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Physical load reduces synchrony effects on agency and ownership in the virtual hand illusion

Jue Qu [a], Yingbing Sun [a], Liping Yang [a], Bernhard Hommel [b,c,*], Ke Ma [a,*]

[a] Key Laboratory of Personality and Cognition, Faculty of Psychological Science, Southwest University, Beibei, Chongqing, China
[b] TU Dresden, Faculty of Psychology & University Neuropsychology Center, Faculty of Medicine, Cognitive Neurophysiology, Germany
[c] Department of Psychology, Shandong Normal University, Jinan, China

A R T I C L E I N F O

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A B S T R A C T

We used the virtual hand illusion paradigm to investigate the effect of physical load on perceived agency and body ownership. Participants pulled a resistance band that required exerting a force of 1 N, 10 N, or 20 N while operating a virtual hand that moved in synchronous or out of sync with their own hand. Explicit agency and ownership ratings were obtained, in addition to intentional binding and skin conductance as implicit measures of agency and ownership. Physical load increased perceived subjective load but showed no main effect, while synchrony effects were found on all agency and ownership measures. Interestingly, load did interact with synchrony in implicit agency and explicit ownership, by reducing and eliminating synchrony effects as movement synchrony was reduced with higher physical load. Furthermore, consistent with previous claims, implicit agency increased with perceived effort associated with higher physical load.

1. Introduction

Sense of agency and ownership are considered to be two dissociable aspects of the 'minimal self' (Gallagher, 2000). The sense of agency refers to the subjective experience of causally producing actions to change the external world (Haggard, 2017); while sense of ownership refers to the feeling of owning one's body. Systematic research on both kinds of senses has been triggered by the discovery of the rubber-hand illusion (RHI, Botvinick & Cohen, 1998), which refers to the observation that people tend to perceive ownership for a rubber hand if it is stroked in synchrony with their own hand. A similar illusion can be evoked by having a virtual hand move in synchrony with people's real hand: the virtual hand illusion (VHI, Slater et al., 2008; Sanchez-Vives et al., 2010). An important advantage of the VHI as compared to the RHI paradigm consists in the fact that participants can carry out unconstrained movements with their real hand (commonly equipped with a data glove) and watch the corresponding movements of the virtual effector, which commonly increases feelings of both agency and ownership. Agency and ownership have been studied by means of explicit ratings (Botvinick & Cohen, 1998; Ma & Hommel, 2015) and more implicit measures, such as intentional binding (IB)—an effect indicating a temporal "attraction" of actions and their perceived effects (Braun, Thorne, Hildebrandt, & Debener, 2014), to assess implicit agency (Haggard, Clark, & Kalogeras, 2002), and proprioceptive drift (Tsakiris & Haggard, 2005) or skin conductance response (Armel & Ramachandran, 2003) as a proxy for implicit ownership.

The relationship between explicit agency and ownership turned out to vary with the particular experimental setup. Studies using the active RHI, in which only one specific finger or the entire palm can be moved, showed a heterogeneous picture (Braun et al., 2018;

* Corresponding authors.
E-mail addresses: bh@bhommel.onmicrosoft.com (B. Hommel), psyke1@swu.edu.cn (K. Ma).

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Tsakiris, Schütz-Bosbach, & Gallagher, 2007). Some studies found that voluntary movements of the real hand palm (i.e., a situation associated with optimal agency: Haggard, 2017) promote illusory ownership for a concurrently observed active rubber hand (e.g., Dummer et al., 2009), and others (Braun, Thorne, Hildebrandt, & Debener, 2014) found an important role of hand identity (i.e., ownership) in predicting the sensory consequences of actions (a process known to be important for judging agency). However, other studies reported double dissociations between ownership and agency, in the sense that some experimental manipulations affected one, but not the other of the two senses (Kalckert & Ehrsson, 2012, 2014). In stark contrast, studies using the VHI hardly found evidence for double dissociations between ownership and agency senses, but rather very substantial positive correlations between them (Ma & Hommel, 2015; Ma, Qu, Yang, Zhao, & Hommel, 2021). The main reason for this dependency on the experimental design is likely to consist in the substantial difference in ecological validity. Even with "active" rubber hands, RHI provide the participant with very limited motor, kinematic, and proprioceptive information to assess the correlation between the felt own movement and the seen movement of the artificial effector. To nevertheless answer questions regarding agency and ownership, participants therefore need to rely on other informational sources, like postural plausibility, familiarity, and other previous experience. These informational sources, or the information they provide may differ for agency and ownership judgments (Ma & Hommel, 2015), which could account for the observed dissociation of explicit agency and ownership judgments (Kalckert & Ehrsson, 2012, 2014). In contrast, VHI designs are much more ecologically valid by allowing the agent to systematically explore the relationship between own movement and the movement of the artificial effector in rather natural ways. This is likely to provide a very rich database for assessing the correlation between the two movements (Haggard, 2017; Ramachandran, 1998; Synofzik, Vosgerau, & Newen, 2008), which is likely to increase the contribution of bottom-up information (which we assume is shared in assessing agency and ownership) and reduce the contribution of top-down informational sources (which, as we argue, are not necessarily shared in assessing agency and ownership).

These observations suggest that agency and ownership might be more tightly related than philosophical reasoning has suggested. Indeed, the two senses have been shown to be partly affected by common factors and, under certain circumstances, they can even promote each other (Braun et al., 2018; Pyasik, Burin, & Pia, 2018)—which fits with observations that, at least in the more ecological VHI experimental paradigm, explicit measures of agency and ownership tend to correlate rather tightly (Ma & Hommel, 2015). Interestingly, these correlations between explicit measures of agency and ownership are sometimes even stronger and more systematic than correlations between explicit and implicit measures of agency and between explicit and implicit measures of ownership (Ma, Qu, Yang, Zhao, & Hommel, 2021; Qu, Ma, & Hommel, 2021).

