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Me, You, and Our Object: Peripersonal Space Recruitment During Executed and Observed Actions Depends on Object Ownership

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Peripersonal space (PPS) is a spatial representation that codes objects close to one's own and to someone else's body in a multisensory-motor frame of reference to support appropriate motor behavior. Recent theories framed PPS beyond its original sensorimotor aspects and proposed to relate it to social aspects of the self. Here, we manipulated the ownership status of an object ("whose object this is") to test the sensitivity of PPS to such a pervasive aspect of society. To this aim, we assessed PPS through a well-established visuo-tactile task within a novel situation where we had dyads of participants either grasping or observing to grasp an object, whose ownership was experimentally assigned to either participant (individual ownership), or to both participants (shared ownership). When ownership was assigned exclusively ("this belongs to you/the other," Experiment 1), the PPS recruitment emerged when grasping one's own object (I grasp my object), as well as when observing others grasping their own object (you grasp your object). Instead, no PPS effect was found when grasping (and observing to grasp) an object that was not one's own (I grasp yours, you grasp mine). When ownership was equally assigned ("this belongs to both of you," Experiment 2), a similar PPS recruitment emerged and, again, both when the action toward the shared object was executed and merely observed. These findings reveal that ownership is critical in shaping relatively low-level aspects of body-object interactions during everyday simple actions, highlighting the deep mark of ownership over social behavior.

Keywords: peripersonal space, multisensory perception, ownership, mirror, extended self

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The representation of the space surrounding our body, termed peripersonal space (PPS), is crucial for detecting and interacting with nearby objects (Brozzoli et al., 2014; di Pellegrino & Làdavas, 2015; Patané et al., 2017; Cléry & Hamed, 2018; Bufacchi & Iannetti, 2018; Serino, 2019). PPS functions are thought to rely on multisensory neurons, identified within premotor-parietal areas

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and the putamen both in human and nonhuman primates, that specifically respond to tactile stimuli presented on the body and visual stimuli presented close to it (Rizzolatti et al., 1997; Fogassi et al., 1996; Duhamel et al., 1998; Graziano & Gross, 1998; Brozzoli et al., 2011; Guipponi et al., 2013). The PPS representation has first been described in the macaque monkey where multisensory neurons have tactile receptive fields on a given body-part, like the hand, that are aligned with visual receptive fields protruding for a few centimeters out of the skin of that body part AQ: 6 (Duhamel et al., 1997; Graziano & Gross, 1998; Graziano et al., 1997; Rizzolatti et al., 1981). These visuo-tactile receptive fields remain aligned when the body part moves. Thus, when the position of the hand changes, the spatial layout of the multisensory interaction relative to the hand is updated coherently. The activity of these multisensory neurons has been interpreted as to coding for the near space in body-parts centered coordinates. For example, hand-centered visuo-tactile neuronal populations show enhanced responses to objects presented near the hand (Brozzoli et al., 2012; Fogassi et al., 1992; Makin et al., 2015; Serino et al., 2015).

The peculiar multisensory mechanism characterizing PPS recruitment in healthy humans is behaviorally captured by well-established visuo-tactile interaction (VTI) effects: Task-irrelevant visual stimuli modulate the speed of responses to tactile stimulation more strongly when presented near than far from the stimulated hand (di Pellegrino et al., 1997; Spence et al., 1998). Because VTI depends on the stimulus distance from the hand, it is considered as a good proxy of PPS recruitment, indexing the strength of the multisensory interaction between visual and tactile stimuli (Spence et al., 2004; Spence et al., 2004). Because of these features, this multisensory space serves as an interface for body—environment interplay that contributes to the efficient guidance of actions and defensive behavior in response to objects presented in PPS (de Vignemont & Iannetti, 2015; Bufacchi & Iannetti, 2018). In this regard, it has been shown that VTI is enhanced while planning to grasp objects (Brozzoli et al., 2009; Brozzoli et al., 2010; Patané et al., 2018; Belardinelli et al., 2018), confirming that PPS interfaces sensory inputs and motor responses to code for nearby objects (Graziano & Gross, 1998).

Interestingly, multisensory enhancement occurs also while observing objects close to other individuals: Touches delivered on one's own hand are boosted by visual stimuli near one's own hand, as well as near someone else's hand (Teramoto, 2018). These behavioral observations in humans indicate that neurons coding for PPS display mirror-like mechanisms (Brozzoli et al., 2013), as previously identified in monkeys (Ishida, Nakajima, Inase, & Murata, 2010). Taken together, these findings seem to suggest that individuals encode the body parts of other people using a representation of their own body parts, a "mapping" mechanism that is functionally similar to how mirror neurons encode one's own and others' actions (di Pellegrino et al., 1992; for a review, Rizzolatti & Sinigaglia, 2016).

Despite being predicted by the above recalled evidence, whether multisensory enhancement is triggered by both execution and observation of object-oriented actions remains unanswered. Actions are often observed in social contexts where another person can be the agent acting in our PPS. In this regard, it has been recently advanced that PPS could be involved in social interactions. This hypothesis is supported by an emerging body of evidence revealing that PPS is affected by the mere presence of another person (Heed et al., 2010; Iachini et al., 2014), as well as by the positive or negative nature of interactions with other individuals (Dell'Anna et al., 2020; Hobeika et al., 2020; Teneggi et al., 2013). For instance, Heed et al. (2010) showed that the strength of visuo-tactile interaction for stimuli within one's own PPS reduces if another person is present within the participant's PPS and performs a task on the same object. Yet, so far studies focused on how PPS is affected by salient social stimuli, such as the presence of other individuals and their behavior. Namely, recent work reported that PPS is influenced by the features of other persons such as morality, emotional valence, and other high-level aspects of human cognition (Ferri et al., 2015; Iachini et al., 2014; Iachini et al., 2015; Patané et al., 2016; Pellencin et al., 2018; Ruggiero et al., 2017). This evidence for PPS sensitivity to other individuals has brought to a novel theoretical frame, whereby PPS is now conceived as an action interface for the Self to interact with objects and other people (Blanke et al., 2015; Cléry & Hamed, 2018; Serino, 2019).

