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RESEARCH ARTICLE

Explicit and implicit measures of body ownership and agency: affected by the same manipulations and yet independent

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Abstract
People are assumed to represent themselves in terms of body ownership and agency. Studies using the rubber- or virtual-hand illusion have assessed ownership and agency by means of explicit ownership and agency ratings and implicit measures, like proprioceptive drift in the case of ownership. These measures often show similar effects but also some discrepancies, suggesting that they rely on data sources that overlap, but not completely. To systematically assess commonalities and discrepancies, we adopted an immersed virtual hand illusion (VHI) design, in which three independent factors were manipulated: the synchrony between the movement of real and virtual effector, the type of effector, which was a virtual hand or triangle, and the spatial congruency between the real and virtual effector. Commonalities and discrepancies in the effects of these factors were assessed by crossing explicit and implicit measures for ownership and agency. While standard ratings were used as explicit measures, implicit ownership was assessed by means of proprioceptive drift and implicit agency by means of intentional binding. Results showed similar effect patterns for the two agency measures, which, however, were not correlated, different effect patterns for the two ownership measures, and a strong correlation between the two explicit measures. Taken altogether, our findings suggest that explicit and implicit measures of ownership and agency partly rely on shared informational sources, but seem to differ with respect to other sources that are integrated or with respect to the processed dimension (shape vs. time). The findings also suggest that some findings obtained with RHI designs might reflect more the unnatural situation that that design puts individuals into rather than generalizable mechanisms of computing perceived ownership and agency.

Keywords Body representation · Sense of ownership · Sense of agency · Intentional binding · Virtual hand illusion

Introduction

Even though recent studies have shed some light on this question, it still remains a mystery how we cognitively represent our body and the actions it performs (Jeannerod 2003).

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Gallagher (2000) has distinguished two key aspects of self-representation, the sense of ownership, which refers to the perception of our body as belonging to us, and the sense of agency, which refers to the perception of our actions as being performed by us. Research on ownership has often used the rubber hand illusion (RHI). In classical-RHI designs producing this illusion, participants face a rubber hand lying in front of them while their own corresponding hand is covered. If then the visible rubber hand and the invisible real hand are stroked in synchrony (vs. asynchronously), participants tend to illusorily perceive the rubber hand as belonging to their own body (Botvinick and Cohen 1998). That is, matched multisensory correlation, specifically the synchronous visuo-tactile stimulation, is sufficient to induce ownership illusion perception. Researchers also designed active-RHI paradigms that allow one-finger (Walsh et al. 2011; Kalckert and Ehrsson 2012, 2014) or palm movement (Dummer et al. 2009) on both real and rubber hand, predicting that synchronous visuo-motor correlation is sufficient to induce ownership

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illusion. However, in active-RHI participants can only lift up or put down their index finger or whole palm, so that the motor and proprioceptive signals are rather limited. In contrast to the use of rubber hands, virtual-reality allows for relatively realistic and complete visuo-motor correlation, and also has been shown to produce reliable ownership illusions through the virtual hand illusion (VHI; Slater et al. 2008). In designs generating this illusion, participants wear a dataglove, so that the movements of their own, invisible hand can be translated into movements of a virtual hand or object synchronously or asynchronously (Sanchez-Vives et al. 2010; Ma and Hommel 2013). As with RHI, synchronous movements produce higher ratings of perceived body ownership than asynchronous conditions.

Importantly, as voluntary action or control over one's body movement was also predicted to be the core of sense of agency (Haggard 2017), active-RHI and VHI allow to investigate both sense of ownership and agency, and also their possible relationship within the same experiment. It is interesting that active-RHI studies have produced more discrepant findings (Braun et al. 2018). Some studies found that voluntary movement promotes hand ownership illusion (Dummer et al. 2009) and hand recognition (Tsakiris et al. 2006; Van Den Bos and Jeannerod 2002), and a recent fMRI study showed that participants take hand identity into consideration when they predict sensory action consequences (important for sense of agency), as for actively versus passively generated feedback, and suppression in posterior parietal, frontal, and temporal regions was stronger when participants were viewing their own as compared to someone else's hand (Uhlmann et al. 2020). Thus ownership and agency promote each other (Kalckert and Ehrsson 2012, 2014; Braun et al. 2014). Some other studies have observed double dissociations between perceived ownership and perceived agency, in the sense that some manipulations affected one but not the other. For example, passive movements diminished the sense of agency but not ownership and incongruent positioning of the rubber hand abolished hand ownership but not agency (Kalckert and Ehrsson, 2012; Braun et al. 2014). Relatedly, no shared neural activations were found in one neuroimaging study (Tsakiris et al. 2010b): while body ownership was linked to activation of midline cortical structures for multisensory integration; agency was linked to premotor and parietal areas for motor intention and action monitoring. This discrepancy has been taken to corroborate the distinct and separable nature of ownership and agency (e.g. Tsakiris et al. 2007). However, VHI studies hardly found any evidence for dissociations between ownership and agency; some studies even showed a very tight relationship (strong correlations) between perceived ownership and agency judgments (e.g. Ma and Hommel 2015b). This is likely to do with the high ecological validity in VHI as compared to the odd movement experience in active-RHI studies. In contrast to active-RHI studies, VHI studies allow participants to freely carry out voluntary actions with their real hand and to observe the corresponding movement of the virtual hand—which is very likely an important data source for both ownership and agency judgments (Ramachandran 1998; Synofzik et al. 2008). Indeed, the rather limited motor and proprioceptive information in the specific active-RHI experimental setup may lead to weak movement consistency, and thus invited other different information sources into the judgement of ownership and agency (Ma and Hommel 2015b). These information sources may contribute to sense of ownership and agency differently and thus show dissociated effects (Kalckert and Ehrsson 2012).

