Psychological Research (2019) 83:175–184
https://doi.org/10.1007/s00426-018-0978-7

ORIGINAL ARTICLE

The roles of consistency and exclusivity in perceiving body ownership and agency

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Received: 10 July 2017 / Accepted: 4 December 2017 / Published online: 23 January 2018

Abstract
Previous rubber/virtual hand illusion studies have established important constraints for the illusion that an artificial effector becomes part of one's own body (perceived ownership), and that its actions are being caused by oneself (perceived agency). We can take these observed constraints to establish two of three Wegner's (Trends Cogn Sci 7:65–69; Wegner, Trends in Cognitive Sciences 7:65–69, 2003) criteria for the perception of personal agency: priority and consistency, but not Wegner's third criterion—exclusivity. In this study we tested with virtual hand illusion, whether exclusivity (participant is certain who was controlling the virtual effector) can also be established. We manipulated two factors: exclusivity and consistency. Our results show that on both ownership and agency judgments, consistency and exclusivity produced main effects, and the two effects interacted in an underadditive fashion. Taken together, these findings provide support for our suggestion to extend Wegner's agency theory to explain perceived body ownership, which in turn provides an integrative framework for interpreting constraints on ownership and agency illusions.

Introduction

How do people create cognitive representations of themselves? While this is an old question with a long philosophical history, it is only recently that research has systematically been devoted to investigate the construction of cognitive selves. Particularly instrumental was the rubber hand illusion (RHI) first reported by Botvinick and Cohen (1998), which consists in the observation that people perceive a seen rubber hand lying in front of them as a part of their own body, if this hand and their own real hidden hand are stroked synchronously. Later studies have extended this design to virtual reality, and shown that people perceive a virtual hand (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008) and even a virtual balloon (Ma & Hommel, 2015a) as a part of their own body if it moves or changes its shape in synchrony with their own, unseen real hand—the virtual hand illusion (VHI).

Studies of that sort are commonly considered to tap into perceived body ownership, a component of self-perception and self-representation that is traditionally considered to be separate from perceived agency—the perception to be the cause of a given event (Gallagher, 2000a). Some studies using the rubber hand setup have indeed suggested that ownership and agency are dissociable (Gallagher, 2000b; Tsakiris, Schütz-Bosbach, & Gallagher, 2007; Kalckert & Ehrsson, 2012). For instance, participants were reported to experience strong agency, but not ownership, over an active rubber hand (participants were able to move one finger of the rubber hand) presented in anatomically implausible positions (Kalckert & Ehrsson, 2012, 2014a) or at a far distance (Kalckert & Ehrsson, 2014b). However, other RHI studies found evidence for a positive relationship between ownership and agency (e.g., Tsakiris, Prabhu, & Haggard, 2006). Interestingly for present purposes, indications that ownership and agency might be dissociable are available from RHI studies only, while strong and positive correlations are the standard observation in VHI studies (Caspar et al., 2015; Kokkinara & Slater, 2014; Ma & Hommel, 2015b).

While more research on this interesting discrepancy is warranted, it makes sense to assume that, compared to the

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rather artificial RHI setup, the VHI setup is much more natural and provides the participant with many more opportunities to test the degree to which the virtual effector can be controlled. This multiplies the data points available for assessing the degree of correlation between one's own movements and the movements of the virtual effector, which in turn provides a solid basis for judgments of ownership and agency. In the absence of such a basis, and in the presence of a rather strange and unfamiliar experience, as with the rubber hand setup and the stroking intervention, it is likely that participants draw on various sources of information to judge ownership and agency (Synofzik, Vosgerau, & Newen, 2008; Ma & Hommel, 2015b). This is likely to increase the variability of the judgments and the probability to consider different data for perceived ownership and perceived agency judgments. Consequently, correlations between the two judgments should become weaker and may even become negative under some circumstances. Considering such a scenario, finding more evidence for dissociations and a greater variability across studies for the RHI than for the VHI should not be too surprising. Even more importantly for our present purposes, this implies that occasional reports of dissociations between ownership and agency from RHI studies should not be taken to speak against the possibility of finding a strong relationship between these two judgments in a VHI study, as the one reported here.