Within this growing interest for including the social aspects and functions of PPS into a more comprehensive theoretical framework, here we reasoned that not only other individuals, but also the social features attributed to the target of an action should be particularly relevant for PPS recruitment. In everyday life, sensorimotor and social interactions are embedded in interpersonal contexts, whereby both executed and observed actions become more salient as they are directed toward socially relevant targets. It therefore stands to reason that the social features of an object that is the target of one's own or someone else's action, may modulate PPS. Additionally, providing evidence for PPS recruitment during action observation would be fundamental to our understanding of the role of PPS in social contexts. Indeed, this would further support the view that one's own PPS also implements a mechanism to map others' PPS to provide a common reference frame to interact with them and to anticipate their actions (Brozzoli et al., 2014, see the space-sensitive mirror neurons in Rizzolatti & Fogassi, 2014). Thus, here we tested the hypothesis that PPS is sensitive to the ownership status of an action target. Object ownership is indeed a psychological construct that pervasively biases both cognitive and sensorimotor processes. Given the ubiquity of object-oriented actions in our daily life, knowing the ownership status of a given object is essential to deal with others successfully. The sense of objects' ownership comes with better and faster processing of one's own, as compared with other people's objects, reflecting an intimate relationship between agents and their objects (Aglioti et al., 1996; Belk, 1988; Cunningham et al., 2008). Accordingly, knowing the ownership status of an object impacts on our sensorimotor system: For example, affordances that emerge for one's own objects are suppressed when objects belong to others (Constable et al., 2011). Due to its relevance, the social status of ownerships could play an important role in shaping the dynamic spatial relationship between agents and objects.

We thus manipulated object ownership to test its effects on multisensory-motor interaction in PPS. In Experiment 1, dyads of participants took turns to grasp a novel object, whose ownership was previously assigned to one or the other participant. As an index of PPS recruitment during both executed and observed actions, we measured the VTI between task-irrelevant visual stimuli placed on the object and target touches delivered to the hand (Belardinelli et al., 2018; Brozzoli et al., 2010, 2009; Senna et al., 2019). We predicted PPS recruitment (larger VTI) when one is acting upon one's own, but not the other's object, that is, when *one grasps one's own object*. Regarding PPS recruitment during action observation, we considered several scenarios. If one's own PPS representation is used to map others' PPS, a similar PPS recruitment should emerge when object ownership is matched to the agent: Grasping one's own object (I grasp my object) and observing another person grasping their object (you grasp your object). AQ: 7 According to this "object status mirroring account" we should therefore expect similar VTI modulations in the agent who grasps their own object and in the observer who watches another person grasping their respective own object. Only this prediction fits with the mirror literature, which emphasizes how one's motor repertoire shapes selectively the responsiveness of the mirror neurons system. For instance, Calvo-Merino and colleagues (2006) found greater activity in the mirror system when dancers viewed moves from their own motor repertoire, compared with opposite sex moves that they frequently saw, but did not perform. A second possible scenario predicts similar VTI when grasping one's own object (I grasp my object) or observing someone else grasping it (you grasp my object). In other words, this could be labeled as an "object status alerting account". This would not be compatible with a mirror-like effect, being more likely due to an alerting mechanism, for which events coming from one's own object would become more relevant. A third possibility is that object ownership has no impact over either executed or observed action. Accordingly, a similar VTI modulation should be found irrespective of object ownership, both in action execution and observation.

The results of Experiment 1 supported the object status mirroring account: Individual ownership modulates PPS during both action execution and observation according to the match between object and agent (I grasp my object—you grasp your object). We therefore ran a second experiment to investigate whether this multisensory-motor resonance is still present with a shared ownership status. In this case, we should expect a similar PPS recruitment not only when *I grasp*, but also when *I observe the other grasping* the shared object. To corroborate the effectiveness of shared ownership attribution, which has never been tested before, we used ad hoc questionnaires assessing the feeling of ownership toward the object. Not last, to exclude that any VTI modulation could be simply driven by differences in movement execution toward one's own or someone else's object (Constable et al., 2011), we recorded the kinematics of the agents' grasping movements.

Experiment 1: Grasping My or Your Object

Method

Participants

A statistical power analysis based on data from a pilot study was performed for sample size estimation. The effect size estimate Cohen's d_z was calculated from the t-value and the number of participants using the formula provided by Rosenthal (1991): Cohen's $d_z = \frac{t}{\sqrt{n}}$ as G*Power to perform power analyses for within-subjects designs relies on Cohen's d_z as input. On the basis AQ: 8 of this analysis, with an effect size Cohen's $d_z = .52$, $\alpha = .05$, and power $= .80$ for our contrast of interest execution mine before versus onset (see experimental conditions), we set a sample target of 32 participants (i.e., 16 pairs) as the total estimated sample was 31. This a priori established sample size was also used as data-collection stopping rule. We tested only same-sex dyads, recruiting half sample of male and the other half of female participants. While this limitation prevented us from assessing whether "mixed-sex" dyads could further modulate our results, it importantly ensured to avoid confounds potentially due to sex-related difference in arm length.

Thirty-two healthy participants (16 men, 16 women, mean age = 22.39 years, $SD = 2.91$) with normal or corrected-to-normal vision took part in the study. Data from one participant were excluded from analyses because of low accuracy in several experimental conditions of the VTI task, so the final sample was $N = 31$. Before the experiment, we measured participants' arm length and care was taken to pair participants with similar arm length (average male arm length = 74.71 cm $SD = 5.09$, average female arm length = 71.53 cm $SD = 3.91$). All participants were right-handed as assessed by the Edinburgh Handedness inventory and had no history of neurological or psychiatric disorders. All participants were naive as to the experimental hypotheses and provided written informed consent. The study was approved by the Inserm ethics board (IRB00003888, IORG0003254, FWA00005831) and complied with the ethical standards outlined in the Declaration of Helsinki (World Medical Association, 2013).

