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Research Report

Me in action: Distinct processing levels shape the relationship between sense of agency and sense of ownership

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ABSTRACT

Competing neurocognitive models offer different accounts of how the sense of agency (the experience of controlling one's actions) and the sense of ownership (the experience that one's body belongs to oneself) relate within bodily self-awareness. The additive model proposes that agency entails ownership, the independence model treats the two experiences as functionally distinct, and the interactive model suggests reciprocal influences between them. However, empirical tests comparing these predictions within a single coherent experimental paradigm remain limited.

Here, we developed an immersive virtual reality paradigm to orthogonally manipulate agency- and ownership-related cues within a goal-directed action task. Fifty-six participants pressed a (virtual) button to switch on a lightbulb. Agency was manipulated by comparing voluntary self-generated and externally induced passive movements and action-outcome delays, whereas ownership was manipulated through the anatomical plausibility of the avatar's hands. Direct and indirect agency and ownership indices were collected.

Direct explicit judgements revealed both domain-specific and reciprocal influences: agency was modulated by action-related cues and by anatomical plausibility, whereas ownership was modulated by anatomical plausibility and by action-related cues, consistent with an interactive account. Indirect measures showed a distinct pattern: intentional binding was influenced by action-outcome contingency and was not affected by ownership manipulations, whereas proprioceptive drift varied as a function of anatomical plausibility.

We propose a hierarchical two-stage account that integrates previous cognitive models across distinct processing levels, in which agency and ownership arise from partly

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independent sensorimotor processes at an implicit level but dynamically interact at the level of metacognitive, explicit self-attribution.

1. Introduction

In everyday life, acting and experiencing our body as our own are typically inseparable. When we grasp an object, for instance, we perceive the moving hand as part of our body – an experience known as the sense of ownership (Tsakiris, Schütz-Bosbach, & Gallagher, 2007) – while simultaneously experiencing ourselves as the authors of the movement and its outcome-referred to as the sense of agency (Haggard, 2017). Yet, this apparent unity can break down under certain conditions: during involuntary movements, the limb still feels like part of our body even when the sense of controlling the action is reduced or absent. Similar dissociations are also observed in clinical conditions, where ownership and agency experiences can be selectively disrupted (Salvato et al., 2025). These observations raise a central question: what is the functional relationship between the sense of agency (SoA) and the sense of ownership (SoO)?

Within the broader framework of bodily self-awareness (Gallagher, 2000), these two dimensions can be distinguished across partially dissociable levels of experience. At an explicit, reflective level, SoA and SoO can be accessed through metacognitive judgements that allow individuals to attribute actions or body parts to themselves (i.e., direct self-report judgements). At a more implicit pre-reflective level, SoA and SoO are experienced as sensorimotor "feelings", arising from distinct computational processes: SoA emerges from the match between internal motor predictions and sensory outcomes (i.e., feeling of agency), whereas SoO arises from the integration of multisensory signals with internal body representations (i.e., feeling of ownership; Synofzik, Vosgerau, & Newen, 2008). These pre-reflective experiences can be investigated through indirect behavioral measures that index the implicit dimensions of SoA and SoO, such as intentional binding (Haggard, Clark, & Kalogeras, 2002) and proprioceptive drift, respectively (Botvinick & Cohen, 1998). It should be acknowledged that these indirect measures are still debated: for example, intentional binding also captures more general temporal or causal processes (e.g., Suzuki, Lush, Seth, & Roseboom, 2019), whereas proprioceptive drift also reflects visuo-proprioceptive recalibration mechanisms (e.g., Rohde, Di Luca, & Ernst, 2011). However, different evidence supports their relevance as implicit indices of SoA and SoO. Intentional binding is typically assessed by comparing active intentional and passive movements, and it is systematically stronger for active ones. Also, it emerges at specific action-outcome time windows only for active movements and correlates with activity in pre-SMA/SMA, regions involved in the preparation and monitoring of voluntary action (Zapparoli et al., 2020b). Moreover, it is altered in clinical populations with disturbed agency experiences (e.g., Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003; Saito et al., 2017; Voss et al., 2010; Zapparoli et al., 2020a). Similarly, proprioceptive drift has been extensively used as an indirect index of SoO, as it reflects a shift in the perceived position of one's own limb toward an embodied artificial or virtual limb and is typically modulated by multisensory and anatomical constraints on ownership experience (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2012; Pyasik, Tieri, & Pia, 2020; Tsakiris & Haggard, 2005).

Different neurocognitive models have proposed distinct accounts of how these two experiences relate to one another (for reviews, see Braun et al., 2018; Seghezzi, Giannini, & Zapparoli, 2019). The *additive model* argues that SoA entails SoO, with an additional experience related to voluntary movement control, such that SoO emerges as a consequence of voluntary motor control (Tsakiris, Longo, & Haggard, 2010). In contrast, the *independence model* considers SoA and SoO as qualitatively distinct and functionally autonomous experiences, with no shared components (Tsakiris et al., 2010). Finally, the *interactive model* proposes that SoA and SoO remain dissociable but dynamically influence one another (Seghezzi et al., 2019). Supporting this view, neuroimaging meta-analytic evidence indicates that SoA and SoO rely on partly overlapping yet dissociable neural substrates (Seghezzi et al., 2019). However, this evidence remains indirect, as it is primarily derived from meta-analyses aggregating neuroimaging findings across tasks that separately probe (mainly explicit) SoA and SoO, rather than from experimental designs that manipulate both components within the same paradigm and quantify their mutual influence. Moreover, these models do not explicitly distinguish between different levels of processing (i.e., implicit *vs* explicit), leaving unclear whether their relationship may vary across these dimensions.

A growing body of behavioral studies has begun to address this question by directly investigating the interplay between SoA and SoO. Some studies suggest that agency-related cues influence SoO primarily at the explicit level (Akselrod et al., 2021; Hapuarachchi, Ishimoto, Kitazaki, Sugimoto, & Inami, 2023), whereas others report effects on both explicit and implicit SoO measures (Berger, Coppi, & Ehrsson, 2023; Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2012). Evidence in the opposite direction – whether ownership-related cues influence the SoA – is comparatively limited but similarly mixed (Möller, Braun, Thöne, Herrmann, & Philipsen, 2020; Zhang et al., 2023; Zopf, Polito, & Moore, 2018). In this context, relevant evidence comes from studies that combine Rubber Hand Illusion (RHI) paradigms with sensory attenuation (i.e., indirect sensorimotor index of SoA; Blakemore, Wolpert, & Frith, 1998). These studies showed that experimentally induced SoO over a fake hand can shape SoA attribution: when an embodied fake hand produced a somatosensory consequence on the participant's real body, participants attributed the movement to their own will (Burin, Pyasik, Salatino, & Pia, 2017, 2018) and showed sensory attenuation comparable to that observed for real self-generated actions (Burin et al., 2017, 2018; Kilteni & Ehrsson, 2017). Related behavioral and neurophysiological evidence further suggests that illusory self-generated touch produced by an embodied fake hand can elicit sensory attenuation and somatosensory responses similar to real self-touch (Pyasik et al., 2019, 2021). This line of research provides direct evidence that ownership-related signals can contribute to agency attribution. Crucially, however, it primarily focused on whether ownership over an artificial effector can induce illusory SoA over that effector's movements or sensory consequences, rather than over self-generated actions and their external outcomes. Here, we focused instead on SoA as the experience of being the author of one's own action and of the external outcomes produced by that action (Haggard, 2017), examining how the configuration of the acting body affects implicit SoA within this full action-outcome loop.

Finally, only a few studies have jointly manipulated agency and ownership while assessing both implicit and explicit measures within the same experimental design (Braun, Thorne, Hildebrandt, & Debener, 2014; Caspar, Cleeremans, & Haggard, 2015; Ma, Qu, Yang, Zhao, & Hommel, 2021). Braun et al. (2014), using the RHI, reported a partial dissociation between SoA and SoO, but the action context involved simple rhythmic movements without a meaningful action-outcome. Caspar et al. (2015) investigated how transformations of embodiment through a robotic hand influence the SoA along a mediated action chain; although the study included both SoA and SoO measures, the experimental manipulation primarily targeted embodiment as a factor modulating agency rather than testing their reciprocal interaction. More recently, Ma et al. (2021) assessed explicit and implicit measures of SoA and SoO within a virtual environment in which participants controlled a virtual effector. However, in this paradigm, the effector was not embedded in a coherent bodily representation and ownership manipulations remained largely centered on non-realistic perceptual and kinematic distortions (i.e., non-hand effector shapes) rather than more naturalistic contexts.

2. Aims and predicted results

In this study, we used immersive virtual reality (VR) to create a controlled yet realistic context in which SoA and SoO could be systematically measured and manipulated within the same participant sample. We adapted a validated experimental paradigm (Mariano et al., 2024b; Zapparoli et al., 2020b), based on an ecological and goal-directed action: switching on a lightbulb. Agency was manipulated by instructing participants to perform either active or passive movements and by varying the temporal interval between each movement and its corresponding visual outcome. Ownership was manipulated by altering the anatomical plausibility of the avatar's hands. In both active and passive trials, the virtual hands moved coherently with the participant's movements, but in anatomically implausible trials the right hand was visually displayed in the position of the left hand and vice versa.