The idea that perceived ownership and agency might rely on partly overlapping informational sources raises an interesting theoretical possibility that we aimed to explore in the present study with our VHI design. From a conceptual viewpoint, the state-of-the-art in the field of perceived ownership and agency for artificial effectors and other body parts suffers from a lack of integration. Numerous studies have shown that the temporal relationship between having one's own hand stroked in seeing an artificial hand being stroked, as in the RHI, or between moving one's own hand and seeing an artificial hand moving, as in the VHI, matters in the sense that more synchrony leads to higher ownership (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005; Costantini & Haggard, 2007) and agency judgments (Caspar et al., 2015; Kokkinara & Slater, 2014; Ma & Hommel, 2015b). Other studies have shown that the spatial relationship between one's own body and hand and the artificial effector matters as well, in the sense that closer and more natural connections lead to higher ownership judgments (e.g., Lloyd, 2007; Maravita, Spence & Driver, 2003; Preston, 2013; Zhang, Ma, & Hommel, 2015). Even other studies have provided evidence that the similarity between one's own hand and the artificial effector contributes to the illusion, at least under some circumstances (Tsakiris, Carpenter, James, & Fotopoulou, 2010; Ma & Hommel, 2015a, b). These observations are certainly interesting and providing important constraints for understanding the emergence of the illusion, but a theoretical framework that would allow for the systematic integration of these factors into a more coherent scenario of how perceived ownership and agency is derived, and that would guide further empirical research, is lacking. However, if we consider that ownership and agency perception may rely on the same informational cues in VHI, we need not restrict ourselves to theoretical approaches to ownership but can extend the scope to theories of agency. The present study was motivated by the idea that the agency theory of Wegner (2003) might be particularly useful for systematizing ownership- and agency-relevant cues.

Wegner's theory claims that people perceive agency for their own actions to the degree that the effects of these actions meet three criteria, which in turn are derived from Michotte's (1946/1963) work on perceived causality: priority, consistency, and exclusivity. The priority principle requires perceived causes to precede, and to be temporarily closely connected to their consequences; the consistency principle requires consequences to be similar to their causes; and the exclusivity principle requires the absence of other salient possible causes. It is interesting to see that two of these principles nicely capture the already known constraints for RHI and VHI. Take the reliance of the illusions on the timing between stroking or moving the real and the artificial hand. This reliance can be taken to reflect the importance of priority, especially in the case of the more dynamic VHI setup: moving one's own hand requires an intention to be formed. According to ideomotor theorizing (Hommel, 2009; Shin, Proctor & Capaldi, 2010), intentions refer to the sensory feedback one expects to emerge from the intended action, and the match between expected and actual feedback is assumed to determine the degree of experienced agency (Blakemore, Wolpert, & Frith, 2002; Frith, Blakemore, & Wolpert, 2000). Arguably, tighter temporal synchrony between the movements of one's real hand and the movements of an artificial effector imply a closer connection between one's intention to move and the perceived movements of the artificial effector, which according to Wegner's priority principle should support the perception of agency. Given the available evidence for a strong reliance of ownership illusions on the temporal synchrony between one's own movements and the movements of artificial effectors, the same would hold for perceived ownership. This suggests a strong relationship between agency and ownership, which fits with our previous observation that these two judgments are significantly correlated in VHI setups (Ma & Hommel, 2015b). Minimal delays between intended action and the action of the artificial effector do not only meet the requirements of the priority principle, they also fit with the consistency principle, in the sense that intended and actual movement are more consistent with each other in the case of temporal synchrony. The consistency principle further captures the observation that greater similarity between

one's own effector and the perceived artificial effector can increase ownership and agency perception, and the findings that artificial effectors induce more ownership and agency if they are closely connected to one's body and/or seem to extend one's actual effector in a natural way.

Aim of study

The fact that two of Wegner's three principles provide a convenient summary and conceptual integration of the available evidence raises an obvious question: how about Wegner's third principle, exclusivity? Accordingly, the present study investigated whether exclusivity can be demonstrated to play a role in the VHI. Our experimental approach resulted from combining our previous virtual effector setup (which gives the rise to the illusion that a virtual balloon that grows or shrinks as the participant opens or closes his or her real hand; Ma & Hommel, 2015a, b) with Wegner and Wheatley's agency study (Wegner & Wheatley, 1999). These authors induced uncertainty about agency by having a task performed by the actual experimental participant and a confederate, who could both contribute to a common action outcome. Wegner and Wheatley did not manipulate exclusivity (i.e., the confederate was always present) but this can be easily achieved by comparing this joint-action setup with a condition in which the participant is working alone. We combined this manipulation with the manipulation of the degree to which the movements of the virtual balloon were actually controlled by the participant's own movements or by computer-generated noise (which in the non-exclusivity condition the participant was thought to attribute to the confederate). We will refer to this manipulation as "consistency", even though it arguably comprises of priority aspects as well (i.e., the label consistency might be taken as shorthand for consistency/priority).