The emerging picture is thus that ownership and agency judgments rely on multiple sources of information (Synofzik et al. 2008; Liepelt et al. 2016) that overlap to degrees that depend on the experimental design and the resulting availability of informational sources. In RHI paradigms, this overlap tends to be low, but it tends to be high in VHI paradigms, as their dynamic nature provides more data points for felt and seen movements that can be correlated (Ma and Hommel 2015b). Similar considerations might explain the fact that implicit measures of ownership sometimes do not correspond to the explicit measures taken from ownership questionnaires. For instance, an often-used implicit measure of ownership is proprioceptive drift, that is, the perceptual illusion that the felt position of one's real hand moves closer to the actual position of the visible rubber or virtual hand (Botvinick and Cohen 1998). Proprioceptive drift measures are commonly affected by the synchrony manipulation the same way as explicit ownership ratings are (Tsakiris and Haggard 2005), which has been taken as evidence that both are measures of the same construct (Tsakiris et al. 2010a, b). However, there are also numerous manipulations that affect explicit ownership ratings and proprioceptive drift differently (Holmes et al. 2006; Ma et al. 2019a). This suggests that explicit ownership ratings and more implicit ownership measures like proprioceptive drift rely on data sources that overlap to some degree, but not completely (Rohde et al 2011; Abdulkarim and Ehrsson 2016).

The aim of the present study was to find evidence how implicit measures of agency might fit into this picture. Applying the considerations we have developed so far suggests that implicit agency measures rely on both data sources that are shared by explicit measures of ownership and agency, and perhaps by implicit measures of ownership, and data sources that are not shared. We thus decided to assess explicit and implicit measures of ownership and agency in the same VHI design, and to test whether and to what degree explicit and implicit measures would be affected differently by experimental manipulations that are known to impact explicit ownership. More specifically, we manipulated the movement synchrony between real and virtual effector, the appearance of the virtual effector, and the spatial congruency between real and virtual effector. Previous studies have shown that all three factors can have an impact on explicit ownership judgments. Temporal synchrony is known to produce higher degrees of perceived body ownership than asynchrony (Tsakiris 2010; Ma and Hommel 2015a), artificial effectors that look like a hand were reported to produce higher ownership ratings than a wooden block (Tsakiris et al. 2010a, b), and artificial effectors lead to higher ownership judgments if they seem to naturally extend (i.e. correspond to the posture of) the real hand (Ehrsson et al. 2004). Given our previous observations of considerable correlations between explicit ownership and agency measures (Ma and Hommel 2015b), we assessed the impact of these three factors on both ownership and agency ratings.

As an implicit measure of ownership, we also assessed proprioceptive drift. In RHI/VHI studies, this measure is commonly affected by synchrony manipulations the same way as explicit ownership ratings and the same tends to be the case for spatial congruency (Tsakiris and Haggard 2005; Kalckert and Ehrsson 2012) and effector appearance (Tsakiris et al. 2010a). So far, there is no widely established implicit measure for agency in RHI/VHI. However, Moore and Obhi (2012) and Jensen et al. (2015) have argued that intentional binding (IB) effect may represent a useful implicit measure of agency in studies isolated from RHI/VHI. There are two kinds of IB paradigms, the Libet-style paradigm and the time interval estimation paradigm. In Libet-style IB tasks, participants carry out voluntary and involuntary movements that produce a particular signal, such as a tone, and judge the timepoint at which the action was performed and the timepoint at which action effect occurred. The interesting observation is that the difference between the perceived timepoints of action and action effect is reduced in the voluntary-action condition. While in time interval estimation IB tasks, participants only need to report the estimated time interval between performed action and received effect, shorter interval estimation was found in the voluntary-action condition. Even though the mechanism underlying this effect is unknown, this reduction has been taken to reflect an “intentional binding” between intentional action and effect, which in turn is taken to represent sense of agency (Haggard et al. 2002).

Following this lead, several authors began to use IB with interval estimate paradigm as an implicit agency measure in active-RHI and VHI. For example, Braun et al. (2014) assessed IB in an active-RHI paradigm with manipulated spatial congruency and agent mode (self vs. other). Results showed a significant effect (more time reduction) for agent mode but not for congruency. Caspar et al. (2015a, b) found more pronounced IB (i.e., more time reduction) with synchronous than asynchronous visuo-motor correlations. More closely to our present purposes, Ma et al. (2019b), found a larger IB for synchrony between movement of one’s real hand and a virtual hand. However, while this observation paralleled comparable synchrony effects in agency ratings and IB with the basic VHI design, Ma et al. (2019b) also found dissociations between explicit agency and IB with respect to other manipulations. Nevertheless, these findings encouraged us to use IB as an implicit measure of agency in VHI, which allowed us to establish a fully crossed experimental design, in which we tracked and compared the impact of synchrony, effector type, and spatial congruency on both explicit and implicit measures of body ownership and agency.

Method

Participants

Forty-six adults (13 male; mean age = 20.46, standard deviation (SD) = 1.09, age range 18–23) from Southwest University, China, volunteered. All participants were recruited through the department’s advertisement system, and they had normal or corrected to-normal vision, were naive with regard to the hypotheses of the experiment, and received payment for their participation. Participants gave their informed consent to participate in the study, which was conducted in accordance with the ethical standards of the Declaration of Helsinki and with the ethical guidelines the local human research ethics committee at Southwest University, the methods were carried out in accordance with the approved guidelines.