Procedure

Two same-sex participants were tested in pairs while sitting at a table in front of each other (see Figure 1). Before starting F1 the experimental session, each pair received two glass-shaped objects (5 cm in diameter and 10 cm in height). The two objects were physically identical, aside from the color band (blue or yellow, 2 cm high) placed on the upper part that served to mark the grasp landing positions (see Figure 1). Participants were informed that the aim of the experiment was to study the representation of the space around the body while grasping an object. For this purpose, participants were told they each owned one of the two glasses (blue or yellow) that they would use during the experiment. The blue and the yellow colors were adopted to attribute individual property and were counterbalanced between participants. An example of the verbal assignment of the ownership status of the object would be: "The blue glass belongs to you, while the yellow one belongs to the other person." The two objects, placed on the table, were assigned when the two participants were sitting across the table and in front of each other, thus ensuring that ownership was attributed at the same time for both members of the dyad. After explicitly assigning glass ownership, the experimenter asked participants to bear it in mind and not to speak to each other. The experimental paradigm consisted in a modified VTI task (Brozzoli et al., 2010, 2009; Patané et al., 2018), whereby visual stimuli were embedded in the to-be-grasped glass and tactile stimuli were delivered to the grasping hand. Both participants had to discriminate whether a tactile target was delivered to their thumb or index finger, while ignoring a visual distractor from the glass. Visual distractors were presented in a spatially congruent or incongruent position with respect to tactile targets

Figure 1
Visuo-Tactile Interaction Task

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AQ: 20 *Note*. One of two participants grasps a glass-shaped object owned either by one or the other participant (Experiment 1, individual ownership) or by both (Experiment 2, shared ownership). In Experiment 1, the blue glass (B panel) was assigned to one participant and the yellow glass (C panel) to the other participant; in Experiment 2, an additional green glass was assigned to both participants as shared property (A). One of the red LEDs (visual distractor depicted as red cylinders protruding from the glass) was lit simultaneously to an electrocutaneous stimulus (not shown) delivered to either the thumb or index finger of both participants. Participants had to discriminate the tactually stimulated finger by releasing one of the two pedals under their right foot. See the online article for the color version of this figure.

when considering the hand posture. A LED lit up on the position on the glass where the stimulated finger would land, congruent, or would not land, incongruent (i.e., index finger and index LED or thumb finger and thumb LED is a VT congruent stimulation; index finger and thumb LED or thumb finger and index LED is a VT incongruent stimulation). At a given signal, participants had to grasp the glass, taking turns. These were indicated by an auditory instruction. An informal debriefing after the study revealed that none of the participants was aware about the real goal of the study.

Apparatus

Either the blue or the yellow glass was located on a support, at a distance of 47 cm from the starting position of each participants' hand (see Figure 1). Two (1.5 × 1.5 cm) squares drawn on the colored band marked the landing positions for the thumb and index fingers. Two red LEDs were fixed at the front and the back of the border of the glass, proximal to the respective contact surfaces of each finger. Visual stimuli consisted of a single flash (200-ms duration) from either the back or front LED, presented concurrently with electrocutaneous stimulation to the grasping hand. Disposable electrodes (700 15-K, Ambu Neuroline, Denmark) were used to deliver suprathreshold electrocutaneous stimuli, consisting of square-wave pulses (100 µs, 400 V) delivered by constant-current stimulators (DS7A, Digi-
AQ: 9 timer Ltd., Welwyn Garden City, United Kingdom) to either the index finger or thumb of the right hand of both subjects. Electro-cutaneous target intensities were set out individually for each finger, so that participants could detect 100% of stimuli in a series of 10 trials. During the experimental task, participants had to discriminate the stimulated finger as fast as possible by releasing one of two foot pedals (Herga Electric Ltd., United Kingdom). The toe pedal indicated stimulation of the index finger and the heel pedal indicated stimulation of the thumb, according to the classical procedure employed in previous studies (Spence et al., 1998; Spence et al., 2004; Spence et al., 2004). See online supplemental materials for movements re- AQ: 10
cording apparatus.

Design

Two participants sat in front of each other at a table with their thumb and index finger of the right hands in a closed pinch-grip posture on the two starting position switches fixed to the table. Either participant was required to grasp and lift the target object up to a height of about 5 cm above its original position with the right hand (see Figure 1). They were instructed to grasp the object using a precision grip by placing their thumb onto the front of the object and their index fingertip onto the back of the object, in correspondence of the marked landing position. Participants also had to respond as fast as possible to the administered tactile stimulus and ignoring a task-irrelevant (congruent or incongruent) visual stimulus from the object. The difference between reaction times (RTs) for incongruent and AQ: 11
congruent trials quantifies the strength of the interaction between visual and tactile stimuli (Brozzoli et al., 2010, 2009; Patané et al., 2018). Participants had to identify the touched finger during trials in which they performed the action (action execution), as well as during trials in which they observed the action (action observation). Simultaneous visual-tactile stimulation was delivered randomly across different trials (a) before the grasping, that is, when the hand was still immobile at the starting position; or (b) at the grasping onset, where movement initiation was detected by the release of the starting position switch. Importantly, participants were instructed to pay attention to the object in each trial, irrespective of their role. Before each trial, a prerecorded voice randomly called the participant who had to grasp the glass by either of two utterances ("TAH" or "TOH" for Participant 1 or 2, counterbalanced across subjects—the "TAH" or "TOH" designation was assigned during the practice trials). After a random delay (800–1,200 ms), the trial started with an auditory warning signal (beep) followed, after a further variable delay (1,500–2,200 ms), by a second beep that constituted the GO for grasping the glass. In the "before" condition, VT stimulation was delivered with a random delay after the warning signal 800–1,000 ms, while in the "onset" condition, VT stimulation was triggered by the release of the starting switch, corresponding to the initiation of the hand displacement.

There were two VTI blocks (128 trials each) with two trial types (half congruent/half incongruent). For each trial type, VT stimulation was given prior to (50%), or at the grasping onset (50%). Across blocks, participants took turns to grasp the glass whose ownership was previously assigned to themselves (mine condition), or to the other participant (other's condition). Participants underwent a practice session for taking turns in grasping the glass while discriminating tactile stimuli by answering with the foot pedals. Blocks were separated by a 5-min break.

Statistics

To assess the effects of grasping an owned object on the recruitment of PPS, we calculated the VTI on correct trials. A three-way ANOVA was conducted with within-subject factors of time (before vs. grasping onset), action (execution vs. observation), and ownership (mine vs. other's). If individual ownership of the glass promotes the recruitment of PPS during executed and observed actions, we should expect larger VTI at the action start, as compared with before, in "execution mine" and "observation other's" conditions. Hereafter, effect sizes are reported in terms of partial eta squared (η_p^2), and averages are reported along with the standard deviation and 95% confidence intervals (CIs). Newman–Keuls post hoc tests were used when appropriate to explore significant effects. Moreover, several kinematics parameters for the transport component were analyzed to assess potential differences in the movement profile across conditions. A series of three-way ANOVAs was conducted with spatial congruency (congruent vs. incongruent), time (before vs. onset movement), and ownership (mine vs. other's) as within-subject factors for both latency and amplitude of acceleration, deceleration and velocity peaks (transport component, see the online supplementary material for other analyses on kinematics).

