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BRIEF REPORT

Social exclusion in a virtual Cyberball game reduces the virtual hand illusion

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Abstract
Sense of ownership and agency are two important aspects of the minimal self, but how self-perception is affected by social conditions remains unclear. Here, we studied how social inclusion or exclusion of participants in the course of a virtual Cyberball game would affect explicit judgments and implicit measures of ownership and agency (proprioceptive drift, skin conductance responses, and intentional binding, respectively) in a virtual hand illusion paradigm, in which a virtual hand moved in or out of sync with the participants' own hand. Results show that synchrony affected all four measures. More importantly, this effect interacted with social inclusion/exclusion in the Cyberball game for both ownership and agency measure, showing that social exclusion reduces perceived agency and ownership.

Keywords Sense of ownership · Sense of agency · Social exclusion · Virtual hand illusion · Intentional binding

Descartes famously asked: "I know that I exist, the question is what is this 'I' that I know?" The exploration of the self has a long history, but the rigorous empirical investigation of the mechanisms underlying this concept began only recently. From a philosophical, conceptual point of view, Gallagher (2000) divided the self into a *narrative self*, which includes knowledge and memories related to oneself, and a *minimal self*, which refers to the perception of oneself in the here and now. The latter, on which the present study was focused, is often further divided into a *sense of ownership*, which refers to the feeling of "mine-ness" with respect to one's body parts, feelings, and thoughts; and a *sense of agency*, which refers to the feeling of being able to control one's actions and their consequences.

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Body ownership and agency are often investigated by testing whether and to what degree participants would perceive ownership and agency with respect to artificial extensions of their body, such as rubber hands lying in front of them or virtual hands presented on a screen. Interestingly, participants tend to perceive a rubber hand as part of their own body if it is stroked in synchrony with their own unseen hand (the rubber hand illusion [RHI]; Botvinick & Cohen, 1998), and the same holds for a virtual hand if it moves in synchrony with their own unseen hand (the virtual hand illusion [VHI]; Sanchez-Vives et al., 2010; Slater et al., 2008). Whereas RHI studies have often found dissociation between perceived agency and ownership, in the sense that some factors impact ownership but not agency, and vice versa; VHI studies commonly yield substantial correlations between explicit ownership and agency judgments (Ma & Hommel, 2015). These and other findings have been taken to suggest that judgments of agency and ownership are based on overlapping, but not completely identical informational sources (Ma et al., 2021; Synofzik et al., 2008).

In addition to explicit ratings of agency and ownership, various implicit measures have been employed: The proprioceptive drift, to represent the perceived position of the unseen hand after as compared with before the illusion (Tsakiris & Haggard, 2005); and the skin-conductance response (SCR) to events threatening the artificial hand (Ma & Hommel, 2015), to assess ownership; as participants perceive the real unseen hand as closer to the artificial hand; and are physiologically more aroused when facing the threat, after the illusion. The intentional binding (IB) effect, which refers to that the compression of the perceived time interval between a voluntary action (vs. an involuntary movement) and ensuing perceptual events (Haggard et al., 2002; Moore & Obhi, 2012), is widely used as a proxy of implicit agency. Different from the relationship between explicit ownership and agency judgement, the relationships between explicit and implicit measures for ownership and agency are usually uncorrelated, but still affected by similar manipulations (Qu Ma et al., 2021a), again suggesting that explicit and implicit measures reflect shared, but not completely identical sources of information.

While the RHI and VHI demonstrate that the minimal self is malleable, it remains to be understood according to which criteria artificial body extensions are integrated into the minimal self. For one, the available evidence points to three relevant bottom-up factors: priority, consistency, and exclusivity, as reflected by the empirical findings that ownership and agency are affected by the temporal synchrony and similarity between own and artificial effector, and the presence of other possible causes of the artificial effector movement (Ma et al., 2019a). For another, perceived ownership and agency also depend on top-down knowledge from memories and knowledge (Apps & Tsakiris, 2014), such as the appearance resemblance (Ma & Hommel, 2015) and anatomical features (Tsakiris & Haggard, 2005); in addition to contextual information, such as past agency (Liepelt et al., 2017) and perceived exclusivity in joint tasks (Ma et al., 2019a). Some authors proposed that individual differences and demand characteristics at the cognitive level may also influence participants' illusion (Lush et al., 2020).

Most of the top-down factors considered so far relate to the characteristics of the artificial effector and the participants. In contrast, not much attention has been devoted to the possible impact of social factors on the minimal self, especially of those factors that an individual would perceive herself in her social environment, among which is the perceived belongingness to a social group (Baumeister & Leary, 1995). The self can be assumed to emerge from and unfold through interaction with others (Verschoor & Hommel, 2017), and the need to belong is one of the most basic and fundamental human motivations (Baumeister, 1999). Accordingly, the experience of being ignored or excluded from social relationships would be a potentially powerful blow (Twenge et al., 2002). More specifically, one would expect that cognitively adjusting to social exclusion would lead to a redefinition of how one perceives oneself, including one's boundaries with respect to the environment. This redefinition would be expected to be less comprehensive, less integrative after social exclusion, as compared with inclusion (Hommel, 2018).

