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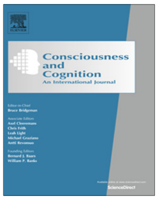

The relationship between human agency and embodiment

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ABSTRACT

Humans regularly feel a sense of agency (SoA) over events where the causal link between action and outcome is extremely indirect. We have investigated how intermediate (here, a robotic hand) events that intervene between action and outcome may alter SoA, using intentional binding measures. The robotic hand either performed the same movement as the participant (active congruent), or performed a similar movement with another finger (active incongruent). Binding was significantly reduced in the active incongruent relative to the active congruent condition, suggesting that altered embodiment influences SoA. However, binding effects were comparable between a condition where the robot hand made a congruent movement, and conditions where no robot hand was involved, suggesting that intermediate and embodied events do not reduce SoA. We suggest that human sense of agency involves both statistical associations between intentions and arbitrary outcomes, and an effector-specific matching of sensorimotor means used to achieve the outcome.

1. Introduction

Recent work on the sensorimotor basis of self distinguishes two key aspects of self-awareness. First, we recognise that we are the authors of our voluntary actions, and of their consequences. This aspect is called sense of agency. Second, we recognise our body as our own, and as the basis of individual experience of the world, even in the absence of any action. This aspect is sometimes referred to as body-ownership, although the key feature is the feeling of 'myness' (Gallagher, 2000) rather than any relation of possession. The feeling of ownership is closely related to the sense of agency because the body is the normal vehicle of our actions.

The sense of agency is a familiar experience, but is difficult to measure experimentally. One route involves using implicit proxy measures. For example, the interval between a voluntary action and its consequence is perceived as shorter than a control interval beginning with an involuntary movement or with another external event (Haggard, Clark, & Kalogeras, 2002). This shortening has been called the 'intentional binding' effect.

The human brain generates a sense of agency even with highly complex, devolved and indirect causal chains. For example, pushing buttons of a coffee machine can obviously involve a feeling of agency. However, the overall feeling of agency depends on a much wider range of events, including the fact that coffee comes out at the end of the brewing sequence, that

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it is delivered into the cup, and that it tastes good. Thus, even when action involves a sequence of several steps involving intermediate events, technologies, or even actions carried out by other agents, we may still feel some feeling of agency over the causal chain as a whole.

In particular, technology can augment and transform causal chains, providing increased productivity and innovative action. Thus, while sense of agency begins with the sensorimotor experience of controlling one's own body, healthy adult humans in advanced societies regularly experience sense of agency over events that are largely independent of the body. It thus remains unclear whether and how mediation by the body is actually relevant to the sense of agency. The cognitive processes underlying sense of agency could be so flexible that intermediaries in the causal chain are readily accommodated, even when these intermediaries are decoupled from, or in conflict with, bodily action. This paper focuses on whether sense of agency is fundamentally "embodied" (i.e., linked to basic sensorimotor processes) or whether it can be abstracted from normal sensorimotor control to cover unusual instrumental associations. This question is of importance in the design of new prosthetics, human interfaces and robotic agents. For example, brain-imaging studies have shown that brain plasticity leads to prostheses being integrated in the neural representation of the body (Ehrsson et al., 2008; Giraux, Sirigu, Schneider, & Dubernard, 2001; Lotze et al., 1999; Maruishi et al., 2004; Schmalzl, Kalckert, Ragnö, & Ehrsson, 2014).

The well-known rubber hand illusion (RHI – Botvinick & Cohen, 1998) has been an important experimental model for embodiment and agency. In the RHI, a fake but human-like hand is felt to be part of one's own body, either due to multisensory stimulation, or because its movements resemble the participant's voluntary actions (Tsakiris, Prabhu, & Haggard, 2006). When RHI is caused by the participant's actions, a sense of agency and a sense of ownership may both be present. Most studies agree that these two aspects of self-awareness are nevertheless dissociable (Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2012, 2014; Riemer, Kleinböhl, Hölzl, & Trojan, 2013), and have different brain bases (Tsakiris, Longo, & Haggard, 2010).

However, to our knowledge, no studies have systematically investigated how the sense of agency generalises outwards from one's own sensorimotor movements, by increasingly transformed mediation, to produce an intended goal outcome. While the concept of agency over external events has been extensively studied in operant learning paradigms, it remains unclear how changes and distortions in the intermediate causal chain may affect the sense of agency. In particular, when people intend to produce a particular external event through their own action, does the sense of agency depend on the body transforming intention into outcome in the normal, predicted way? Or can sense of agency persist when mediated by altered embodiment?

In Experiment 1, participants estimated the interval between a voluntary (or involuntary) action and a tone. The comparison between these conditions provides a convenient proxy measure of agency. In these two conditions, participants viewed a robotic hand moving congruently with their action. In a third condition, participants made voluntary actions, but viewed a robotic hand moving incongruently with their action. This active incongruent condition could thus represent an altered form of embodiment, and instantiate a deviant causal chain between the participant's action and the intended outcome. To address whether the intermediary presence of a robotic hand *per se* would affect the experience of agency, we included a fourth condition in which the robot hand was not present, and participants simply viewed their own hand while they made voluntary actions.

2. Experiment 1

2.1. Method

2.1.1. Participants

A total of 24 naïve participants were recruited. The sample size was based on previous studies of agency and embodiment (e.g. Kalckert & Ehrsson, 2012, 2014). Participants received £4 for their participation. The following exclusion criteria were decided in advance of the experiment: failure to produce temporal intervals covarying monotonically with actual action-tone interval, or failure to follow instructions. One participant's data was lost due to a technical error. Of the 23 remaining participants, 9 were males. The main age was 23.34 (SD = 4.558). All participants provided written informed consent prior to the experiment. The study was approved by the local ethical procedures of the Institute of Cognitive Neuroscience at University College London.