Given the relationship between experimental design and informational basis of agency and ownership judgments, it is interesting to compare their underlying mechanisms as proposed in the literature. The first studies on RHI/VHI tended to attribute illusory ownership to either bottom-up or top-down factors (for a first attempt to integrate the two, see Tsakiris, 2010). For instance, the multisensory integration account (Braun et al., 2018) considered the illusions to be driven by bottom-up information about the temporal relationship between codes processed by different sensory modalities, while others have highlighted the role of internal body representations and expectations derived from them (Apps & Tsakiris, 2014; Tsakiris, 2017). Similarly, agency was considered to emerge mainly from bottom-up information about the relationship between action and outcome (Ebert & Wegner, 2010) or from top-down expectations derived from motor control (Moore & Fletcher, 2012; Moore, Wegner, & Haggard, 2009). Notably, bottom-up and top-down factors may interact, in the sense that perceived agency and ownership derive from the integration of both bottom-up and top-down cues, which might be weighted according to their reliability (Moore & Fletcher, 2012; Synofzik, Vosgerau, & Newen, 2008; Synofzik, Vosgerau, & Voss, 2013). For example, working with VHI, Ma et al. (2019a) investigated the role of synchrony and exclusivity in perceiving ownership and agency, where exclusivity was implemented as control of a virtual effector either by the participant alone or jointly with a partner. Results showed that exclusivity influenced agency and ownership only when real and seen movement were out of synchrony, suggesting that synchrony is more important than exclusivity, but the latter becomes important in the absence of the former. Similarly, Lafleur et al. (2020) found that the weight of contextual (top-down) cues for explicit agency judgements increases if sensorimotor (bottom-up) cues are highly unreliable. The mutually compensatory roles of bottom-up and top-down factors are consistent with the emerging picture that measures of agency and ownership are based on the integration of various bottom-up and top-down cues that partly, but not completely overlap.

One empirical way to disentangle the various contributions of bottom-up and top-down cues to indicators of agency and ownership consists in the analysis of the impact of experimental manipulations that are likely to target some cues more than others. A promising candidate for such a manipulation is physical load, on which the present study was focused. Increasing physical load is likely to increase the sense of willed effort (Preston and Wegner, 2009; Lafargue & Franck, 2009), which in turn may act as a bottom-up/sensorimotor cue to agency and, possibly, to ownership. A possible link between physical load (and/or perceived effort) and agency is suggested by several studies. For example, physical load was found to enhance the sense of agency in non-illusion studies (Demanet, Mühle-Karbe, Lynn, Blotenber & Brass, 2013; Minohara et al., 2016). Demanet et al. (2013) used a Libet-style IB task (Haggard, Clark, & Kalogeras, 2002) to assess the impact of physical load on implicit agency. Physical load was manipulated by requiring participants to pull stretch bands of varying resistance levels with their left hand while carrying out the IB task with their right hand, so that the two tasks and the respective activities were nominally and physically unrelated. Nevertheless, greater physical load increased temporal binding, suggesting increased agency. Minohara et al. (2016) manipulated physical load by using three types of buttons that differed in the amount of force needed to depress them, and measured explicit agency with a self-attribution task. The assumption was that physical load might increase intentional effort and, thus, enhance self-attribution—which was confirmed by the findings.

If we follow the idea that higher physical load invites stronger intentional effort, the observations of Demanet et al. (2013) and Minohara et al. (2016) are consistent with cue integration theory (Moore & Fletcher, 2012; Synofzik et al., 2008, 2013), according to which sense of agency is determined by integrating bottom-up/sensorimotor and top-down/cognitive cues. Perceived effort serves as a bottom-up cue that tags the action event as one involving agenthood (assuming that exerting effort often coincides with actual agency, which should make effort-related cues particularly diagnostic), which in turn might provide strong evidence for agency. This interpretation would fit with findings of Haggard et al. (2002), who compared intentional actions with involuntary actions triggered by transcranial magnetic stimulation (TMS). Findings show that voluntary actions induced more pronounced IB than involuntary actions/movements (Haggard, Clark, & Kalogeras, 2002), which might be due to the lack of perceived effort when performing the latter (cf., Lafargue & Franck, 2009).

This interpretation might be taken to be challenged by findings showing opposite effects. For instance, Howard et al. (2016) reported that, no matter whether the physical load was task-related or not, higher physical load weakened the IB. According to Howard and colleagues, this might be because physical load depletes the cognitive resources needed for motor awareness (an assumption that fits observations of Colzato, Szapora, Pannekoek & Hommel, 2013), which in turn might disrupt perceived agency. However, the empirical discrepancies might be accounted for by methodological differences between the three mentioned studies. For one, Demanet et al. (2013) used low and high physical loads of 28 N and 49 N for females and 37 N and 67 N for males, which rendered these loads much higher than those used by Minohara et al. (2016; 0.1 N, 0.65 N and 2.70 N) and Howard et al. (2016; 4.9 N and 24.5 N). For another, Demanet et al. (2013) employed a Libet-style paradigm to assess implicit agency, while Howard et al. (2016) used an interval reproduction paradigm, which arguably requires more cognitive resources than the Libet-style task (Minohara et al., 2016, assessed explicit agency only). Hence, while there might be limitations regarding the amount of the physical load and the difficulty of the task employed for assessment, the available evidence is consistent with the possibility that at least implicit agency is affected by physical load. Moreover, given the available evidence that perceived agency and ownership might rely on partly overlapping informational sources, such as movement synchrony (Caspar et al., 2015), task-unrelated cognitive load (Qu et al., 2021), effector appearance (Ma et al., 2021), postural congruency, and agency identity (Braun et al., 2014), load effects on perceived agency might also generalize to perceived ownership, which is why we considered both kinds of senses in the present study.

