. Given that the computer mouse did not share any obvious similarity with any existing body part of the participants, this observation seems to provide evidence against pure top-down modulation approaches to perceived ownership assuming that the external object is always compared against an internal body model (e.g., Tsakiris, 2010). Our findings rather support bottom-up approaches or a weaker version of the top-down-modulation approach, in which bottom-up and top-down contributions are weighted in reference to the object stimuli and available information instead. The observation supports the claim of Ma and Hommel (2015a, b) that ownership perception may extend to non-corporeal objects, provided some degree of synchrony between felt and seen stroking. However, in contrast to previous agency-related studies (Ma & Hommel, 2015b; Tsakiris, Prabhu, & Haggard, 2006), our findings demonstrate that current agency may not be needed to produce an explicit ownership illusion (Kalckert & Ehrsson, 2012) for a non-corporeal object; the mere recall of past agency experience may do.

While the lack of an interaction between Object and Synchrony does not suggest that bottom-up information is always censored by top-down expectations informed by an internal body model, the main effect of object shows that expectation did indeed play a role. This observation is consistent with previous findings of Ma and Hommel (2015a, b), showing that objects that differ in the pre-experimental plausibility of being a body part can bias the general tendency of ownership perception. In the present experiment, people were apparently more willing to accept a rubber hand than a computer mouse as part of their body. Given that this general bias did not modulate the synchrony effect in the explicit ownership measure of the present study, it makes sense to assume that ownership judgments are based on the integration of information from various sources (as Synofzik, Vosgerau, & Newen, 2008, have assumed for agency), including bottom-up signals and top-down expectations (Ma & Hommel, 2015b; Tsakiris, 2010).

Somewhat less clear were the findings for the proprioceptive drift scores, the implicit measure of body ownership. The main effect of synchrony suggests that we were able to replicate the RHI for the implicit drift measure in principle. The synchronization-induced changes in drift scores were not statistically larger for the rubber hand than for the computer mouse, and the intermodal-synchrony effect was not significant for the latter object. Given this lack of a significant interaction, we hesitate to present a strong interpretation of this observation. However, it is possible that proprioceptive drift rates are more sensitive to differences between the objects than subjective measures are.

Experiment 2

Given the observation that at least subjective perception showed equivalent ownership illusions for the rubber hand and the computer mouse in Experiment 1, Experiment 2 went one step further and compared a rubber hand with a personal smart phone. With our smart phones, we have an extended personal history of agency experiences, but in a more indirect and personalized way than with a computer mouse. To test whether recalled agency based on our extended personal history of agency experiences with the smart phone may matter, we replicated Experiment 1 but replaced the computer mouse by the participant's personal smart phone (see Fig. 1b).

Methods

Participants

A new sample of 21 right-handed adults (15 females; mean age 23.5; age range 19–38) who were all experienced smart phone (iPhone) users (range 1–6 years) participated, fulfilling the same criteria as in Experiment 1.

Stimuli and apparatus

Stimuli were the same as in Experiment 1, except that we replaced the computer mouse of Experiment 1 by the participant's smart phone (iPhone).

Task and procedure

Procedure and design were identical to Experiment 1, except that we replaced the computer mouse condition by a smart-phone condition.

Results

Data were analyzed as in Experiment 1.