We used the virtual balloon (rather than, say, a virtual hand) as virtual effector for two reasons. Firstly, our adaptation of the Wegner and Wheatley task required two individuals (the actual participant and a confederate) to sit side-by-side and putting one of their hands (the hand that would operate the virtual effector) inside a box. Asking both individuals to use their right (dominant) hand for that purpose would have had the disadvantage of creating a substantial distance between the two operating effectors. We therefore chose to seat the actual participant on the left, so that he/she could use his/her right hand, and the confederate on the right, so that he could use his left hand. Had we used a virtual hand as virtual effector, this would have created unequal relationships between the two operating, real hands, however: using a right virtual hand would have fit with the participant's but not with the experimenter's hand, in the opposite would have been true when using a left virtual hand. Secondly, we thought that the experience of random movements of the virtual effector, which we needed to introduce in our design, might be easier to tolerate and still find relatively natural for a virtual effector that does not look like a hand—over which perfect control is the standard experience. As we found no difference with respect to perceived ownership and agency between a virtual human hand and a virtual balloon varying in size in a previous study (Ma & Hommel, 2015a), we considered the balloon a reasonable solution to these two problems. One may object that previous RHI studies (e.g., Tsakiris et al., 2010) were taken to suggest that people are unable to incorporate non-corporeal objects into their perceived self. However, findings demonstrating the contrary were not only obtained by Ma and Hommel (2015a) but in a number of other VHI studies (e.g., Short & Ward, 2009; Ma & Hommel, 2015a, b) and RHI (Armel & Ramachandran 2003; Liepelt, Dolk, & Hommel, 2017) as well. Hence, the available evidence provides some support for the assumption that perceived ownership in VHI is not restricted to corporal effectors but extends to non-corporal objects, where they can induce the same degree of perceived ownership and agency as corporal effectors, provided that they move with, and exhibit some degree of perceived connectedness with one's real effector (Ma & Hommel, 2015a).

We considered three dependent variables: perceived body ownership and perceived agency, which served for testing our hypotheses, and proprioceptive drift. The latter, which we included for explorative purposes, is a more implicit measure of ownership that previously was found to pick up different aspects than ownership and agency questionnaires (Rohde, Di Luca, & Ernst, 2011), but is widely used as an objective measurement for the perceived illusion (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2014a). Our predictions regarding perceived ownership and agency were threefold. First, we expected an effect of consistency (i.e., an increase of ownership and agency with increasing consistency), which can be considered a conceptual replication of previous observations of increased ownership and agency with synchrony between one's own, real movements and the movements of a seen artificial effector (Ma & Hommel, 2015a). Second, and this would be one novel contribution of the present study, we expected an effect of exclusivity (i.e., more ownership and agency with exclusivity), which would support our claim that Wegner's theory (Wegner 2003) can be used to interpret rubber hand and virtual effector illusions.

Third, we were interested to see how consistency (i.e., consistency/priority) and exclusivity would relate to each other. Wegner's theory does not suggest a particular kind of relationship between its agency criteria, which might be taken to suggest an additive model, but others have been more specific. In particular, Synofzik et al. (2008) have suggested that agency perception may emerge from the integration of multiple sources of information, and there is evidence

that the same holds for ownership perception (Ma & Hommel, 2015b). If so, it is possible that information from some sources can compensate for the lack of information from others, which would suggest an underadditive relationship, in the sense that a particular source is considered more the less informative other sources are. Finally, as a more explorative endeavor, we were interested to see whether proprioceptive drift, a more implicit measure of ownership and agency, would show the same pattern as the questionnaire data.

Method

Participants

Thirty-three participants (9 males; mean age = 18.82 years, standard deviation (SD) = 1.014, range 17–21) were recruited from Southwest University, China, in exchange for pay. Participants were naive with respect to RHI/VHI. Written informed consent was obtained from all participants before the experiment, the study was approved by the local human research ethics committee at Southwest University, the methods were carried out in accordance with the approved guidelines.

Setup

The setup was similar as in our previous study (Ma & Hommel, 2013), where a balloon (that grew or shrank as the participant opened or closed his or her real right hand) served as artificial effector. We used a virtual reality environment (Vizard); a dataglove (5DT, measurement frequency = 75 Hz, latency = 13 ms), which participants wore with their right hand; a black box (width 54.4 cm × depth 23 cm × height 12 cm), in which the participant put his or her right hand along the depth axis, so to shield it from view; and a cape placed over the participant's right shoulder to cover the space between the participant and the virtual effector. We designed a virtual balloon and imported it, together with the dataglove module, into Vizard, so that the virtual balloon that was shown in the middle of the computer screen on the box was controlled by the data from the dataglove, i.e., by the participant's hand movement (see Fig. 1) in all relevant conditions.