To summarize, we were interested to see whether evidence for an impact of physical load on explicit and implicit agency could also be found in a VHI task, and whether these effects would generalize to explicit and implicit ownership. We thus combined the VHI task, in which participants could operate a virtual hand synchronously or asynchronously, with three levels of physical load within a modest range. We manipulated the levels of physical load by asking participants to pull different stretch bands during the VHI (Demanet et al., 2013; Howard et al., 2016). We assessed explicit agency and ownership by means of standard questionnaires (Kalckert & Ehrsson, 2012; Ma, Hommel, & Chen, 2019b) and used a Libet-style IB task and Skin Conductance Responses (SCRs) to threats of the virtual hand to assess implicit agency and ownership, respectively.

2. Method

2.1. Participants

Thirty-eight participants were recruited from Southwest University, China, in exchange for pay. Two participants were excluded as outliers because their some IB data were more than three SD from the sample mean, leaving 36 participants (11 males; mean age = 20.78 years, standard deviation (SD) = 1.533, range 18–23). All had normal or corrected to-normal vision, were right hand and naive with respect to RHI/VHI. This sample size was determined according to previous studies (Howard et al., 2016), in which 35

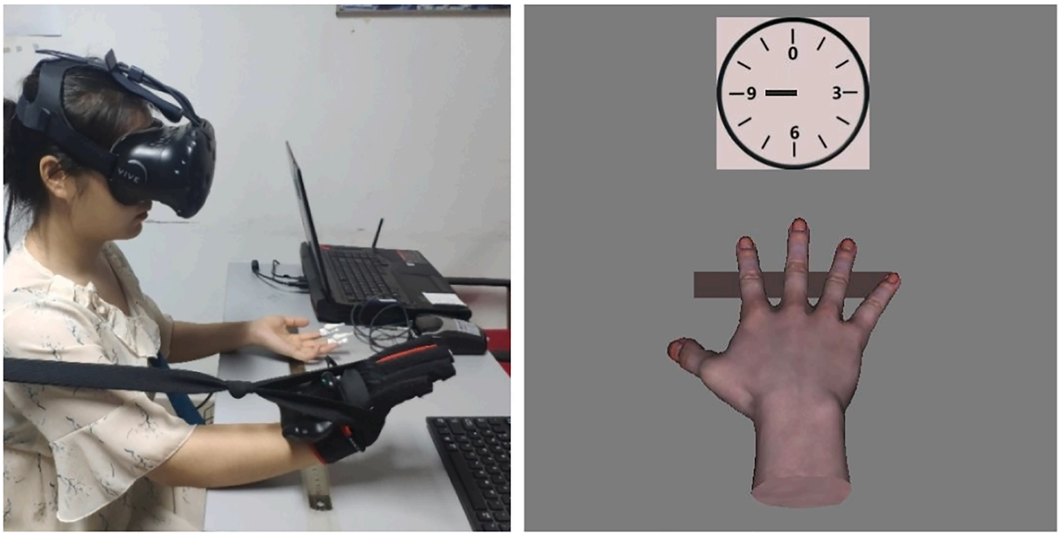

Fig. 1. Experimental setup. Participants wore an orientation tracker and a data glove on their right hand, and an SCR remote transmitter on their left hand; SCR electrodes were attached to the index and middle fingers of the left hand (left panel). The right panel shows the virtual hand, the virtual clock and its pointer, and the virtual button, in the virtual environment.

participants were tested. We also conducted an a-priori power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007), specified a medium effect size (f = 0.25), and obtained a power (1-β) of around 0.99. 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, and the methods were carried out in accordance with the approved guidelines.

2.2. Virtual environment and apparatus

The setup was similar as in previous studies (Ma, & Hommel, 2015; Ma et al., 2019), as shown in Fig. 1. The virtual environment was scripted using the virtual reality software Vizard. A virtual hand module was designed and imported into the virtual environment, participants were immersed in the virtual environment through an HTC vive head-mounted display (HMD) and saw the virtual environment and objects from a first-person perspective. Participants wore a right-hand data glove (Manus) on their right hand and the 6-DOF orientation tracker (HTC vive tracker) on their right wrist. The virtual hand's finger movements were controlled by means of a dataglove, and rotation was controlled using the orientation tracker. These devices capture the kinematics of the real hand of the participants and transform it online into the virtual hand movement. In the synchrony condition, the virtual hand movement was consistent with the real hand movement of the participant. In the asynchrony condition, the virtual hand movement was delayed by three seconds to the movement of the real hand (Ma & Hommel, 2015). Participants wore the SCR sensor on their left hand fingers (Ma & Hommel, 2013, 2015) (See Figs. 2–5).

We manipulated physical load by requiring participants to pull stretch bands of varying resistance levels. The levels of effort were operationalized using three different resistance bands, the other ends of which were fixed to the wall behind the participants. Participants had to hold the band with their task-related right hand for the duration of each experimental block. As Fig. 1 shows, participants held the resistance band between the thumb and the index finger, so that they could still freely open, close, rotate their hand.

2.3. Design

We manipulated physical load in three levels: the amount of force required to hold the bands was approximately 1 N, 10 N and 20 N for the Low, Medium, and High load condition, respectively. Piloting revealed that forces higher than 25 N can really be challenging for the participants we tested. Accordingly, the High load force was set to be 20 N, which is similar to Howard et al. (2016), and the Low load to 1 N, which is similar to Minohara et al. (2016) and Howard et al. (2016). In a 3 × 2 repeated measures design, participants completed six experimental blocks differing across two factors: physical load (High, Hedium, and Low) and synchrony (synchronous and asynchronous). Participants were not informed about the degree of synchrony and physical load. The sequence of the six conditions was fully counterbalanced across participants.