2.1.2. Procedure and material

Prior to the experiment, participants were first invited to listen to verbal instructions. They were instructed to fixate the robotic hand during the entire experiment. The experimenter was seated in front of the participant, on his/her right side (see Fig. 1A), from where she could verify the participant's gaze. The robotic hand was placed above the table at the same height as their real hand would be (see Caspar, De Beir, Magalhaes de Saldanha da Gama, Yernaux, & Cleeremans, 2014; De Beir et al., 2014 for more information about the robotic hand). The participant's arm and the box containing the motors of the robotic hand were hidden under a blanket. One keyboard was placed under the robotic hand and one under the participant's hand. Only the second was connected to the computer (see Fig. 1B). The index finger of the robotic hand was placed to visually convey the impression of pressing exactly the same key as the participant. There were four blocked conditions. In the *active congruent* condition, participants performed a voluntary key press with the index finger, and saw the robotic

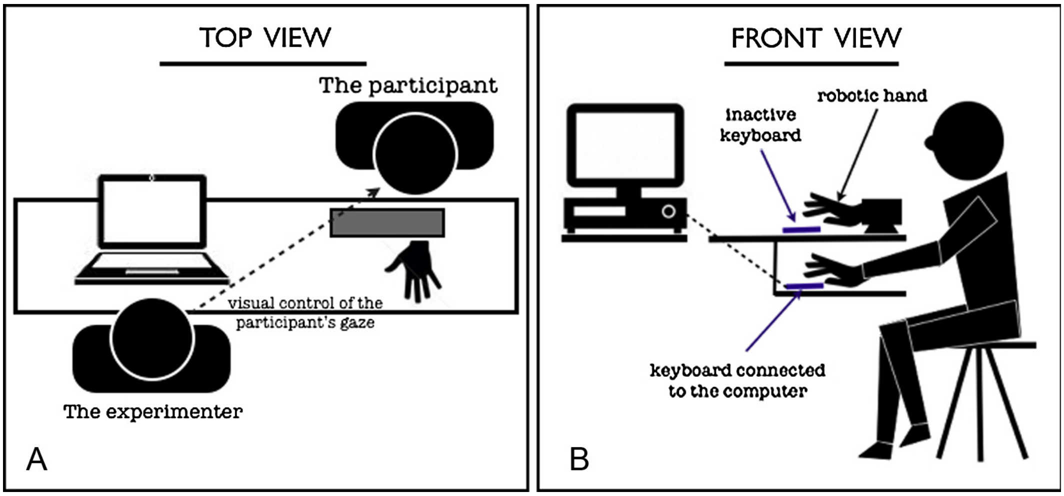

Fig. 1. Top view (A) and front view (B) of the experiment set-up.

hand replicate the same movement at the same time. In the *passive congruent* condition, the experimenter, wearing the glove, pressed the participant's passive index finger. The experimenter's finger movement triggered an index finger movement of the robotic hand. This design was developed so as to have the same number of events in each condition (a movement of the participant, a movement of the robotic hand, and a tone), while intentional action was either present or absent. In a third, *active incongruent* condition, participants again made a voluntary key press with their index finger, but this triggered movement of the *little* finger of the robotic hand. In the *control condition*, participants viewed their own hand rather than the robot hand. In this control condition, participants placed their own hand above the table (at the same location as the robotic hand in other conditions) and the robotic hand was removed. They were instructed either to gaze at their own hand or at the robotic hand, depending on the condition. The order of conditions was counterbalanced. Prior to the experiment, participants could manipulate the robotic hand for a short period (5 s), so that they could experience the fact that the hand was accurate in reproducing their movements, both spatially and temporally.[2] In all four conditions, participants heard a tone after the key press, and were asked to directly report the duration of the interval (in ms) between their index finger action and the tone (e.g. Moore, Wegner, & Haggard, 2009). We favoured interval estimation rather than event timing (e.g. Haggard et al., 2002) to avoid dividing visual attention between the computer screen and the robotic hand. Participants were instructed that the delay varied randomly on a trial-by trial basis, and never exceeded 1000 ms. In reality, only three delays were used, i.e. 300, 500 and 700 ms. Each interval (300, 500 and 700) was presented 20 times randomly and equiprobably, giving 60 trials per condition.

2.2. Results

2.2.1. Interval estimation

A Condition (active congruent, passive congruent, active incongruent, control) × Delay (300, 500, 700) repeated-measures ANOVA was conducted on participant's mean interval judgement (see Fig. 2). The main effect of Condition was significant, $F(3,66) = 11.305$, $p < .001$, $\eta^2_{partial} = .339$. Paired sample t-tests showed a shorter mean interval estimation in the active congruent condition (370.018, 95% CI: 324.893–415.144) than both the passive congruent condition (492.479, 95% CI: 432.25–552.69), $t(22) = -4.480$, $p < .001$, and active incongruent condition (443.018, 95% CI: 387.80–498.23), $t(22) = -3.017$, $p = .006$. Estimates in the active congruent condition (370.018, 95% CI: 324.893–415.144) and the control condition (383.52, 95% CI: 326.02–441.037) did not differ significantly, $p > .5$. Estimates in the passive congruent condition were increased relative to both the active incongruent condition, $t(22) = 2.963$, $p = .007$, and the control condition, $t(22) = 3.503$, $p = .002$. The difference between the active incongruent and the control condition was also significant, $t(22) = 2.208$, $p < .04$. The mean effect of Delay was unsurprisingly significant, $F(2,44) = 87.664$, $p < .001$, $\eta^2_{partial} = .799$. Participants judged shorter mean delay for the 300 ms delay (316.12, 95% CI: 277.43–354.81), than for the 500 ms delay (414.63, 95% CI: 365.22–464.04) and the 700 ms