Thus, the first aim of our study was to directly investigate the possible effect of social exclusion on ownership and agency, using the VHI paradigm. There was little related literature: Preliminary evidence consistent with this expectation has been reported by Malik and Obhi (2019). Without investigating ownership, these authors observed that activating social exclusion memories can reduce the IB effect, as compared to recalling social inclusion. Given that IB effect is considered an implicit agency measure, and given that agency and ownership often correlate, it is not far-fetched to assume that social exclusion might also reduce body ownership. However, there were several drawbacks in that study so that we needed to modify the paradigm. Firstly, the authors did not assess explicit agency judgments. Without self-report assessment, implicit IB effects alone may not be so convincing as measure of the sense of agency, as social exclusion may have a different impact on explicit and implicit agency (SoA), just like other manipulations: Even though explicit SoA and IB effect are both affected by predictions, causal relationships, and multisensory information (Haggard, 2017; Moore & Fletcher, 2012), some studies did show dissociations of them (Ebert & Wegner, 2010; Lafleur et al., 2020; Ma et al., 2019b). Secondly, the method to induce social exclusion and inclusion may not be so effective, as the perceived severity and the affective consequences of exclusion may be different from person to person and depend on numerous factors, such as the particular exclusion context, the observers, and the relationship between participants and the agent who ostracized them (Nezlek et al., 2015). Even if participants may have recalled something else or make up a story under the experimental instruction. Accordingly, participants might have substantial differences in the episodes they recalled, and this may have invited unwanted variability (Sun et al., 2023).

Accordingly, in the present study, we adopted the widely used Cyberball game (Kassner et al., 2012) to induce social exclusion and also included both implicit and explicit measures of SoA and ownership, using the VHI setup. We considered five measures: explicit ratings of ownership and agency, proprioceptive drift and SCR as implicit measures of ownership (Riemer et al., 2019), and IB as an implicit measure of agency. We hypothesized that exclusion should reduce explicit and implicit ownership and agency, and expected comparable findings in all measures.

The second aim of our study was to find out whether some precursors associated with social exclusion (e.g., the widely used indices in traditional exclusion studies, such as the negative mood (Zadro et al., 2004) and basic need threat (Williams, 2009)) mediate the impact of social exclusion on ownership and agency. If so, we might account for the possible cognitive mechanism underlying this phenomenon. There are a few related findings supporting our hypothesis.

For example, on the one hand, the authors in Chow et al. (2008) showed a mediational effect of anger on the relationship between social condition and some antisocial behaviors. On the other hand, these indices were also revealed to be related to ownership to some extent: Researchers suggest that prior induced negative mood may facilitate explicit ownership (Schroter et al., 2021) and proprioceptive drift (Kaneno & Ashida, 2023); self-esteem as a basic need was also predicted to be positively related to ownership (Romano et al., 2021). For this aim, we added a questionnaire to measure the affective states and participants' perceived basic needs threat. We hypothesized that these indices mediate the impact of social exclusion on ownership and agency.

Method

Participants

Thirty female participants (mean age = 20.30 years, *SD* = 1.32, range: 18–23) were recruited from a Chinese university. The reason that only female participants were included was that females are assumed to be more likely to be influenced by social exclusion (Benenson et al., 2013). All participants were right-handed, neurologically healthy, with normal or correct-to-normal vision, naïve with respect to RHI/VHI and the tested hypotheses. Participants provided written informed consent and were financially compensated according to their overall performance. The sample size was determined according to the previous studies of Malik and Obhi (2019), in which 27 females were tested. We also conducted an a-priori power analysis G*Power (Faul et al., 2007), specified a medium effect size ($f = 0.25$), a power ($1 - \beta$) of 0.80, and found that the required sample size is 24. The study was approved by the local human research ethics committee, and the methods were carried out in accordance with approved guidelines.

Virtual environment and apparatus

Previous research has shown that the experience of being excluded from a virtual-reality-based ball-tossing game is approximately comparable to experiences observed in real interactions (Kassner et al., 2012). In this study, we set up a virtual reality Cyberball game scene (see Fig. 1). There were two virtual avatars in the environment and a ball in the front of the participant's first-perspective viewpoint. The participants were instructed to press buttons with their right index finger, at a time of their own choosing. When participants pressed the left button with their right index finger, the ball was tossed to the left avatar; when they pressed the right button with their right middle finger, the ball was tossed to the right avatar.

The equipment was similar to that used in previous studies (Ma & Hommel, 2015; Ma et al., 2019b).We used the software Vizard to build a virtual reality environment. Participants wore a right-hand data glove (Manus,12 sensors, record frequency 200HZ, latency around 5 ms) to record their hand and finger joint movements. A virtual hand module was designed and import into virtual environment, participants were immersed in the virtual environment through an HTC VIVE head-mounted display (HMD) and saw the virtual environment and virtual avatars from the first-person perspective. In the synchrony condition, the participants' virtual hand movement was consistent with the real hand movement. In the asynchrony condition, the virtual hand movement was 3 seconds slower than the real hand movement (Ma & Hommel, 2015). Participants wore the SCR electrodes on their left-hand fingers (Ma & Hommel, 2015).

Fig. 1 Experimental setup. Left panel: Participants wore a head-mounted display on their head and an orientation tracker and data glove on their right hand. Skin-conductance response electrodes were attached to the index and middle fingers of the left hand; the keyboard for IB task or two keys for Cyberball game were placed before the right hand. Right panel: The ball, virtual hand, and two virtual avatars for the Cyberball game in the virtual environment

Design and Cyberball game

We manipulated social inclusion and exclusion by means of the virtual Cyberball game, which in our virtual environment should generate particularly strong feelings of social inclusion or exclusion. Participants were instructed to press one of two keys on the table to throw the ball if the ball was in their hand during the interaction. Following previous studies (Kassner et al., 2012), at the beginning of each ball game, participants threw the ball to one of the two agents (chosen randomly) and received one ball tossed back from them. Then, in the exclusion condition, participants received no more ball tosses, while in the inclusion condition, participants received 30% of the ball tosses (one third of total ball-toss numbers).