2.4. Procedure

Participants were to put on the dataglove (to which the resistance band was connected) on their right hand and place the hand and

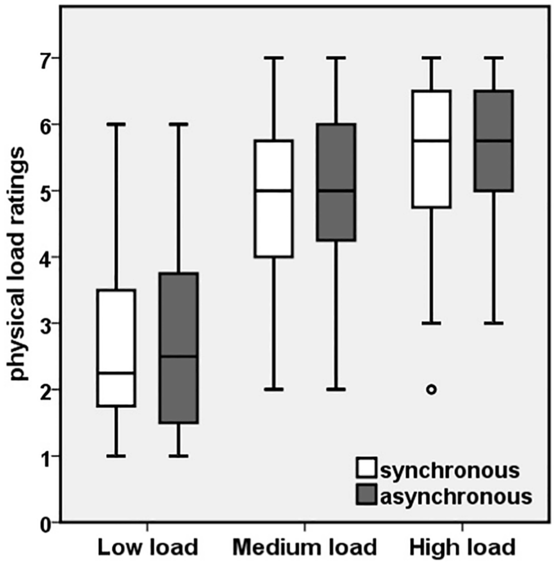

Fig. 2. Participants' ratings of perceived physical load. The middle lines of the box-plot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum. Circles represent outliers that fall between 1.5 and 3 X the interquartile range.

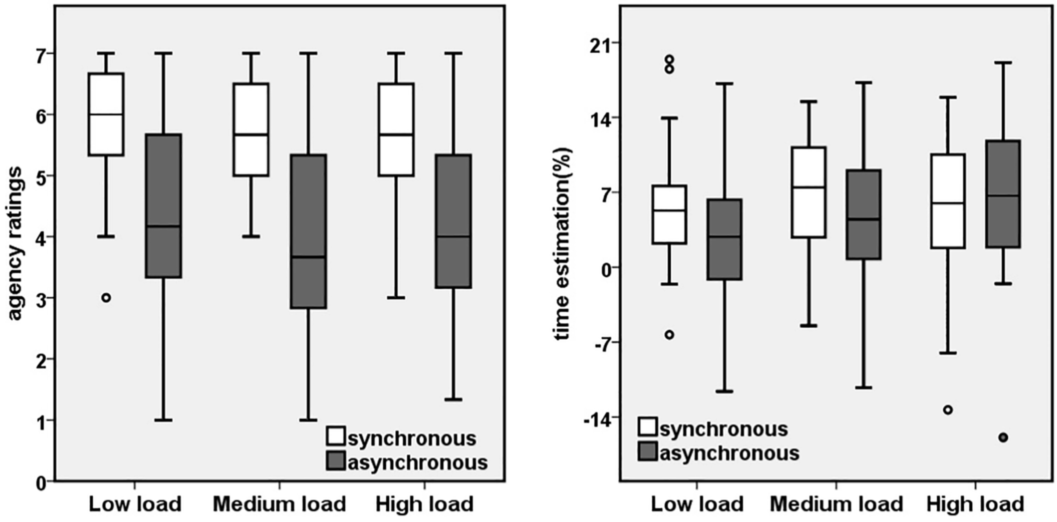

Fig. 3. Aggregated questionnaire scores for perceived agency (left panel); and time estimation errors (%) across synchrony and physical load (right panel). The middle lines of the box-plot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum. Circles represent outliers that fall between 1.5 and 3 X the interquartile range.

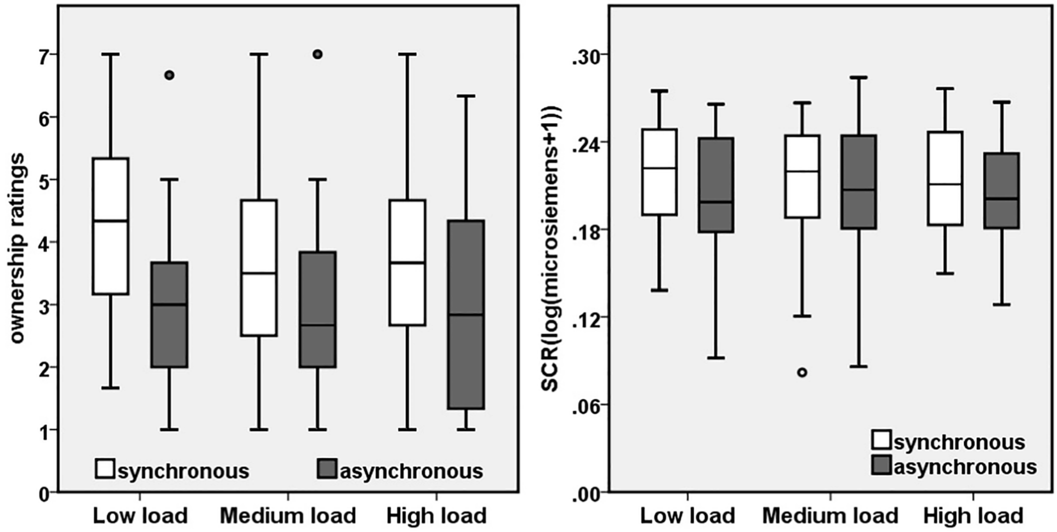

Fig. 4. Aggregated questionnaire scores for perceived ownership (left panel), and results for SCR, higher SCR indicates stronger arousal following the threatening of the virtual hand (right panel). The middle lines of the box-plot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum. Circles represent outliers that fall between 1.5 and 3 X the interquartile range.

their body into the previously calibrated position. The left hand rested on the table, with SCR electrodes attached to the index and middle fingers of the left hand.

