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Contributions of Tactile Information to the Sense of Agency and Its Metacognitive Representations

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Despite the ubiquitous presence of tactile information in our daily activities, studies of how we experience agency of our actions have rarely relied on manipulated visuo-tactile feedback. Instead, what is often manipulated are the distal (and arbitrarily associated) consequences of our actions. The few studies that did investigate whether tactile information contributes to the experience of agency have been limited to the binary assessment of tactile feedback about the outcome of an action being present or absent. Here, we went beyond the coarse comparison of agency with versus without tactile feedback and introduced instead an experimental manipulation where we could control the amount of mismatch between predictions and observations. Participants ($N = 40$) reached with their right hand toward a ridged plate with a specific orientation and saw online feedback that could match or differ from their action in one of three ways: the physical plate's orientation, the action's timing, or the hand's position in space. Absolute subjective ratings revealed that an increased mismatch in tactile information led to a diminished sense of agency, similar to what has been reported for spatial and temporal mismatches. Further, estimations of metacognitive efficiency revealed similar Mratios in identifying visuo-tactile violation predictions as compared to visuo-temporal violations (but lower than visuospatial). These findings emphasize the importance of tactile information in shaping our experience of acting voluntarily and show how this important component can be experimentally probed.

Public Significance Statement

The sense of agency is the feeling that we are the authors of our actions. It is an essential aspect of the control we assert over our bodies and how we interact with the world around us. Despite the central role of touch in our daily activities, the role of tactile information in forming our sense of agency is often overlooked. In this project, we used an experimental approach that allowed us to compare the role of tactile information relative to two other sources of information that have been previously reported to affect our agency, namely, the timing of our actions and the position of our body in space. We provide evidence that tactile information is crucial for our subjective experience of agency and a tool to study this role further.

Keywords: sense of agency, tactile information, motor metacognition, action–outcome, metacognition

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Previous versions of this work have been presented at the annual meeting of the Association for the Scientific Study of Consciousness, New York, 2023, and at the MindBrainBody Symposium Berlin, 2024, and posted on a public server as a preprint at https://doi.org/10.1101/2023.12.15.571840. Web link to raw data and materials, as well as R and MATLAB scripts for the analyses are publicly available at the Open Science Framework at https://osf.io/4tesr.

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Being and feeling in control of one's actions is an essential component of the self. This feeling of control that normally accompanies our voluntary movements is referred to as the sense of agency (Haggard, 2017). The study of agency has been predominantly driven by the comparator model (Frith et al., 2000), originally used to describe how people can control their movements online using forward and reverse modes of motor commands (Miall et al., 1993; Miall & Wolpert, 1996). The comparator model posits that an *efference copy* results from the motor command issued to make the movement. This efference copy constitutes the predicted sensory consequences of a movement (Blakemore et al., 1999; Haggard, 2005). The result of the comparison between the efference copy and the actual sensory feedback is used to update the forward model for online movement correction and is also thought to inform the experience of agency.

One common approach to study the sense of agency experimentally is to create a mismatch in the comparison between expected and perceived visual and proprioceptive information. Participants see a stimulus external to their body (e.g., a mouse pointer on the screen, Ritterband-Rosenbaum et al., 2014; Wen et al., 2023, or a virtual hand, Farrer et al., 2008; Stern et al., 2020) that moves differently, either in time or in space, from what participants expect under conditions of complete control. That is, the visual stimulus moves with a temporal lag or spatial distortion. Experimenters then often ask participants to rate their feelings of agency. Violations in both the temporal and spatial characteristics of visual and proprioceptive predictions decrease participants' reported agency over their actions. In other instances, participants perform an action followed by an outcome (a sound, Haggard et al., 2002, or a visual stimulus, Ruess et al., 2018), and researchers measure the sense of agency implicitly using intentional binding that manifests as a compression in the perceived time between a voluntary movement and its outcome (Haggard et al., 2002). The magnitude of the intentional binding is reduced when there is a delay between the action and its outcome (but see Wen, 2019). Together, these studies offer compelling evidence for the role of both the temporal and spatial characteristics of visual and proprioceptive predictions in participants' agency over their actions.