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[2] In order to determine the actual delay between the participant's key press and the robot key press in this paradigm, we have analysed the mean and the standard deviation of the number of video frames displayed between these two events. Fifty trials were recorded using a Matlab script. The script was constructed in order to calculate the number of frames between the participant's and the robot key presses. Each frame is equal to 16.66 ms (=1 cycle refresh) on the testing computer. Results indicated a mean of 14.32 ms (SD = 17.16) between the participant's action and the robot action. Because the robot action is slaved to sensors in a glove, the actual delay depends on how the hand and glove are moved, both during initial calibration and during the experiment. In order to avoid too many variations between participants, the experimenter always calibrated the hand herself before giving the glove to the participants and showed to participants how to move their fingers to produce a clear and low-latency robot movement.

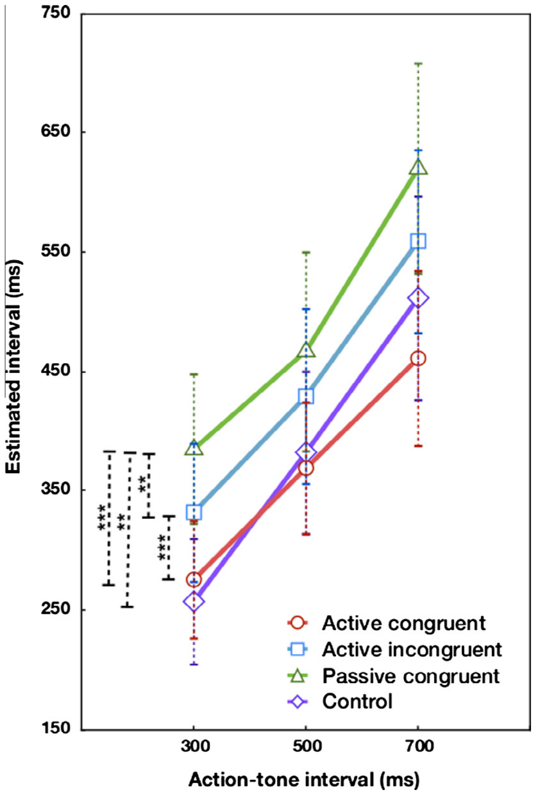

Fig. 2. Interval judgment estimation in the active congruent, the active incongruent, the passive congruent and the control conditions of experiment 1. ** indicates a significant difference (two-tailed $p < .01$), and *** indicates a significant difference ($p < .001$) between conditions. Error bars refer to standard errors.

delay (536.02, 95% CI: 476.60–595.43). The interaction between Condition and Delay was also significant, $F(6,132) = 2.254$, $p = .042$, $\eta^2_{\boldsymbol{partial}} = .093$. However, as this interaction was not predicted and not of central interest for our hypothesis, we chose not to perform post hoc comparisons.

Instead, in a supplementary analysis, we explored more systematically the possibility that the near-significant interaction between condition and delay could reflect differences between conditions in the rate of passage of time, for example due to changes in the period of an internal clock. We estimated the slope of the relation between actual and perceived action-outcome intervals for each participant, and comparing these estimates across conditions. No significant differences were found ($p > .1$). A further supplementary analysis addressed potential differences in learning across trials, by investigating whether interval estimates changed over the course of a block in similar ways for each condition. We found stronger evidence of learning for passive than for active conditions. There was no difference in learning rate between active congruent and active incongruent conditions, suggesting that any learning of agency is independent of embodiment transformations (see supplementary analyses, supplementary Figs. 1 and 2).

2.3. Discussion

The active incongruent embodiment condition was judged to involve longer durations than the active congruent condition and than the passive congruent condition. This confirmed that the transformed embodiment also affected the sense of agency over an external event (the tone), as measured using the intentional binding effect. Based on the normal interpretation of intentional binding effects (Haggard & Tsakiris, 2009), we therefore conclude that transformed embodiment reduced the sense of agency. Interestingly, however, intervals in the active-incongruent condition were still perceived as shorter than in the passive-congruent condition. This pattern of results emphasises the fact that the sense of agency is not fully flexible: transformed embodiment reduced sense of agency.

Importantly, congruent movements of the robotic hand resulted in interval estimates that were comparable to the 'natural' situation of viewing one's own hand during action. Thus, different both biological and technological means of instrumental action appear to produce similar sense of agency, if their effectors move in a way that is congruent with the voluntary motor command.

Based on previous studies (e.g. Caspar et al., 2014), we know that the active incongruent condition leads to a reduced feeling of ownership over the robotic hand. However, in Experiment 1, we did not directly measure embodiment in the active-incongruent condition. In Experiment 2, we replicated the same paradigm with only three experimental conditions: active congruent, active incongruent and passive congruent. At the end of each condition, participants completed a short questionnaire assessing agency and ownership over the robotic hand.