Before the experimental blocks, participants completed the baseline IB task. In the IB task, we recorded the reported action-consequence interval. Participants were immersed into the virtual environment and faced a virtual clock, its pointer, and a virtual button, and were to press the space key with their unseen real hand on a real keyboard (positioned in front of their unseen real finger on the desk) at any timepoint they wanted. They would watch the pointer start rotating and wait for the subsequent tone to occur. When the pointer stopped rotating, they were to report the timepoint of the tone occurrence. Participants performed 10 IB trials for the baseline IB task (Ma, Hommel, & Chen, 2019b). Thereafter, virtual clock, pointer, and button disappeared, and one of the six experimental blocks started.

Each of the six experimental blocks was divided into four parts. First, a virtual right hand was presented in the virtual environment. As the resistance band was fixed to the dataglove, all movements with the participant's right hand were directly affected by the

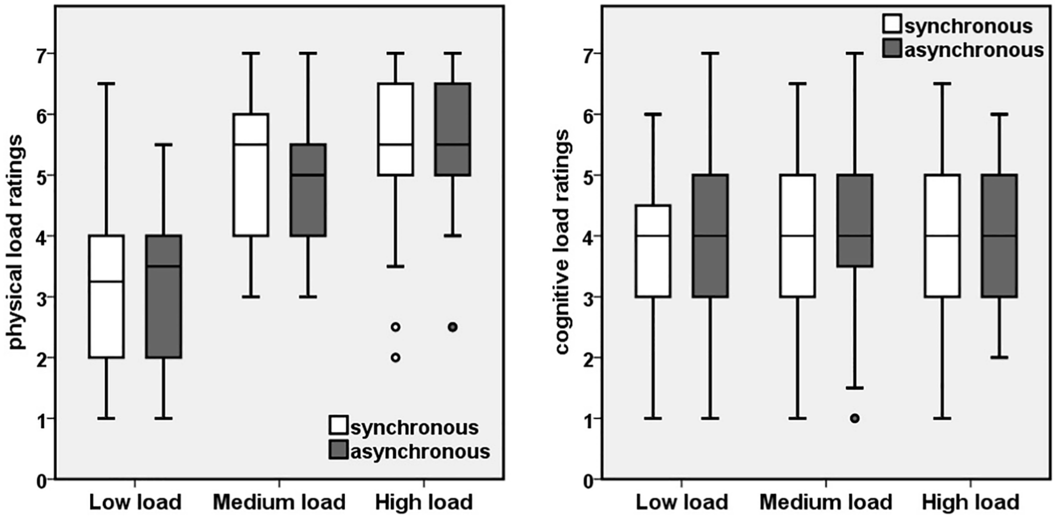

Fig. 5. Participants' ratings of perceived physical load (left panel) and cognitive load (right panel) in replication experiment (see 3.6). The middle lines of the box-plot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum. Circles represent outliers that fall between 1.5 and 3 X the interquartile range.

particular resistance strength. Apart from that, participants were to move their right hand freely, and watch the corresponding movement of the virtual hand, for two minutes. Second, participants performed the experimental IB task. The virtual clock, pointer, and button were shown again, and participants pressed the space key on the real keyboard at their will, while watching the corresponding synchronous or asynchronous contact of the virtual hand and virtual button in the virtual environment. Participants were to attend the position of the time pointer, and the subsequent tone and the virtual hand movements. When the pointer stopped rotating, they reported the pointer position at tone occurrence. This phase contained 10 IB trials. The third phase was the threat phase to assess SCR. After the virtual clock disappeared, participants were to put the right hand on the desk and keep it still. A virtual knife appeared in the virtual environment and cut the virtual hand every 10 s. This procedure was repeated four times. Finally, participants were to fill in the agency and ownership questionnaire. There was a 2-min break between blocks, to reduce fatigue and possible transfer between conditions.

2.5. Questionnaire measurement for explicit ownership and agency

In line with earlier studies (Ma et al., 2015, 2019a; Howard et al., 2016), we used an adapted Chinese version of the RHI/VHI questionnaire. We presented participants with eight questions assessing perceived agency (Q1–3), ownership (Q4–6), and physical load perception (Q7-8). To each statement of agency and ownership, participants responded by choosing a score on a 7-point (1–7) Likert scale, 1 indicating 'strongly disagree', 4 indicating 'uncertain', and 7 indicating 'strongly agree'. For the assessment of perceived physical load, participants rated how much physical load they experienced (scale from 1 to 7; 1 indicating low subjective load). The statements were:

Q1. The movement of the hand in the virtual environment was caused by me.
Q2. I can control the hand in the virtual environment.
Q3. The hand in the virtual environment moved as I wished.
Q4. I felt as if I was looking at my own hand when I was looking at this hand in the virtual environment.
Q5. I felt as if the hand in the virtual environment was my own hand.
Q6. I felt as if the hand in the virtual environment were a part of my body.
Q7. Please rate the physical load you perceived in current block.
Q8. How much physical effort did you exert in the current block.