However, vision and proprioception are not the only senses involved in driving voluntary movements. Moscatelli et al. (2019) found that when participants moved their index finger over a ridged surface in the absence of visual feedback of the hand, the orientation of the ridges biased participants' forward movements toward the orientation of the ridges. This suggests that tactile information might play a role in guiding our movements and aligns with results from the literature showing that the gating of tactile information follows an action as it unfolds, with a distortion of tactile perception before and during action execution (Colino et al., 2014) and increased sensitivity during active touch (for a review, see Juravle et al., 2017). Thus, ignoring the potential contributions of tactile information in experimental investigations on agency neglects not only important information but also a uniquely embodied source of perceptual information on voluntary actions. Because the tactile predictions that are associated with our actions are so intimately tied to the body, violations of visuo-tactile predictions, unlike violations of visuo-proprioceptive (e.g., spatial and/or temporal) predictions of an action, need not rely on arbitrary associations between movement and effects, like pressing a button and hearing a tone (e.g., with a certain delay) or moving a computer mouse cursor (e.g., which moves differently than expected). Investigations on if and how tactile information informs our agency can extend our understanding of the differences and similarities between the embodied and external agency (Christensen & Grünbaum, 2017; Kalckert & Ehrsson, 2012; Wen, 2019). The former concerns the control we experience over our bodily movements, and the latter concerns the control over the consequences of our actions in the environment. The benefit of undertaking this approach goes beyond simply unifying the role and the weight that different sensory modalities have in our sense of agency; it can help address the necessity of forward models in the sense of agency. This is important in light of the criticism that the comparator model has received on its explanatory power for experiencing agency for sensory feedback that accompany our actions distal from the body (for a discussion on this topic, see Carruthers, 2012; Christensen & Grünbaum, 2018; Synofzik et al., 2008).

Previous research has probed the role of tactile information in the sense of agency primarily using the intentional binding effect and comparing conditions in which tactile information was either present or absent. For movements done in the absence of tactile feedback (operationalized as button release movements as opposed to button presses or as movements over two laser beams) intentional binding disappears (Zhao et al., 2016), and temporal binding effects decrease when local anesthesia is applied (Driller et al., 2023). Further, introducing vibrotactile feedback on button presses or midair touchless haptic feedback during touchless (under an infrared Leap Motion camera) button presses leads to stronger intentional binding effect relative to conditions with visual feedback alone (Cornelio Martinez et al., 2017). Similarly, introducing tactile feedback by asking participants to tap with their index finger on their contralateral arm and record this to elicit a response leads to stronger intentional binding effect compared to tapping on a button (Bergström et al., 2022; Bergström-Lehtovirta et al., 2018; Coyle et al., 2012) or on a touchpad device (Bergström et al., 2022; Bergström-Lehtovirta et al., 2018). Taken together, the results show that additional tactile information can sharpen agency-related representations of voluntary actions, above and beyond those formed by spatial and temporal properties of actions alone. This emphasizes the importance of tactile information in forming the sense of agency.

To the best of our knowledge, only two studies have investigated the role of tactile predictions with subjective measures of agency. Similar to the previous studies, they measured reported agency in conditions with or without tactile feedback. First, Falcone et al. (2022) measured participants' sense of agency in the context of embodiment in a virtual environment. Participants reached toward visual targets repeatedly, during 1-min trials. Upon contact, the targets changed color. For each interaction, participants also received (or did not receive) feedback in the form of vibrations. After completing all reaching movements, participants responded to a series of questionnaires. Tactile information ranked as the second perceptual cue, following visuo-proprioceptive synchronicity, that most affected participants' sense of agency. Further, Bergström et al. (2022) asked participants to tap with their fingers on their contralateral arm, a touchpad, or a button (in separate blocks of 3 min each) to hit moving targets. At the end of each block, participants completed a series of questionnaires, which included three questions on their sense of agency. Skin-to-skin tappings resulted in higher overall agency ratings than tapping on the touchpad, while lower only for one agency question compared to button presses. While both studies exemplified the involvement of tactile information on participants' sense of agency, the number of trials participants completed was very low (32 trials in total for testing five different conditions for the former and a 3-min game for each condition in the latter), and agency ratings were collected only at the end of each task. This constrains the scope for robust interpretation of these results regarding the role of tactile information on participants' subjective reports on agency.