From the beginning, participants wore the dataglove with their right hand, put their right hand in the box, wore the cape on their shoulder, and looked at the computer screen placed on the box (see Fig. 1a, b). The virtual balloon was visible on the screen in front and to the right of the participant, and it changed in size (becoming 1.0 times bigger

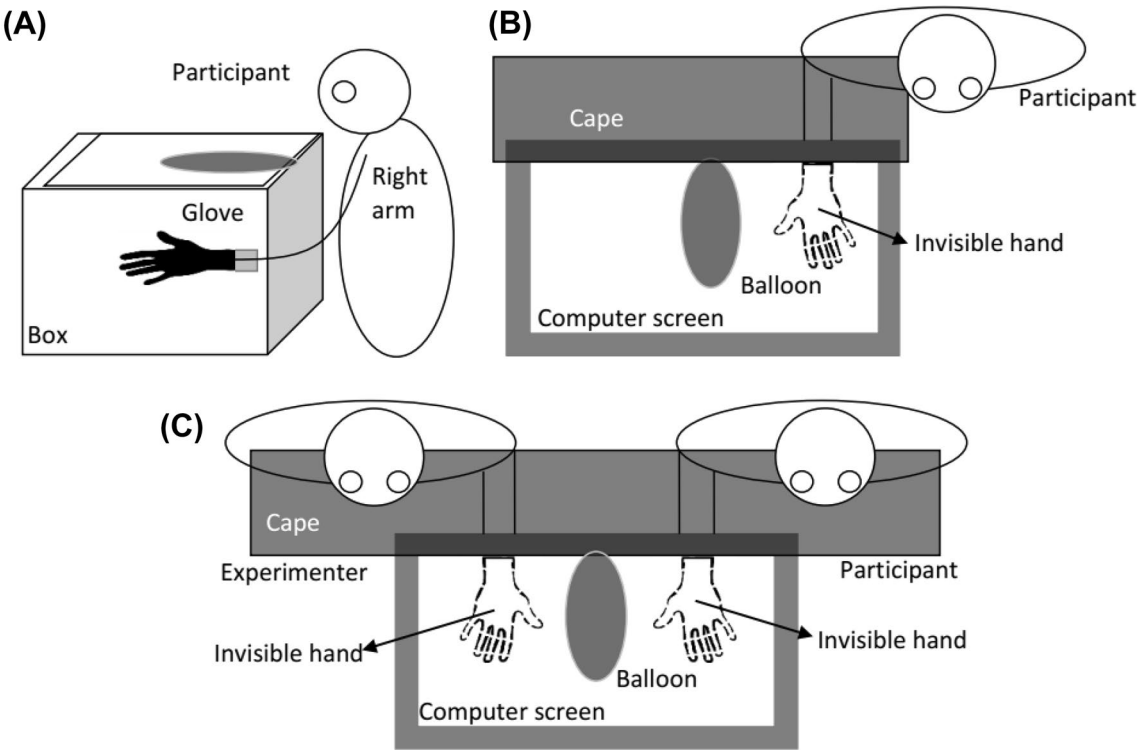

Fig. 1 The experimental setup used to manipulate exclusivity. **a** Side and **b** top view of participants when experiencing the virtual balloon (exclusive condition); **c** top view of participant (seated on the left, using the right hand) and experimenter (seated on the right, using the left hand) when experiencing the virtual balloon together (non-exclusive condition)

or 0.5 times smaller) when participants opened and closed their hand.

In the exclusive conditions, the participant was performing alone (see Fig. 1b). In the non-exclusive conditions, however, the experimenter would also wear a dataglove (covered by the same box) and a cape, and sit side-by-side with the participant, as shown in Fig. 1c. The computer screen showing the virtual balloon was 54.4 cm wide, with the left edge of the computer screen set as zero position, the position of the virtual effector was 27.2 cm. In the exclusivity conditions, the position of participants' real right hand middle finger tip was 22.2 cm; while in the non-exclusivity conditions, the position of participants' real right hand middle finger tip was still 22.2 cm, the position of experimenter's left hand middle finger tip of experimenter was 32.2 cm; the position of virtual balloon was in the middle of participant and experimenter. Unbeknownst by the participant, the experimenter's dataglove was not connected to the computer, and all contributions to the balloon's size changes that were not produced by the participant were actually generated by the computer. However, the experimenter did move his or her real hand, there were no any instructions whether this would or would not be the case, so to create a plausible degree of uncertainty about who is controlling the balloon.

The consistency condition was determined by the control scripts, so that the virtual balloon size change was actually controlled by a particular combination of the participant's real hand movement and computer-generated noise. The participant's hand movement was multiplied by a weight (1, 0.5 or 0) and mixed with different percentages weight (0, 0.5 or 1) of noise. In the 100% consistency condition, the contribution of noise was set to zero, so that the size of the balloon was perfectly correlated with the real hand movement of the participant. In the 50% consistency condition, the contribution from the real hand movement and noise was 50% each, and in the 0% consistency condition, only noise was considered to control the size of the balloon. This means that the consistency between the movements of the real hand and the virtual balloon was 100, 50 and 0% in these conditions, respectively. Participants were not informed about the degree of consistency or, in the non-exclusive conditions, about the contribution from the experimenter.