In a 2 × 2 repeated-measures design, participants completed four experimental blocks differing across the two factors: social condition (social exclusion or social inclusion) and synchrony (synchronous and asynchronous). As before, the virtual hand movement was consistent with participant's real movement in the synchronous conditions; but delayed when asynchronous. Participants were not informed about the degree of synchrony and the social condition. The sequence of the four conditions was fully counterbalanced across participants. The experimental manipulation was checked by means of two items assessing the subjective perception of exclusion ("I felt included" or "I felt excluded"), and the percentage of ball tosses they received. As dependent variables we recorded explicit judgments of agency and ownership (Ma & Hommel, 2015), and three implicit measures: IB (Haggard et al., 2002) to assess agency, and SCR and proprioceptive drift (Ma & Hommel, 2015) to assess ownership.

Procedure

When arriving at the lab, participants were informed that the study they had signed up for considered two aspects: the "mental visualization in a virtual environment" study and a "motor control" experiment to avoid the possible impact of demand characteristics and expectations of participants. The experimenter then helped the participants to put on the HMD and enter into the virtual-reality environment, to wear the data glove on their right hand, the orientation tracker on their right wrist, and the SCR electrodes on the index and middle fingers of their left hand, which was placed in a relaxed state on the table; participants were asked not move the left hand throughout the experiment.

Before the experiment, participants were asked to complete the IB baseline test (Ma et al., 2019b). Participants were put in an immersive virtual environment with a virtual clock in front of them; the pointer of the virtual clock was set to zero, and virtual buttons appeared under the virtual clock. Participants were asked to press the space bar at their leisure with their real finger on the real keyboard space bar in front of their real right hand. Pressing the real space bar (and seeing the virtual button move down and back up) would cause the pointer to start moving clockwise and a tone to play. Participants were required to report the pointer position when the tone was played. The baseline test comprised 10 IB trials, and then the virtual clock with its pointer and button disappeared (Qu, Ma et al., 2021a).

After the IB baseline test, participants completed the four experimental conditions. There were several steps in each condition: Firstly, the virtual right hand was presented in the virtual environment, and it was placed on the midway between the midline and real hand—that is, in a position near the participant's body middle line, and to the left of the participant's real right hand. Also, a virtual number array was shown on the top of the virtual hand. Participants were asked to verbally report the felt position of their real hand using one specific number in the array. The experimenter recorded this number. This was the premeasure proprioceptive drift.

Secondly, participants were asked to freely move their unseen right hand for two minutes and to observe the corresponding movement of the virtual hand. To avoid different degrees of movement and attention engagement in synchronous and asynchronous conditions, such as where participants might perform less movement and passively wait for the virtual hand movement or pay less attention to these movements, we reminded participants to keep moving their hand freely and voluntarily in both synchrony conditions and focus their attention on the virtual hand movement. Thirdly, participants would engage in a virtual social interaction. The experimenter told participants that two computer-controlled agents would be present in the environment and would start a ball-toss game. Participants were instructed to press one of two keys on the real table to throw the ball if the ball came to them during the game. After 40 rounds of playing, the ball-toss game was over.

Then, the measurements started: Participants were asked to place their real right hand in a relaxed state on the real table, it is the same fixed position as in the first step, and a virtual knife appear, approach and cut the virtual hand. In this threat phase, the SCR data was recorded (Figner & Murphy, 2011). The virtual knife then disappeared, and the numerical array appeared again. Participants needed to verbally report the felt position of their real right hand again. This was the postmeasure proprioceptive drift. When finished, the numerical array disappeared and the virtual clock, pointer, and button appeared. Participants were asked to perform the IB test, which was similar to the baseline IB test, except that the virtual hand was shown to participants.

At last, participants were asked to estimate the percentage of ball tosses they received and answer two questions to indicate their perceived exclusion or inclusion in the last experience, for manipulation check. They also needed to fill in the Basic Needs Scale (Williams, 2009), Affect Grid (Russell et al., 1989), and agency and ownership questionnaire. Each condition lasted for about 10 minutes, and there was a 2-min break between each two conditions in order to reduce participant tiredness and prevent possible interference between conditions. The experimental procedure is shown in Fig. 2.

Measurements

Manipulation checks

Manipulation checks were conducted to confirm participant's perception of exclusion or inclusion. Participants were asked to estimate the percentage of the ball they had received (Kassner et al., 2012; Williams et al., 2000) and rate how much they felt excluded/included while playing the last virtual Cyberball game, on a 7-point Likert scale, ranging from 1 (*not at all*) to 7 (*very much*), on their felt exclusion and inclusion, separately. The inclusion item was reversed rated, and then the mean of the two ratings were computed as the felt exclusion intensity (Williams et al., 2000).