VTI Results

Overall, a significant action-dependent modulation of VTI was observed, as revealed by the main effect of time, $F(1, 30) = 8.83$, $p = .006$, $\eta_p^2 = .23$. Participants displayed greater VTI at the onset ($M = 26$ ms, $SD = 27$, 95% CI [16, 38]) than before movement ($M = 11$ ms), $SD = 18$, 95% CI [5, 18]. Crucially, this effect was modulated by individual ownership during action execution and observation, as witnessed by the significant highest order interaction Time × Action × Ownership, $F(1, 30) = 15.78$, $p < .001$, $\eta_p^2 = .35$. Post hoc test showed that, as compared with before movement initiation ($M = 4$ ms, $SD = 28$, 95% CI [−6, 14]), VTI was enhanced when the participant's hand started moving to grasp one's own glass ($M = 36$ ms, $SD = 51$, 95% CI [17, 54], $p = .013$, see Figure 2 Execution Mine). In sharp contrast, such a VTI modulation during action execution was not found when the glass belonged to the other participant (before $M = 12$ ms, $SD = 28$, 95% CI [1, 22] vs. onset $M = 19$ ms, $SD = 48$, 95% CI [2, 36], $p = .64$, see Figure 2 Execution Other's). A similar ownership-dependent pattern was observed during mere action observation: VTI increased at the onset of the observed movement ($M = 38$ ms, $SD = 34$, 95% CI [25, 50]), as compared with before ($M = 6$ ms, $SD = 34$, 95% CI [−6, 18], $p = .008$; see Figure 2 Observation Other's), but only when the observed agents grasped their own glass. Instead, VTI enhancement was absent when the observed agents grasped the observers' glass (before $M = 23$ ms, $SD = 35$, 95% CI [10, 36] vs. Onset $M = 12$ ms, $SD = 38$, 95% CI [1, 26], $p = .40$; see Figure 2, Observation Mine).

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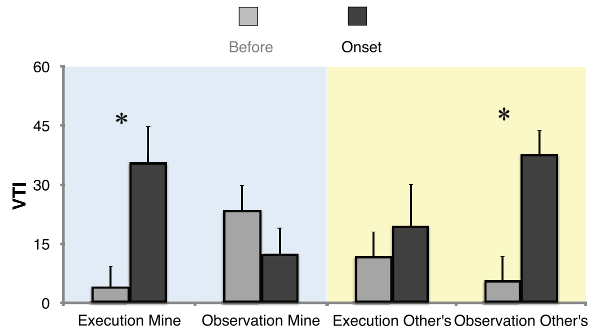
Kinematic Results

Kinematic analyses showed a consistent interaction Time × Spatial Congruency × Ownership: Movements in the incongruent,

Figure 2
Grasping My or Your Object



Note. Bar plots display mean VTI (+*SEM*) as a function of time (before vs. onset), action (execution vs. observation) and ownership (mine vs. other's). Asterisks indicate significant differences. VTI is larger at the onset of grasping movements toward one's own object ($p = .013$). VTI also increases when merely observing movements toward the other's object ($p = .008$). See the online article for the color version of this figure.

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as compared with the congruent condition, were characterized by a decrease of *acceleration*, $F(1, 30) = 8.56$, $p = .007$, $\eta_p^2 = .22$; *velocity*, $F(1, 30) = 11.11$, $p = .002$, $\eta_p^2 = .27$; and *deceleration peaks*, $F(1, 30) = 11.89$, $p = .002$, $\eta_p^2 = .28$ only when stimuli were delivered at the onset of the grasping movement and specifically for those directed toward one's own object (see the online supplementary materials for all the results and complementary analyses).

Discussion

The first experiment explored the impact of the status of ownership of an object on PPS during action. We found that the multisensory enhancement (i.e., PPS recruitment) arose only when participants grasped the object that had been previously assigned to themselves, resulting thus as "their own object" (mine execution). This VTI difference before and during action disappeared when the participants grasped the object that had been assigned to the person in front of them (other's execution). To note that the two glasses were identical aside from the color band denoting whom the object belonged to. Interestingly, similar ownership-dependent effects emerged during mere action observation: VTI increased when observing the others grasping their own object (other's observation). Crucially, if the target of the action was the observer's object (mine observation), no difference in terms of VTI emerged. In sum, VTI increased selectively when a participant grasped—or observed grasping—the glass belonging to the agent. This suggests that PPS recruitment depends on the arbitrarily assigned ownership status of the object.

To further test this hypothesis, we conducted a second experiment in which we explored another facet of such ownership-dependent modulation of PPS. In particular, we reasoned that if the object is "shared," that is, equally attributed to both participants, it should be simultaneously experienced as "mine" and "other's." We then expect PPS to be recruited both when grasping and observing the other grasping the shared object. To assess the dual

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(i.e., mine and other's) nature of shared ownership, we also asked participants to explicitly report their feelings of ownership by means of an ad hoc questionnaire.

Experiment 2: Grasping Our Object

Method

Participants

On the basis of power analysis of Experiment 1, with an effect size Cohen's $d_z = .55$, $\alpha = .05$, and power = .80 for our contrast of interest execution mine before versus onset, we set a priori a sample of 28 participants (i.e., 14 pairs) for Experiment 2. Twenty-eight healthy participants (12 women, 16 men, mean age = 22.93 years, *SD* = 3.53; average male arm length = 75.54 cm *SD* = 3.54, average female arm length = 68.38 cm, *SD* = 3.03) with normal or corrected-to-normal vision took part in the study. All participants were right-handed but one ambidextrous as assessed by the Edinburgh Handedness Inventory and had no history of neurological or psychiatric disorders. They were naive as to the experimental hypotheses and provided written informed consent to participate. The study was approved by the Inserm ethics board (IRB00003888, IORG0003254, FWA00005831), in line with the ethical standards of the Declaration of Helsinki (World Medical Association, 2013).

Design

The procedure was identical to Experiment 1, with the following exceptions. Before the experimental session started, each same-sex pair received three glasses, physically identical aside from the (blue, yellow, or green) colored band denoting glass ownership. Participants were told they would own the yellow or blue glass (color mapping counterbalanced between participants): "The blue glass belongs to you, while the yellow belongs to the other person." The third (always the green) glass was assigned to both participants: "The green glass belongs to both of you." To stress both individual and shared ownership, all participants had a practice VTI session of 25 trials for each object. After a break, participants performed the experimental VTI task with the green glass only. At the end of the VTI task they were asked to complete a questionnaire to assess their perceived feeling of ownership over the shared green glass.