Direct SoA and SoO ratings, together with the temporal estimates used to compute intentional binding, were collected after each trial. In addition, proprioceptive drift (i.e., indirect index of SoO) was assessed at repeated time points within each anatomical plausibility block. This difference has a direct effect on which model predictions could be tested. The trial-by-trial measures of explicit SoA, explicit SoO, and implicit SoA allowed us to examine the effects of both agency-related and ownership-related cues within the full factorial design. By contrast, implicit SoO was assessed through proprioceptive drift at the block level, after exposure to blocks containing both active and passive trials with different action-outcome delays. Therefore, this measure allowed us to test whether anatomical plausibility modulated implicit SoO, but did not allow us to isolate the specific contribution of agency-related manipulations to implicit SoO. Accordingly, the model predictions outlined below were directly tested for explicit measures and implicit SoA, whereas conclusions regarding implicit SoO should be considered more limited.

Based on current neurocognitive models, we formulated different predictions about the expected results:

1. *Additive model* (Tsakiris et al., 2010). According to the additive account, SoA entails SoO. Therefore, active movements should elicit a strong SoA and SoO in both anatomically plausible and implausible conditions. In other words, SoO should never be absent when SoA is present, even when anatomical plausibility is violated. In passive movements, the SoA should be lower or absent, while SoO may still emerge when anatomical plausibility is preserved.
2. *Independence model* (Tsakiris et al., 2010). SoA and SoO should dissociate. SoA should be higher during active movements compared to passive movements, regardless of anatomical plausibility. Conversely, SoO should be higher under anatomically plausible than under anatomically implausible conditions, regardless of whether movements are active or passive. As a result, conditions combining active movements with anatomically implausible hands should elicit high SoA but low SoO, whereas passive movements with anatomically plausible hands should elicit low SoA but high SoO.
3. *Interactive model* (Seghezzi et al., 2019). SoA and SoO should influence one another. During active movements, violations of anatomical plausibility are expected to reduce the SoA, such that SoA should be stronger in anatomically plausible than in anatomically implausible active trials. In passive movements, SoA should remain low and largely insensitive to anatomical plausibility. With respect to SoO, the strongest experience is expected when active movements are combined with anatomically plausible hands, whereas SoO should be reduced in passive trials or when anatomical plausibility is violated. Overall, this model predicts graded patterns of SoA and SoO across conditions, reflecting reciprocal modulation rather than strict dependence or independence.

3. Materials and methods

3.1. Participants

To determine the required sample size, we conducted an a priori power analysis for the predicted three-way interaction in the repeated-measures 2 × 2 × 3 design (Anatomical plausibility × Action × Action-Outcome Delay, see below) using the software Jamovi (version 2.6.26) with the *Pamlj* module (v.0.2, Gallucci, 2024). The expected effect size was derived from a previous study employing a closely related experimental paradigm, which reported a three-way interaction (Interactive Condition × Action × Delay) with an effect size of $\eta^2p = .16$ (Zapparoli et al., 2024). Importantly, this interaction has the same factorial structure as the one tested in the present study. Assuming this effect size, an alpha level of .01, and a desired statistical power of .90, the analysis indicated that a minimum sample size of 50 participants would be required to detect the predicted interaction. To account for potential exclusions due to outliers, missing data, or unexpected technical issues, we recruited a slightly larger sample (i.e., 10% more participants than the target sample size).

We studied fifty-six healthy adult participants (mean age: 22.71 ± 3.45 years; mean education: 14.21 ± 1.82 years; female/male ratio: 33:23) with no history of neurological or psychiatric diseases (inclusion and exclusion criteria were defined prior to the study being conducted). Participants were university students recruited *via* word of mouth and through official university channels. The protocol was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by the local Ethics Committee of the University of Milano-Bicocca (n. Protocol: RM-2022-510). Written informed consent was obtained from all participants before the experiment.

3.2. Experimental setting and procedure

We adapted a previously used experimental paradigm to an immersive VR setting to manipulate and measure both the explicit and implicit SoA and SoO while performing an everyday goal-directed action, namely, switching on a lightbulb (Mariano et al., 2024b; Zapparoli et al., 2020b). The virtual environment and task were developed in Unity3D (version 2022.3.19f1) using C# scripting. Participants were seated on a chair in front of a table while wearing a Meta Quest 2 headset, a standalone VR head-mounted display equipped with an LCD screen (1832 × 1920 pixels per eye), an approximately 90° field of view, and a refresh rate of up to 90 Hz, allowing the delivery of the immersive virtual environment. Their index fingers were placed on two physical buttons; only the left button was connected to the computer and enabled switching on the virtual lightbulb. A tape measure was fixed in front of the participant to collect proprioceptive localization responses (see Fig. 1a; Pyasik et al., 2020). Before starting the experiment, participants completed an embodiment phase in which the avatar's body representation and movements were fully congruent with their real body and actions. During this phase, participants performed both predefined and spontaneous hand movements while observing the avatar's hands (in line with Mariano et al., 2026).

Before the task, we recorded the participant's actual left index position relative to the tape measure. In the virtual environment, participants embodied a first-person avatar seated at a table with two virtual buttons (spatially aligned with the physical ones) and a virtual lightbulb whose base could turn green or red. The experimental design manipulated both agency-related and ownership-related cues. SoA was manipulated by contrasting voluntary self-generated and externally induced passive movements and by varying the action-outcome delay. When the base of the virtual lightbulb turned green, participants were instructed to press the button with their left index finger (active condition). When the base turned red, participants were instructed not to initiate or voluntarily control the button press. In these trials, the experimenter pressed the physical button using a rigid rod, causing the participant's left index finger to move downward passively together with the button, without direct contact between the rod and the finger. The participants therefore experienced an externally induced finger movement while observing the corresponding movement of the virtual hand (passive condition). After the button press, the lightbulb switched on following a variable delay of 200, 400, or 600 msec. Importantly, the passive condition served as a control baseline for the active condition: participants experienced the same button press, the same visual outcome, and the same action-outcome delays, but voluntary motor generation was absent (Akselrod et al., 2021; Caspar et al., 2015; Haggard et al., 2002; Mariano, Kuster, Tartufoli, & Zapparoli, 2024a; Mariano, Stanco, et al., 2024b; Zapparoli et al., 2024; Zapparoli et al., 2020a; Zapparoli et al., 2020b). This contrast was therefore intended to more effectively isolate agency-related contributions from more general temporal or causal processes.

SoO was manipulated through the anatomical plausibility of the avatar's hands (see Fig. 1b). The task was performed in two experimental blocks differing in this factor and counterbalanced across participants. In the anatomically plausible condition, the avatar's hands were spatially aligned with the participant's real hands. In the anatomically implausible condition, the hands were swapped across sides, such that movements of the participant's left index finger were displayed on the contralateral side of the virtual environment. Importantly, visuomotor contingency was preserved across plausible and implausible conditions: the participant's finger movement was still temporally and kinematically matched by the movement of the corresponding virtual finger. Thus, the manipulation was intended to target ownership-related cues by violating anatomical plausibility and body-related spatial constraints, while keeping the agency-related factors of movement generation and action-outcome delay constant across anatomical plausibility conditions.

Each block (anatomically plausible *vs* implausible) consisted of 60 trials, organized into five sequences of 12 trials randomized and equally distributed across action conditions (active *vs* passive) and action-outcome delays.

We collected direct and indirect measures of SoA and SoO. After each trial, participants verbally reported all their