3. Experiment 2

3.1. Participants

A total of 24 naïve participants were recruited. Participants received 5 euros for their participation. One participant was excluded due to failure to follow instructions (did not fixate the robotic hand, despite oral reminders). Of the 23 remaining participants, 5 were males. The mean age was 21.65 (SD = 2.33). All participants have provided written informed consent prior to the experiment. The study was approved by the local ethical committee of the Faculty of Psychological Science and Education of the Université Libre de Bruxelles (ULB).

3.2. Procedure and material

The procedure for active congruent, active incongruent and passive congruent conditions was as in Experiment 1. At the end of each condition, participants answered an 8-item questionnaire assessing their feeling of ownership and agency over the robotic hand (see Table 1). Four items assessed the feeling of ownership, and four items assessed the feeling of agency. Interval estimates between action and tone were measured.

3.3. Results

3.3.1. Questionnaires

The data were tested for normality with a Shapiro–Wilk test ($p > .05$). Both agency scores and ownership scores were analyzed into two separates repeated-measures ANOVA, with Condition (active congruent, passive congruent and active incongruent) as factor (see Fig. 3A). *For ownership scores*, the main effect of condition was significant ($F(2,44) = 7.911$, $p = .001$, $\eta^2_{\textit{partial}} = .264$). As expected, paired sample *t*-tests indicated that ownership scores did not differ between the active congruent (0.90, 95% CI: 0.415–1.390) vs passive condition (0.54, 95% CI: 0.051–1.036), $p > .1$, but that both were significantly higher than scores in the active incongruent condition (−0.196, 95% CI: −0.743 to 0.352), respectively, active congruent vs active incongruent: $t(22) = 3.864$, $p = .001$ and passive congruent vs active incongruent: $t(22) = 2.480$, $p = .021$. *For agency scores*, the main effect of Condition was also significant ($F(2,44) = 7.755$, $p = .001$, $\eta^2_{\textit{partial}} = .261$). As expected, agency was higher in the active congruent condition (1.435, 95% CI: 1.050–1.819) than in the passive congruent condition (0.043, 95% CI: −0.642 to 0.728), $t(22) = 3.725$, $p = .001$, and marginally higher than in the active incongruent condition (0.815, 95% CI: 0.294–1.336) than in the passive congruent condition ($t(22) = -2.041$, $p < .06$). This marginal result does not really clarify differences in agency scores between the active incongruent and the passive congruent conditions. Therefore, we computed Bayes factor (BF) analyses (Dienes, 2011) to refine our results. A BF between 1/3 and 3 indicates a lack of sensitivity. A BF below 1/3 or above 3 is typically interpreted as supporting for the null hypothesis, or for the alternative hypothesis, respectively. To compute the BF, we determined, based on previous studies, the expected mean and SD of the difference between these two scores. The result was a BF of 2.98 (just below 3), which is at the boundary between lack of sensitivity and a result in favour of H1. Further, there the active congruent condition produced marginally higher agency scores than the active incongruent condition ($t(22) = 2.028$, $p < .06$). Here, the BF was 4.90, which strongly supports H1. This implies that congruency of embodiment enhances sense of agency for active hand movements.

Globally, these results are congruent with our predictions, except for the fact that participants experienced a higher-than-expected agency score in the passive congruent condition, i.e. “0.043” (previous studies found negative agency scores in equivalent conditions).

Table 1

Questionnaire assessing agency and ownership, adapted to the robotic hand.

	Ownership
1	I felt as if I was looking my own hand
2	I felt as if the robotic hand was part of my body
3	It seemed as if I were sensing the movement of my finger in the location where the robotic finger moved
4	I felt as if the robotic hand was my hand
	Agency
5	The robotic hand moved just like I wanted it to, as if it was obeying my will
6	I felt as if I was controlling the movements of the robotic hand
7	I felt as if I was causing the movement I saw
8	Whenever I moved my finger I expected the robotic finger to move in the same way