Ownership Questionnaire

To measure feeling of ownership over the shared object through self-anchoring scaling, we devised an ad hoc questionnaire, shaped after the well-established ownership questionnaires within the Rubber Hand Illusion domain (Botvinick & Cohen, 1998). Items were nine sentences describing different relations of participant-object ownership: "I feel like the object **I** (**the other/we**) was (were) grasping during the experiment was **mine** (**other's/ours**)" in all the nine possible combinations. Participants had to indicate how well each sentence described their feeling by setting a mark along a 20 cm-long horizontal line, from extreme left (fully agree) to extreme right (fully disagree). An experimenter recalled them that all sentences (randomly administered) referred only to the shared object.

Statistics

To examine the effects of shared object ownership over the PPS recruitment, a two-way ANOVA was conducted with within-subject factors of time (before vs. grasping onset) and action (execution vs. observation) on VTI. As in Experiment 1, we also analyzed the kinematic profile of movements toward the shared object with a series of two-way ANOVAs with spatial congruency (congruent vs. incongruent) and time (before vs. onset movement) as within-subject factors on the transport component. An ANOVA was also computed on the average score of the ownership questionnaire with agent (I vs. the other vs. we) and ownership (mine vs. other's vs. ours) as within-subject factors. Because Kolmogorov–Smirnov Lilliefors corrected test showed that data from the ownership questionnaire were not normally distributed, we applied a Cox-Box transformation on raw data before statistical analysis. For sake of clarity, bar plots display untransformed means and standard deviation, and the 95% CI are also reported. Finally, to explore the relationship between PPS recruitment and reported feeling of ownership toward the shared object, we computed a series of correlations, corrected for multiple correlations, between VTI and ownership scores.

VTI Results

Similar to Experiment 1, the analysis revealed a significant action-dependent modulation of VTI, as indicated by the main effect of time, $F(1, 27) = 13.11$, $p = .001$, $\eta_p^2 = .33$. Regardless of whether the participant was grasping, or observing the other grasping the glass, VTI increased at action onset ($M = 37$ ms), $SD = 38$, 95% CI [22, 51], as compared with before start ($M = 15$ ms), $SD = 26$, 95% CI [4, 25]; see Figure 3). As the two-way interaction was not significant, $F(1, 27) = 0.39$, $p = .54$, $\eta_p^2 = .01$, the VTI enhancement at the beginning of the movement was present both during action execution (before $M = 15$ ms, $SD = 33$, 95% CI [2, 28] vs. onset $M = 41$, $SD = 59$, 95% CI [18, 64] and action observation (before $M = 15$ ms, $SD = 38$, 95% CI [0, 29] vs. onset $M = 32$ ms, $SD = 34$, 95% CI [19, 45]). Thus, whether executed or observed, grasping the glass previously assigned to the dyad resulted in PPS recruitment. F3

Kinematic Results

The Time × Spatial Congruency interaction showed that, as compared with VT congruent stimulation, VT incongruent stimulation delivered at movement onset lowered the peak amplitude of some transport component parameters: *velocity peaks,* $F(1, 27) = 7.14$, $p = .013$, $\eta_p^2 = .21$; and *deceleration peaks,* $F(1, 27) = 4.57$, $p = .04$, $\eta_p^2 = .15$ (see the online supplementary materials for analyses on all the kinematic parameters).

Ownership Questionnaire AQ: 12

Response to the questionnaire revealed a main effect of agent, $F(2, 54) = 82.55.68$, $p < .001$, $\eta_p^2 = .75$: Participants reported higher scores when the agent was "we" compared with "I" and "the other" ($ps < .001$) Interestingly, the effect of agent signifi-

Figure 3
Grasping Our Object

Note. Bar plots display mean VTI (+*SEM*) of the nonsignificant time (before vs. onset) by action (execution vs. observation) interaction. Regardless of whether the grasping action toward the shared object was executed or observed, VTI is larger at grasping onset, compared with before. See the online article for the color version of this figure.

ONLINE COLOR

cantly interacted with ownership, $F(4, 108) = 7.97$, $p < .001$, $\eta_p^2 = .23$. Participants attributed object ownership more to themselves when they were grasping the glass (the object I was grasping was mine, $M = 10.05$, $SD = 7.19$, 95% CI [7.27, 12.84]), than when they were observing the other (the object the other was grasping was mine, $M = 6.83$, $SD = 6.33$, 95% CI [4.37, 9.28]), or when both were agents (the object we were grasping was mine, $M = 7.18$, $SD = 6.53$, 95% CI [4.65, 9.71], $ps < .001$). Conversely, participants attributed object ownership more strongly to the other when the action of grasping was referred to the other person (the object the other was grasping was other's, $M = 8.76$, $SD = 6.06$, 95% CI [4.65, 9.71]), than to themselves (the object I was grasping was other's, $M = 3.98$, $SD = 4.81$, 95% CI [2.12, 5.85]) or to both agents (the object we were grasping was other's, $M = 3.86$, $SD = 3.77$, 95% CI [2.40, 5.32], $p < .017$). Finally, whoever was the agent, the object was perceived as belonging to both members of the pair: whether the subject of the action was "I" ($M = 13.23$, $SD = 6.32$, 95% CI [10.78, 15.62]), "the other" ($M = 13.23$, $SD = 6.42$, 95% CI [10.47, 15.72]), or "we" ($M = 13.78$, $SD = 6.21$, 95% CI [4.91, 8.44]), the feeling of "our" shared ownership did not differ ($ps > .05$; see Figure 4). There was no significant correlation between VTI and reported ownership scores.

AQ: 13

F4

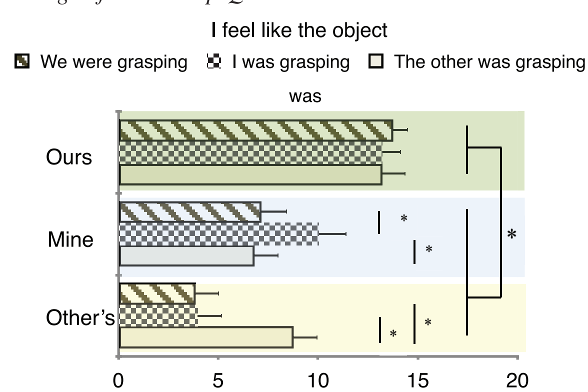
Discussion

The second experiment was designed to address the relevant issue of whether ownership of an object belonging to two agents can also affect multisensory interactions in one's own PPS. We found higher VTI as soon as one of the two agents initiated the movement toward the object previously assigned to both of them. In other terms, either executed or merely observed, the action of grasping a shared object triggers multisensory enhancement. Such modulations of PPS during execution and observation were present in the previous experiment, but in two different action conditions with two different glasses: when grasping one's own glass and when observing to grasp the other's glass. In the current experiment, we reveal that such effects co-occur when acting upon the same glass if it is considered a shared ownership (i.e., at the same time "mine" and "other's"). Results from questionnaires confirmed that the participants perceived the object as truly shared ("ours") and belonging to both agents with similar feeling of shared ownership when either grasped the object.