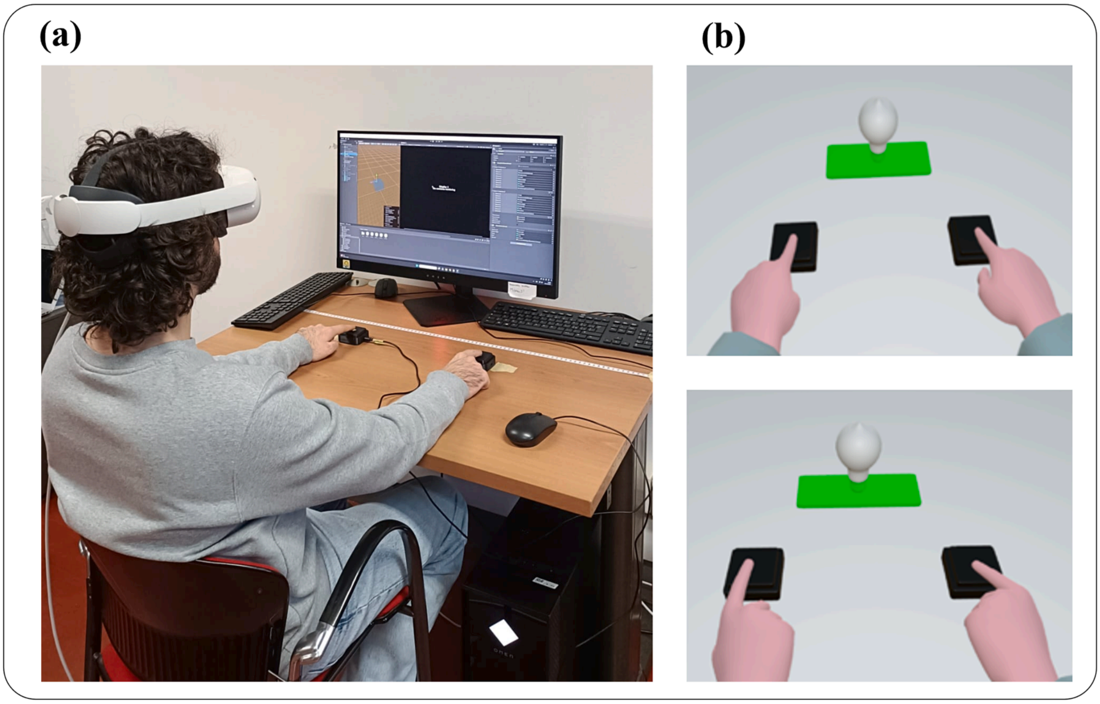

Fig. 1 – (a) Experimental setting and (b) anatomically plausible (top) and implausible (bottom) avatars' hands (ownership manipulation) in the VR environment.

responses while continuing to observe the virtual environment. Participants first estimated the perceived time interval between their action and the lighting of the lightbulb by selecting one of five response options (1, 200, 400, 600, or 800 msec), which was recorded by the experimenter. The lowest and the highest options were included to allow both underestimation and overestimation of the actual delay. This measure was used to compute intentional binding, an indirect index of implicit SoA reflecting the subjective compression of the temporal interval between voluntary actions and their sensory outcomes (Haggard et al., 2002).

Participants also verbally reported explicit ratings of their experience. They directly reported how much they felt they had caused the lightbulb to switch on (explicit SoA) on a scale from 1 ("not at all produced by me") to 5 ("entirely produced by me"), and how much the virtual left index finger felt like part of their body (explicit SoO) on a scale from 1 ("not at all") to 5 ("entirely"). All responses were recorded by the experimenter.

To assess implicit SoO, we measured proprioceptive drift. A tape measure was positioned in front of the participant, and the actual position of the left index finger was recorded before the task. With the VR display occluded, participants indicated the perceived position of their real left index finger by moving their right index finger along the tape measure without touching the left hand. This judgment was collected once before exposure and then every 12 trials during each block. Proprioceptive drift was calculated as the difference between the perceived and actual finger positions and served as an indirect index of SoO (Botvinick & Cohen, 1998; Pyasik et al., 2020).

Finally, at the end of each block, participants completed additional questionnaires, including the adapted version of the Virtual Embodiment Questionnaire (VEQ; Roth & Latoschik, 2020) and the Visual Analogue Scales (VAS) related to overall SoA and SoO experiences separately for the virtual left and right index fingers (items adapted from Kalckert & Ehrsson, 2012). For the VEQ and VAS analyses and results, see Supplementary Materials and Tables S1–S4.

Fig. 2 provides a graphical illustration of the trial timeline.

3.3. *Data handling and statistical analyses*

We ran four separate statistical models, one for each dependent variable indexing the dimension of interest (explicit SoA, explicit SoO, implicit SoA, and implicit SoO). Anatomical plausibility, Action, and Action-Outcome Delay were entered as within-subject factors, except for implicit SoO (see below). Table 1 provides an overview of the statistical models.

Explicit SoA and explicit SoO. Data were analyzed using *R* (version 4.5.0) with a within-subject (repeated-measures) $2 \times 2 \times 3$ design for each dimension. Agency ratings were considered a direct index of explicit SoA, and ownership ratings were considered an index of explicit SoO; in both cases, higher ratings indicated a stronger experience of SoA or SoO, respectively. Separate statistical models were conducted for each dimension. For each participant, ratings were averaged across trials for each combination of Anatomical plausibility,

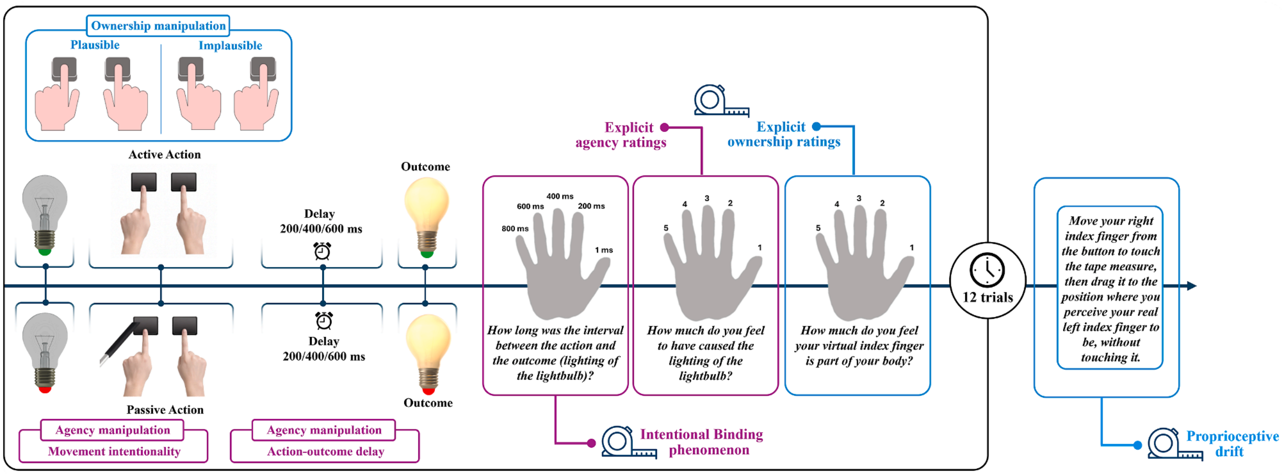

Fig. 2 — Trial timeline of the experiment (same for both anatomically plausible and implausible blocks). Participants were immersed in a VR scenario in which a lightbulb was off. They were instructed to press a button with their left index finger if the virtual lightbulb's base was green (active condition) or not to initiate or voluntarily control the button press if the virtual lightbulb's base was red (passive condition). After the movement, the lightbulb turned on after a variable delay (200, 400, or 600 msec). Then, participants were asked to rate the perceived time interval between the button press and the light turning on (to measure the intentional binding phenomenon, i.e., indirect SoA measure), to rate how much they felt they caused the light to turn on with their action (judgment of agency, i.e., direct SoA measure), and to report how much the virtual left index finger felt like part of their body (judgment of ownership, i.e., direct SoO measure). Additionally, every 12 trials, a measure of the participant's perceived position of the real left index finger was taken (proprioceptive drift, i.e., indirect SoO index).

Action, and Action-Outcome Delay, yielding a single mean per experimental condition. These mean ratings served as dependent variables, while the within-subject factors "*Anatomical plausibility*" (anatomically plausible, anatomically implausible), "*Action*" (active, passive), and "*Action-Outcome Delay*" (200, 400, 600) were the independent variables. Outliers were defined as values exceeding ±2.5 SD from the sample mean. After exclusion, the final sample comprised 51 participants for explicit SoA and 53 participants for explicit SoO. Given the non-parametric distribution of the data (through visual inspection of the Q–Q plot, Jamovi, 2023), we performed a non-parametric Aligned Rank Transform (ART; Wobbrock, Findlater, Gergle, & Higgins, 2011) repeated-measures ANOVAs using the ARTool package in R. Significant interactions were explored using ART-C contrast implemented in ARTool, and *p*-values were adjusted for multiple comparisons using Tukey's method (Elkin, Kay, Higgins, & Wobbrock, 2021; Wobbrock et al., 2011).

Implicit SoA. Data were analyzed by using the software Jamovi (version 2.6.26) with a within-subject (repeated-measures) 2 × 2 × 3 design. We first calculated the "time compression" (TC) value, namely the difference between the perceived and actual duration of the action-outcome delay. In line with the intentional binding phenomenon (Haggard et al., 2002), TC represents an indirect index of the implicit SoA: the greater the compression (i.e., the more negative value), the higher the implicit agency experience. Importantly, a stronger TC in the active than in the passive condition indicates the presence of the intentional binding phenomenon. The TC values represented the dependent variable of the model, while the within-subject factors "*Anatomical plausibility*" (anatomically plausible, anatomically implausible), "*Action*" (active, passive), and "*Action-Outcome Delay*" (200, 400, 600) were the independent variables. Outliers were identified as values exceeding ±2.5 SD from the sample mean; after exclusion, the final sample for this analysis comprised 50 participants. Given the parametric distribution of the data (through visual inspection of the Q–Q plot), we tested the statistical model using a parametric repeated-measures ANOVA. Significant interactions were explored using Tukey-corrected post-hoc comparisons.