2.6. Intentional binding (IB) task

Previous studies indicated that IB can serve as an indicator of implicit agency in RHI (Braun et al., 2014; Caspar, Cleeremans & Haggard, 2015) or VHI (Ma et al., 2019b) studies. We used the same method to assess IB as in a previous study in our lab (Ma et al., 2019b). Participants were to watch the virtual hand, which they controlled by moving their real hand, and a virtual clock with a quickly rotating pointer. When they pressed a real key with their unseen real hand, the pointer started to rotate at a speed of 1200 ms per full cycle. Pressing the real key translated into the pressing of the virtual key with the virtual hand. 600–1000 ms after the keypress, a tone was presented and participants were to report the pointer position at the time they perceived the tone to occur. The baseline IB task was run to record the baseline of time perception with the same experimental setup, but before the experimental manipulation. Both baseline and experimental IB tasks consisted of 10 trials. Notably, in all baseline and experimental IB tasks, the real and virtual button presses were always synced in both synchronous and asynchronous conditions. The only difference between synchronous and asynchronous conditions was the seen virtual hand movement, whether it was in synchrony or out of sync with the real unseen hand movement. The difference between baseline and experimental IB tasks thus consisted in the visibility of the virtual hand.

For each trial, we subtracted the reported time from the real time recorded with the script and divided it by the real time interval (Braun et al., 2014), so to represent the estimated time as percentage. We then computed the median of the 10 trials for each condition (Dewey & Knoblich, 2014) and subtracted the estimated time in baseline from that in each condition (Haggard et al., 2002). The expected compression of the perceived time interval would correspond to an underestimation of the temporal interval, so that more positive values of estimated time correspond to greater time compression (reduction), which in turn is thought to reflect stronger agency (Ma et al., 2019b).

2.7. Skin conductance response (SCR) measurement

To derive SCR, our implicit ownership measure, we defined a latency onset window between 1 and 8 s after the stimulus/event onset, namely when the virtual knife cut the virtual hand, with the skin conductivity before event onset serving as baseline (Ma & Hommel, 2013; 2015). After participant-wise standardization, we then calculated the magnitude of the event-induced SCR by subtracting baseline skin conductivity from the peak amplitude of the SCR during the analyzed time window, and took the log(magnitude + 1) per participant and condition (Figner & Murphy, 2011).

3. Results

All data were analyzed by means of 3 (physical load) × 2 (synchrony) repeated-measures ANOVAs.

3.1. Physical load manipulation check

The physical load manipulation was successful: The averaged physical load (Q7–8) ratings represent the participant's subjective evaluation of the perceived physical load or effort under different conditions. The main effect of physical load perception was significant, $F(2,70) = 72.819$, $p < 0.001$, $p\eta^2 = 0.675$, suggesting significant difference among the three physical load conditions going into the predicted direction. Post-hoc analyses revealed higher physical load ratings for the High condition ($M = 5.472$, $SE = 0.187$) than for the Medium condition ($M = 4.826$, $SE = 0.217$), with mean difference = 0.646, $SE = 0.162$, $p < 0.001$; and for the Low condition ($M = 2.757$, $SE = 0.244$), with mean difference = 2.715, $SE = 0.282$, $p < 0.001$; and higher physical load ratings for the Medium condition than for the Low condition, with mean difference = 2.069, $SE = 0.245$, $p < 0.001$. No other effect was found, $ps > 0.56$.

3.2. Explicit agency

In the ANOVA of the means of the agency data (Q1–3), the main effect of synchrony was significant, $F(1,35) = 53.202$, $p < 0.001$, $p\eta^2 = 0.603$, indicating significantly higher agency ratings under synchrony (mean = 5.778, $SE = 0.135$) than in the asynchrony condition (mean = 4.142, $SE = 0.220$). No other effect was found, $ps > 0.16$.

3.3. Implicit agency (IB)

While the main effects of synchrony and physical load were not significant, $ps > 0.11$, the interaction was, $F(2,70) = 3.486$, $p = 0.036$, $\eta p^2 = 0.091$. Separate two-tailed t-tests (Bonferroni corrected for multiple comparisons; $p \le 0.008$) showed that the time estimation was higher than zero, confirming that IB effects were present in all conditions, $ts(35) \ge 3.187$, $ps \le 0.003$, $ds \ge 0.531$.

We firstly compared synchrony difference in each load condition, and two-tailed paired t-tests confirmed that synchrony modulated time estimation under Low load, $t(35) = 2.082$, $p = 0.045$, $d = 0.442$; but not under Medium or High load, $ps \ge 0.122$. We then compared load conditions separately for synchrony and asynchrony, and found significantly longer time estimations under asynchrony-High load than asynchrony-Low load, $t(35) = 2.762$, $p = 0.009$, $d = 0.592$; while the difference between High and Medium just missed significance with asynchrony, $t(35) = 1.978$, $p = 0.056$, $d = 0.331$. No other significant effect was found, with $ps > 0.12$.

3.4. Explicit ownership

The ANOVA of the means of the ownership data (Q4–6) revealed a significant main effect of synchrony, $F(1,35) = 22.533$, $p < 0.001$, $p\eta^2 = 0.392$, indicating more perceived ownership for the virtual hand when the movement of real and virtual hand were in sync (mean = 3.914, $SE = 0.223$), than when they were not (mean = 2.951, $SE = 0.218$). No load main effect was found, $p = 0.215$, but the interaction was significant, $F(2,70) = 4.841$, $p = 0.011$, $\eta p^2 = 0.122$. No physical load effect was found, with $ps > 0.17$.

We firstly tested synchrony effects in each load condition by means of two-tailed paired t-tests, which confirmed that synchrony modulated ownership ratings under Low load, $t(35) = 5.392$, $p < 0.001$, $d = 0.947$; Medium load, $t(35) = 3.494$, $p = 0.001$, $d = 0.570$; and High load, $t(35) = 3.534$, $p = 0.001$, $d = 0.472$. We then tested load effects separately for synchrony or asynchrony, and found significantly higher ownership ratings for synchronous-Low load than synchronous-Medium load, $t(35) = 2.642$, $p = 0.012$, $d = 0.359$; and than for synchronous-High load, $t(35) = 2.037$, $p = 0.049$, $d = 0.324$. No other significant effect was found, with $ps > 0.46$.