Questionnaire

A significant Synchrony main effect was obtained, $F(8, 13) = 4.47$, $p = 0.009$, partial $\eta^2 = 0.73$. As shown in Fig. 2b, synchronous stroking increased the body ownership scores as compared to asynchronous stroking for all statements assessing the presence of the RHI (Q1–Q3: Fs > 10.36, ps < 0.005), which indicates that participants experienced an increased RHI after synchronous stroking. Synchronous as compared to asynchronous stroking also produced a stronger perceived drift of the own hand to the objects (Q4: $F(1, 20) = 5.27$, $p = 0.033$, partial $\eta^2 = 0.21$). A similar change in the experience of tactile stimulation after synchronous stroking as compared to asynchronous stroking was obtained for Q5 and the experience of body transformation (Q6: Fs > 6.13, ps < 0.023), but not for the perceived position of the object (Q7: $F(1, 20) < 1$, $p = 0.800$). We found a numerically larger experience of body resemblance after synchronous than after asynchronous stroking, which did, however, not reach significance (Q8: $F(1, 20) = 3.33$, $p = 0.083$, partial $\eta^2 = 0.14$). We observed no significant modulation of the Synchrony effect by object, $F(8, 13) = 1.20$, $p = 0.371$, which was confirmed for all questions (Q1–Q8: Fs < 2.88, ps > 0.104). An Object main effect was obtained, $F(8, 13) = 4.01$, $p = 0.013$, partial $\eta^2 = 0.71$, which was mainly due to a main effect in Q1, Q6 and Q8 (Fs > 5.23, ps < 0.034) reflecting higher scores for the rubber hand than for the smart phone. These findings were supported by our non-parametric test, which revealed a quite specific stroking effect for the smart phone for all three ownership items, but not in any of the control items. The specificity of the ownership items was even higher for the smart phone than for the rubber hand, as the rubber hand also showed a significant stroking effect for one-control item (body transformation).[2]

[2] For the smart phone, the non-parametric Friedman test of the questionnaire data showed a significant increase for all three body ownership items after synchronous than asynchronous stroking, Q1 ($\chi^2(1) = 4.77$, $p = 0.029$), Q2 ($\chi^2(1) = 14.22$, $p < 0.001$), and Q3 ($\chi^2(1) = 5.56$, $p = 0.018$), but not in any other item (Q4–Q8: χ^2s$(1) < 2.28$, ps > 0.13). For the rubber hand, there was a significant increase after synchronous than asynchronous stroking in body ownership items Q2 ($\chi^2(1) = 11.84$, $p = 0.001$) and Q3 ($\chi^2(1) = 8.00$, $p = 0.005$) and a marginal numerical, but non-significant increase in the same direction in Q1 ($\chi^2(1) = 2.88$, $p = 0.09$). Q4, Q5 and Q7 showed no significant effect of Synchrony (χ^2s$(1) < 2.58$, ps > 0.10), while we found a significantly increased rating after synchronous than asynchronous stroking in Q6 ($\chi^2(1) = 7.12$, $p = 0.008$) and a numerical, but non-significant increase in the same direction for the rating in Q8 ($\chi^2(1) = 3.56$, $p = 0.059$).

Proprioceptive drift

The analysis revealed a significant main effect of Synchrony, $F(1, 20) = 10.33$, $p = 0.004$, partial $\eta^2 = 0.34$, indicating an overall larger proprioceptive drift after synchronous than after asynchronous stroking (Fig. 3b). No significant difference in proprioceptive drift between the smart phone and the rubber hand was found, as indicated by a non-significant interaction, $F(1, 20) = 1.24$, $p = 0.278$. There was no significant main effect of object, $F(1, 20) = 0.14$, $p = 0.713$.

Discussion

The outcomes were very similar to Experiment 1. Not only did we again replicate the classical RHI for the rubber hand, but we also found an illusion of comparable size for the smart phone in the explicit ownership measure. In line with these findings, we observed a significant stroking effect for the proprioceptive drift rate, while the interaction between Object and Synchrony was far from significant. Hence, this time not even the general bias (i.e., the object main effect) was significant for the drift. This suggests that past agency experience with a non-corporeal object can produce an ownership illusion. In Experiment 2 this ownership illusion was indicated in both, explicit and implicit measures of the RHI. It thus seems that the past-agency effect is moderated by the degree of personal history with the object.

Experiment 3

The observation of comparable explicit illusion effects for rubber hands, computer mice, and smart phones in Experiments 1 and 2 does not suggest particularly strong constraints on the object that is subjectively perceived as a part of one's body, while we found differences between these objects with regard to the implicit proprioceptive drift measure. And yet, both non-corporeal objects must have reminded the participants of a rather extended personal history with comparable objects. To test the importance of this fact, we replicated the smart-phone condition of Experiment 2 and compared it to a condition where we replaced the smart phone by a wooden block of comparable size without any history of personal experiences. Armel and Ramachandran (2003) have already investigated the degree to which a wooden table can be perceived as part of one's body. However, their dependent measure was rather indirect (galvanic skin reflex) and their experimental design was likely to invite transfer effect (as the order of conditions was not balanced).