Implicit SoO. Data were analyzed using Jamovi (version 2.6.26). For each participant and anatomically plausibility condition (anatomically plausible vs. anatomically implausible), we computed a proprioceptive drift (PD) value expressed in centimeters, following a procedure consistent with Pyasik et al. (2020). Participants provided one pre-exposure proprioceptive judgment (collected before starting the experiment) and five post-exposure judgements during each block. For all six judgements, we first subtracted the actual position of the participant's left index finger from the perceived finger position. Then, for each post-exposure judgment, we subtracted the pre-exposure judgment, obtaining a PD value for each of the five post-exposure assessments. Finally, these five PD values were averaged to obtain a single PD value per condition for each participant.

PD was considered an indirect behavioral index of SoO, typically described as a shift in the perceived location of the real hand toward the rubber/virtual hand (Pyasik et al., 2020; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005). In our

Table 1 – Overview of the statistical models across outcome measures.

Bodily self-awareness dimension	Dependent variable	Independent variables	Design
Explicit SoA	Judgements of agency	*Anatomical plausibility* *Action* *Action-Outcome Delay*	Within-subject (repeated-measures) 2 × 2 × 3
Explicit SoO	Judgements of ownership	*Anatomical plausibility* *Action* *Action-Outcome Delay*	Within-subject (repeated-measures) 2 × 2 × 3
Implicit SoA	Time compression values	*Anatomical plausibility* *Action* *Action-Outcome Delay*	Within-subject (repeated-measures) 2 × 2 × 3
Implicit SoO	Delta proprioceptive drift values (ΔPD = PD_implausible − PD_plausible)	–	One-sample Wilcoxon signed-rank test

setting, positive (rightward) PD values indicate a drift toward the location of the left virtual hand, which, in the anatomically implausible condition, was displayed on the right side of the virtual environment. Conversely, negative (leftward) PD values indicate a drift away from that location. Outliers were defined as values exceeding ±2.5 SD from the sample mean; after exclusion, the final sample for this analysis comprised 55 participants. To quantify the effect of anatomical implausibility relative to the plausible baseline condition, we computed a delta score (ΔPD = PD_implausible − PD_plausible) and tested whether ΔPD significantly differed from zero using a one-sample Wilcoxon signed-rank test, given the non-parametric distribution of the data (through visual inspection of the Q–Q plot).

An additional exploratory analysis on the five repeated PD measurements was conducted to assess whether implicit SoO varied over time within each anatomical plausibility block; this analysis and the corresponding results are reported in the Supplementary Materials.

Bayesian analyses. To complement the frequentist analyses, we conducted Bayesian repeated-measures ANOVAs for the dependent variables. These analyses were used to quantify the strength of evidence for the inclusion or exclusion of specific effects. This approach was particularly relevant because some theoretical predictions tested in the present study concerned the absence of specific effects or interactions, which cannot be directly evaluated using frequentist statistics (full details are reported in the Supplementary Materials).

4. Results

4.1. *Explicit SoA*

We found that explicit agency judgements were influenced not only by agency-related cues, such as mode of movement generation and action-outcome delay, but also by ownership-related cues, such as anatomical plausibility (see Fig. 3).

Results showed a significant *Action* × *Action-Outcome Delay* [F (2,550) = 4.88, p = .008] and *Anatomical plausibility* × *Action* [F (1,550) = 9.18, p = .002] interactions (other non-significant or non-informative effects are reported in Table S5). These interactions were followed up using Tukey-corrected ART-C contrasts. See Fig. 3 and Table S6 for descriptive statistics.

Explicit agency ratings were higher during active than passive movements at each delay [Active *vs* Passive, *200*: t (550) = 27.97, p_{Tukey} < .0001; *400*: t (550) = 26.61, p_{Tukey} < .0001; *600*: t (550) = 26.63, p_{Tukey} < .0001]. Within the active condition, ratings were higher at 200 msec than at 600 msec, whereas no delay-related differences emerged in the passive condition [200 *vs* 400, *Active*: t (550) = 2.06, p_{Tukey} = .311; *Passive*: t (550) = .70, p_{Tukey} = .982; 200 *vs* 600, *Active*: t (550) = 2.88, p_{Tukey} = .047; *Passive*: t (550) = 1.54, p_{Tukey} = .638; 400 *vs* 600, *Active*: t (550) = .822, p_{Tukey} = .963; *Passive*: t (550) = .84, p_{Tukey} = .960].

Follow-up contrasts showed that participants reported stronger SoA for the anatomically plausible than the implausible positions of the avatar's hands in the active condition, whereas the same comparison was not significant in the

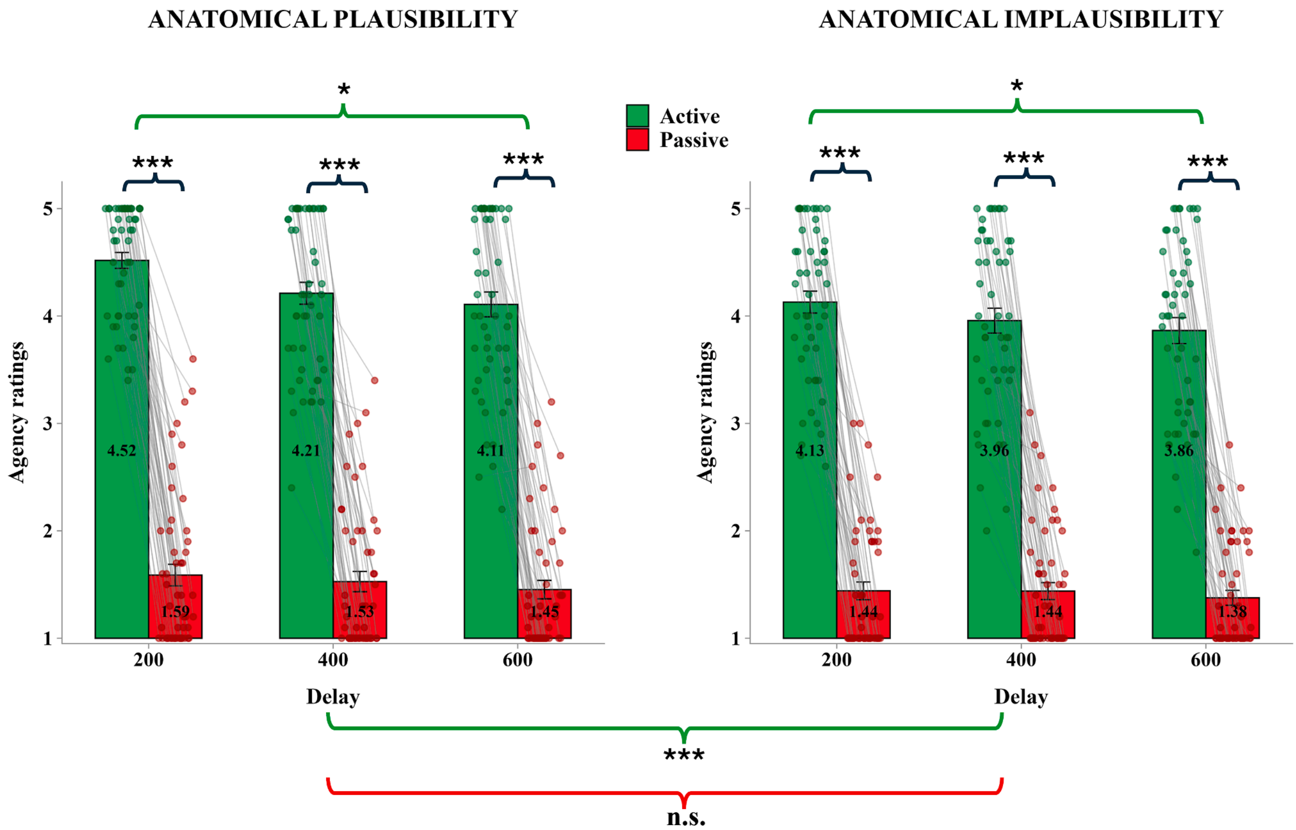

Fig. 3 – Mean and standard error values of agency ratings (index of explicit SoA). Points represent individual participants' mean values in each condition. Explicit agency ratings were higher for active than passive movements across all delays, decreased with increasing action-outcome delay in the active condition, and were higher for the anatomically plausible than implausible avatar's hands only in the active condition. * $p_{Tukey} < .001$, ** $p_{Tukey} < .01$, * $p_{Tukey} < .05$.**

passive condition [Plausible *vs* Implausible, *Active*: t (550) = 4.12, $p_{Tukey} = .0003$; *Passive*: t (550) = 2.11, $p_{Tukey} = .150$].

Bayesian repeated-measures ANOVA showed that the best-supported model included the main effects of *Action*, *Anatomical plausibility*, and *Action-Outcome Delay*, although support for a model additionally including the *Anatomical plausibility* × *Action* interaction was very similar (see Table S7). Inclusion Bayes factors strongly supported the three main effects, whereas evidence for *the Anatomical plausibility* × *Action* interaction was inconclusive, and the remaining interaction terms were favored for exclusion. Overall, the Bayesian results support the contribution of the three main effects to explicit SoA, while providing no clear evidence for reliable interaction effects (see Supplementary Materials).