Basic Needs Scales

We adopted the brief Basic Needs Scales (BNS), which has been previously used in the Cyberball paradigm (Williams, 2009). This scale consists of 20 items, including four dimensions: sense of belonging, self-esteem, the significance of presence, and sense of control, each with five items, and rated on a 5-point Likert scale, 1 (*completely inconsistent*) to 5 (*very consistent*). Participants were required to rate the extent to which the description of the item was consistent with their own, with higher ratings indicating that the participants felt more consistent with the item. The higher the total score, the lower the threat of the basic needs of the participants. Participants were asked to complete the BNS after each virtual Cyberball block according to how they felt while playing the last game.

Affect Grid scale

During the experiment, we used the Affect Grid scale to measure participants' subjective affective states (Russell et al., 1989). There are 81 grids (9 × 9) in the scale, the horizontal axis represents affective valence, ranging from unpleasantness to pleasantness, and the vertical axis represents perceived arousal, ranging from high arousal to sleepiness. Accordingly, arousal and affective valence can be derived independently from the scale. Participants were required to rate their mood in terms of pleasant and arousal whenever the grid appeared in the virtual environment during the time of answering the questionnaires.

Questionnaire for explicit ownership and agency

In line with earlier studies (Botvinick & Cohen, 1998; Ma & Hommel, 2015; Qu, Ma et al., 2021a), we used an adapted Chinese version of the RHI/VHI questionnaire. Eight questions were presented to the participants for assessing perceived agency (Q1–4) and ownership (Q5–8). For each statement, participants responded by choosing a score on a 7-point (1–7) Likert scale: 1 (*strongly disagree*), 4 (*uncertain*), and 7 (*strongly agree*). The statements were:

Q1. The movement of the virtual hand in the virtual environment was caused by my movement.
Q2. I can control the virtual hand in the virtual environment.

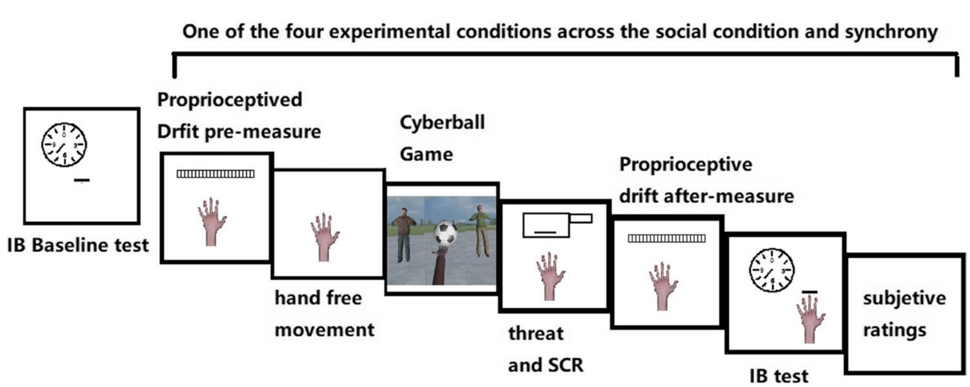

Fig. 2 Experimental procedure. IB baseline test was conducted before the experiment, and each experimental condition started with the proprioceptive drift premeasure, and ended with the questionnaires. There was a 2-min break between each two conditions. The sequences of the four conditions were counterbalanced

Q3. The virtual hand in the virtual environment moved as I wished.
Q4. When I make a movement with my real hand, I expected the virtual hand in the virtual environment to do the same movement.
Q5. When I looked at this virtual hand, I felt like I was looking at my own hand.
Q6. I felt that this virtual hand was my own hand.
Q7. I felt like this hand on the screen was a part of my body.
Q8. My real right hand and virtual hand seem to be at the same place.

Proprioceptive drift

The experimenter helped participants place their real hands on the fixed position on the desk, and in the virtual environment a number array (Qu, Ma et al., 2021a) was presented above the virtual hand, and each number occupied a space 1 cm wide. Participants were asked to verbally report a number in the array to represent the felt position of their real right middle finger. The sequences of numbers in the arrays were different in different conditions to prevent possible experimental strategies. This step was done both before and after each condition experience, and we recorded the positions of the reported number as compared with the left end of the array. In the end, proprioceptive drift was calculated by subtracting the pointed position at the postmeasure from that at the premeasure, for each condition and each participant. Because the virtual hand was placed midway of the participants' body midline and real right hand, positive proprioceptive drift value implied a drift of the perceived real right-hand position towards the virtual hand.

SCR measurement

As previous findings showed that after participants gain illusory ownership towards the virtual hand, their SCR will become higher when they see the virtual hand was threatened (Ehrsson et al., 2007), we used SCR to assess ownership indirectly. Compared with questionnaires, SCR is a physiological measure participants cannot control voluntarily, which thus makes it relatively reliable.

During the threat phase of each condition, we presented a virtual knife on top of the virtual hand. It would descend to cut the virtual hand, then raise back up to its original position, wait for 10 seconds, and then cut again. The knife cut the virtual hand a total of four times for each condition. For each cut, 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, and with the skin conductivity before event onset serving as SCR baseline (Ma & Hommel, 2015). We then calculated the magnitude of the event-induced SCR by subtracting the SCR baseline from the peak amplitude of the SCR during the time window, and computed the log(magnitude +1) per cut (Figner & Murphy, 2011). Lastly, the mean of the four cut-induced SCRs, to avoid possible noise, was taken as the SCR result in a specific condition for each participant (Qu, Ma et al., 2021a).