Of these studies, on both implicit and explicit components of participants' agency, no one has addressed the important question of how tactile information is incorporated—namely, whether an increase in the mismatch between visuo-tactile predictions and feedback leads to a more salient experience of lost agency, just as stronger visuo-proprioceptive (temporal or spatial) mismatches do. We aimed to tackle this question, using a virtual goal-oriented task with physical tactile stimuli that allow for a controlled and gradual increase in the mismatch between the predictions (based on the virtual information) and what was perceived (in the physical world). Importantly, we went beyond previous research to ask not only whether the mere presence of any violation of tactile predictions leads to a loss of agency, but whether it does so in a similar fashion as violations of visuo-proprioceptive predictions have been shown to, namely, in a graded manner, with increasingly lower reported agency for increasingly larger deviations.

We were interested in explicit agency ratings; but comparing the absolute value of subjective ratings across conditions might be problematic, as differences between conditions can be driven or masked by trivial response biases. Hence, to compare the subjective experience of agency across conditions, we built on a recent suggestion in the literature on agency where a standard agency task is adapted into a metacognitive task (Wang et al., 2020). Participants performed actions and discriminated which of two stimuli presented on a screen they felt more control over. Then, they reported their confidence in the correctness of their response. By doing so, it is possible to measure participants' metacognition of agency using an estimate of metacognitive efficiency (Mratio; Maniscalco & Lau, 2012). The Mratio depends on the relationship between participants' confidence and their discrimination accuracy. Simply put, a participant with a high Mratio reports high confidence when accurately assigning agency to themselves in those trials when they were in complete control—and low confidence in those where they made an agency misattribution. Conversely, a participant with low Mratio may rate with high confidence those trials where they made agency misattribution while they effectively had little control. The Mratio is a measure of relative efficiency between informational levels, as it quantifies which proportion of the information available for the discrimination response is also available for the confidence judgment. It is therefore unit-free, enabling comparisons of Mratio between conditions. Unlike direct comparisons of subjective ratings that are plausibly subject to response biases, it is valid to directly compare violations of different aspects of action (visuo-tactile and visuo-proprioceptive: spatial or temporal) in their effect on participants' metacognitive representations of agency.

In this study, each participant completed a standard agency and a metacognitive agency task. In each task, we included three experimental conditions. In the first condition, we introduced a mismatch between the visual and tactile feedback. Participants saw on the screen a plate with a specific orientation while touching a plate with a different orientation. In the other two conditions, we introduced a mismatch in the visual and proprioceptive feedback by manipulating the virtual hand to move with a temporal lag or spatial distortion. For readability, we call these three conditions tactile, spatial, and temporal, respectively. We had two hypotheses. First, we expected that visuo-tactile prediction violations would lead to diminished subjective agency ratings. Second, we reasoned that the precision of metacognitive representations of agency following violations of different kinds could serve as a proxy for their relative importance. Hence, we expected the precision of the metacognitive representations following visuo-tactile violations to be at least as high as those following visuo-proprioceptive (spatial and temporal) violations. To test for this null effect, we deploy Bayesian hypothesis testing. In a set of exploratory analyses, we then tested the relationship between agency measures, subjective and metacognitive, to investigate how these estimates relate between the conditions. These analyses were meant to inform current discussions on the link between subjective and metacognitive representations of agency. According to one line of research, judgments of agency are metacognitive by virtue of their role in monitoring a cognitive process (e.g., see Metcalfe et al., 2012; Metcalfe & Greene, 2007; Miele et al., 2011; Potts & Carlson, 2019). However, more recently, it was shown that agency judgments do not monitor the precision of the sensory signal in a computational sense, as the processes that are typically called metacognitive do (Constant et al., 2022). Thus, we wanted to investigate the link between subjective and metacognitive representations in all three conditions. We also tested whether the sensitivity in the predictions' violation, for both subjective and metacognitive judgments, is correlated across conditions to better understand how different sources of information contribute to each representation type. Last, we fitted linear mixed-effect models to test whether this approach, borrowing measures from the literature on perceptual metacognition to study the sense of agency, is indeed devoid of response biases.