Design

Participants underwent six conditions, which resulted from crossing the two factors, exclusivity (two levels) and consistency (three levels). Each level of exclusivity was combined with three consistency conditions. In the 100% consistent condition, the size changes of the virtual balloon were effectively controlled by the participant's own hand movements, so that the felt real hand movement and seen virtual balloon size changes matched completely. In the 50% consistent condition, only 50% of the actual size changes of the virtual balloon were controlled by the participant's hand movement (i.e., that was true for 100% of the trials), so that the match between felt real hand movement and seen virtual balloon size changes was noticeably imperfect. In the 0% consistent condition, the size changes of the virtual balloon were entirely unrelated to the participant's hand movements. Consistency varied within exclusivity and participants always experienced the exclusive conditions before the non-exclusive conditions. The order in which the three consistency conditions varied within each exclusivity condition was counterbalanced across participants, but the same for both exclusivity conditions.

Procedure

When participants first came to the lab, they were asked to put on the cape and the dataglove on their right hand and put their right hand into the box. The cape was arranged in such a way that it covered the box and participants' arm, so that participants could not see their real right hand but only watch the virtual balloon on the computer screen. Participants then performed in three consistency conditions alone, before they were joined by the experimenter and performed the remaining three consistency conditions.

There were four phases in each of the six conditions. First, in the proprioceptive drift pre-measurement phase, participants were asked to verbally report a letter in the letter array shown on the top of computer screen to represent the felt position of their real right hand. Letter sequences in the letter array were changed in each condition to prevent individual strategies (Ma & Hommel, 2015b). Second, participants were asked to keep their real right hand palm upwards, freely open and close their right hand but not to move their hand horizontally, and watch the corresponding movement of the virtual balloon for 2 min. Third, participants were asked to rest their right hand with the same posture as in the first phase, again to verbally report a letter in the letter array to represent the felt position of their real right hand middle finger tip: the proprioceptive drift post-measurement. Fourth, participants were asked to fill in the questionnaire. There was a 2-min time break between each two conditions, a rest image was shown on the computer screen and participants were asked to take a rest, so to reduce possible transfer effects.

Questionnaire

To assess the extent to which participants felt the agency and ownership sense when experiencing the VHI, we used an adapted Chinese version of the RHI/VHI questionnaire (Botvinick & Cohen, 1998; Slater et al., 2008; Kalckert & Ehrsson, 2014a). In particular, we presented participants with

eight questions assessing perceived body ownership (Q3–4) and agency (Q1–2). We included four more questions for explorative purposes (e.g., I felt as if the virtual balloon on the screen was a part of my body; How much of the size changes of the virtual balloon was controlled by me?), but will focus here on the four traditional ownership and agency questions. 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:

Q1. The size changes of the virtual balloon on the screen were caused by me.
Q2. I can control this virtual balloon as I wish.
Q3. I felt as if I was looking at my own hand when I was looking at this virtual balloon.
Q4. I felt as if the virtual balloon on the screen was my own hand.

Proprioceptive drift

Participants were asked to only open and close their right hand, but not to change its horizontal position, and there were two baffles in the box around the real hand to block its horizontal replacement; hence, the spatial relationship between virtual effector and participant's real right hand was always the same in all conditions. During the experiment, we recorded the letters in the letter array corresponding to the felt position of the real hidden hand middle finger tip before and after the illusion induction (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2014a; Tsakiris, Prabhu, & Haggard, 2006). We measured the actual position of each letter in the letter array shown on the screen. The letter sizes differed depending on their alphabetic shape, with the biggest letter measuring approximately 0.4 cm. We calculated the proprioceptive drift by subtracting the participants' felt position at the pre-measure from the felt position at the post-measure, so that positive values imply a drift towards the virtual balloon.

Results

We aggregated the four relevant questionnaire ratings into the two respective categories: ownership (Q3,4) and agency (Q1,2) (Kalckert & Ehrsson, 2014a; Ma & Hommel, 2015b). Ownership and agency ratings, each questionnaire item rating, as well as the drift rates were analyzed by means of 2(exclusivity) × 3 (consistency) two-way ANOVAs for repeated measures. All results are shown in Table 1 and Fig. 2. We considered it appropriate to analyze our data by means of ANOVAs, because they are known to be robust against violations of normality assumptions and because we applied Greenhouse–Geisser corrections in case of violations of sphericity assumptions. However, as our data are maybe argued to be ordinal in nature, we also analyzed the data by means of non-parametric Friedman tests and two-tailed Wilcoxon signed-rank post hoc tests—without any change of the outcome. We also analyzed the two items for each category separately, by means of both ANOVAs and non-parametric tests, which revealed only one deviation from the reported pattern, which will therefore be the only finding from these extra analyses that we will report below.