Time estimation task for IB effect

The IB effect reflects the perceived temporal distance between a voluntary action and its sensory consequence, and it consists in the observation that this interval is perceived to be shorter than the interval between involuntary and comparable sensory events (Haggard et al., 2002). Previous studies (Moore & Obhi, 2012) suggested that the IB effect can be used as the assessment of the implicit SoA. In our current work, we used the same time estimation task to assess IB as in a previous study (Qu, Ma et al., 2021a): Participants immersed in the virtual environment were asked to watch their virtual hands, a virtual clock with a pointer, and a virtual button. When participants pressed the real key with their unseen real hand, the virtual pointer started to rotate at a rate of 1,200 ms of a whole cycle, always from zero back to zero. The real pressing movement was translated into the virtual pressing movement of the virtual hand and corresponding movement of the virtual button, but this happened either synchronously or with a delay (asynchronously). After a randomly chosen time between 600 and 1,000 ms after the real key press, a tone was presented. As soon as the pointer finished rotation, participants were to report the pointer position at the time they perceived the tone.

We recorded the participants' baseline IB in a test before the experimental manipulation and recorded four conditional IB in each experimental condition. The only difference is that in baseline IB test, no virtual hand was presented. Both baseline and experimental IB tasks consisted of 10 trials (Qu, Ma et al., 2021a). When computing the IB results, for each trial, we subtracted the reported time by participants from the real time recorded with the software script and divided it by the real time (Braun et al., 2014), to represent the estimated time as percentage. Then we computed the median of the 10 trials for each condition and baseline separately (Qu, Ma et al., 2021a), we subtracted the estimated percentage 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 reported temporal interval, so that more positive values of the estimated percentage correspond to greater time compression, and reflect stronger agency.

Results

Analysis of all behavioral measures were performed using 2 (social condition: inclusion vs. exclusion) × 2 (synchrony: synchronous vs. asynchronous) repeated-measures analysis of variance (ANOVA).

Manipulation checks

The effectiveness of social condition manipulation was checked. The ANOVA yielded only a significant main social condition effect, on the estimated percentage of the ball participants had received, $F(1, 29) = 388.41$, $p < .001$, $\eta_p^2 = 0.93$, and on the subjective feeling of exclusion, $F(1, 29) = 515.71$, $p < .001$, $\eta_p^2 = 0.95$. No other significant effect was found (*p*s > .11). See Fig. 3.

Mood results from the Affect Grid scale

The arousal scores showed only a significant social condition main effect, $F(1, 29) = 4.86$, $p = .036$, $\eta_p^2 = 0.14$. No other significant effect was found (*p*s > .36). Pleasant scores also showed a significant social condition main effect, $F(1, 29) = 62.10$, $p <.001$, $\eta_p^2 = 0.68$. The synchrony main effect was not significant, $p = .179$, but the interaction was, $F(1, 29) = 9.11$, $p = .005$, $\eta_p^2 = 0.24$. With two-tailed paired *t* test, a significant synchrony effect was found with social inclusion, $t(29) = 2.83$, $p =.008$, $d = 0.57$, but not social exclusion ($p =.136$). See Fig. 4.

Basic need scale

For the social condition, the main effect was significant, $F(1, 29) = 175.36$, $p < 0.001$, $\eta_p^2 = 0.86$; as were the synchrony main effect, $F(1, 29) = 22.40$, $p < .001$, $\eta_p^2 = 0.44$, and the interactions, $F(1, 29) = 14.90$, $p = .001$, $\eta_p^2 = 0.34$. Two-tailed paired *t* tests showed the synchrony effect under social inclusion, $t(29) = 4.64$, $p < .001$, $d = 0.83$, but not under social exclusion, $p = .100$. See Fig. 5.

Explicit ownership

The ANOVA revealed a significant synchrony main effect, $F(1, 29) = 46.04$, $p < .001$, $\eta_p^2 = 0.61$, and the interaction, $F(1, 29) = 5.74$, $p = .023$, $\eta_p^2 = 0.17$, but not the social condition effect ($p = .057$). Two-tailed paired *t* tests revealed that ownership ratings were significantly higher for the synchronous than for the asynchronous condition under social inclusion, $t(29) = 7.58$, $p < .001$, $d = 1.34$, and also

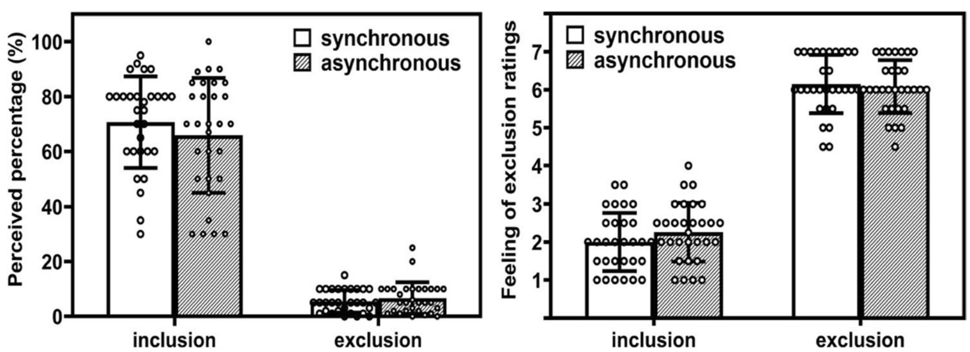

Fig. 3 Manipulation check results as a function of social condition and synchrony. Error bars represent ±1 *SD*. The dots represent individual data