4.2. Explicit SoO

We found that explicit ownership judgements were influenced not only by ownership-related cues, such as anatomical plausibility, but also by agency-related cues, such as mode of movement generation.

We found a significant main effect of *Action* [F (1,572) = 155.51, $p < .001$] and *Anatomical plausibility* [F (1,572) = 485.41, $p < .001$]. No interactions were significant (other non-significant or non-informative effects are reported in Table S8). See Fig. 4 and Table S9 for descriptive statistics. These main effects indicate that ownership ratings differed both between action conditions and anatomical plausibility conditions: participants reported stronger SoO during active than passive trials, and higher SoO for the anatomically plausible than the implausible avatar's hands position (see Fig. 4).

Bayesian analyses indicated that the best-supported model included the main effects of *Anatomical plausibility* and *Action* (see Table S10), with evidence against the contribution of *Action-Outcome Delay* and higher-order interactions. This pattern was consistent with the frequentist results (see Supplementary Materials).

4.3. Implicit SoA

Our results confirm the presence of the intentional binding phenomenon and indicate that implicit SoA was primarily driven by action-outcome temporal contingencies (i.e., greater time compression in active *vs* passive trials, at 200 msec of action-outcome delay). On the other hand, ownership-related cues did not influence the magnitude of the effect.

We found a significant *Anatomical plausibility* × *Action* × *Action-Outcome Delay* interaction [F (2,98) = 3.77, $p = .026$, $\eta^2p = .071$], that

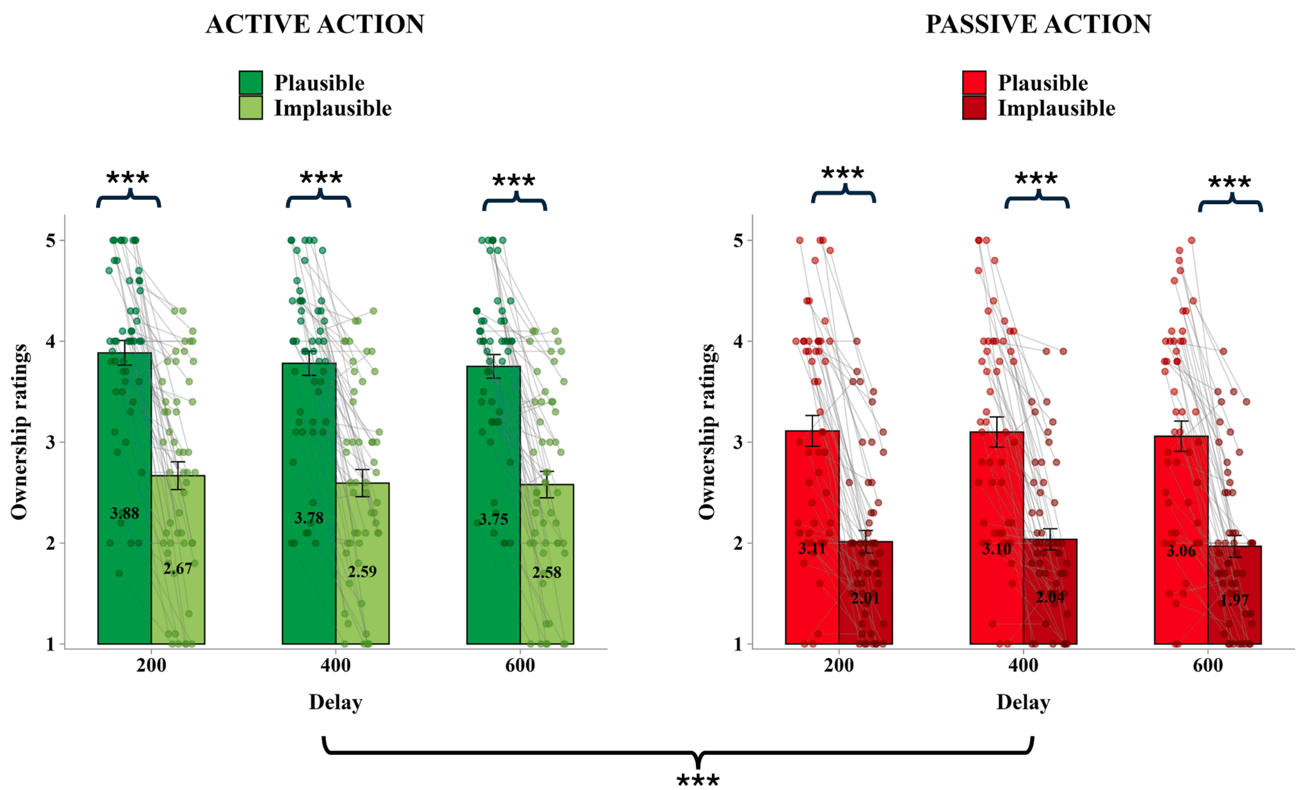

Fig. 4 — Mean and standard error values of ownership ratings (index of explicit SoO). Points represent individual participants' mean values in each condition. Ownership ratings were higher in active than passive trials and for the anatomically plausible than the anatomically implausible avatar's hands, with no evidence that these effects varied across action-outcome delays.
***** $p_{Tukey} < .001$, ** $p_{Tukey} < .01$, * $p_{Tukey} < .05$.**

we explored with Tukey-corrected post-hoc comparisons (other non-significant or non-informative effects are reported in Table S11). See Fig. 5 and Table S12 for descriptive statistics. We were specifically interested in answering two questions: (a) whether the intentional binding phenomenon was present, and (b) if present, whether it differed between the different anatomical plausibility conditions.

TC was significantly stronger in active movements compared to passive ones, specifically when there was a temporal contingency between the active actions and the outcome (200 msec). This pattern was observed in both the anatomical plausibility and implausibility conditions. Moreover, only in the anatomically plausible condition, TC was significantly higher for passive than for active actions at 600 msec [Active *vs* Passive, *Plausible*, 200: t (49) = 4.79, $p_{Tukey} < .001$; 400: t (49) = −1.22, $p_{Tukey} = .984$; 600: t (49) = −4.27, $p_{Tukey} = .005$; *Implausible*, 200: t (49) = 4.07, $p_{Tukey} = .008$; 400: t (49) = .57, $p_{Tukey} > .99$; 600: t (49) = −1.81, $p_{Tukey} = .802$. See Fig. 5].

For each delay and movement condition, comparisons between the anatomically plausible and implausible avatar configurations were not significant, indicating comparable TC across the two conditions [Plausible *vs* Implausible, *Active*, 200: t (49) = −1.50, $p_{Tukey} = .933$; 400: t (49) = 1.12, $p_{Tukey} = .992$; 600: t (49) = 2.89, $p_{Tukey} = .177$; *Passive*, 200: t (49) = −1.13, $p_{Tukey} = .992$; 400: t (49) = −.69, $p_{Tukey} > .99$; 600: t (49) = −.02, $p_{Tukey} > .99$. See Fig. 5].

Bayesian analyses indicated that the best-supported model included *Action*, *Action-Outcome Delay* and their interaction (see Table S13), while providing evidence against a contribution of *Anatomical plausibility* to intentional binding (see Supplementary Materials). This converges with the frequentist pattern, indicating that implicit SoA was primarily driven by action-outcome temporal contingencies.

4.4. *Implicit SoO*

ΔPD significantly differed from zero ($W = 249$, $p < .001$, r_{rb} = −.68; $M = -1.30$, SE = .29), indicating that proprioceptive drift in the anatomically implausible condition differed from the anatomically plausible baseline (see Fig. 6). Moreover, the negative ΔPD indicates a leftward shift in the perceived position of the left index finger, i.e., a drift away from the virtual left hand, which is displayed on the right side in the anatomically implausible condition. Thus, as expected, these results confirmed that the ownership manipulation reliably modulated implicit SoO. The additional exploratory analysis