Ownership ratings

The two significant main effects of exclusivity, $F(1,32) = 18.32$, $p < .001$, $\eta p2 = 0.36$; and consistency, $F(2,64) = 36.48$, $p < .001$, $\eta p2 = 0.53$; were further mediated by a significant interaction, $F(2,64) = 10.37$, $p < .001$, $\eta p2 = 0.25$. Follow-up t tests (all two-tailed) revealed that the effect of exclusivity was significant for the 0%-consistency condition, $t(32) = 5.24$, $p < .001$, $d = 1.37$; but not for 50% consistency, $p = .085$, or 100% consistency, $p = .426$. That is, participants perceived less ownership for the virtual balloon in the non-exclusive than in the exclusive condition when the movements of the participant's real hand and the virtual balloon were entirely inconsistent, while exclusivity did not matter if there was at least some degree of consistency.

Table 1 The two criteria, means and standard errors for the ratings of ownership and agency questions, proprioceptive drift, in all six conditions, +: exclusive; −: non-exclusive; 100%: 100% consistent; 50%: 50% consistent; 0%: 0% consistent

Consistency	Exclusivity	Ownership (Q3–4)	Agency (Q1–2)	Proprioceptive drift (cm)	Q3	Q4	Q1	Q2
100%	+	4.35/0.26	6.39/0.15	1.00/0.54	4.39/0.31	4.30/0.32	6.58/0.11	6.21/0.23
50%	+	3.27/0.28	5.18/0.28	0.25/0.18	3.12/0.28	3.42/0.30	5.24/0.29	5.12/0.31
0%	+	3.23/0.30	3.06/0.28	0.26/0.54	3.18/0.30	3.27/0.30	3.18/0.28	2.94/0.30
100%	−	4.20/0.30	6.68/0.09	0.66/0.16	4.24/0.32	4.15/0.33	6.76/0.09	6.61/0.11
50%	−	2.70/0.25	4.56/0.23	0.24/0.21	2.61/0.25	2.79/0.26	4.33/0.25	4.79/0.25
0%	−	1.42/0.16	1.26/0.10	0.21/0.17	1.36/0.16	1.49/0.16	1.27/0.11	1.24/0.11

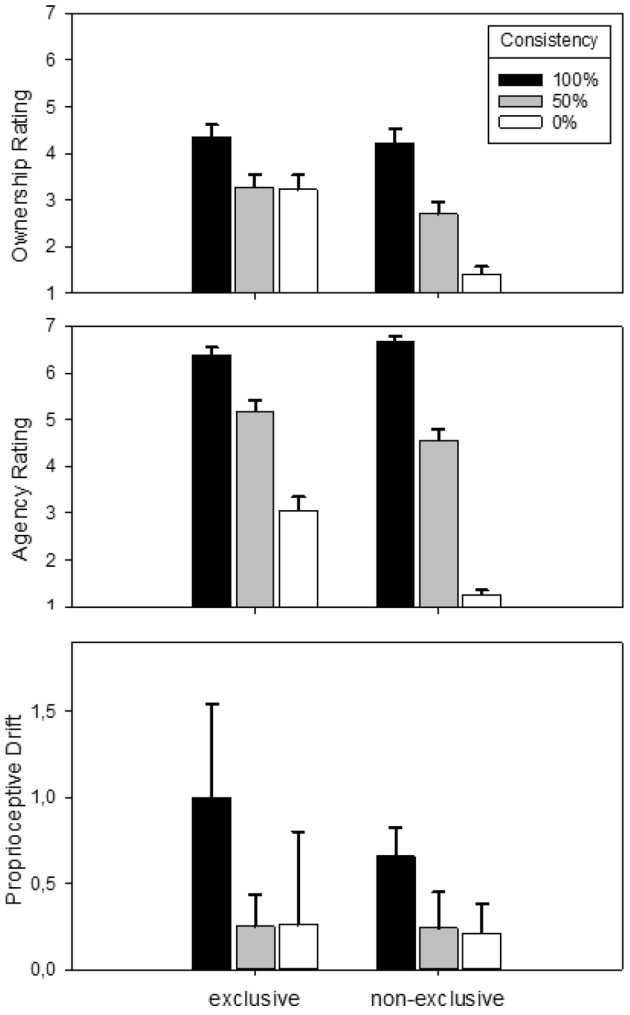

Fig. 2 Ownership and agency, proprioceptive drift rating results as a function of consistency and exclusivity. The unit for proprioceptive drift is cm, and all error bars represent ± 1 standard error