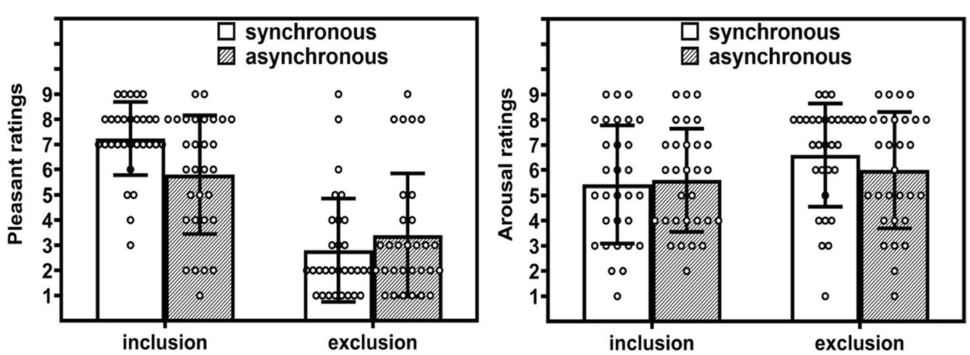

Fig. 4 Arousal and valence results. Error bars represent ±1 *SD*. The dots represent individual data

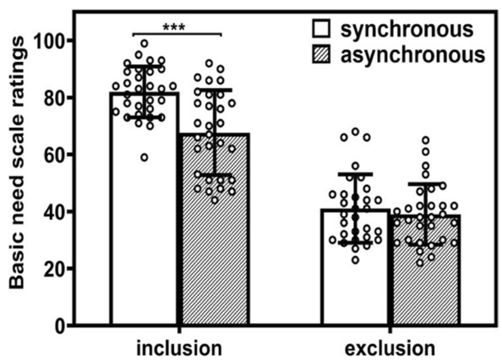

Fig. 5 Basic need scale results. Error bars represent ±1 *SD*. The dots represent individual data

significantly higher for the synchronous than the asynchronous condition under social exclusion, $t(29) = 3.35$, $p = .002$, $d = 0.60$. See Fig. 6.

Proprioceptive drift

The ANOVA revealed a significant synchrony main effect, $F(1, 29) = 10.02$, $p = .004$, $\eta_p^2 = 0.26$, indicating that proprioceptive drift was higher under synchrony than under asynchrony; and a significant interaction, $F(1, 29) = 5.38$, $p = .028$, $\eta_p^2 = 0.16$, but no social condition effect ($p = .759$). Two-tailed paired *t* tests revealed that proprioceptive drifts were significantly higher for the synchronous than for the asynchronous condition under social inclusion, $t(29) = 5.84$, $p < .001$, $d = 1.05$, but not under exclusion ($p = .735$).

SCR results

The ANOVA revealed a significant synchrony main effect, $F(1, 29) = 6.62$, $p = .015$, $\eta_p^2 = 0.19$. No other effect was significant, *p*s > .15. Two-tailed paired *t* tests (with Bonferroni correction for multiple comparisons; $p \leq .0083$) showed that the synchrony effect was significant with inclusion, $t(29) = 2.97$, $p = .006$, $d = 0.53$, but not with exclusion ($p = .601$).

Explicit agency

The ANOVA revealed a significant main effect of synchrony, $F(1, 29) = 127.97$, $p < .001$, $\eta_p^2 = 0.82$, and also the interaction, $F(1, 29) = 5.32$, $p = .028$, $\eta_p^2 = 0.16$, but not the social condition main effect ($p = .518$). Two-tailed paired *t* tests revealed a significant synchrony effect under social inclusion, $t(29) = 10.93$, $p < .001$, $d = 2.12$, and under social exclusion, $t(29) = 6.90$, $p < .001$, $d = 1.45$. See Fig. 7.

Time estimation

One-sample *t* tests (with Bonferroni correction for multiple comparisons; $p \leq .0125$) showed that the IB effect was significantly different from zero in all conditions, $ts(29) > 3.45$, $ps \leq .002$, $ds \geq 0.63$, showing time compression in