Method

We explored the contribution of tactile information to judgments of agency and motor metacognitive representations. Participants completed two tasks (Agency and Meta-Agency) across two sessions within a week (M_{days} between sessions = 2.3, SD = 2.1). The Agency and Meta-Agency tasks were both based on participants making the same kind of action: Participants saw a virtual hand that followed the movement of their own real hand while moving to reach their goal. In the Meta-Agency task, we measured participants' metacognition of agency. In the Agency task, we measured subjective agency ratings. Due to time constraints, for all participants, we tested the first two blocks of the Meta-Agency task on the first day of the experiment and the last block on the second day, prior to the Agency task. We opted for testing the Meta-Agency task first, as this allowed us to visually inspect participants' staircases in all conditions, particularly the staircase of the tactile condition, as a sanity check to verify that the levels of magnitude of manipulation used in the Agency Task fall within the staircase's range for all the participants. Prior to the first block of the Meta-Agency task, participants completed 16 trials in which the virtual feedback matched their action and then they filled out an Embodiment Questionnaire (Gonzalez-Franco & Peck, 2018; Peck & Gonzalez-Franco, 2021). Although it is well-documented that participants can experience ownership over a variety of virtual bodies (Kondo et al., 2018), we wanted to ensure that the results we obtained were not influenced by participants' experience of low ownership and agency over the virtual hand.

Participants

We followed our preregistered plan to collect data from a sample of $n = 40$ participants and to exclude full conditions from participants with very low accuracy (<60%) in their discrimination performance on the Meta-Agency task. We initially collected complete data sets from 47 right-handed participants ($M_{\mathrm{age}} = 25.6$ years, $SD = 4.8$, 37). Participants filled out a form and indicated their gender as "M" (male), "F" (female), or "D" (diverse). Ten participants identified as male, and 37 as female. Their mean reported handedness score was 88.6, $SD = 22.1$ (Oldfield, 1971). We excluded the complete data sets from seven participants because they had low accuracy in at least two conditions. We excluded the data from six participants in the tactile condition and two participants in the spatial condition because their discrimination accuracy was below 60% only in these conditions. For these participants, we included only the data from the other conditions in our analyses. Finally, due to technical problems, one block of 40 trials from the tactile condition from one participant and one block of 40 trials from the spatial condition from another participant were not collected.