Agency ratings

The two significant main effects of exclusivity, $F(1,32) = 16.79$, $p < .001$, $\eta p2 = 0.34$; and consistency, $F(2,64) = 267.11$, $p < .001$, $\eta p2 = 0.89$; were further mediated by a significant interaction, $F(2,64) = 14.62$, $p < .001$, $\eta p2 = 0.31$. Follow-up t tests revealed that the effect of exclusivity was significant for the 0% consistency condition, $t(32) = 6.16$, $p < .001$, $d = 1.65$, but not for 50% consistency, $p = .08$, or 100% consistency, $p = .144$ [item-specific t tests showed the same pattern for Q2, where exclusivity was significant for 0% consistency, $t(32) = 5.43$, $p < .001$, $d = 1.47$, but not for 50%, $p = .4$, or 100% consistency, $p = .16$; while for Q1 exclusivity was significant for both 0%, $t(32) = 6.51$, $p < .001$, $d = 1.71$, and 50% consistency, $t(32) = 2.58$, $p = .015$, $d = 0.59$; but not for 100% consistency, $p = .226$]. Overall, this pattern perfectly mimics the one obtained for ownership, with exclusivity playing a role only in the absence of any consistency. This similarity was also confirmed by an ANOVA with question dimension (ownership vs. agency), exclusivity, and consistency as within participant factors. Most importantly, the three-way interaction was far from significance, $F(2,64) = 0.495$, $p = .612$, suggesting that both scores were affected by the experimental factors in a similar way.

We also computed the correlations between the questionnaire ratings of ownership and agency (one-tailed Spearman, $n = 33$), which revealed significant positive correlations for 0% consistency under exclusivity, $r = 0.573$, $p < .001$, close-to-significant correlations for 50% consistency under exclusivity, $r = 0.286$, $p = .053$, but far-from-significant correlations for all other conditions, with $rs < 0.197$, $ps > .136$.

Proprioceptive drift

The main effect of consistency was significant, $F(2,64) = 3.52$, $p = .035$, $\eta p2 = 0.10$, but the main effect of exclusivity and the interaction was not, $Fs < 0.229$. Least-significant difference (LSD) post hoc tests revealed that the 100% consistency condition differed from both the 50% condition (mean difference 0.59, SE 0.29, $p = .049$) and the 0% condition (mean difference 0.60, SE 0.21, $p = .007$), while the latter two did not differ (mean difference 0.01, SE 0.27, $p = .96$). That is, participants perceived a stronger drift of their right hand towards the virtual balloon when the movements of real hand and balloon were 100% consistent, while there was no difference if consistency was less or absent.

Discussion

The key question motivating this study was whether exclusivity, one of Wegner's (2003) three-agency criteria, could be established as a factor impacting both perceived body ownership and agency. The outcome of the study supports this assumption.

First, we did not only observe an effect of consistency (or consistencies/priority), which we take as a conceptual replication of previous synchrony effects (Ma & Hommel, 2015a), but also a significant main effect of exclusivity. The former confirms the contribution of objective controllability, i.e., priority and consistency, to subjective ownership and agency (Ma & Hommel, 2015b). The consistency effect is in line with previous findings (Sanchez-Vives, Spanlang, Frisoli, Bergamasco & Slater 2010) and suggests that visuomotor correlations are sufficient for the illusory ownership perception. The latter extends previous demonstration of an impact of priority and consistency on perceived ownership and agency to exclusivity, suggesting that all three of Wegner's (2003) key factors play a role in ownership and

agency. This in turn suggests that his action recognition approach may provide a suitable theoretical framework for understanding both agency and ownership phenomena and reinforces the assumption that agency and ownership rely on overlapping, if not identical informational sources, at least in the VHI paradigm (Ma & Hommel, 2015a, b). Indeed, we found that ownership and agency ratings were equally affected by the manipulated variables.

Second, we also found that consistency and exclusivity interacted, showing that consistency has a stronger effect if exclusivity is absent, and that exclusivity has a stronger effective when consistency is low or absent. This outcome pattern supports the assumption that judgments of both agency (Synofzik et al., 2008) and ownership (Ma & Hommel, 2015b) rely on multiple informational resources that are integrated in such a way that the lack of one kind of information can be compensated by the presence of another. Our finding also shows that, when priority and consistency criteria were perfectly met, the exclusivity itself was not able to modulate subjective ownership and agency. This corroborated the (apparently greater) importance of a match between seen virtual balloon movement and participants' intention and voluntary action and is consistent with some previous studies. In particular, Wegner et al. (2004) observed that participants perceive the movements of two "alien hands" (of an unseen person standing behind them) as their own as long as they heard the instruction describing the action that followed. In other words, spatiotemporal consistency between an action and a represented "action intention" (which apparently does not even need to belong to the participant) can be strong enough to fully compensate for the obvious absence of exclusivity. This might suggest that other things being equal to some of Wegner's three principles might be more important than others but, in the absence of a common metric that allows comparing the strength of manipulations of these principles, this possibility will be difficult to test.