Setup

We adopted the basic experimental setup from our previous study that was also using an IB task (Ma et al. 2019b). The virtual reality environment (VR) was designed by making use of the software Vizard. We then designed a virtual hand and a virtual triangle (for the effector type manipulation) with software 3ds Max and imported them into the VR environment. As shown in Fig. 1, participants wore a HTC vive head mounted display (HMD) on their head, so that they were immersed into the VR environment, while the real environment was occluded from their view. Participants needed to wear a right-hand dataglove (5DT, 14 joint sensors, measurement frequency = 75 Hz, latency = 13 ms) on their real right hand, a HTC vive 6-Dof orientation tracker on their right wrist, so the hand rotation, position and finger joint movement data of the real hand could be recorded and transmitted to the virtual effector. The virtual effector was placed in front of and in the midline of the participant’s body for the proprioceptive drift measurement (Ma and Hommel 2015b).

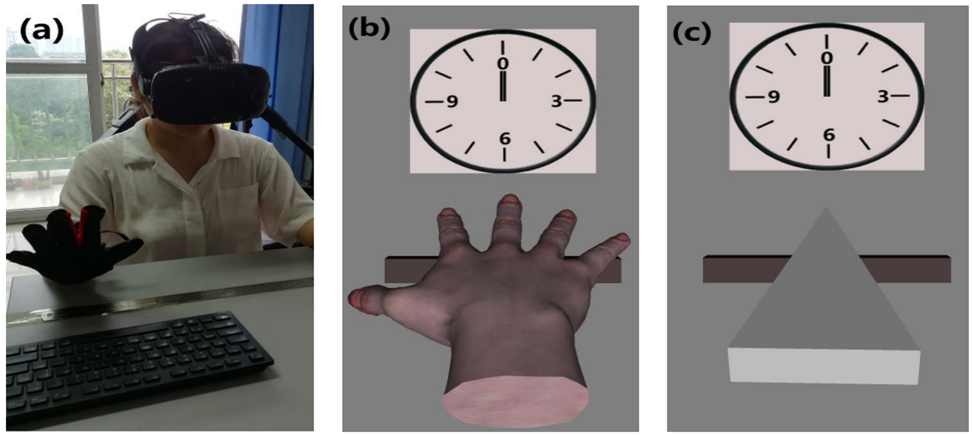

Fig. 1 **a** The experimental setup: participants wore the dataglove and HMD, with ruler and keyboard in front of them on the desk; **b** an example of the clock as viewed by participants together with the virtual hand; **c** the clock together with the virtual triangle

Design

We manipulated three independent variables within participants. In the synchronous condition of the synchrony manipulation, participants controlled the movement of the virtual effector directly and without perceivable delay through the dataglove by moving their real hand (Ma and Hommel 2015b). In the asynchronous condition, we used the software Vizard to generate random data and applied it to the movement or rotation of virtual effector, so that there was no relationship between real hand movement and the movements of the virtual effector (Ma et al. 2019a). Effector type was manipulated using a virtual effector that either looked like a human hand or like a triangle (similar to Yuan and Steed 2010). When participants freely moved their hand to control the movement of the hand or triangle in the synchronous condition, movements data of the real hand were translated into corresponding movements of the virtual effector in real time, and opening or closing of the real hand were translated into either the opening or closing of the virtual hand or a visually similar growing larger or smaller of the triangle size. In the congruent condition of the spatial congruency manipulation, the virtual effector was presented un-rotated as an extension of the participant's real hand. In the incongruent condition, the virtual effector was rotated by 180 degree. Fully crossing the three experimental factors resulted in eight conditions, which were fully counterbalanced across participants.

Procedure

When participants first came to the lab, they were asked to put on the dataglove, orientation tracker on their right hand and the HMD on their head. Then they were seated at a desk, with the keyboard in front of them, as shown in Fig. 1. There were six phases in each of the eight conditions.

First, we performed the IB baseline condition. Participants could not see any real hand and real keyboard but only the virtual clock and button in the virtual environment, however, a real QWERTY computer keyboards was put under their real hand as shown in Fig. 1. Participants needed to press the real space key two times to reported the timepoints with reference to the virtual clock of keypress and tone presentation per trial, and they needed to finish 21 trials in total for IB baseline condition. Please see below for the detail information for IB. Second, the virtual effector appeared in the VR environment, seemingly extending the midline of the participants' body. For the proprioceptive drift premeasurement phase, participants were asked to place their right hand on the desk, with palm downwards, at a fixed location which was parallel to their right shoulder, and manually point with their left hand index finger to a position that represents the felt vertical position of the middle finger of their real right hand (Botvinick and Cohen 1998); the experimenter recorded this position with a ruler. Third, participants were asked to freely open and close, rotate or horizontally or vertically move their right hand, and watch the movement of the virtual effector for two minutes, which was synchronous with or completely unrelated to the real movement. Fourth, participants were asked to perform the IB task again. A virtual button was shown near to the fingers of the virtual hand and a virtual clock and its pointer were also shown in the VR environment. Following the same procedure as the first experiment of Haggard et al. (2002), participants were asked to voluntarily press the button (the QWERTY space key in reality) for two times when they want, and report the clock-pointer's positions for the press action and the following tone per trial, they needed to finish 21 trials in total for each condition. Fifth, participants were asked to assume the same posture with their right hand as in the second phase so to exclude a possible influence of posture difference on hand position perceiving and pointing, again to manually point with their left index finger to a position on the desk that represents the felt position of their real right hand middle finger—the proprioceptive drift post-measurement; the experimenter recorded this position with a ruler too. Sixth, participants were asked to fill in the questionnaire for ownership and agency.

There was a 2-min break between each two of all eight conditions during which a "break" image was shown on the computer screen, so to reduce possible transfer effects.

Questionnaire for ownership and agency

To assess the extent to which participants experienced ownership and agency, we used an adapted Chinese version of the RHI/VHI questionnaire (Botvinick and Cohen 1998; Kalckert and Ehrsson 2014). In particular, we presented participants with eight questions assessing perceived body ownership (Q5–8) and agency (Q1–4). For each statement, participants responded by choosing a score on a 7-point (1–7) Likert scale, ranging from 1 for 'strongly disagree' to 7 for 'strongly agree'. The statements were as below, only that for the virtual triangle conditions, the term "hand" was changed to "triangle".