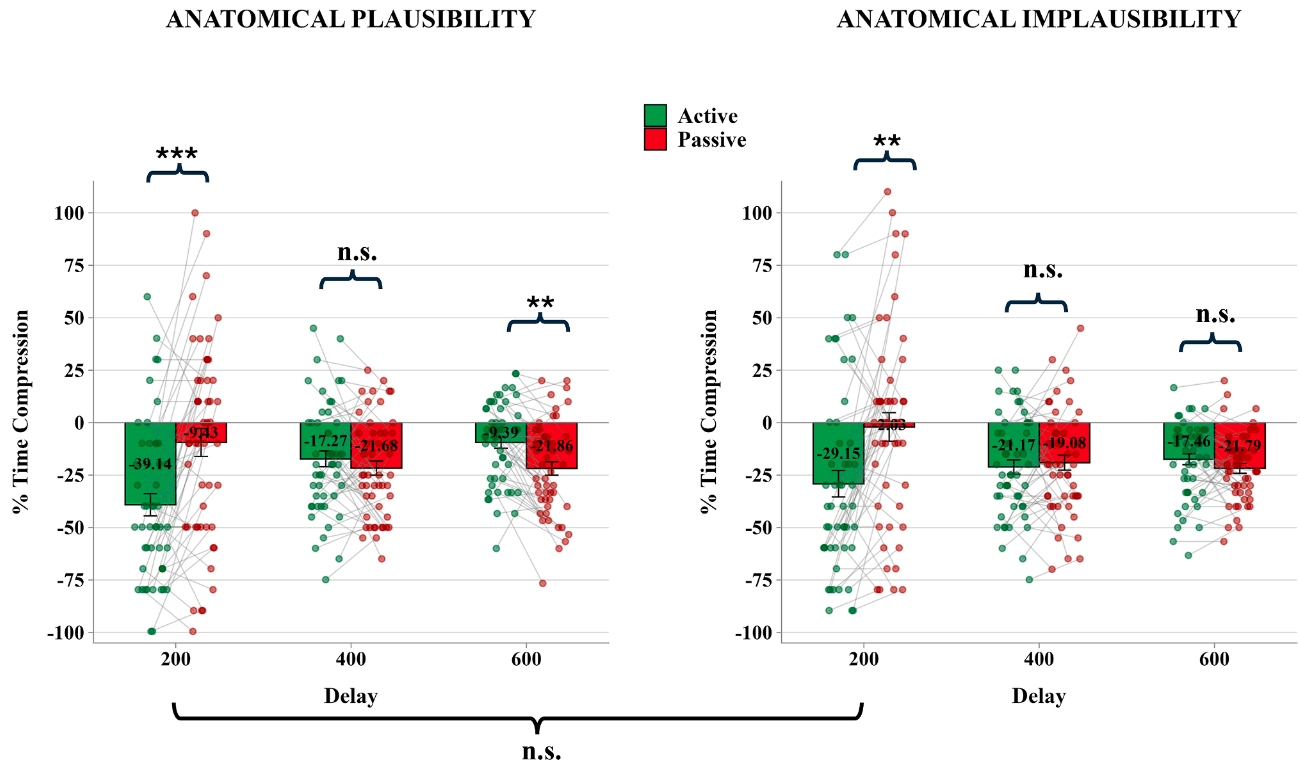

Fig. 5 – Mean and standard error of TC values (index of implicit SoA). Points represent individual participants' mean values in each condition. Participants exhibited stronger intentional binding for active than passive movements only when consequences were temporally contingent on the outcome (200 msec), with similar effects across anatomically plausible and anatomically implausible conditions. TC values are reported as a percentage of the temporal delay considered. * $p_{Tukey} < .001$, ** $p_{Tukey} < .01$, * $p_{Tukey} < .05$.**

on the five repeated PD measurements, reported in the Supplementary Materials, confirmed that the effect of *Anatomical plausibility* on PD was stable across time.

A summary of the effects of the experimental manipulations and their interactions across all direct and indirect measures of SoA and SoO is reported in Table 2.

5. Discussion

The relationship between the sense of agency (SoA) and the sense of ownership (SoO) is a central issue in the study of bodily self-awareness. Although these dimensions are typically integrated in everyday experience, neurocognitive models have proposed different accounts of their functional relationship, ranging from independence to interactive and additive frameworks (Seghezzi et al., 2019; Tsakiris et al., 2010). However, empirical studies directly comparing these models within a single experimental paradigm remain scarce.

Here, we addressed this gap using immersive VR to orthogonally manipulate agency- and ownership-related cues within the same goal-directed action context. At the explicit level, our findings are broadly consistent with accounts proposing reciprocal influences between agency- and ownership-related cues. Specifically, explicit agency judgements were influenced not only by cues related to voluntary movement generation and action-outcome contingency, but also by the anatomical plausibility of the virtual body. Importantly, the effect of anatomical plausibility on explicit agency judgements emerged only during active movements and was not observed in passive conditions. This pattern is compatible with the possibility that voluntary action facilitates the integration of ownership-related information into explicit agency judgements. However, because passive ratings showed a restricted range, the present design cannot fully establish whether this modulation is genuinely specific to self-generated action. Explicit SoO showed a complementary pattern: as expected, ownership judgements were higher when the avatar's hands were anatomically plausible, reflecting the role of structural body constraints in SoO experience. Interestingly, ownership ratings were also enhanced during active relative to passive movements, indicating that voluntary action-related signals can contribute to reflective ownership judgements. This asymmetry may reflect a facilitating role of self-generated action in the integration of agency- and ownership-related information at the level of explicit judgements. Similar patterns have been reported in moving rubber-hand paradigms, in which SoA and SoO can dissociate yet still influence one another when individuals evaluate their bodily experience (Braun et al., 2014; Kalckert &

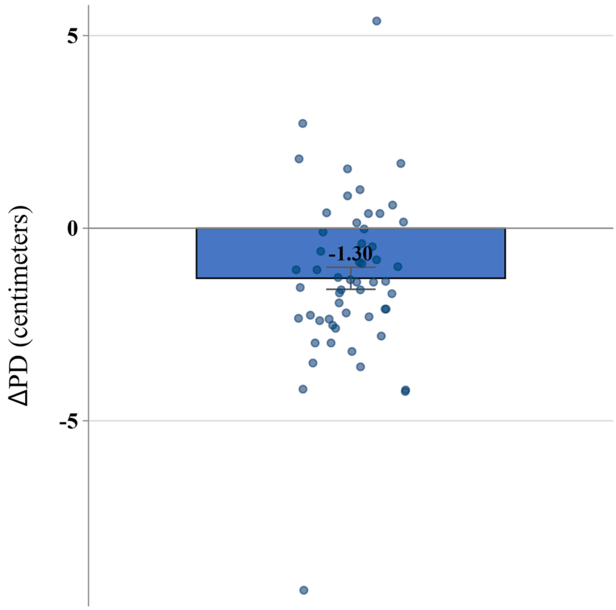

Fig. 6 – Mean and standard error of ΔPD value (index of implicit SoO). Points represent individual participants' mean values. The negative ΔPD indicates a leftward shift in the perceived position of the left index finger, i.e., a drift away from the virtual left hand. PD values are reported in centimeters.

Ehrsson, 2012). Importantly, explicit SoO was not modulated by action-outcome delay, suggesting that ownership judgements are influenced by agency-related cues primarily when these cues are strong and directly tied to voluntary motor generation (i.e., presence *vs* absence of self-generated action) rather than by more subtle manipulations of action-outcome timing.

A different pattern emerged when considering the implicit dimension. The intentional binding effect, a widely used indirect index of implicit SoA (Haggard et al., 2002; J. W. Moore & Obhi, 2012), was primarily sensitive to the mode of movement generation and action-outcome contingency (in line with previous studies, see Zapparoli et al., 2020b) but was not influenced by anatomical plausibility, remaining comparable in terms of magnitude across anatomically plausible and implausible body configurations. This finding is consistent with theoretical accounts linking implicit SoA to predictive sensorimotor mechanisms (Gentsch, Kathmann, & Schütz-Bosbach, 2012; Goldberg, Busch, & Van Der Meer, 2017; Mariano et al., 2024b; J. Moore & Haggard, 2008; Veillette, Cheng, Joshi, & Nusbaum, 2025), while body-related cues may play a limited role. This apparent limited role of body-related cues at the implicit level may seem at odds with evidence that experimentally induced SoO over an artificial effector can modulate sensory attenuation (e.g., an indirect index of SoA; Burin et al., 2017, 2018; Pyasik et al., 2019, 2021). Two considerations may reconcile these findings. First, in those paradigms, ownership operates in the absence of self-generated movements, such that body-related cues become the only available source of an agency signal and therefore

Table 2 – Overview of the results across outcome measures.

Bodily self-awareness dimensions	Dependent variables	Effect of agency-related manipulations	Effect of ownership-related manipulation	Significant interactions
Explicit SoA	Judgements of agency	*i. Action* *ii. Action-Outcome Delay*	*Anatomical plausibility*	*i. Action × Action-Outcome Delay* *ii. Anatomical plausibility × Action*
Explicit SoO	Judgements of ownership	*Action*	*Anatomical plausibility*	None
Implicit SoA	Time compression values	*i. Action* *ii. Action-Outcome Delay*	None	*i. Anatomical plausibility × Action × Action-Outcome Delay*[a]
Implicit SoO	Delta proprioceptive drift values	–	*Anatomical plausibility*	–

[a] Although the three-way interaction was significant, time compression values were significantly stronger for active than passive movements, at 200 msec of Action-Outcome Delay, in both anatomically plausible and anatomically implausible conditions, indicating similar implicit agency.

drive the implicit measure. In the present design, by contrast, participants performed voluntary actions, so the sensorimotor predictions underlying intentional binding were supplied by the actual motor command and remained robust to ownership manipulations, which instead modulated only the higher-level, explicit attribution of SoA. Second, intentional binding and sensory attenuation, although both are considered implicit indices of SoA, are empirically dissociable (Borhani, Beck, & Haggard, 2017; Dewey & Knoblich, 2014), suggesting that they may index partly distinct processes; ownership could therefore influence one without necessarily affecting the other. On this view, we may speculate that ownership-related signals shape implicit SoA primarily when action-outcome predictions are unavailable, whereas they become subordinate to sensorimotor prediction when a real, self-generated action is performed.