Methods

Participants

A new sample of twenty right-handed adults (15 male; mean age 25.2; age range 21–32) who were all experienced smart phone (iPhone) users (range 1–4 years) participated, fulfilling the same criteria as in Experiment 1 and 2.

Stimuli and apparatus

Stimuli were the same as in Experiment 2, except that we replaced the rubber hand by a wooden block of about the same size as the smart phone (see Fig. 1c).

Task and procedure

Procedure and design were identical to Experiment 2, except that we replaced the rubber-hand condition by a wooden-block condition.

Results

Data were analyzed as in Experiment 1.

Questionnaire

A significant main effect of Synchrony was obtained, $F(8, 12) = 3.86$, $p = 0.018$, partial $\eta^2 = 0.72$, indicating higher overall ownership scores for synchronous stroking as for asynchronous stroking (see Fig. 2c). We found a stronger agreement for all statements assessing the presence of the RHI (Q1–Q3) after synchronous than asynchronous stroking (Fs > 7.63, ps < 0.013) indicating that participants experienced an enhanced RHI after synchronous stroking. Participants also perceived a stronger drift of their own hand to the objects after synchronous than asynchronous stroking (Q4: $F(1, 19) = 5.54$, $p = 0.029$, partial $\eta^2 = 0.23$). The questions measuring the experience of tactile stimulation, the experience of body transformation and the perceived position of the object showed no synchrony effect (Q5–Q7: Fs < 2.52, ps > 0.129). We found a stronger experience of body resemblance after synchronous than asynchronous stroking (Q8: $F(1, 19) = 4.73$, $p = 0.043$, partial $\eta^2 = 0.20$). There was no significant interaction between synchrony and object, $F(8, 12) = 1.42$, $p = 0.282$, which was true for all questions (Q1–Q8: Fs < 1.86, ps > 0.189). Finally, no main effect of Object was obtained, $F(8, 12) = 1.08$, $p = 0.439$. However, for some questions the main effect of Object reached significance (Q2, Q3, Q4 and Q6: Fs > 4.49, ps < 0.049) showing higher ratings for the smart phone as for the wooden block. The significant increase after synchronous than after asynchronous stroking found for all three body ownership items indicate a relative increase in perceived ownership for both objects. This finding was confirmed by our non-parametric analysis, showing that especially the smart phone showed a highly specific synchrony effect for the ownership items, but not for the control items.[3]

Proprioceptive drift

The analysis revealed a significant main effect of synchrony, $F(1, 19) = 7.89$, $p = 0.011$, partial $\eta^2 = 0.29$, indicating an overall larger proprioceptive drift of the left index finger towards the objects after synchronous than after asynchronous stroking. This effect was modified by a significant synchrony-by-object interaction, $F(1, 19) = 5.68$, $p = 0.028$, partial $\eta^2 = 0.23$, showing a larger and significant proprioceptive drift for the smart phone (15 mm, $t(19) = 3.416$, $p = 0.003$, two-tailed), as for the wooden block (2.8 mm, $t(19) = 0.756$, $p = 0.46$, two-tailed), which was not significant (see Fig. 3c). There was no main effect of object, $F(1, 19) = 1.7, p = 0.207$.

Discussion

The subjective measures replicated previous observations: the ownership illusion was equally pronounced for the smart phone and the wooden block, and only for two ownership items, there was a general bias towards the smart phone. However, the proprioceptive drift rates showed a larger and significant drift effect for the smart phone than for the wooden block. This finding indicates the importance of an extended personal history with an object to induce an ownership effect for proprioceptive drift rates. For the smart phone, with which individuals had an extended personal history, we found a significant ownership effect for drift rates. In contrast, the drift rate effect was absent for the wooden block lacking such history of personal experiences. This dissociation between subjective, explicit and objective, implicit measures of body ownership is in line with recent findings of Riemer et al. (2015), showing that physiological responses (skin conductance and startle reflexes) to threat (i.e., the affective component of the RHI) increased with the sense of ownership for an artificial limb, but not with the proprioceptive drift towards its location. Our findings provide convergent evidence for the assumption that ownership ratings and proprioceptive drift may capture partly different aspects of the RHI (Riemer et al., 2015). While the proprioceptive drift measure was only significant for non-corporeal objects people had a history of personal experiences with, the questionnaire measure provided evidence for ownership effects for all objects that we tested.