Q1. The movement of the virtual hand was caused by me.

Q2. I can control this virtual hand.

Q3. The virtual hand moved just as I wish.

Q4. Whenever I moved my hand I expected the virtual hand to move in the same way.

Q5. I felt as if I was looking at my own hand when I was looking at this virtual hand.

Q6. I felt as if the virtual hand in front of me was my own hand.

Q7. I felt as if the virtual hand in front of me was a part of my body.

Q8. I felt as if my hand was located on the same position as the virtual hand.

Proprioceptive drift

We recorded the pointed positions of participants with the ruler fixed on the desk as shown in Fig. 1. With the position of the virtual hand set to be zero, the real position of real hand (extending from the right shoulder of participants) was measured along the ruler. We calculated the proprioceptive drift by subtracting the participants' pointed position at the post-measure from the pointed position at the pre-measure, so that positive values imply a drift towards the virtual hand.

Time estimation (IB) task

We used the original Libet-style clock paradigm (Haggard et al. 2002) to assess IB, different from interval estimated IB in previous RHI and VHI studies (Braun et al. 2014; Caspar et al. 2015a, b; Ma et al. 2019b). Participants were asked to place their right hand on a fixed place on the desk and the experimenter put the keyboard close to their real right hand—corresponding to the spatial configuration in the virtual environment. Participants could press the space key with their real right hand, which in the VR translated into a comparable movement of the virtual effector towards the virtual button. Participants also saw a virtual clock and a pointer, appearing at the top of the VR environment, far from the virtual effector and button. The clock face was marked with conventional intervals (0, 3, 6, 9), and the clock pointer rotated with a period of 2560 ms.

Participants were instructed to press the (unseen but touchable) space key whenever they wanted, and they were to do that twice in each trial. The first keypress initiated the pointer rotation and the second caused the presentation of a tone 250 ms later. Then the clock pointer stopped after a randomly chosen interval 1500–2500 ms after tone presentation. Participants were to pay attention to both the virtual finger movement and its contact with the virtual button, and the positions of clock pointer. After the clock pointer had stopped, participants were to verbally report the pointer positions for both the onset of the second keypress and the onset of the tone. The task contained 21 trials, so that participants reported 21 clock positions corresponding to the keypress and 21 clock positions corresponding to the tone onset. They were asked to make fast and discrete key pressing movements to ensure that the time points of real hand press movement and sound could be easily identified. They were also encouraged to verbally report the time as precisely as possible, not just the numbers shown on the clock face. As in our previous study (Ma et al. 2019b), the tone and the virtual button movements were always triggered by the contact between real hand and space key, but the seen movements were different in synchronous and asynchronous conditions—as a result of the random generation of the movement in the asynchronous condition.

We did not analyze the timepoint of keypress and tone judgments separately but, like Haggard et al. (2002), the degree to which the time interval between keypress and tone was reduced as compared to control conditions. Thus we first computed the average for keypress and tone judgments, then subtracted the perceived time interval (judged tone time—judged action time) from the real time interval (250 ms), and computed the ratio between this subtraction and the real time interval (Braun et al. 2014; Ma et al. 2019b). Next, we subtracted the baseline IB ratio from the ratio in each condition (Haggard et al. 2002). The expected compression of the perceived keypress-sound interval (the IB effect) would correspond to a positive estimated time interval—i.e., more positive values correspond to more time compression (reduction) regarding the interval between keypress and tone.

Results

We performed 2 × 2 × 2 repeated measures ANOVAs on the data, with synchrony, effector type, and spatial congruency as within-participants factors. The dependent measures were explicit ownership ratings (Q5–8), explicit agency ratings (Q1–4), proprioceptive drift (the implicit ownership measure) and IB (the implicit agency measure). A significance level of $p < 0.05$ was adopted for all tests.

Responder proportions

Followed Kalckert and Ehrsson (2012; also Braun et al. 2014), we classified participants with ownership ratings into responders (rate 5 or higher) or non-responders (< 4), and calculated proportion of responders in each condition. Responder proportion was 34.8% in the hand-congruent-synchronous condition; 2.2% in the hand-congruent-asynchronous condition; 30.4% in the hand-incongruent-synchronous condition; 4.3% in the hand-incongruent-asynchronous condition; 10.9% in the triangle-congruent-synchronous condition; 4.3% in the triangle-congruent-asynchronous condition; 17.4% in the triangle-incongruent-synchronous condition; and 2.2% in the triangle-incongruent-asynchronous condition.

Following Perez-Marcos et al. (2017), we classified participants with ownership ratings difference into responders (rating difference higher than or equal to 1) or non-responders (< 0), and calculated proportion of responders in each condition. Responder proportion was 65.2% in the hand-congruent condition; 58.7% in the hand-incongruent condition; 45.7% in the triangle-congruent condition; and 37.0% in the triangle-incongruent condition.

Ownership questionnaire

The analysis revealed significant main effects of synchrony, F (1,45) = 63.38, $p < 0.001$, $p\eta^2 = 0.59$, indicating higher ownership ratings for synchronous (mean = 3.44, SE = 0.20) than for asynchronous (mean = 2.19, SE = 0.14) conditions, and of effector type, F (1,45) = 11.99, $p = 0.001$, $p\eta^2 = 0.21$, indicating higher ownership ratings for hand (mean = 3.04, SE = 0.17) than for triangle (mean = 2.58, SE = 0.16) conditions. The only other effect was the two-way interaction between synchrony and effector type, F (1,45) = 14.34, $p < 0.001$, $p\eta^2 = 0.24$, all other effects, ps > 0.13 (see Fig. 2).