To identify the cause of the interaction, we subtracted the ratings under asynchrony from ratings under synchrony for each load condition to obtain load-specific sizes of the synchrony effect (Tsakiris, Tajadura-Jiménez, & Costantini, 2011). These were analyzed by means of an ANOVA with load as repeated factor, followed by LSD post hoc comparisons. The sync effect was significantly stronger under Low load (mean = 1.306, SE = 0.242) than under Medium load (mean = 0.833, SE = 0.238), with mean difference = 0.472, SE = 0.188, $p = 0.017$, and than under High load (mean = 0.750, SE = 0.212), with mean difference = 0.556, SE = 0.197, $p = 0.008$; while Medium and High load conditions did not differ, $p = 0.669$.

3.5. Implicit ownership (SCR)

The ANOVA revealed only a significant synchrony effect, $F(1,35) = 6.069$, $p = 0.019$, $\eta p2 = 0.148$, while the main load effect and interaction effect were not significant, $ps > 0.58$.

3.6. Replication

As for some of our effects the numerical differences were small and just reached the significance level, we decided to run an exact replication study—so to make sure that our conclusions are not based on spurious, non-reproducible findings. Thirty new participants were tested (7 males; mean age = 19.43 years, standard deviation (SD) = 1.040, range 17–22), with a power higher than 0.99 computed with the obtained effect size in the initial experimental results. The ethical criteria were the same as in experiment. The statistical findings were exactly as in the experiment.

Importantly, in the replication experiment we added two questions to the questionnaire: *Q9.* "How high did you feel your cognitive load to be during the experiment?" and *Q10.* "How much cognitive effort did you spend during the experiment?". By comparing the two cognitive load questions and two physical load questions, we aimed to further investigate the possible relationship between perceived physical load and cognitive load with our experimental setup and procedure. Results showed no significant effect, $ps \geq 0.227$, suggesting that cognitive load was unaffected by physical load.

4. Discussion

The major aims of the present study were to test whether evidence for an impact of physical load on explicit and implicit agency could also be found in a VHI task, and whether these effects would generalize to explicit and implicit ownership. The outcomes do not provide any evidence for these expectations, which is obvious from the absence of any main effect of load on any of the measures except subjective load. While the latter confirms that our manipulation worked, the former seems to support the claim that effort contributes to IB (Demanet et al., 2013), but to contrast with previous findings and claims suggesting that physical load hampers IB (Howard et al., 2016) and that effort enhances explicit agency (Minohara et al., 2016). This might be taken to suggest that multiple informational sources in a VHI setup contribute to both explicit and implicit agency and ownership. We assume that there are several possible information sources that might affect agency and ownership as a function of physical load.

The first one is synchrony. As previous studies showed, voluntary and synchronous movement may lead to causal learning and strong causal inference and belief, which apparently affect explicit and implicit agency (Hoerl, Lorimer, Mccormack, Lagnado, & Buehner, 2020), and ownership (Samad, Chung, Shams, 2015). Indeed, as our results show, synchrony effects were found for all four measurements (agency, ownership, SCR, and IB), which is also consistent with previous studies showing that synchrony affects agency and ownership (Ehrsson, Spence, & Passingham, 2004; Minohara et al., 2016), with respect to both explicit and implicit measures (Armel & Ramachandran, 2003; Ma & Hommel, 2013; Caspar, Cleeremans, & Haggard, 2015).

The second source is the possibly reduced synchrony related to higher physical load. Holding the higher-load resistance band may make it difficult for participants to move freely, and thus the intended/predicted action may not be completely consistent with the actual action (Frith, Blakemore, & Wolpert, 2000). Hence, the visual hand movements might have been harder to predict with higher physical load, and this uncertainty may have led to reduced synchrony perception, especially in synchronous conditions, which may have impaired perceived agency and ownership.

The third source is the feeling of effort, which may have served as additional bottom-up cue to facilitate IB (Demanet et al., 2013), and possibly agency and even ownership (Preston & Wegner, 2007). As Demanet et al (2013) have considered, when performing a task, the experience of effort may give intentional actions some unique phenomenological signature and boost the feeling of being in control, which may enhance IB. This explanation is consistent with the cue integration theory (Moore & Fletcher, 2012), according to which implicit sense of agency can be boosted with more cues. Indeed, Preston & Wegner (2007) found that physical effort can serve as a cue for authorship ascriptions for mental actions, such as when solving problems with a partner.

The fourth source is cognitive load caused by physical load. Howard et al (2016) proposed that physical load may indirectly draw on cognitive resources. Hence, if the IB task itself is assumed to be cognitively costly, then with less available cognitive resource at higher load, temporal binding would be weaker. While Howard et al (2016) did not measure perceived cognitive load/effort in their physical load experiment, in our replication experiment we obtained contrary findings, as cognitive load did not differ for different physical load conditions. Even though we cannot rule out that the specific IB (interval reproduction) task of Howard et al. (2016) was so cognitively demanding that holding a resistance band competed for cognitive resources, cognitive load was not a factor in our current VHI setup (RHI is not cognitively costly anyway; see Fahey, Charette, Francis, & Zheng, 2018). Lastly, besides bottom-up information, top-down modulations (Tsakiris, 2010) may also play a role, but given that the postural properties of the virtual hand were the same in all conditions of the experiment, it is hard to see how that could account for our findings.