Grasping My, Your, and Our Object

These results suggest that acting and observing to act upon a shared object may trigger a PPS recruitment similar to that involved when acting upon one's own object and observing others acting upon their own. To assess this view, we compared the effects reported in Experiment 1 ($N = 31$) and Experiment 2 ($N = 28$) with a series of planned unpaired t tests on the delta VTI. Given our a priori predictions (see below), we ran a series of one-tailed t tests, corrected for repeated testing of the same dataset. Computed by subtracting the VTI values at the different timings (onset VTI minus before VTI), deltas provide a measure of amount of the VTI modulation, and thus a more direct index of PPS recruitment. As compared with the analyses on VTI ran by experiment, which merely indicate the presence/absence of PPS recruitment, VTI deltas allow for directly comparing across experiments the changes in the amount of VTI increase (taking into account baseline fluctuation before action), as a function of the ownership status of the object. Importantly, we complemented this approach by performing Bayesian analyses on the same contrasts. We lev-

Figure 4
Feelings of Ownership Questionnaire



Note. Bar plots display untransformed mean scores (+*SEM*) as a function of agent (I vs. the other vs. we) and ownership (mine vs. other's vs. ours). Asterisks indicate significant differences among conditions. Participants perceived ownership of the object as truly shared. The feeling of "*ours*" did not differ, whether the agent of the action was oneself (*the object I was grasping was ours*), the other person (*the object the other was grasping was ours*), or both (*the object we were grasping was ours, ps* > .58). Moreover, participants perceived it more as their own object (*mine*) when they were the agents (I), and more as *other's* when the other was the agent of the action (other). Regardless of the agent, participants reported higher scores of perceived *ours* as compared with perceived individual *mine* and *other's* object (*ps* < .005). See the online article for the color version of this figure.

ONLINE COLOR

eraged the advantages of the Bayes factors that provide a comparison of how likely the null hypothesis is, compared with the alternative hypothesis (Rouder et al., 2009). Our main predictions were that PPS recruitment when grasping our object involves mechanism similar to those recruited (a) when I grasp my object, and (b) when observing others grasping their own object. Accordingly, we expected PPS recruitment not to differ when grasping our objects (execution ours, Experiment 2), or grasping one's own object (execution mine, Experiment 1). We also expected similar PPS recruitment when observing someone else grasping a shared object (observation ours, Experiment 2), or their own object (observation other's, Experiment 1). In keeping with these predictions, there was no significant difference in delta VTI between Experiment 1 and 2 during either action execution (mine vs. ours $p = .722$), or observation (other's vs. ours $p = .211$). To assess whether these nonsignificant results provide evidence to our hypotheses, we used the Bayesian factor comparing the null hypothesis against its complementary hypothesis (Kaplan & Depaoli, 2013; Konijn et al., 2015), reporting the inverse Bayes factor (BF01) if the Bayes factor implies support for the null hypothesis. We found the Bayesian analysis favors the null hypothesis according to which there is no different amount of delta VTI both when grasping one's own or a shared object, BF01 = 3.59, and when observing the other grasping their own or a shared object, BF01 = 2.34. These findings from complementary analyses converge in supporting our predictions, and indicate similar processes operate when interacting with exclusively owned and shared objects.

In addition, our secondary predictions were that PPS recruitment would differ between observation mine and observation ours, as well as between execution other's and execution ours. As expected, delta VTI differed between observation mine and ours ($p = .017$). The Bayesian analysis also supported the hypothesis that observation mine < observation ours (BF10 = 6.279) confirming a different PPS recruitment when observing to act on one's own object versus a shared object. The delta VTI in execution other's did not differ from that observed in execution ours ($p = .20$); the Bayesian analysis not providing support for the hypothesis action others < action ours, (BF01 = 0.94 and additional robustness check plots seem to suggest that this contrast is not robust). This could imply that PPS recruitment could be comparable when grasping someone else's or a shared object, or may reflect we were not fully powered to also detect this difference across experiments (16 vs. 14 pairs). To summarize, the comparison between Experiment 1 and 2 satisfies both our main predictions and three out of four predictions when including the secondary ones. Hence, these results may shed lights into the composited nature of the shared ownership. Although to a different extent, PPS recruitment seems to share similar processes when interacting with objects whose status entails either exclusive or shared ownership. We speculate here that the resulting multisensory-motor encoding of the shared object could thus result from a weighted contribution of mine- and others-related PPS recruitment. Such a weighting could allow the system to efficiently deal with the requests of the environment and adapt to the task at hand. Overall, these findings support our proposal that humans behave and resonate similarly when dealing with objects whose status entails ownership, whether exclusive or shared.

General Discussion

This study tests the permeability of PPS during action execution and observation to one of the most important social dimensions that virtually affects every aspect of our life, namely, object ownership. Consistent with previous evidence (Brozzoli et al., 2010, 2009), visual signals from the target object affect touch perception (VTI, visual tactile interaction) more strongly, thus indicating PPS recruitment, when the hand starts moving as compared with rest. Here we revealed that when the ownerships status of the object to be grasped is manipulated (is mine or other's), such a PPS recruitment emerges only when grasping the object that has been assigned to oneself, that is, "one's own object" (execution mine). Most interestingly, multisensory modulations were triggered by *both* execution *and* observation of object-oriented actions: The effect of ownership also emerged during mere action observation, resulting in PPS recruitment when watching others grasping their own object (observation other's). Conversely, no multisensory modulation was found when one grasps the other's object (execution other's) or when one observes the other grasping the observer's object (observation mine). In a second experiment, we investigated whether similar multisensory enhancement arises when ownership of the target object is not individual, but shared, that is, assigned to both agents. As predicted, multisensory enhancement was detected both when executing and merely observing the action of grasping the object whose ownership was shared. Altogether, these results document for the first time that the status of ownership of an object selectively affects PPS recruitment; further, this occurs during action execution and observation, thus displaying mirror properties. In addition, these findings indicate that PPS modulations are sensitive to both individual and shared ownership of the object.