General discussion

Using the body ownership questionnaire, a well-established explicit measure of body ownership (Botvinick & Cohen, 1998), and proprioceptive drift rates, the present study investigated whether and to what degree people integrate non-corporeal objects into their body representation and whether the feeling of or knowledge about past agency regarding an object might be sufficient to create ownership illusions. The outcomes we obtained allow for three main conclusions.

First, our findings show that synchronous stroking (i.e., the provision of multisensory correlations) increases the subjective tendency to perceive a computer mouse, a smart phone, and even a wooden block as a part of one's own body. This confirms previous considerations that objects may not need to be anatomically similar to body parts to induce the perception of body ownership (Armel & Ramachandran, 2003) and supports the assumption that body ownership emerges from multisensory integration of vision and touch signals (Makin et al., 2008). In contrast, our questionnaire findings provide evidence against the view that the incorporation of objects into one's body representation depends on both multisensory input and agreement with an internal body model (Tsakiris, 2010). The main effect of Object found for the questionnaire ratings of Experiment 1 and 2 shows that anatomical similarity between a given object and the internal body model might induce some general subjective biases to integrate the object (Synofzik et al., 2008). However, multisensory integration of visual and tactile signals appears to provide the actually relevant information for the integration into the self-representation. This would allow for top-down biases of self-representation but it is not consistent with the assumption of body model approaches that bottom-up multisensory information must be filtered according to the perceived anatomical similarity between a given object and real body parts (Tsakiris, 2010). Rather,

[3] For the smart phone, we found a significantly enhanced score in body ownership items after synchronous than asynchronous stroking in Q1 ($\chi^2(1) = 4.77$, $p = 0.029$) and Q3 ($\chi^2(1) = 4.00$, $p = 0.046$), but not in Q2 ($\chi^2(1) = 0.89$, $p = 3.46$). There were no significant differences after synchronous than asynchronous stroking in all other items (Q4–Q8: χ^2s(1) < 1.93, $ps > 0.165$). For the wooden block, we observed significantly enhanced scores after synchronous than asynchronous stroking in Q1 ($\chi^2(1) = 12.25$, $p < 0.001$) and Q2 ($\chi^2(1) = 10.89$, $p = 0.001$), while there was a small, but non-significant increase after synchronous than asynchronous stroking in Q3 ($\chi^2(1) = 3.77$, $p = 0.052$). For Q4 ($\chi^2(1) = 3.77$, $p = 0.052$) and Q8 ($\chi^2(1) = 3.60$, $p = 0.058$) we similarly found a numerical, but non-significant increase after synchronous than asynchronous stroking, and all other items (Q5, Q6 and Q7) showed no significant effect of synchrony (χ^2s(1) < 0.34, $ps > 0.55$).

body part similarity and visuo-tactile synchrony seem to be independent components that contribute to the degree to which novel objects are integrated into one's bodily self, which parallels Synofzik et al.'s (2008) conclusion regarding agency judgments. When bottom-up information does not provide enough information for an agency judgment, subjects may also consider additional top-down information. With regard to body ownership, multisensory integration of vision and touch signals may provide enough information for an ownership judgment, but may also consider top-down signals related to the body model (Tsakiris, 2010) when bottom-up information is not sufficient.

Second, the findings of our implicit proprioceptive drift measure did discriminate between these objects: while there was replicable evidence for the integration of the smart phone and the rubber hand, no evidence for the integration of the wooden block and the computer mouse was obtained. These findings suggest that past agency is sufficient to create ownership illusions for objects we have an extended personal agency history with, given that visuo-tactile synchrony is provided during the experiment. This conclusion is in line with Ma and Hommel's (2013, 2015a, b) demonstration of the importance of agency for perceived ownership, but goes beyond these studies by showing that past agency can have comparable effects as current agency. Hence, perceived ownership can be obtained for virtual non-corporeal objects that either currently move with our body or that have been moving with our body in the past. This suggests that what we perceive as our body is affected by knowledge about our past interactions with objects.