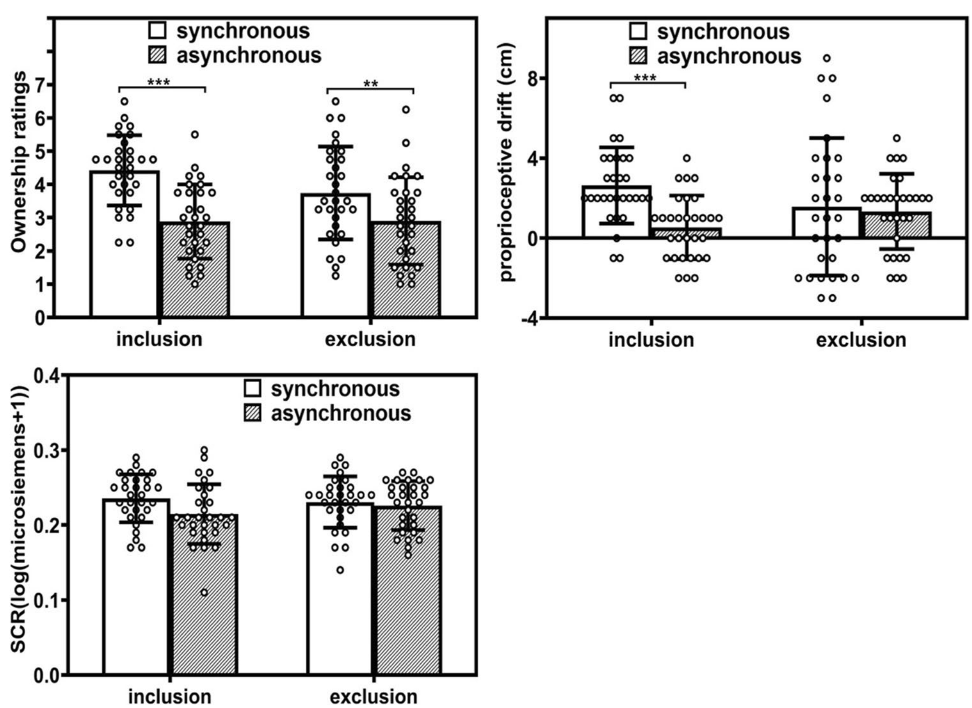

Fig. 6 Explicit ownership, proprioceptive drift and SCR results. Error bars represent ±1 *SD*. The dots represent individual data

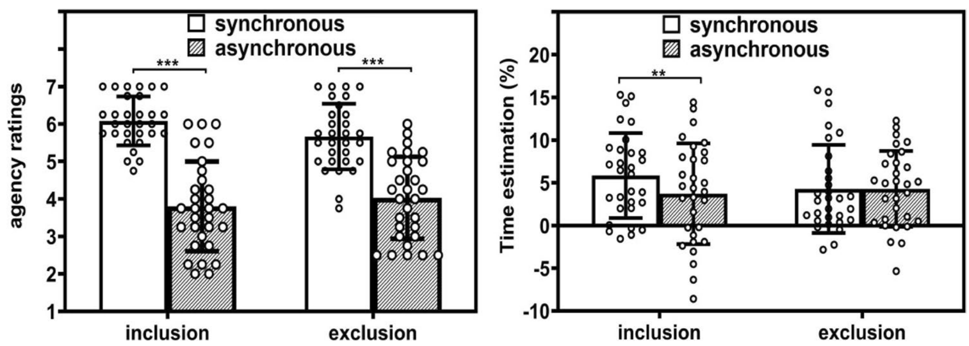

Fig. 7 Explicit agency and time estimation results. Note that for time estimation results, higher ratio (%) indicates more underestimation, and stronger IB. Error bars represent ±1 *SD*. The dots represent individual data

all conditions. The ANOVA yielded a marginal significant synchrony main effect, $F(1, 29) = 4.40$, $p = .045$, $\eta_p^2 = 0.13$, and a significant interaction effect, $F(1, 29) = 5.64$, $p = .024$, $\eta_p^2 = 0.16$, but no social condition main effect ($p = .47$). A two-tailed paired t test revealed significant synchrony effect with social inclusion, $t(29) = 3.53$, $p = .001$, $d = 0.66$; but not with social exclusion ($p > .99$).

Correlational and mediational analysis

Taking the asynchronous conditions as a control, we subtracted asynchronous from synchronous results (Ehrsson et al., 2022), for all measures, separately for the two social conditions. We then analyzed the correlational relationships between explicit ownership and agency: consistent with previous findings (Ma & Hommel, 2015), significant correlations were found for all conditions, with $rs > .37$, $ps < .022$. For the correlations between explicit and implicit measures, for ownership, the explicit ratings correlate to proprioceptive drift under exclusion-synchronous only, $r = .32$, $p = .044$; for agency, the explicit ratings correlate to the IB effect under inclusion-synchronous only, $r = .35$, $p = .030$. No other significant correlation was found ($ps > .08$).

Additionally, for our second aim, we investigated whether the impact of social exclusion on both explicit and implicit ownership/agency was mediated by a change of mood or BNS in the two social conditions. However, in the mediation analysis (Montoya & Hayes, 2017), no mediation effect was found for mood or BNS scores ($ps > .10$).

Discussion

The purpose of the present study was to test the hypothesis that social exclusion reduces the sense of agency and the sense of ownership. We manipulated social condition and movement synchrony by means of a virtual Cyberball game and VHI paradigm, assessed explicit ownership and agency by means of standard rating scales, and implicit ownership and agency by means of the proprioceptive drift, SCR, and IB task, respectively. Findings confirm that the social-exclusion manipulation was effective, as manipulation checks showed, and suggest that the VHI effect was replicated, as all ownership/agency measures showed significant effect of synchrony. Interestingly, none of the ownership/agency measures was directly affected by the social condition, as this would have yielded a social condition main effect. Rather, we only obtained interactions of the social condition with synchrony, suggesting that it was especially the integration process of the artificial effector that was hampered by social exclusion.

Firstly, the interaction obtained for the explicit ownership indicated that social exclusion decreased the synchrony effect, which is consistent with our expectation that being excluded from a particular group triggers the perceived self as less integrative (Hommel, 2018). This apparently went beyond the group one is excluded from and generalized to the reluctance to integrate a synchronized artificial effector into one's self-representation. This presumably reflects top-down modulations of bottom-up sources (Lafleur et al., 2020); thus, social exclusion diminished the contribution of multisensory stimulation integration to body ownership. In other words, being excluded by others makes one more exclusive as well. This would also fit with assumptions that social exclusion may induce the feeling of the body as a mere tool (Ataria, 2015), and thus may cause disownership.