As we did not find any effect of spatial congruency, but a significant interaction between synchrony and effector type, we aggregated results across the two spatial congruency levels for the different synchrony and effector types. Follow-up two-tailed paired *t* tests revealed that the synchrony effect was significant for both virtual hand, t (45) = 7.82, $p < 0.001$, $d = 1.15$, and triangle conditions, t (45) = 5.71, $p < 0.001$, $d = 0.71$, but the size of the effect (synchronous ratings—asynchronous ratings) was significantly larger in the virtual hand condition, t (45) = 3.79, $p < 0.001$, $d = 0.56$.

Proprioceptive drift

The analysis revealed only a main effect of effector type that just missed significance, F (1,45) = 4.03, $p = 0.051$, $p\eta 2 = 0.08$, indicating numerically higher proprioceptive drift for hand (mean = 0.43, SE = 0.21) than for triangle (mean = −0.16, SE = 0.20) conditions; all other effects, ps > 0.12 (see Fig. 2).

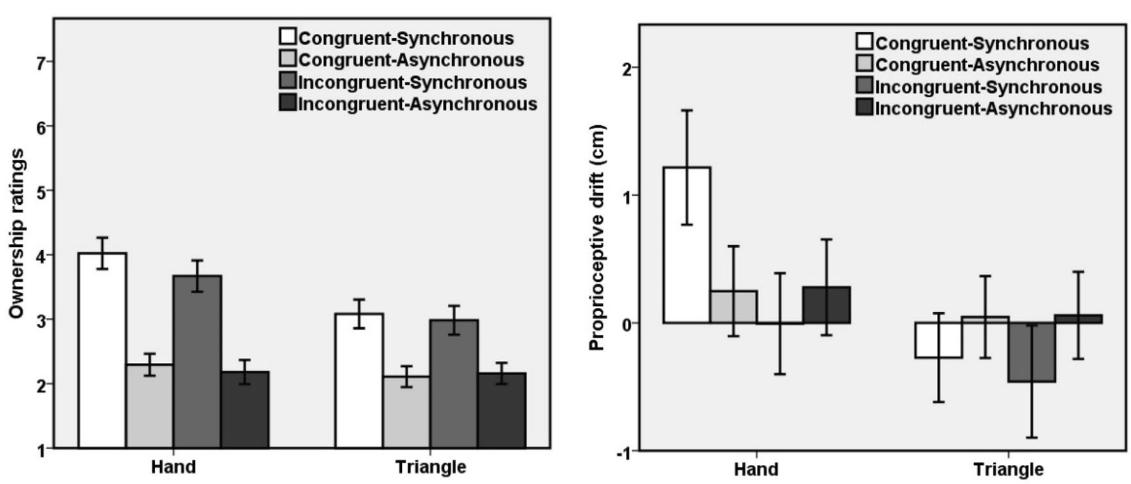

Fig. 2 Explicit and implicit ownership measures as a function of effector type, synchrony and spatial congruency. Left panel: questionnaire scores for ownership; Right panel: proprioceptive drift results. Error bars represent ± 1 SE

Agency questionnaire

The main effect of movement synchrony was significant, F (1,45) = 119.50, $p < 0.001$, $p\eta^2 = 0.73$, indicating stronger perceived agency in the synchronous (mean = 5.29, SE = 0.13) than the asynchronous (mean = 3.47, SE = 0.17) condition. The interaction between synchrony and effector type was also significant, F (1,45) = 13.86, $p = 0.001$, pη2 = 0.24, while no other significant effect was found, ps > 0.08 (see Fig. 3).

As we did not find any effect of spatial congruency but a significant interaction between synchrony and effector type, we aggregated results across the two spatial congruency levels for different synchrony and effector types. Follow-up two-tailed paired *t* tests revealed that the synchrony effect was significant for both virtual hand, t (45) = 10.97, $p < 0.001$, $d = 1.88$, and triangle conditions, t (45) = 7.39, $p < 0.001$, $d = 1.20$, but the size of the effect (synchronous ratings—asynchronous ratings) was significantly larger in the virtual hand condition, t (45) = 3.71, $p = 0.001$, $d = 0.59$.

Time estimation (IB) task

The results were very similar to those for agency judgments: the main effect of synchrony was significant, F (1,45) = 4.90, $p = 0.032$, $p\eta^2 = 0.10$, indicating numerically more pronounced IB (time compression) in the synchronous (mean = 11.52, SE = 4.41) than the asynchronous (mean = 8.73, SE = 4.36) condition, as was the interaction between synchrony and effector type, F (1,45) = 4.04, $p = 0.050$, $p\eta^2 = 0.08$. No other significant effect was found, ps > 0.26 (see Fig. 3).

As we did not find any effect of spatial congruency but a significant interaction between synchrony and effector type, we aggregated results across the two spatial congruency levels for different synchrony and effector types. Follow-up two-tailed paired *t* tests revealed that the synchrony effect was significant in virtual hand condition, t (45) = 2.69, $p = 0.01$, $d = 0.18$, but not in the triangle condition, $p = 0.998$.

Correlations

The relationships between explicit and implicit measures of ownership and agency were assessed by means of one-tailed Spearman, with $N = 46$. Significant correlations between explicit ownership and agency questionnaire ratings were found for all eight conditions, rs > 0.25, ps < 0.047.

Ownership ratings correlated with proprioceptive drift in the hand/postural congruent/asynchronous condition, $r = 0.27$, $p = 0.036$, but not for any other condition, rs < 0.2, ps > 0.09.

Agency judgments correlated with proprioceptive drift in the hand/postural incongruent/asynchronous condition, $r = 0.27$, $p = 0.032$, but not for any other condition, rs < 0.2, ps > 0.09.