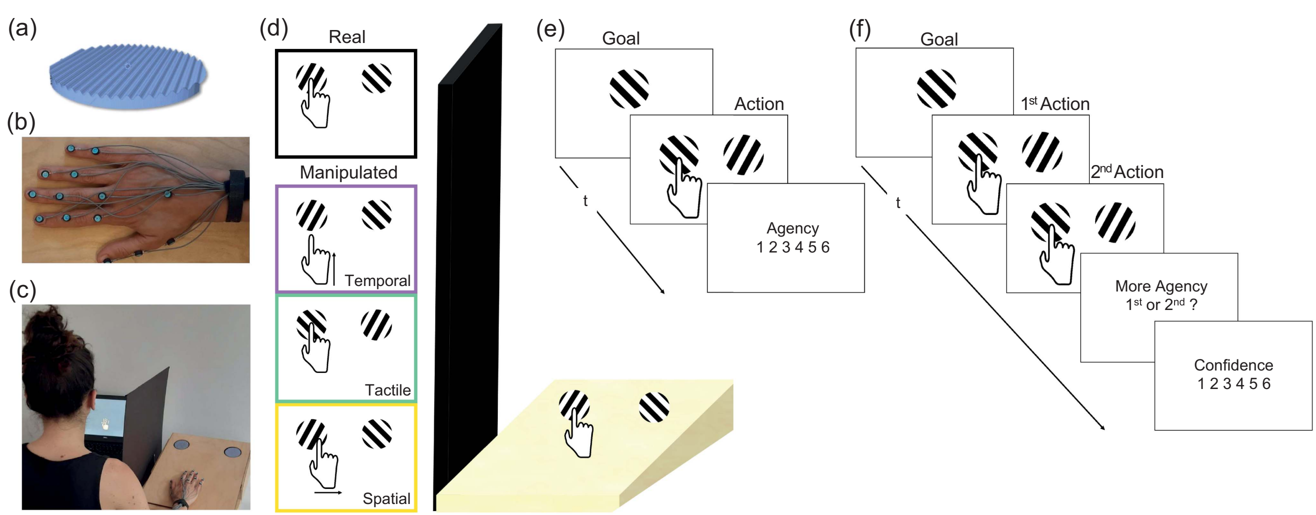
Participants reported no neurological or psychiatric history, had normal or corrected-to-normal vision, and no motor impairment in either hand. They received 8 €/hr or course credits for their time. Testing took place in English. All participants signed written informed consent. The experiment was approved by the ethics committee of the Institute of Psychology of Humboldt-Universität zu Berlin (2022-57) and was conducted according to the Declaration of Helsinki.

Apparatus and Tactile Stimuli

We aimed to capture the ecologically valid experience of expecting a specific tactile sensation in visually guided touch. Hence, we used two circular, ridged, 3D-resin-printed plates as tactile stimuli (60 mm in diameter; Figure 1a) centered in 70-mm diameter holes in the top of a custom-made 10-mm thick wooden box. The plates were attached to the drive shafts of two stepper motors (Dual Shaft, D-cut Shaft, Nema 17, 17HM19-1684D, Step size 0.9°), which allowed the plates to rotate clockwise or counterclockwise before the beginning of each trial. The plates were flush with the surface of the box, leaving a 5-mm gap between the resin plates and the wood. The motors were controlled by two digital stepper drivers (DM332T, for Nema 17), two rotary encoders (AMT102-V, CUI Devices, Lake Oswego, Oregon, United States), and a microcontroller (Arduino UNO Wi-Fi Rev2, Arduino, Monza, Italy; a description of all components and technical aspects of how to build this custom-made box can be found at the Open Science Framework accessible at https://osf.io/4tesr).

We placed 14 sensors connected to a VIPER (Polhemus, Colchester, Vermont, United States) electromagnetic motion tracking system (Micro Sensor 1.8 Extra Flex, TX2 source, and VIPER 16 System Electronic Unit) on the dorsal side of participants' right hand (Figure 1b). These sensors tracked and recorded participants' hand position in space (location and orientation). During the experiment, participants could not see their right hand, which was hidden behind a black occluding board. Instead, they could see only a virtual hand on the screen of a laptop (Dell Latitude 5591, a 15.6″

Figure 1
Experimental Design



Note. The tactile stimulus was a 3D-resin-printed plate (a) that rotated clockwise and counterclockwise along the vertical axis passing through its center. Participants controlled a virtual hand via 14 sensors attached to their right hand (b). Participants faced a computer and placed their right hand behind an occluder (c). The basic motor task involved participants moving their hand and touching a specific target. The online visual feedback either matched the action participants performed or was presented with an added manipulation. For the latter, either the timing of the movement (temporal), the hand position in space (spatial), or the orientation of the virtual plates (tactile) did not match what the participants were doing or touching (d). At the beginning of each trial of the Agency task, participants saw the goal plate that they had to interact with on the screen. Then, they moved their hand forward toward the plate with the same orientation as the goal and touched the center of the plate with their index finger. Participants then rated how much they felt in control of the virtual hand (e). On each trial of the Meta-Agency task, participants repeated the same action twice (moving toward and touching the target plate). The online feedback of the action was congruent with what participants did for only one of the two actions. At the end of the second action, participants reported whether they felt more in control of the virtual hand during the second action compared to the first and then rated their confidence in that decision (f). See the online article for the color version of this figure.

screen: 34.42 × 19.35 cm, refresh rate 60 Hz) placed approximately 60 cm away from them and to the left of the occluder (Figure 1c), which they could control with the sensors. The experiment was programmed in Unity (Unity Technologies, San Francisco, California, United States) using the Unity Experiment Framework (Brookes et al., 2020).