Even though our findings do not support previous observations and claims of a systematic relationship between physical load and IB (Demanet et al., 2013; Howard et al., 2016) or between physical load and explicit agency (Minohara et al., 2016), there are four reasons that prevent us from jumping to conclusions too soon. First, even though the main effect of load on IB clearly missed significance, it did go into the same direction as in previous IB studies (Demanet et al., 2013), showing numerically higher IB scores for higher load. Especially the interaction effect between synchrony and physical load is of theoretical interest. The synchrony effect was only obtained with Low physical load, suggesting that, when exerted effort is low, the positive impact of synchrony is hardly affected, which fits with previous findings (Caspar, Cleeremans & Haggard, 2015; Ma, Hommel, & Chen, 2019b). In the three asynchronous conditions, IB was significantly higher for High than for Low load, suggesting that physical load increased exerted effort, which in turn boosted implicit sense of agency, suggesting that load/effort effects are better visible if synchrony no longer plays a role. This fits with the observation that there was no significant effect for the three synchronous conditions, suggesting that, if present, the impact of synchrony is stronger than the impact of load/effort. One may wonder why the IB with High load is numerically higher for the asynchronous than the synchronous conditions. We assume that this is related to our experimental design, as in asynchronous conditions, the virtual hand movement was delayed to the movement of the real hand, so that when participants were experiencing high physical load and exerted high effort, their real and predicted action may have looked more sluggish than intended and may thus have seemed more consistent with the delayed seen action. From the numerical increase in overall IB and the significant increase in the asynchronous conditions, and considering that our loads were lower than in the study of Demanet and colleagues, one may hypothesize that including higher loads would have rendered the main effect significant. Accordingly, we consider the absence of a main effect on IB not necessarily inconsistent with the previous observations of Demanet et al (2016).

Second, our IB results mirror the agency judgments in Minohara et al. (2016), where load effects were absent with synchrony, while load boosted the sense of agency with asynchrony. At the same time, our explicit agency judgement did not reveal any load or interaction effect. This discrepancy might have to do with the experimental setup. In Minohara et al. (2016), participants were asked to press a key that required the exertion of very low force (2.7 N in higher load condition) while watching a square jumping with a delay. In contrast, our participants were asked to move freely while holding a resistance band requiring 20 N in the higher load condition while watching movements of a virtual hand. It is much easier to imagine a square to jump without moving ones hand than to do the same for a virtual hand, which might have promoted no-agency judgments with longer delays with regard to the square than with regard to the virtual hand. This interpretation fits with feedback from some of our participants after the experiment, suggesting that they noticed the delay. Nevertheless, given that we obtained a clear effect of physical load on subjective load (which according to Demanet et al., 2013, should translate into perceived effort) in the absence of any significant load effect on explicit agency, we conclude that perceived effort is not a strong driver of explicit agency. That participants freely moved their hand to explore the operational characteristics of the virtual hand multiplied the amount of bottom-up (visual, kinematics and proprioceptive) information that can be used to compute multimodal correlations (Ma & Hommel, 2015), so that possible additional effort cues may not necessarily impact agency significantly. Furthermore, our explicit agency ratings were around point 4 for even asynchronous conditions (Kalckert & Ehrsson, 2012) and in Minohara et al. (2016) the 50% agency ascription conditions did not reveal any effort effect. It thus seems that only when the explicit agency ascription is quite low, effort manipulations start to work. Conversely, the explicit agency ratings were so high that rating decreased due to reduced synchrony caused by higher load, at least numerically.

Third, while we obtained no main effect of load on ownership measures, we did observe significant interactions between load and synchrony. The synchrony effect was found to be significantly higher for Low load than for Medium and High load conditions, which might be due to a reduced perception of synchrony. With higher physical load, the unseen real hand movement was restricted by holding the resistance band. Accordingly, synchrony may not have looked as synchronous as in the Low physical load condition. Note that explicit ownership ratings were relatively low, so that a reduction of perceived reduced synchrony may have been more important. Synchrony is commonly assumed to represent a particularly important bottom-up signal for driving agency and ownership, which is witnessed by the significant synchrony effects we obtained in the present study, so that interference with processing information about the degree of synchrony would reduce the impact of synchrony on perceived agency and ownership. Hence, higher loads would be more likely to reduce the difference between synchrony and asynchrony, which actually fits the numerical trend obtained for all four agency and ownership measures, including the pattern underlying the two significant interactions. Notably, effort may not contribute to ownership, suggesting that agency judgements may be more sensitive to action-related effort than ownership judgement. Indeed, feeling weak and thus needing more effort to move may lead to a feeling of losing control but not necessarily to the feeling of losing ownership of one's hand.

Fourth, we only found a synchrony effect for SCR, but no interaction with physical load. This suggests that people generally care more about an effector that they perceive as their own, irrespective of physical load or exerted effort.

Taken altogether, we thus suggest that physical load can affect perceived agency and ownership. Not only through an increase of perceived effort, but also by interfering with the processing of synchrony information and/or the integration of multiple sensory streams to estimate the current degree of synchrony between people's real movements and movements of possible additional effectors or tools, like a virtual hand. Moreover, while the different measures of ownership and agency do show some similarities, there are also obvious discrepancies, suggesting that the measures rely on overlapping, but not completely identical data sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

influence the work reported in this paper.

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Author contributions

J. Q. and K. M. developed the study concept. All authors contributed to the study design. Participants testing and data collection were performed by J. Q., Y. S., and L.Y.. Data analysis and manuscript drafting was performed by J. Q. and K. M., and B. H. provided critical revisions. All authors approved the final version of the manuscript for submission.

Compliance with Ethical Standards

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article. 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 consents were obtained from all participants included in this study.

Open practices statement

Raw data of the study are available on the Open Science Framework (https://osf.io/a9cfv/); the experiment was not preregistered.

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