An additional finding concerned the longest action-outcome interval (600 msec), where the typical intentional binding pattern disappeared and, in the anatomically plausible condition, the opposite pattern emerged, with passive trials showing greater temporal compression than active trials. This pattern has been consistently observed in our previous studies using similar paradigms (Mariano et al., 2024b; Zapparoli et al., 2024) and may reflect a weakening of the perceived causal link between actions and outcomes at longer delays.

With respect to implicit SoO, proprioceptive drift indicated that the anatomical plausibility manipulation influenced body representation, as the perceived position of the hand shifted away from the virtual hand in the anatomically implausible condition relative to the anatomically plausible condition. Such sensitivity to structural body constraints aligns with evidence that body ownership depends not only on visuo-tactile congruence but also on internal representations of body structure, which determine whether a seen body configuration is anatomically plausible. This pattern is consistent with previous evidence showing that anatomically incongruent configurations reduce or abolish the typical proprioceptive drift effect (Kalckert & Ehrsson, 2012; Tsakiris & Haggard, 2005).

A potential concern is that the virtual hand-swap manipulation is primarily spatial, as it remaps the location of the acting effector (see also Yizhar et al., 2021). However, this interpretation is difficult to reconcile with the selective pattern of results observed. The manipulation affected ownership-related indices and modulated explicit agency judgements, but only during active movements, while leaving intentional binding unchanged. If the manipulation had introduced a general spatial alteration, its effects should not depend on the mode of movement generation (Costantini & Haggard, 2007; Ehrsson, Spence, & Passingham, 2004; Tsakiris & Haggard, 2005) and would be expected to extend across direct and indirect measures. Instead, the observed pattern suggests that the manipulation cannot be reduced to a general spatial distortion.

Overall, this pattern suggests that SoA and SoO can be independently modulated at the implicit level, as recently suggested by a systematic review (Girondini, Mariano, Stanco, Gallace, & Zapparoli, 2025). These results are at odds with with the interactive account of the -SoA-SoO relationship observed for explicit measures. Instead, they are partially compatible with the independence model (Tsakiris et al., 2010). However, a full validation of this model is not possible because our design does not allow direct conclusions about the influence of agency-related cues on implicit SoO. Specifically, proprioceptive drift was assessed at the end of blocks containing both active and passive trials with variable delays, and therefore, the specific contribution of agency manipulations to this measure could not be isolated. Importantly, this constraint is confined to proprioceptive drift, which is conventionally assessed at discrete intervals rather than on every trial (Botvinick & Cohen, 1998; Pyasik et al., 2020; Tsakiris & Haggard, 2005). The explicit measures and the implicit index of SoA were instead all collected trial-by-trial. The dissociation we observe on the agency side between explicit SoA, modulated by anatomical plausibility, and implicit SoA, which was not, therefore, cannot be explained by differences in the temporal structure of the measures. Although this represents a limitation of the study, it reflects a deliberate design choice based on our previous studies (Mariano et al., 2024a; Mariano et al., 2024b; Zapparoli et al., 2020b): structuring blocks around a single, constant agency condition would have increased the risk of habituation, potentially biasing both explicit ratings and the implicit indices of SoA and SoO. Consequently, at the implicit level, our data provide only partial support for the independence model and do not allow a direct test of the additive model. Accordingly, the comparison among competing theoretical accounts should be considered complete for explicit measures and implicit SoA, but necessarily partial for implicit SoO.

5.1. *Towards an integrated neurocognitive model of the SoA–SoO interplay*

We propose a hierarchical, two-stage neurocognitive model to explain the interplay between the SoA and the SoO (see Fig. 7). The model integrates bottom-up sensory processing with top-down cognitive modulation, distinguishing between an initial independent stage and a subsequent interactive level of processing. The model builds on and integrates previous influential theoretical models while also being informed by the empirical findings of the present study. Specifically, it draws on comparator models of SoA based on efference-copy mechanisms (Blakemore, Wolpert, & Frith, 2002; Frith, Blakemore, & Wolpert, 2000), cue-integration frameworks that distinguish pre-reflective feelings from explicit judgements of agency and ownership (Synofzik et al., 2008), and neurocognitive models of body ownership emphasizing the role of structural body representations and multisensory integration (Tsakiris, 2010; Tsakiris et al., 2010).

At the foundational “sensorimotor” level, the model assumes a shared pool of sensory signals that provide a common bottom-up input (i.e., exteroceptive and proprioceptive signals). From this shared foundation, the processing stream bifurcates into two distinct, parallel comparators operating at this pre-reflective stage. On one side, the implicit SoA is generated by a comparator that compares the shared sensory feedback (exteroceptive and proprioceptive) with the desired sensorimotor state (i.e., the efference copy). On the other side, the implicit SoO arises from a separate comparator that evaluates the exact same shared sensory signals against an online body schema (i.e., the implicit tracking of postural and

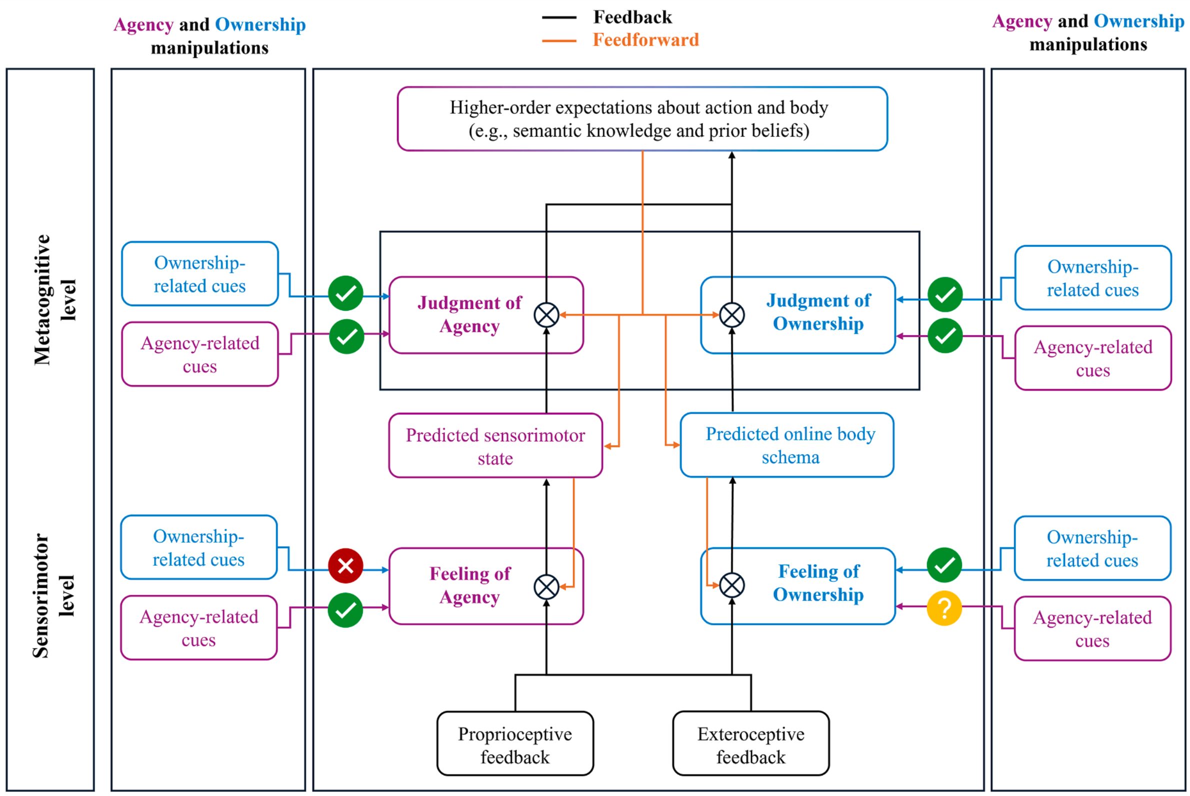

Fig. 7 — Graphical illustration of the neurocognitive model of SoA and SoO interplay.