No other correlation was found: either between explicit ownership judgments and IB, the implicit agency measure, rs < 0.18, ps > 0.12; between explicit agency ratings and time estimates were found, rs < 0.2, ps > 0.08; or between time estimates and proprioceptive drift, rs < 0.2, ps > 0.09.

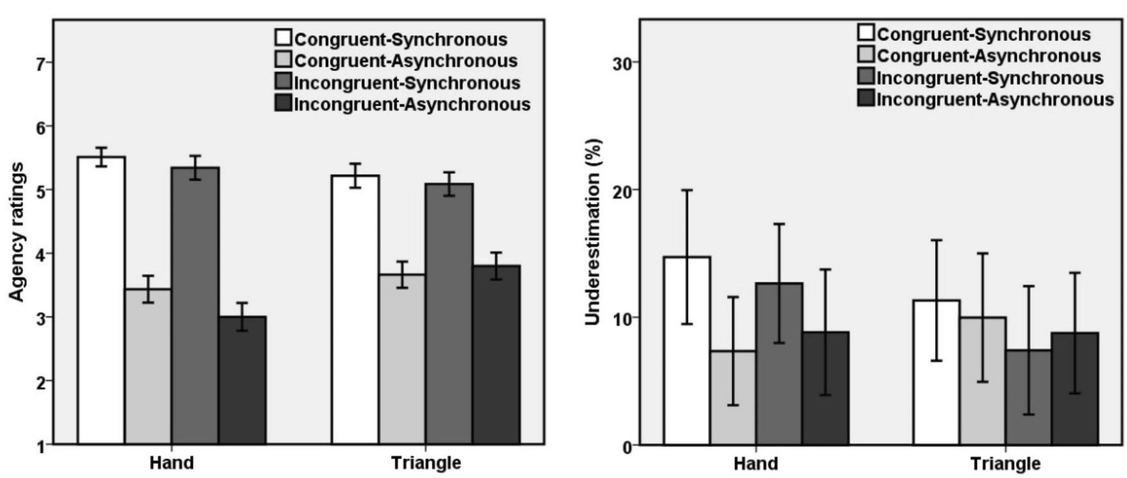

Fig. 3 Explicit and implicit agency measures as a function of effector type, synchrony and spatial congruency, Left panel: questionnaire scores for agency; Right panel: time estimates (IB). Error bars represent ± 1 SE

Discussion

The aim of the present study was to investigate whether and how explicit and implicit measures of ownership and agency relate to each other. On the one hand, we were able to replicate the previously observed strong relationship between explicit judgments of ownership and agency, which is visible in the very similar ways how these two measures were affected by our independent variables and also in the direct correlations. On the other hand, however, the two explicit measures were differently affected by effector type and their otherwise close relationship was not observed for any other variable. The two ownership measures did not correlate and were very differently affected by the independent variables. The effect of effector type found for ownership judgments was at least close to significance in proprioceptive drift, but no difference was found for synchrony effects in explicit judgments and proprioceptive drift. Even the interaction between synchrony and effector, which was rather strong in ownership ratings, was not reflected in drift rates and the lack of correlations also suggest that the two measures rely on different data sources to at least a considerable degree. The two agency measures also failed to correlate, even though they were equally affected by synchrony and the interaction between synchrony and effector type. This suggests that the two measures also rely on different data sources, which, however, seemed to be sensitive to the same manipulations.

Taken together, our findings provide strong evidence for the assumption that explicit and implicit measures of ownership and agency rely on different sources of information, as suggested previously (Synofzik et al. 2008; Ma and Hommel 2015b; Dewey and Knoblich 2014). Of what kind might these sources be? In the absence of more dedicated studies on this issue, we can only speculate about possible contributions, but a few possibilities present themselves. With respect to the two explicit measures, it is interesting to note that they do not only correlate often in VHI studies (e.g. Ma and Hommel 2015b) but are also often affected by the same manipulations, with one exception: so far, effector type has only been shown to impact perceived ownership but not perceived agency. This is what we found in the present study, but the same pattern was reported by Ma and Hommel (2015a), in which actively and synchronously operated virtual non-corporeal objects were incorporated into one's own body representation, and suggested that this might reflect that explicit agency judgments in VHI studies are directly taken from the sensory correlations between felt movements of one's own hand and seen movements of the virtual hand, whereas explicit ownership judgments might combine these correlations with past experience with one's own body and its possible extensions.

Regarding perceived agency, there is a general consensus that the match between expected and actual sensory action effects plays an important role (for an overview, see Hommel, 2015). According to the comparator model of action control (Blakemore et al. 2002; Frith et al. 2000), action planning generates predictions regarding the sensory consequences of the planned action, which are then compared against the actual consequences. It is the degree of this match that is assumed to determine the degree of perceived agency. Ideomotor theories and Wegner's action model are less explicit regarding this comparison, but they are generally consistent with the comparator model's emphasis on the role of predicted and actual sensory action effects (Hommel 2015; Elsner and Hommel 2001). In designs using active rubber hands, in which only one specific finger can be moved up and down as effector, participants can hardly move, so that the generated predictions and sensory action effect that could be matched against available predictions are rather limited. The VHI design, in contrast, provides ample opportunity to both form predictions of one's actual movement and process sensory changes in the virtual effector that can be matched against such predictions. Hence, in contrast to the active-RHI design, the synchronous condition of the VHI design can be assumed to create multiple opportunities for generating information regarding the match between predictions and outcomes, which are assumed to underlie agency judgments.