As an anonymous reviewer noted, the finding of a PPS recruitment when executing actions toward one's own, but not someone else's object could seem at odds with previous results using a similar task (e.g., Brozzoli et al., 2010), where VTI increased when participants grasped an object that was not explicitly assigned to the participant. Actually, both theoretical and empirical work show that when ownerships is not explicitly attributed (like in Brozzoli et al., 2010), a sense of ownership toward the object we interact with can nevertheless emerge implicitly. According to Furby's (1978) model (see also McClelland, 1951), the greater the amount of control a person can exert over objects, the more these will be experienced as part of themselves. Prelinger (1959) provided empirical support to this notion demonstrating that the objects participant could manipulate were more likely perceived as parts of themselves. Most interestingly, even merely touching an object, in absence of any ownership instructions, increases one's perceived ownership and valuation of that object, as well as the sense of control over it (Newman, Bloom, & Knobe, 2014; Peck & Shu, 2009, see also Wolf et al., 2008). It is thus likely that in previous studies the ownership status of the objects to be acted upon was attributed to the agent implicitly. Furthermore, it has been shown that a "negative" (i.e., not-mine) ownership status may inhibit the enhancing of sensorimotor processes: Object affordance compatibility effects are typically observed for self-owned objects, but disappear if participants are told the objects are owned by someone else (Constable et al., 2011). In these respects, our findings concur in showing that explicit manipulation of ownership may bring both active promotion and suppression of sensorimotor effects.

When considering the potential neural substrates of our findings, these results could fit with electrophysiological work on nonhuman primates: A recent study by Livi and colleagues indeed showed agent selectivity of visuomotor neurons in monkey's area F6, which responded differently and according to the agent that was going to grasp an object. Namely, this class of visuomotor neurons was selectively activated by the presentation of an object as a function of whether it was grasped by the monkey, by another agent, or by both. These neurons did not discharge when the object was presented in the monkey's extrapersonal space, indicating that objects have to be represented as a potential target for monkey's own action to elicit such an agent selectivity (Livi et al., 2019). In light of these observations, we speculate that a similar computation taking into account the agent of action could be applied to humans. The result that ownership modulates PPS recruitment both during action execution and observation is compatible with the notion that PPS is sensitive to both whose object is grasped and who is the agent of the action. Because the agent selectivity of visuomotor neurons in F6 is present when the object is located in the monkey's PPS, but not in the extrapersonal space, future studies should test whether the behavioral effects reported here are no longer present when observing grasping in the participants' extrapersonal space.

Our findings clearly indicate that PPS is sensitive to the combination of agent and ownership of the object. Such a sensitivity of PPS allows us to disentangle the alternative predictions set out in the introduction. First of all, our results exclude the prediction that ownership does not affect PPS recruitment, as this would result in similar VTI when one grasps, or observes grasping, one's own or the others' object. Second, we can dismiss the "object status alerting account" prediction, that should imply similar VTI when one grasps the owned object (execution mine) or observe the other grasping it (observation mine). Although we pay more attention to our own objects (Turk, van Bussel, Brebner, et al., 2011) and ascribe more value to things merely because we own them (Knetsch, 1989), our results do not support an attentional and/or affective hypothesis. Instead, they are in well agreement with mirror system work, showing that observing another person's action induces an action-based somatosensory resonance (Bolognini et al., 2014; Calvo-Merino et al., 2006; Livi et al., 2019). This is well instantiated by a recent EEG study (Deschrijver et al., 2016) revealing an early stage of an action-based somatosensory resonance that reflects a mirror-like mechanism, together with a later stage of mismatch detection between self-generated and observed actions, related to higher-order self-other distinction. We could thus speculate that similar processes could be involved in PPS recruitment during action observation: an earlier mirror-like mechanism maps others' PPS and a later process distinguishes what is mine from what is other's.

Furthermore, it's worth noting that our findings cannot be explained in terms of different attentional demands among experimental conditions. One could argue that participants were not paying equal attention when grasping their own or the other's object (or when it was their turn to grasp vs. the other's turn). However, because of the well-known effects of crossmodal attention (Driver & Spence, 1998; Spence, 2010), would attention be deployed unevenly we should have observed different levels of VTI in these conditions, which was not the case. One might also argue that object ownership per se could affect action execution, irrespective of PPS recruitment. Object ownership can indeed influence motor behavior: For example, it has been shown that participants lifted the object belonging to the experimenter with greater care (i.e., reduced acceleration) as compared with their own object (Constable et al., 2011). However, the results of hand kinematics did not reveal any significant effect of ownership on either the transport or the grip component of the movement (see Experiment 1 results in the online supplemental materials). Rather, the kinematic results parallel the multisensory effects. Just as the multisensory processing was enhanced at the onset of movement toward one's own property, movement parameters also differed when VTI occurred at the onset of movements toward one's own property (see Experiment 1 and 2 results in the online supplemental materials). These results confirm that kinematics and multisensory measures can provide complementary evidence (Brozzoli et al., 2010), supporting the notion that PPS is a multisensory-motor interface to guide the interaction between body-parts and surrounding objects (Brozzoli et al., 2014; di Pellegrino & Làdavas, 2015; Patané et al., 2018; Rizzolatti et al., 1997; Senna et al., 2019; Serino, 2019).

In addition, the similarity of movement profiles across Experiment 1 (individual ownership) and 2 (shared ownership) suggests that also from a kinematic point of view, the shared object was experienced as each agent's own object. Corroborating this claim, results from questionnaires importantly document the effectiveness of the shared property manipulation and shed light onto the nature of the ownership feeling experienced over the shared object. Indeed, participants reported similar feelings of shared ownership when the action of grasping the object was ascribed to oneself, the other or both. Intriguingly, this shared sense of ownership seems to depend on the contribution of the individual sense of ownership and by the agent: Participants felt ownership over the object more strongly when they, rather than the other, acted upon it. The opposite was also true: Participants attributed ownerships more to the other person when the latter grasped the object.