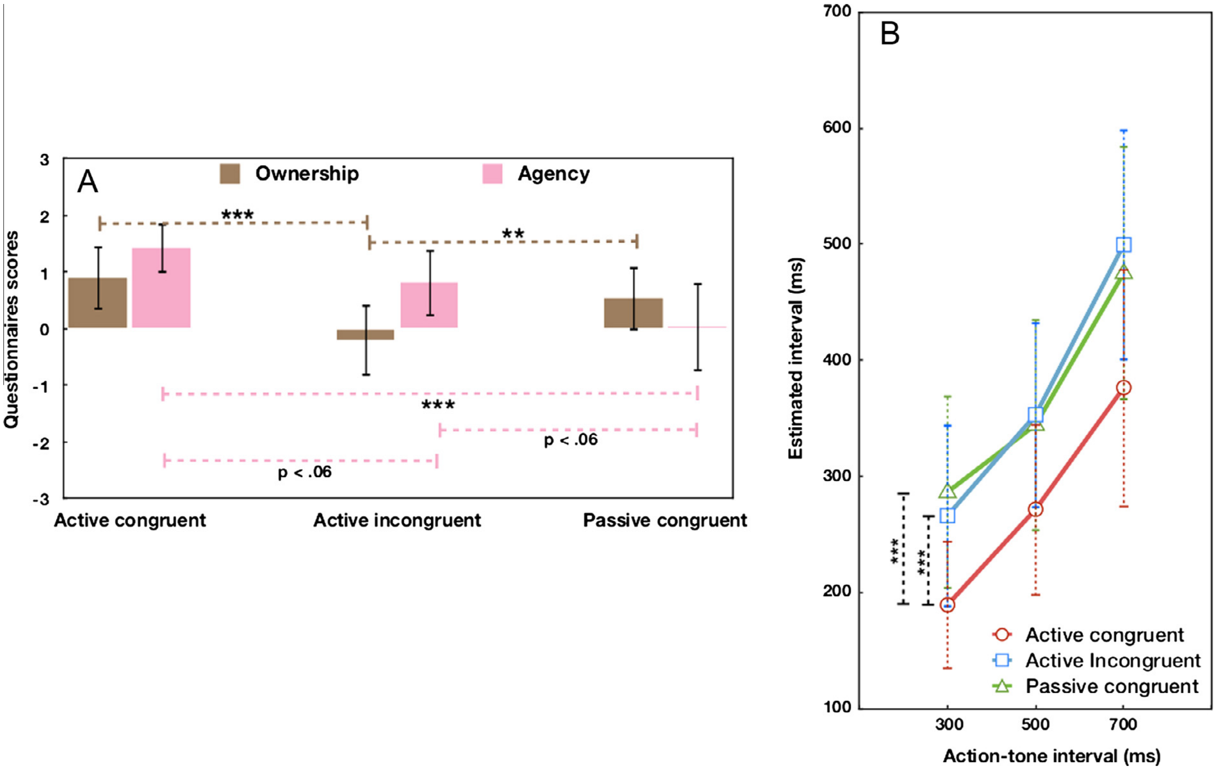

Fig. 3. (A) Questionnaires were scored from −3 («strongly disagree») to +3 («strongly agree»). Pink columns represent the mean score of the four items assessing agency, and brown columns represent the mean score for ownership. Error bars refer to standard errors. (B) Interval judgment estimation in the active congruent, the active incongruent and the passive congruent conditions, as a function of actual interval durations. Error bars show standard errors. In both graphs, all tests were two-tailed. ** indicates a significant difference ($p < .01$), and *** indicates a significant difference ($p < .001$) between conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.2. Intentional binding

The data were tested for normality with a Shapiro–Wilk test ($p > .05$). A Condition (active congruent, passive congruent, active incongruent) × Delay (300, 500, 700) repeated-measures ANOVA was conducted on participant's mean interval judgement (see Fig. 3B). The main effect of Condition was significant ($F(2,44) = 8.911$, $p = .001$, $\eta^2_{partial} = .288$). Pairwise comparisons showed shorter mean interval estimation for the active congruent condition (279.33, 95% CI: 215.39–343.281) than for the passive congruent (368.87, 95% CI: 290.28–447.46; $t(22) = -3.384$, $p < .01$) and the active incongruent condition (372.44, 95% CI: 303.97–440.91; $t(22) = -3.966$, $p = .001$), while the latter two conditions did not differ ($t(22) = -0.090$, $p > .9$). The mean effect of Delay was unsurprisingly significant, $F(2,44) = 45.701$, $p < .001$, $\eta^2_{partial} = .675$. Participants judged shorter mean delay for the 300 ms delay (247.51, 95% CI: 189.93–305.09), than for the 500 ms delay (322.85, 95% CI: 257.52–388.18) and the 700 ms delay (450.29, 95% CI: 368.67–531.90). The interaction between Condition and Delay was also significant, $F(4,88) = 2.990$, $p < .030$, $\eta^2_{partial} = .120$.

3.4. Discussion

Consistent with previous studies, we observed a reduced sense of ownership in the active incongruent condition in comparison with both the active congruent condition and the passive congruent condition. The active incongruent embodiment condition was judged to involve longer durations than the active congruent condition. In contrast with Experiment 1, we found no significant difference in interval estimations between the active incongruent and the passive congruent conditions. One explanation is that agency scores in the passive congruent condition were close to 0, and substantially higher than in a previous study (−0.73 in Caspar et al., 2014). In addition, Bayes factor analysis revealed a score just below 3, which generally indicates a lack of sensitivity of our data. Thus, it remains unclear whether the active incongruent condition leads to a sense of agency similar to the passive congruent condition.

In Experiment 3, we replicated the same design as in Experiment 2, using more sensitive embodiment questionnaire items, related to location and ownership factors identified by Longo, Schüür, Kammers, Tsakiris, and Haggard (2008). The agency questionnaire was similar. In addition, we measured the proprioceptive drift, a behavioural measurement whereby participants judge the location of their own real hand. Ownership of the fake rubber hand has been associated with perceiving the location of one's own hand as shifted towards that of the rubber hand (e.g. Botvinick & Cohen, 1998). Thus, proprioceptive drift provides a useful behavioural proxy for the RHI – although dissociations between drift and questionnaire responses have been reported (Rohde, Di Luca, & Ernst, 2011).

4. Experiment 3

4.1. Method

4.1.1. Participants

A total of 26 naïve participants were recruited. Participants received 2 course credits for their participation. Three participants were excluded because they failed to produce mean temporal intervals increasing monotonically with actual action-tone interval. Of the 23 remaining participants, 3 were males. The mean age was 19.65 (SD = 1.33). All participants have provided written informed consent prior to the experiment. The study was approved by the local ethical committee of the Faculty of Psychological Science and Education of the Université Libre de Bruxelles (ULB).