This scenario would explain why agency judgments are so dependent on synchrony, and it would also fit with previous evidence suggesting that the synchrony effect does not interact with, or depend on effector type (Ma and Hommel 2015a, b). So, why did we obtain such an interaction in the present study? We speculate that this might have to do with the particular shape of the virtual effector. Moving shapes that resemble a human hand provide a particularly rich data source for relating sensory changes to the sensory predictions generated by planning the movements of one's own hand. On the one hand, the richness of the information about sensory changes should not directly depend on the particular shape of the virtual effector, as long as there are sufficient opportunities to match them against the predicted changes. This would explain why virtual effectors that do not look like human hands may affect perceived agency the same way as virtual effectors that do. On the other hand, however, shapes that are less differentiated than the human hand might reduce the possibility of matching, simply because the type of predictions can no longer be compared to the sensory changes related to the virtual effector. It is possible that this was the case in the present study. While this necessarily remains a speculation, it offers interesting hypotheses for a more systematic manipulation of the shape of the virtually factor. In particular, it suggests that the degree to which perceived agency is reduced by presenting non-biological virtual effectors is diagnostic to the kind of predictions that are involved in human action planning. In other words, understanding how the shape of virtual effectors changes perceived agency may also increase our insight into the mechanisms of action planning. Findings from a recent active-RHI study may be informative regarding this speculation. In Zopf et al. (2018), the authors manipulated effector type as a rubber hand or small sphere (similar size as fingertip), and asked participants to move their real finger up and down while watching the movement of a rubber hand finger or sphere. Similar agency ratings were found: viewing a hand increased explicit agency more than viewing the sphere, suggesting that the sphere was too small for participants to track its movements.

According to Ma and Hommel (2015b), the correlations between explicit agency judgments and explicit ownership judgments may rely on the shared use of information about the match between predictions and action outcomes. However, given that ownership judgments also show main effects of effector type, which have not yet been demonstrated for agency judgments, there must be another informational source that perceived ownership relies on. Indeed, there is emerging evidence that past experience with objects or events has an impact on whether they are or are not perceived as part or extension of one's body. Such past experience has been argued to be integrated into a body model (Tsakiris 2010), which should make individuals to be more likely to accept objects or events as body parts if they look more similar to body parts or body extensions the individual has past experience with (Tsakiris et al. 2010a; Liepelt et al. 2016). Given that this bias is a general one, it would be expected to add on top of possible bottom-up effects, such as synchrony. Hence, this bias would be expected to show up as a main effect, on top of any possible interaction with synchrony.

Let us now turn to the relationship between explicit and implicit measures. Regarding agency, we have emphasized the presumed strong role of expectations and predictions in determining explicit judgments. An important role of expectations and predictions has also been suggested for IB. Evidence supporting this possibility was provided by Haering and Kiesel (2016), who showed that the size of the IB strongly depends on whether the action effect appears at the time that participants have expected, irrespective of whether this timepoint was temporarily closer or further away from the action. Along the same lines, when participants moved objects by pushing joysticks forward or backward, IB was stronger for action effects that shared more features with (i.e., moved into the same direction as) the participant's actual movement (Ebert and Wegner 2010). These observations suggest that explicit agency judgments and IB might both rely on predictions, which would account for the main effects of synchrony on both measures (which is consistent with Tsakiris and Haggard 2005; Kalckert and Ehrsson 2012; Ma and Hommel 2015b, and others). Indeed, in Pyasik et al. (2018), the authors manipulated synchronous voluntary action and only observation conditions, and found both agency ratings and IB significantly stronger in voluntary action than in an observation condition.

Given that IB also shows an interaction between synchrony and effector type, it is also tempting to assume that the IB effect also relies on matching predictions against outcomes, which might be more difficult with virtual effectors that are as simple as the triangle be used in this study. Zopf et al. (2018) manipulated movement synchrony with a rubber hand or small sphere and found no interaction effect between effector type and movement synchrony. This might reflect a role of past agency experience: participants are more likely to have seen a sphere (Zopf et al. 2018) moving up and down in daily life than a triangle (used in current work) getting bigger or smaller. Corroborated evidence was also reported by in Braun et al. (2014), who found that time interval underestimation was significantly higher for movement of a spatially congruent other-agent finger than in neutral conditions, suggesting that IB may be sensitive to any hand form that implies ample past agency experience, no matter whether it belongs to oneself or not. Indeed, other IB studies already showed similar findings (Poonian and Cunnington 2013), such as perceived shortening of the interval for both self-made and observed other-made actions.

Along these lines, past agency experience may also account for the synchrony-by-effector interactions in explicit ownership and agency. Liepelt et al. (2016) investigated the influence of past agency experience on body ownership by stroking the participant's real hidden hand synchronously or asynchronously with a commonly used phone. Results showed that both ownership ratings and proprioceptive drift were higher after synchronous stroking, and comparable to the rubber hand condition. Given the tight relationship between ownership and agency (Ma and Hommel, 2015b), it is possible that past agency experience also contributes to current agency sense. Ma et al. (2019b) indeed observed that participants experienced higher agency over a 50%-controlled virtual hand after having experienced a 100%-controlled than a 0%-controlled virtual hand. Thus, expectations and predications, and perhaps even familiarity caused by past agency experience, may play a role for perceived agency. However, given the strong reliance of the IB on time and the possible reliance of agency judgments on shape, it makes sense that the individual effects related to IB and perceived agency did not correlate (Dewey and Knoblich, 2014; Ma et al. 2019b; Lafleur et al. 2020). Hence, it is possible that the explicit and implicit measure of agency was affected by the same factors, presumably indicating a role of prediction-outcome matching, but the feature dimensions being affected (shape vs. time) might have been too different to generate reliable correlations.