To the best of our knowledge, this study is the first to empirically test whether "ours" may induce effects similar to those observed for "mine." As noted by Pierce et al. (2003), from a Western and individualistic cultural tradition, *our* is a double possessive in form. It implies that the object has a connection with oneself while simultaneously having a possessive relationship with one or more other individuals. "It is *our* car" means that it is *my* car as well as the car of my partner. While individual feelings of ownership emerge through interactions between the owner and the object, the shared sense of ownerships (i.e., "our-ness") depends upon the interaction between the owner, another owner, and the object. Including others creates a new kind of ownership, through a shift from the "self" (i.e., the target is MINE) to "us" (i.e., the target is OURS; Pierce & Jussila, 2010). The findings of our questionnaire could thus be considered as empirical evidence supporting what Pierce and Jussila (2010) advanced about the development of a shared sense of ownership. As a note of caution, a limitation of the study is that our questionnaire is not validated, although it was shaped after well-established ones typically used to quantify the sense of ownership in Rubber Hand Illusion paradigms (Botvinick & Cohen, 1998; Ehrsson et al., 2005; Tsakiris et al., 2010; Rohde et al., 2011). Furthermore, when considering PPS recruitment, the comparison between the results from Experiment

1 and 2 provides positive support to this view, although further research, assessing the weighted contribution of mine- and others-related PPS recruitment when interacting with a shared object, is needed to precisely quantify the extent to which this merge may occur.

When testing ownership-dependent effects, a variety of factors may be at stake, including the mere exposure effect (familiarity with an object increases an individual's preference for that object, see Zajonc, 1968), visual cues of physical control over the object (like spatial proximity to an object or being the first to see that object, see Scorolli et al., 2018), the amount of touch (see Peck & Shu, 2009; Wolf et al., 2008), as well as the type of action performed (like physically moving or not the object or pushing/pulling it, see Truong et al., 2016). Our design controlled for potentially confounding variables that could account for different PPS modulations. First at all, we gave and assigned object property at the same time to both dyad members: The experimenter explicitly assigned objects by telling participants they belonged to them. Second, we kept the duration of experience during which participants were exposed to objects equal across all conditions. Third, objects were placed at equal distance from the starting positions of each participant. Last, participants had to follow external instruction as to when taking their turn (unpredictable random order) to grasp the object. Yet, ownership affected PPS consistently across two experiments.

Altogether, these results line up with previous research in showing that tagging an object as one's own establishes a special association between the owner and the owned object (Beggan, 1992; Cunningham et al., 2008; James, 1890; Kim & Johnson, 2013; Salerno et al., 2012). As James (1890) noted "We feel and act about certain things that are ours very much as we feel and act about ourselves" (p. 291). According to him, the Self can indeed "incorporate" possessions, including those that one is frequently in physical contact with (e.g., clothing, jewelry, sentimental objects, etc., see Aglioti et al., 1996 for an intriguing neuropsychological report). In keeping with James's original insight, there seems to be a continuum between the Self and the owned external objects, so that ownership can be considered as symbolic extension of the Self (Belk, 1988). Because of their association with the Self, owned objects are believed to enjoy a special psychological status (Beggan, 1992; James, 1890; Sartre, 2003). Further insight into the basis of the relationship between the Self and the extended self comes from recent neuroscientific investigations. For instance, Salerno et al. (2012) found similar increase in corticospinal motor excitability induced via TMS, while participants watched both pictures of one's own hand and pictures of one's own mobile phone (see also Kim et al., 2010; Kim & Johnson, 2013; Krigolson et al., 2013; Turk, van Bussel, Waiter, et al., 2011 for fMRI studies showing an overlap between regions processing the self and self-owned objects). These findings have been proposed to "provide neural evidence for the idea that personally relevant external stimuli may be incorporated into one's sense of self" (Kim & Johnson, 2013, p. 1). The multisensory PPS is thought to underlie a general representation of the self as distinct from the environment and the others. As the continuous and coherent integration of multisensory bodily signals is a key element underlying subjective bodily experience (Blanke, 2012; Ehrsson, 2012; Makin et al., 2008; Tsakiris, 2010), PPS has been suggested to be directly involved in underlying self-location, that is, the subjective experience that the self occupies a specific location in space (Blanke et al., 2015; Cléry & Hamed, 2018; Ehrsson, 2007; Guterstam et al., 2015; Legrand et al., 2007; Noel et al., 2015; Serino, 2019). Our study provides further support to the notion of the extended self, suggesting that the self-space "extends" toward objects we owe. Indeed, our findings suggest that the self-space extends to grasped objects only if they are one's own property; such extension also emerges when merely observing other people grasping their own belongings. Not last, the two effects merge when ownerships is shared. Here we speculate that, as PPS originated as a multisensory interface to support and to predict the sensorimotor consequences of actions, its ontogenetic recruitment is likely to be particularly relevant for objects close to us. As babies, we could have associated ownership status to objects which are most often in our proximity: The objects we are allowed to interact with are those close to us and, likely, those that belong to us. By reverse, objects close to—but that do not belong to—us, like parents' cell phones, are most often grasped by others (our parents). Thanks to these putative developmental associations, PPS recruitment could have developed to guide our actions toward our objects, as well as others' actions toward their own objects. Thus, PPS recruitment could have been recycled to map, and to maybe "understand" the ownership status of others' actions, resulting in a particular tuning to objects belonging to another person. The "social" effects we have disclosed could be just an epiphenomenon of these associations that evolution and/or society reinforced. Finally, we want to sound a note of caution by concluding that further studies in human and nonhuman primates are needed to identify the precise social role played by the ownership-dependent recruitment of PPS we newly report in the present study. However, by showing that ownership intimately links perception and action to an object, our study shows the importance of this feature of human society in affecting social and sensorimotor behavior.

Summary

AQ: 14

In everyday life, sensorimotor and social interactions take place in contexts where other persons are present and the targets of our actions are defined by conceptual features such as to whom they belong. Inspired from our interests in how space is shaped by both social cognition and action, here we show that PPS is modulated by object ownership, being differently affected when I grasp my object, compared with someone else's. Furthermore, a similar PPS modulation emerges when I grasp my object or I observe others grasping their object. This holds true when object ownership is shared by agents and observers. These findings reveal that ownership impacts the multisensory-motor processes behind everyday actions, when executed and merely observed. Moreover, they open several questions for future studies exploring the "social" component of our objects. We are thankful to the anonymous reviewers for the suggestions they made in this respect. It could be interesting to consider some real personal objects as experimental stimuli. Is PPS similarly recruited when manipulating our cell phone or another object that is not relevant to us? Could our findings be extended also when we observe another person interacting with an owned object in a space far from our body (i.e., extrapersonal space)? Does the emergence of ownership effects on PPS take place gradually, because of increasingly interacting with objects? The answers to these questions have the potential to make mean-

ingful contributions to the neuroscientific and psychological study of how the ownerships status shapes social perception and action.

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