Third, the finding that reported self-perceptions did not discriminate much between rubber hands, computer mice, smart phones, and wooden blocks, while indirect drift measures did; this shows that direct, subjective and indirect, objective measures of body ownership are not equivalent and do not seem to rely on the exact same information. This observation fits with previous dissociations between assessments of spatial body localization and explicit judgments of ownership (Riemer et al., 2015; Rohde et al., 2011; Tsakiris & Haggard, 2005). But why should drift rates be more sensitive to agency experiences than conscious reports? For one, drift rates may be more sensitive because of their greater resolution. For another, attention may play an indirect (or even direct) role. As drift rates are likely to rely on the integration of spatial information across several sources, which is often weighted according to the amount of attention devoted to a particular source (Bertelson & Radeau, 1981; Spence & Driver, 2004), it makes sense to assume that objects for which we perceive current or past agency attract more attention. If so, drifts may be more biased towards objects we have an extended personal history with, which would explain the outcome pattern we obtained. The smart phone, however, might also attract more visual attention by itself, which may facilitate multisensory integration of visual and tactile signals more directly.

Many would consider the objects we used in our study as tools. Research on tool use has shown that the representations coding the body and the space around the body are adapted after tool use (Holmes & Spence, 2004; Farnè, Serino, & Ladavas, 2007; Macaluso & Maravita, 2010; Maravita & Iriki, 2004). Consistent with our findings, Bassolino, Serino, Ubaldi, and Làdavas (2010) showed that extensive everyday experience with a computer mouse results in a durable extension of the peripersonal space toward the space surrounding the tool. This extension was dynamically evoked for the hand that was actively used to control the computer mouse during practice, even if participants only passively held the mouse during the test session. As in our study, recalled agency based on past experience was enough to induce changes in body representations. Interestingly, the Bassolino study found that effects of long-term experience with the mouse did not generalize to the left hand, which was not used to operate the mouse. However, a short time period of active practice with the left hand was enough to induce a dynamic extension also of the left hand's representation. These observations fit with our assumption that the significant proprioceptive drift effects we obtained for the iPhone and the rubber hand, but not for the wooden block and the computer mouse, may be due to an extended personal history with the former objects but not with the latter. Our right-handed participants were unlikely to have extensive experience with operating wooden blocks and computer mice with their left hand, which we used to induce the RHI. In contrast, smart phones are often controlled with both hands, for example when typing a text, and people have a lot of experience with their real left hand—which was similar to the left rubber hand we used to induce the illusion. We originally opted for using the left hand of right-handers to induce the RHI because we thought that a less practiced hand might be more sensitive to ownership illusions. While that might have been the case, it could have worked against proprioceptive-drift effects for the wooden block and the computer mouse, which may explain our findings. This leads us to the question how tool representation relates to body representation. Interestingly, De Preester and Tsakiris (2009) have considered the possibility that some tools can become part of the internal representation of one's body, to the degree that they substitute a missing body part or in some other ways "complete" the agent, such as in the case of a musician and her instrument. As musicians have an extended personal history of agency experiences with their instrument, we suggest that a personal smart phone alike might be a key candidate for entering body representations.

A limitation of the present study is that we did not use physiological measures of psychological and autonomic arousal to quantify body ownership (Armel & Ramachandran, 2003). However, we note that such measures have also been dissociated from explicit measures (Ma & Hommel, 2013), suggesting that they may not reflect the same processes anyway. Indeed, more research will be necessary to understand the relationship and the informational basis for the different measures to assess body ownership. Among other things, future studies may combine subjective, objective and physiological measurements of body ownership manipulating the effects of current and past or potential agency more directly. In any case, our observations suggest that self-representation reflects a rather flexible, constructive process that apparently extends beyond the physical body to technologically advanced objects we share an extended personal history of agency experiences with. This conclusion is in line with the assumption of William James arguing that the distinction between me and mine is by no means trivial (Constable, Kritikos, Lipp, & Bayliss, 2014; James, 1890/1981).

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Compliance with ethical standards

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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