Given the not yet fully understood relationship between ownership and agency judgments, on the one hand, and more implicit measures such as proprioceptive drift, on the other, we had no specific hypotheses regarding the drift rates. We did find an effect of consistency, which fits with previous observations (Kalckert & Ehrsson, 2014a), but no effect of, or including exclusivity. While we have no explanation for this particular pattern to offer, we note that this finding is consistent with previous suggestions that proprioceptive drift and questionnaire ratings may not assess the same mechanisms, and that self-judgments may integrate more and/or different sources of information (Holmes, Snijders, & Spence, 2006; Ma & Hommel, 2015b; Rohde, Di Luca, & Ernst, 2011; Abdulkarim & Ehrsson, 2015). It is not impossible that the presence of two people in our setup has played a role in dissociating explicit and implicit measures. With respect to the explicit judgments, our findings demonstrate that VHI can be induced in joint setups. However, it might be interesting to note that Obhi and Hall (2011) reported dissociation between explicit and implicit measures in a joint-action task. In their study, one participant acted as initiator and another as responder, and it turned out that explicit feelings of agency were only reported by the initiator, while both initiator and responder showed evidence of agency in implicit measures. Numerous differences in rationale and setup between this study and ours make a comparison difficult and speculative, but the possibility that the sociality of the situation may affect explicit and implicit measures differently raises interesting questions that call for further investigation.

One may raise objections against our interpretation based on the fact that the questionnaire ratings were relative low overall, and in fact lower than in many investigations of the RHI (e.g., Tsakiris et al., 2010; Kalckert & Ehrsson, 2012, 2014a). As already discussed at some length elsewhere (Ma & Hommel, 2015a), this is, however, likely to do with our particular experimental setup (i.e., the reliance on VHI rather than RHI) rather than with a possible weakness of the induced illusion. This is for instance suggested by the observation that the rating effects obtained with a virtual hand and with a virtual balloon are almost identical (Ma & Hommel, 2015a), which rules out the possibility that a biologically plausible effector induces a stronger illusion than a biologically less plausible effector and suggests that whatever kind of illusion a virtual hand might induce is also induced by a virtual balloon. Indeed, other experiments with virtual effectors have reported equally low ratings (Sanchez-Vives et al., 2010).

Why virtual setups induce lower ratings is an interesting question that we at present can only speculate on. As compared to the rather artificial RHI setup, the VHI setup is much more natural and the participant has many more opportunities to test the degree to which the virtual effector can be controlled. As we have discussed in the introduction, this multiplies the data points available for assessing the degree of correlation between one's own movements and the movements of the virtual effector, which in turn is likely to reduce the strength of the correlation (as the translation of real into virtual movements still underlies some technical limitations). It might also be that the substantial artificiality of the RHI induces different criteria for judging ownership and agency, which might boost the ratings. In any case, more research on this issue will be necessary.

To summarize, we were able to demonstrate the relevance of exclusivity for subjective body ownership and agency, and found that both judgments were equally affected by this factor. As we have discussed, previous findings already showed that temporal synchrony between the movements of one's own and an artificial effector, spatial alignment between one's own body and an artificial extension, and similarity

between one's own and an artificial effector are crucial for obtaining RHIs and VHIs. If we take these findings to indicate Wegner's (2003) priority and consistency principles, our present findings provide the missing third link by establishing the importance of the exclusivity principle. This implies that Wegner's theoretical account provides a systematic, comprehensive framework to integrate the various, not yet well-connected observations of temporal, spatial, and similarity constraints for obtaining ownership and agency illusions. Moreover, given that Wegner's theory is based on systematic work on causality perception from Michotte (1946), this provides us with a broad and solid theoretical basis for systematically exploring the informational cues and perceptual mechanisms underlying self-perception.

Author contributions KM and BH developed the study concept. All authors contributed to the study design. Testing and data collection were performed by KM. Data analyses were performed by KM and BH. KM drafted the manuscript, and BH and HC provided critical revisions. All authors approved the final version of the manuscript for submission. We would like to thank two anonymous reviewers for their suggestions.

Compliance with ethical standards

Funding This research was supported by National Natural Science Foundation of China (31700942), China Postdoctoral Science Foundation (2017M622936), Chongqing Postdoctoral Science Foundation (Xm2017066), and Fundamental Research Funds for the Chinese Central Universities (SWU116055) to K. M. in China, and an infrastructure grant of the Netherlands Research organization (NWO) to B. H.

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 standards 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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