4.1.2. Procedure and material

The procedure was globally the same as in Experiment 2, with the addition of proprioceptive drift measurement, and a different set of questionnaire items. A first measure of proprioceptive drift was taken before each experimental condition, and then after every 20 trials, giving a total of 4 measures spanning the 60 trials in each blocked condition. For each measure, participants were instructed to indicate, using their left hand, where they felt their own hand was located in the vertical dimension (see Fig. 4). To this end, a sheet of graph paper with a millimetre grid was placed on the left vertical support of the table. Participants were instructed to make a rapid and accurate pointing movement by placing the left index finger at the vertical location of their right hand. The experimenter then used a pen to mark the position of the top of the participants' finger on the sheet. The questionnaire included the ownership and location questions identified by Longo et al. (2008), and the same agency questions than in Experiment 1 (see Table 2 in supplementary material).

4.2. Results

4.2.1. Questionnaires

The data were tested for normality with a Shapiro–Wilk test. Agency scores in the Active condition and Location scores in the passive condition did not respect normality ($p < .05$). Agency scores, location scores and ownership scores were analyzed in two separate repeated-measures ANOVAs, with Condition (active congruent, passive congruent and active incongruent) as factor (see Fig. 5A). For *ownership scores*, the main effect of condition was significant ($F(2,44) = 5.363$, $p = .001$, $\eta^2_{partial} = .196$). As expected, paired sample t-tests indicated that ownership scores between the active congruent (0.83, 95% CI: 0.357–1.313) and the passive congruent condition (0.34, 95% CI: −0.330 to 1.025) did not differ ($p > .08$), and ownership scores in the passive congruent condition were statistically higher than in the active incongruent condition (−0.07, 95% CI: −0.705 to 0.549), $t(22) = 4.931$, $p < .001$. Ownership scores did not differ between passive congruent and active incongruent condition ($p > .1$). For *location scores*, the main effect of condition was significant ($F(2,44) = 6.883$, $p = .003$, $\eta^2_{partial} = .238$). Location scores were higher in the active congruent condition (1.20, 95% CI: 0.867–1.539) than in the passive congruent condition (0.049, 95% CI: −0.059 to 1.044), $t(22) = 2.818$, $p = .01$, and than in the active incongruent condition (0.033, 95% CI: −0.084 to 0.75), $t(22) = 3.927$, $p = .001$. Paired sample t-tests indicated that location scores between the passive congruent and the active incongruent condition did not differ ($p > .1$). For *agency scores*, the main effect of condition was also significant ($F(2,44) = 20.415$, $p < .001$, $\eta^2_{partial} = .481$). Paired sample t-tests indicated that agency scores were statistically higher in the active congruent condition (1.60, 95% CI: 1.249–1.968), than in the passive congruent condition

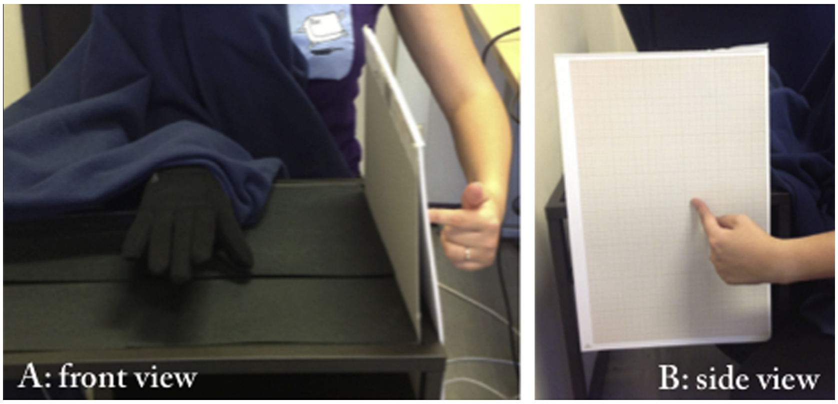

Fig. 4. Front view (A) and side view (B) of the vertical proprioceptive drift in the (robotic) rubber hand illusion.