The implications of the findings relating the explicit and implicit measure of ownership are more difficult to judge, because none of the effects related to proprioceptive drift reached conventional levels of significance. We speculate that this might have to do with the pointing procedure we used. So far, most studies have used one of two methods to measure proprioceptive drift: the classical study of Botvinick and Cohen (1998) introduced the pointing method, in which participants use a finger of the non-stimulated hand to point to the position of a particular finger of the stimulated hand. Later, Tsakiris and Haggard (2005) introduced a perceptual judgment approach to measure drift, in which participants verbally report the position of the critical finger of the stimulated hand by referring to a number on a ruler placed above the stimulated hand. Kammers et al. (2009) found that the ruler-based verbal reports were significantly biased by synchrony, while the manual pointing accuracy was not. Conversely, Riemer et al. (2013) reported that proprioceptive drift was stronger for the active-RHI than the classical passive paradigm if drift was measured using a manual pointing procedure, but not with a perceptual judgment procedure. Hence, it seems clear that the two methods operate differently and may not produce the same results, but at this point it remains unclear why that is, what it implies, and which method should be preferred. Accordingly, we are reluctant to interpret the relationship between explicit ownership judgments and proprioceptive drift in the absence of at least a significant synchrony effect.

Another issue that we would like to emphasize is the rather low explicit ownership ratings and low overall responder proportion especially in comparison to the ratings from RHI studies (e.g. Tsakiris et al. 2010a; Kalckert and Ehrsson 2012). We assume that there are two main reasons. First, our designed virtual hand texture is less similar to real hands than a rubber hand. It is assumed that the seen virtual hand texture is an important feature for participants to consider when comparing an artificial effector against their body model (Tsakiris 2010). While in RHI studies participants' real hand and the rubber hand are commonly both covered with the same kind of latex glove (Kalckert and Ehrsson 2012), so to make the textures much more similar; in VHI the virtual hand is commonly uncovered, so that its texture seems more different from participants' real hand. Second, as found in a previous study (Ma and Hommel 2015a), the perceived connectedness of the virtual hand and the real body is important. In RHI studies, participants usually wear a cape that covers the space between the real body and the rubber hand (Kalckert and Ehrsson 2012), which increases the impression that they are connected. In contrast, in our current experiment setup, the virtual hand was clearly seen as separate from participants' real body, as shown in Fig. 1. Thus, we would like to argue that directly comparing the ratings obtained in the current VHI setup with ratings from previous RHI studies is misleading, as there are many other design factors involved, such as differences in the hand texture or connectedness. It is more reasonable to compare questionnaire ratings related to RHI and VHI within the same experiment setup, with comparable hand texture and connectedness, as we did in a previous study (Ma and Hommel 2015b)—with the result that VHI induced stronger ownership ratings than classical-RHI.

What remains to be discussed is why spatial congruency did not show any effect for any measurement. This is inconsistent with previous RHI studies, where congruency affected both ownership (Tsakiris 2010) and agency judgements (Kalckert and Ehrsson 2012; Braun et al. 2014). Similar to our argument regarding the relationship between explicit ownership and agency measures, we assume that the experimental setup may account for this empirical discrepancy. In the highly artificial RHI paradigms, where spatial congruency effects are commonly found, the rubber hand cannot be moved and even the more active versions of the paradigm (e.g. Kalckert and Ehrsson 2014) offered no more than the opportunity to control the horizontal movement of a single finger. In contrast, VHI paradigms like ours, performed and perceived movements are entirely natural in the synchronous condition, which we have argued provides a much richer database for all kinds of judgments. It may thus be the absence of this database that more or less artificially motivates individuals to rely on other sources, and spatial congruency might be such an example. Indeed, we (Ma et al. 2019a) found evidence that people trade informational sources like synchrony and exclusivity for each other, depending on the availability and reliability of the respective source. Hence, it is possible that in our immersed VHI design, synchrony provided so much data that considering other sources, like congruency, was unnecessary. It is also possible that, because of the lacking connectedness of virtual hand to real body, participants were more likely to perceive the effector as separate from the body, so that the spatial congruency did not matter as much as in RHI studies (Kalckert and Ehrsson 2012). However, this may in turn suggest that the importance of spatial congruency may at least partly derived from perceived connectedness between the rubber hand and the real body by participants.

We did not include any control questions for ownership and agency judgement. While this might be seen as a methodological shortcoming, there are reasons to assume that truly suitable neutral questions are hard to find for VHI studies. The traditional control questions were introduced to account for the RHI (Botvinick and Cohen 1998) and VHI studies simply took them over. However, as our previous VHI study showed (Ma and Hommel 2015a, b), all questions (illusion, agency and control questions) tend to show significant synchrony effects, suggesting that RHI related control questions are not suitable for VHI anymore—an issue we discussed earlier (Ma and Hommel 2015a). This may be the reason why in several active-RHI studies, the control questions were not used either (Zopf et al. 2018; Caspar et al. 2015a, b). Thus we also did not include the RHI control questions in the current study. However, we do think control questions may contribute to exclude participants' response bias or possible suggestibility, thus it would be necessary to design specific, theoretically more transparent, truly neutral control questions for VHI in future studies.

Taken altogether, our findings suggest that explicit and implicit measures of ownership and agency partly rely on shared informational sources, but may differ with respect to other sources that are integrated, like in the case of explicit ownership and agency, or with respect to the processed dimension, like in the case of explicit agency judgments and IB. Our findings also suggest that some findings obtained with RHI designs might reflect more the unnatural situation that that design puts individuals into rather than generalizable mechanisms of computing perceived ownership and agency.

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Author contributions KM and BH developed the study concept. All authors contributed to the study design. Testing and data collection were performed by WZ, JQ, and LY. Data analysis was performed by KM, JQ, and LY. Manuscript drafting was performed by KM, and BH provided critical revisions. All authors approved the final version of the manuscript for submission.

Availability of data and materials The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Ethical approval All procedures performed in this study were in accordance with the ethical standards of ethics committee in Southwest University and with the 1964 Helsinki declaration and its later amendments.

Informed consent Informed consents were obtained from all participants included in this study.

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