Secondly, for implicit ownership, proprioceptive drift was again revealed to be similarly affected by the same manipulations as ownership (Abdulkarim et al., 2021). When analyzing the interaction effect, however, we found a subtle difference: The synchrony effect was found for explicit ownership in both social conditions, but for proprioceptive drift only in social inclusion. This result pattern is similar to previous studies (Liepelt et al., 2017; Ma & Hommel, 2015), in which both a virtual hand and a rectangle (or wooden block) were investigated and both explicit ownership and proprioceptive drift were measured. Even though the rectangle did not match the real hand's appearance in memory and knowledge, synchronous multisensory stimulation still induced stronger ownership as compared with asynchronous manipulation, while it failed to do so for proprioceptive drift. If we consider the previous finding that social exclusion may induce the feeling of the body as a mere tool (Ataria, 2015), it may be that the rectangle meets more criteria of a tool than a virtual hand. It is thus reasonable to assume that, similar to the mismatched appearance in previous studies, social exclusion in the current study modulated synchrony stimulation integration in the proprioceptive drift results. However, why did the appearance and social exclusion not eliminate the synchrony effect on ownership judgement? As previously stated, body ownership judgement and proprioceptive drift are based on overlapping, but non-identical kinds of information (Ma et al., 2021), and the indirect measure might be more sensitive to past experiences and knowledge (Liepelt et al., 2017) than the direct one.

As for the SCR results, no significant interaction effect was found. The comparison with Bonferroni correction still presented us with a similar results pattern as ownership and proprioceptive drift—that is, participants were physiologically more aroused when synchronous as compared to synchronous only with social inclusion, confirming that SCR reflects ownership perception.

Thirdly, from the correlational analysis, we can see that explicit agency was again highly correlated with explicit ownership, consistent with previous findings (Ma & Hommel, 2015) This suggests that with the VHI design, explicit ownership and agency ratings were affected by the manipulation in comparable ways. These two measures rely on at least some overlapping information, and sometimes one can promote the other (Braun et al., 2018).

Fourthly, the IB effect findings in two synchronous conditions were consistent with previous observations (Malik & Obhi, 2019), despite using a different exclusion induction, experiment design, and operationalization, and the time estimation task paradigm. Nevertheless, the findings corroborated the impact of social exclusion on the IB effect. It is also interesting to see that explicit agency and IB both showed interactions; similarly, Sun and colleagues (Sun et al., 2023) found that both IB and agency judgment decreased under social exclusion. However, the synchrony effects were found for agency judgment for two social conditions but for IB only for social inclusion. Researchers suggested that internal or external information from different sources, with different reliability, are differently weighed in the perception and attribution of SoA (Moore & Fletcher, 2012). It was thus possible that some specific information was weighted differently for IB and explicit agency. IB might be more sensitive to such social contextual cues than explicit agency, as social exclusion leads to a threat defense response (Jiang et al., 2021) and so possibly interfered with the immediate memorizing of the clock pointer positions and retrieval of this information when reporting.

Lastly, as we assumed that the interaction effect might reflect an impact of social exclusion on ownership by undermining the motivation (i.e., the mood or need threat), of the individual (Baumeister et al., 2005), but we found no mediation effect of mood and BNS results on the impact of social conditions on ownership/agency, even though mood and BNS changed with social exclusion.

In addition, data analysis showed that the demand characteristics did not confound our ownership/agency results, as no significant correlations between subjective perceived exclusion and ownership/agency results was found ($ps > 0.14$); neither was a mediation effect of subjective perceived exclusion on the impact of social conditions on ownership/agency results found ($ps > 0.47$). Indeed, the claims by Lush et al. (2020) were not considered to be stable or consistent—for example, Slater and Ehrsson (2022) reanalyzed the original data from Lush et al. (2020) and predicted that expectations (demand characteristics) had a tiny effect on the ownership illusion ratings; and Ehrsson et al. (2022) predicted no significant associations between expectation and the illusion. Taken overall, the effect of demand characteristics on ownership using VHI requires further investigations in future studies.

Our findings suggest that social exclusion affects both explicit and implicit ownership and agency similarly, and suggests that the integration of internal sensorimotor and social contextual cues is selective and interactive, rather than just additive, with the later modulating the former and impacting the evaluation of this illusion at a metacognitive level. But detailed discrepancy between the explicit and implicit measure results existed: The synchrony effect was found for all explicit and implicit measures with social inclusion, but with social exclusion, it was only found for explicit, but not implicit, measures. This finding is consistent with one previous study (Qu, Ma et al., 2021a), in which cognitive load affected ownership and agency and only interacted with synchrony manipulation for explicit measures, but directly impacted implicit measures. It thus seems that task characteristics, like whether the measures are explicit and implicit, matters, while the difference between agency and ownership does not play a major role. This may refer to the theoretical controversy about top-down and bottom-up contributions (Apps & Tsakiris, 2014; Ma & Hommel, 2015; Synofzik et al., 2008). Explicit and implicit ownership and agency are accounted for by multiple bottom-up and top-down factors and their possible correlations. It is likely that some factors are more important for certain measures than others, according to the different natures of the underlying cognitive mechanisms and different sensitivities to the experimental manipulations of the measures.

Taken overall, we investigated and showed that social interaction has an effect on bodily ownership and agency sense, and thus implies a possible effect from other social aspects of individuals or virtual avatars (Peck et al., 2013) and their complicated relationship, especially in larger groups.

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

Declarations 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.

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