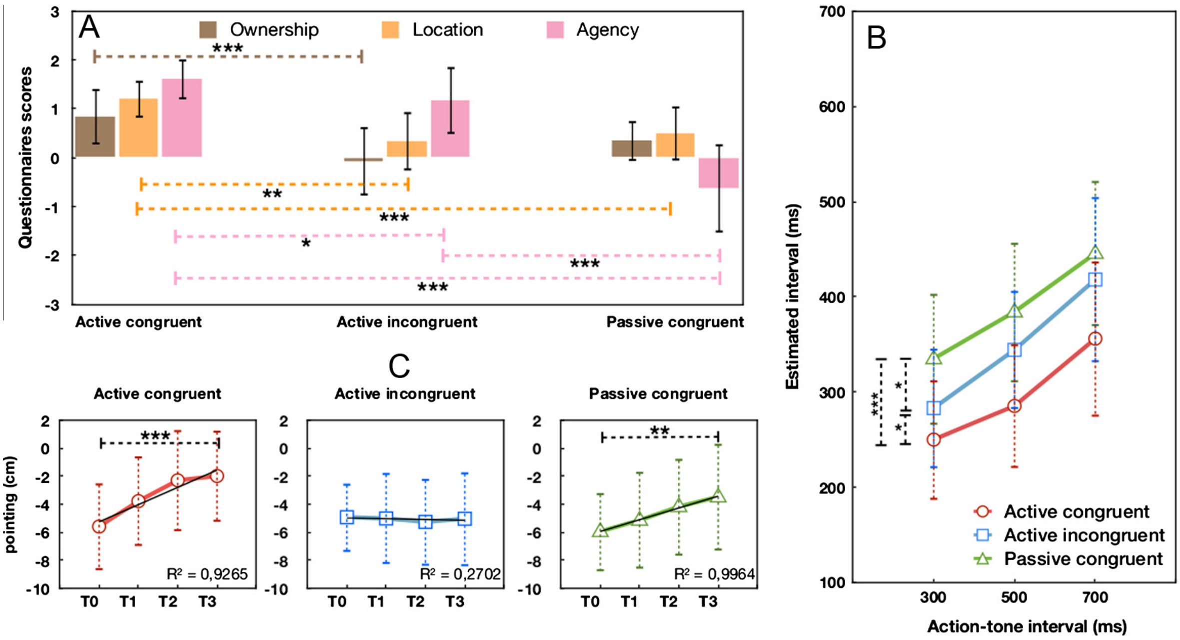

Fig. 5. (A) Questionnaires were scored from −3 («strongly disagree») to +3 («strongly agree»). Pink columns represent the mean score of the four items assessing agency, orange columns represent the mean score of location, and brown columns represent the mean score for ownership. Error bars refer to standard errors. (B) Interval judgment estimation in the active congruent, the active incongruent and the passive congruent conditions. The interval estimates are averaged across all three actual interval durations (i.e., 300 ms, 500 ms, and 700 ms). (C) Separate trend analysis on the proprioceptive drift measure for each condition. In all graphs, all tests were two-tailed. ** indicates a significant difference ($p < .01$), and *** indicates a significant difference ($p < .001$) between conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(−0.54, 95% CI: −1.254 to 0.167), $t(22) = 5.722$, $p < .001$, and than the active incongruent condition (1.08, 95% CI: 0.614–1.560), $t(22) = 2.157$, $p < .05$. Agency scores in the active incongruent condition were statistically higher than agency scores in the passive congruent condition ($t(22) = -3.949$, $p = .001$).

4.2.2. Interval estimation

The data were tested for normality with a Shapiro–Wilk test ($p > .05$). A Condition (active congruent, passive congruent, active incongruent) × Delay (300, 500, 700) repeated-measures ANOVA was conducted on participant's mean interval judgement (see Fig. 5B). The main effect of Condition was significant, $F(2,44) = 8.131$, $p = .001$, $\eta^2_{partial} = .270$. Paired sample *t*-test indicated significant shorter mean interval estimation in the active congruent condition (297.26, 95% CI: 239.39–355.137) than in the active incongruent condition (348.64, 95% CI: 292.48–404.809), $t(22) = -2.508$, $p = .02$, and than the passive congruent condition (388.38, 95% CI: 326.79–449.96), $t(22) = -3.516$, $p = .002$. In contrast with Experiment 1, the active incongruent condition was now significantly different from the passive congruent condition, $t(22) = 2.162$, $p < .05$. The main effect of Delay was unsurprisingly significant, $F(2,44) = 31.027$, $p < .001$, $\eta^2_{partial} = .585$. The interaction between Condition and Delay was not significant ($p > .1$).

4.2.3. Proprioceptive drift

Our interest focussed on whether proprioceptive drift of the perceived position of the hand towards the rubber hand varied across conditions. Therefore, linear trend analyses were performed, with contrast coefficients −3, −1, 1, 3 for the four successive measures spanning each block (see Fig. 5C). This linear trend analysis assesses how proprioceptive drift depends on linear progression of time. Conceptually, linear trend can be thought of as a specific form of difference score. Separate trend analyses on each condition indicated a significant trend in the active congruent condition, $t(22) = 5.779$, $p < .01$, and in the passive congruent condition, $t(22) = 2.744$, $p < .025$. This implies a gradually-developing percept that the participants' hand is located close to the robotic hand. In the active incongruent condition, the trend was not significant ($p > .1$). Repeated-measures ANOVA on the trend values identified a mean effect of Condition, $F(2,44) = 6.073$, $p = .005$. Paired sample *t*-test indicated no difference between the active congruent and the passive congruent condition ($p > .1$). In comparison, both the active congruent condition (12.31, 95% CI: 7.88–16.74) and the passive congruent condition (8.391, 95% CI: 2.05–14.73) showed stronger trends than the active incongruent condition (−.573, 95% CI: −6.62 to 5.48), respectively, $t(22) = 3.062$, $p < .01$ and $t(22) = 2.607$, $p < .02$.

4.3. Discussion

Incongruent movements of the robotic hand reduced judgements of location, ownership and agency compared to the active congruent condition, in which the robotic hand moved congruently with the participant's hand. An implicit measure of embodiment, based on proprioceptive drift, showed a similar result. Importantly, we replicated the results of Experiment 1. We found that interval estimates in the active incongruent condition were also significantly shorter than the passive congruent condition. Importantly, explicit judgements of agency from the questionnaire were also significantly higher in the active incongruent condition than in the passive congruent condition. Thus, the non-significant difference between these two conditions in Experiment 2 could be the result of a high sense of agency over the robotic hand in the passive congruent condition. This consistent set of results could be interpreted as evidence for a partial sense of agency in the active incongruent condition. Thus changes in the means of action, in this case due to transformed embodiment, do not entirely abolish the sense of agency, but merely reduce it.

5. General discussion

The present results suggest that acting through a robotic hand intermediary does not necessarily affect the sense of agency, relative to instrumental actions involving only one's own body (Experiment 1). However, if participants view an intermediary hand that moves in conflict with the intended voluntary motor command, in this case by transposing the movement to a different finger, then the sense of agency was reduced (Experiments 1, 2 and 3). Interestingly, in both experiments 1 and 3, this reduced sense of agency nevertheless remained stronger than in the passive congruent condition. This suggests that visual incongruency alone does not entirely abolish the sense of being the agent of an action. Taken together, our results indicate that the sensorimotor means by which an external event is achieved play some role in the human sense of agency. Put another way, human sense of agency appears to two components. The first is a mere statistical contingency between intention and outcome, consistent with some accounts of instrumental learning in animals (Dickenson, 1981). The second component is an appropriate match between the effector-specific content of the voluntary motor command, and the effector involved as the *means* of producing the outcome appears to be contributed. That is, human sense of agency makes reference to the details of sensorimotor control, as well as to statistical association between events.