anatomical constraints). This distinction draws on complementary theoretical traditions: the comparator generating implicit SoA derives from efference-copy models of action awareness (Blakemore et al., 2002; Frith et al., 2000), whereas the body-schema comparator underlying implicit SoO builds on neurocognitive models of ownership that emphasize structural body representations and multisensory integration (Tsakiris, 2010; Tsakiris et al., 2010). Under typical and optimal conditions, at this initial stage, the processes underlying the SoA and SoO may operate relatively independently, computing distinct prediction errors based on different reference signals. As a result, perturbations affecting one process need not systematically alter the other. A key observation informing the present level of the model is that the anatomical plausibility manipulation affected implicit SoO while leaving implicit SoA unchanged. Indeed, an anatomical incongruency, which generates a large spatial prediction error (Apps & Tsakiris, 2014) and alters implicit SoO, may leave the action-effect contingency underlying implicit SoA largely unaffected. We propose, however, that this independence is conditional on cue reliability rather than absolute. When the defining input of one comparator is weak, absent, or ambiguous, the output of the other process may be weighted more heavily and come to support it, disambiguating the self-attribution at this pre-reflective stage. This reliability-dependent weighting is itself a central point of the cue-integration framework (Synofzik et al., 2008), in which agency- and ownership-related signals are combined as a function of their reliability rather than being processed in strict isolation; the relative independence we observe thus corresponds to the limiting case in which each cue is reliable enough to dominate its own comparator process. In rubber-hand paradigms, for instance, participants do not voluntarily generate the movement. Nevertheless, experimentally induced ownership over the artificial hand can elicit implicit signatures of SoA, such as sensory attenuation when the hand's movement produces a somatosensory consequence on the participant's body (Burin et al., 2017, 2018; Pyasik et al., 2019, 2021). Conversely, when efferent and contingency cues are strong and reliable, as in the goal-directed actions used here, the implicit SoA is dominated by these signals and remains comparatively insensitive to subtler ownership-related cues. As noted above, our findings do not resolve whether agency-related cues specifically may propagate to implicit SoO. Nevertheless, the present framework puts forward a plausible account at the sensorimotor level and generates testable predictions that can be directly examined in future studies. Following pre-reflective processing, the SoA and SoO are further elaborated at a higher-order, metacognitive level, characterized by dynamic cross-influence in which the conscious attribution of action and the conscious experience of the body may become mutually informative. This stage corresponds to what Synofzik et al. (2008) described as the judgment of agency and the judgment of ownership: conceptual, reflective attributions that integrate the pre-reflective feelings arising at the sensorimotor stage with contextual information, prior beliefs, and semantic knowledge. The reciprocal influences observed between explicit agency and ownership judgements in the present study led us to propose such a higher-order stage, in which action- and body-related information become integrated during conscious self-attribution. For instance, the intentional execution of a movement can serve as a potent contextual signal that enhances the explicit SoO, partially overriding structural anatomical anomalies. Conversely, violations of the body schema may attenuate explicit judgements of agency, even when low-level sensorimotor contingencies remain intact. One possible mechanism underlying this interaction is the influence of higher-order expectations about the body and action. These metacognitive attributions do not occur in isolation; rather, they are likely shaped by higher-order expectations about the body and action, such as semantic knowledge and prior beliefs, which may act as interpretive filters when individuals evaluate their bodily experience. In this way, the model reconciles the apparent discrepancy between explicit and implicit findings, suggesting that SoA and SoO experiences may rely on partially independent computations at the sensorimotor level while interacting at the level of metacognitive self-attribution. This interpretation is consistent with the pattern observed in the present study: ownership-related cues modulated explicit SoA but not implicit SoA, whereas agency-related cues influenced explicit SoO. More generally, reciprocal influences between SoA and SoO emerged in explicit judgements, while the indirect measures assessed in the present study appeared to be selectively sensitive to the specific cues manipulated within each domain. Although, as discussed above, the present design does not allow conclusions about all possible cross-domain effects at the implicit level, the divergence between direct and indirect measures is compatible with the distinction between a relatively independent sensorimotor level and an interactive metacognitive level.

5.2. *Converging neuropsychological and neuroimaging evidence*

Converging evidence from neuropsychology and neuroimaging further supports the idea that SoA and SoO rely on partially distinct yet interacting mechanisms. Clinical conditions affecting bodily self-awareness often reveal selective disturbances in one component while leaving the other relatively preserved. For instance, after right-hemisphere stroke, some patients may report a disturbed sensation of limb ownership while retaining motor awareness (Salvato et al., 2025), whereas others show anosognosia for hemiplegia (i.e., an alteration of motor awareness) without necessarily reporting disownership (Berti et al., 2005; Salvato et al., 2025). Conversely, disturbances of agency attribution have been clinically documented in schizophrenia, where patients may misattribute self-generated actions or thoughts to external sources (i.e., passivity symptoms) despite a largely preserved SoO at a clinical level (Rossetti, Mariano, Maravita, Paulesu, & Zapparoli, 2024, 2026).

Neuropsychological evidence also suggests that SoA and SoO partly rely on common sensorimotor mechanisms, particularly proprioceptive signals. Studies of deafferented patients have shown that the absence of proprioceptive feedback disrupts the ability to distinguish self-generated movements from externally generated ones, highlighting the contribution of proprioception to the SoA (Balslev, Cole, & Miall, 2007). Similarly, lesion studies in stroke patients indicate that reduced proprioceptive abilities can predict both disturbances of limb ownership and impairments of motor awareness, suggesting that proprioception may represent a shared sensory source for both body ownership and agency processes (Salvato et al., 2025). Interestingly, the importance of proprioceptive signals in both agency and ownership processes had already been highlighted in the cue-integration framework proposed by Synofzik et al. (2008). In that model, proprioception contributes to the perceptual representation underlying both experiences, although it may be weighted differently in agency- and ownership-related computations.

Neurofunctional findings complement this picture. While SoO has been consistently associated with multisensory integration regions such as the premotor cortex, intraparietal sulcus and extrastriate body area (Ehrsson et al., 2004, 2005; Gentile, Guterstam, Brozzoli, & Ehrsson, 2013), the SoA has been linked to brain regions involved in motor intention and action monitoring, including the supplementary motor area, the posterior insula, the inferior parietal cortex and the superior temporal cortex (Farrer et al., 2003; Farrer & Frith, 2002; Kühn, Brass, & Haggard, 2013; J. W. Moore, Ruge, Wenke, Rothwell, & Haggard, 2010; Zapparoli et al., 2020b). Importantly, a quantitative meta-analysis directly comparing the neural correlates of SoO and the SoA identified partially distinct networks for each process: SoO being associated with activity in the inferior parietal lobule and the extrastriate body area, and SoA with activity in the supplementary motor area, posterior insula, superior temporal cortex and postcentral gyrus, while also revealing a shared activation cluster in the left middle insula (Seghezzi et al., 2019). Future studies could extend the present paradigm to neuroimaging investigations and to clinical populations characterized by disturbances of bodily self-awareness. This will help clarify how agency- and ownership-related signals are represented and integrated at the neural level, and whether alterations of these mechanisms contribute to the disturbances of bodily self-experience observed in neurological and psychiatric conditions.

5.3. *Limitations and future directions*

Some limitations should be considered when interpreting the present findings. First, although the experimental design enabled a direct comparison of competing models of the SoA-SoO relationship at the explicit level, it provided only a partial test of their predictions at the implicit level. Specifically, because proprioceptive drift was assessed at the block level, the specific contribution of agency-related manipulations to implicit SoO could not be isolated.

Second, the active and passive conditions differed in how the finger movement was generated. Although both conditions involved displacement of the participant's finger and observation of the corresponding virtual movement, only the active condition involved voluntary motor generation. The conditions may therefore have also differed in muscle activation, force production, and movement kinematics. Because these components were not independently recorded, their respective contributions cannot be disentangled. The active-passive contrast should thus be interpreted as a comparison between voluntary self-generated and externally induced passive movement, rather than as a selective manipulation of mode of movement generation. Moreover, explicit agency ratings were concentrated toward the lower end of the scale in the passive condition, which may have reduced sensitivity to the anatomical plausibility manipulation.

Third, the present paradigm primarily investigated agency and ownership processes related to a specific acting effector, namely the hand/index finger involved in the task. Although participants embodied a complete avatar, the experimental manipulations and outcome measures were centered on the acting hand. Future studies should therefore determine whether the present findings generalize to full-body agency and ownership experiences.

Finally, the relationship between explicit and implicit measures remains an important topic for future research. While the present findings suggest that SoA and SoO may interact differently across processing levels, additional paradigms employing complementary measures will be necessary to further clarify the mechanisms underlying these dissociations.

Scientific transparency statement

DATA: All raw and processed data supporting this research are publicly available: https://osf.io/sz5ty/overview.

CODE: All analysis code supporting this research is publicly available: https://osf.io/sz5ty/overview.

MATERIALS: All study materials supporting this research are publicly available: https://osf.io/sz5ty/overview.

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Data availability statement

The data are available at the following link: https://osf.io/sz5ty/overview.

Author contributions: CRediT

Marika Mariano: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing–original draft, Writing–review and editing. **Giulia Stanco**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review and editing. **Caterina Negrone**: Data curation, Formal analysis, Investigation, Methodology, Writing–review & editing. **Francesca Massaro**: Data curation, Investigation, Methodology, Writing–review & editing. **Antonio Sterlicchio**: Software, Writing–review and editing. **Alessandro Gabbiadini**: Conceptualization, Resources, Supervision, Software, Writing–review and editing. **Gerardo Salvato**: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing. **Laura Zapparoli**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Declaration of competing interest

The authors have no competing interests to declare.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2026.08.008.

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