When participants perform an action with their own hand, agency and ownership cannot easily be disentangled (Marcel, 2003; Synofzik, Vosgerau, & Newen, 2008; Tsakiris, Schütz-Bosbach, & Gallagher, 2007). Nevertheless, several studies attempted to clarify the relation between agency and ownership. The 'additive model' views agency as body ownership plus intentional or goal-directed motor representation. The 'independence model' views agency and body ownership as different experiences. In normal and voluntary sensory experience, the two co-occur. Several behavioural (e.g. Kalckert & Ehrsson, 2012, 2014; Sato & Yasuda, 2005; Tsakiris et al., 2006) and neuroimaging studies (Tsakiris et al., 2010) support the independence model. The present study provides new and relevant information. Experiment 2 found no sense of agency under conditions of altered embodiment (consistent with the additive model), while experiments 1 and 3 found partial sense of agency under the same conditions (consistent with the independence model). We conclude that the visual representation of effector-specific motor information *partly* contributes to sense of agency. Thus, on the present evidence, neither the strict additivity nor the strict independence models seem correct. In future research, we hope to address what *components* of the experiences of agency and ownership are additive, and what components are independent.

Explicit (e.g. Daprati, Wriessnegger, & Lacquaniti, 2007; Tsakiris et al., 2007; Sato & Yasuda, 2005; Wegner and Wheatley, 1999) and implicit measures (e.g. Haggard et al., 2002) have both been used as measures agency. However, they may measure different aspects (Ebert and Wegner, 2010; Synofzik et al., 2008) of agency. In the present study, we used intentional binding as our main measure, as measured by interval estimates. First and foremost, there is strong evidence to support the idea that intentional binding is a reliable measure of agency (for a review see Moore & Obhi, 2012). Second, implicit measures are less affected by task demands and expectations than explicit measures. Third, and most importantly, where we did obtain explicit measures about differences between experimental conditions using questionnaires, these were in broad agreement with differences between the same experimental conditions in intentional binding measures. Thus, in Experiment 3, we found that differences in intentional binding between our experimental conditions recapitulated differences in *specific* aspects of the RHI experience, as revealed by location, ownership and agency subscales of established questionnaires. In particular, both implicit and explicit judgement showed a partial experience of agency when the robot hand moved incongruently with the participant's own hand. Interestingly, explicit judgements of embodiment, and implicit measures of body ownership based on proprioceptive drift consistently pointed to an influence of incongruent vs congruent embodiment on experience of agency.

The difference between "external agency" (agency over changes in our environment) and "body agency" (agency over one's own body) has been recently discussed by Kalckert and Ehrsson (2012). As one might predict, agency over the body was more tightly linked to body ownership than agency over external events. Specifically, ownership and agency scores in the RHI were positively correlated only in an active congruent condition, i.e. when the rubber hand was in a congruent anatomical position and was controlled by the participant. Ownership and agency scores were not significantly correlated when the RHI condition was incongruent or passive. In addition, agency scores were higher when the hand was perceived as one's own body. Our questionnaire results broadly concur with those of Kalckert and Ehrsson.

Nevertheless, the boundary between body and external agency is unclear, as demonstrated by many studies of tool use. At some point in development, the brain must learn agency over the body, presumably in the same way that the mature brain learns agency over a novel external object, such as a machine. Body agency may, from the brain's points of view, simple be agency over a very familiar external object.

The history of technology is an ample testament to the flexibility of human agency. The human mind has developed a remarkable ability to achieve instrumental goals, and to act upon the world using abstract and arbitrary machines to achieve those goals. In contrast, most animals act on the world largely or only through the immediate movements of their own body. For example, human tool use abilities vastly outstrip those of other species. Our finding shows that some sense of agency can persist even when sensory evidence from the body is conflicting. The possibility of a basic, "non-embodied" sense of agency that does *not* depend on congruent body movement may underlie capacities for using instrumental technologies. Current research on neuroprosthetics and brain-machine interfaces may potentially harness this "non-embodied" sense of agency.

6. Conclusion

To conclude, we have shown that an intermediary sensorimotor step that respects the normal causal chain does not alter the human sense of agency, as measured by an implicit proxy of temporal association. 'Deviant' intermediary steps do reduce the sense of agency, if they alter the effector-specific content of the means of acting on the external world. However, such altered embodiment did not abolish sense of agency entirely in our experiments. We suggest that sense of agency involves both a basic means-independent, embodiment-independent associative mechanism, and an additional, embodied, effector-specific matching mechanism. Human agency is multifaceted: this may potentially explain our astonishing capacity to transform the environment, and human life more generally.

Authors' contribution

E.A. Caspar developed the study concept. All authors contributed to the study design. Testing and data collection were performed by E.A. Caspar. E.A. Caspar performed the data analysis and interpretation under the supervision of P. Haggard and A. Cleeremans. E.A. Caspar drafted the manuscript, and P. Haggard and A. Cleeremans provided critical revisions. All authors approved the final version of the manuscript for submission.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2015.01.007.

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