Experimental Conditions

The online visual feedback of each action either matched what participants were doing (based on the sensor positions) and touching (orientation of physical plates) or was displayed with one of three types of manipulation: tactile, temporal, or spatial. In the tactile manipulation, the orientation of both physical plates did not match that of the virtual plates. In the temporal manipulation, the virtual hand was displayed on the screen with an added delay. Finally, in the spatial manipulation, the virtual hand deviated a number of degrees to the left or right of the participant's real hand as measured from the starting position (Figure 1d). We tested all three types of manipulation on separate blocks of trials on both tasks. During action execution, directing attention to different visual or proprioceptive cues affects their weight while participants make inferences about their bodies (Limanowski & Friston, 2020). Therefore, to ensure consistency across participants and that all of them had equal chances of performing well, we explicitly pointed their attention toward the aspect of the action that was manipulated before each block, namely, the sensation of their index finger while touching the plate, the timing of their movement, or the position of their hand in space while trying to interact with the plate with the correct orientation successfully.

Meta-Agency Task

On each trial of the Meta-Agency task, participants repeated the same action two consecutive times (Figure 1e). Each trial started with a white fixation cross (starting position) presented in the middle of the lower part of the screen. Participants started the trial by placing their right virtual palm over the fixation cross, which then turned black, for 0.5 s. Then the hand disappeared from the virtual display. This was to prevent participants from visually identifying manipulated intervals from the "jump" in the position of the virtual hand. After the hand disappeared from the screen, a picture of a rotated ridged plate (constituting the action goal) was shown in the center of the screen for 0.5 s. At 0.2 s after the offset of the goal, the two virtual plates appeared at the top of the screen in positions that corresponded to the physical positions of the real plates. Participants were tasked with using their index finger to touch the center of the plate with the same orientation as the goal. On all trials, the ridges of the two plates were rotated 45° from each other. We instructed participants to move their hand straight toward the plate (goal) and to avoid interacting with the plate at any other point aside from the center. As soon as participants placed their index finger on the center of the plate (marked with a black circle), the plates first turned blue and later turned green if participants maintained their finger on the center of the plate for the required 0.4 s. Once the plates turned green, participants could return their hand to the starting position to continue. If participants did not complete the cued action within 5 s, the plates turned red, marking the trial for exclusion. Once the plates turned green, both plates disappeared, and participants returned their hand to the starting position, whereupon the whole process was repeated identically one time. On each trial, only one of the two actions shown on the screen matched participants' actions, whereas the other was manipulated. After completing the second action, participants used a standard computer keyboard to report with their left hand whether they felt more ("F" key) or less ("A" key) in control of the second action, relative to the first. The question is analogous to asking which of the two intervals they felt more in control. Participants then rated how confident they were in their discrimination decision on a scale from 1 to 6, by pressing the corresponding buttons on the keyboard, again with their left hand. Participants could press a combination of two keys to skip the trial whenever they made a procedural error. The Meta-Agency task consisted of three blocks of 120 trials each, one for each type of manipulation. We counterbalanced the sequence of the blocks between participants.

For the Meta-Agency task, we used separate online staircases (two-down, one-up) for each condition to define the magnitude of manipulation used on each trial. The staircases were meant to keep participants' discrimination accuracy at approximately 71% (Levitt, 1971). We determined the starting value of each staircase for each participant and condition separately with a training session of 16 trials. During the training session, the starting value of the tactile staircase was a 67.5° difference in orientation between the real and virtual plates, the step size was 4.5°, and the maximum possible value was 90°. The starting value of the temporal staircase was a 200-ms delay between the real and virtual hands, and the step size of the staircase was 20 ms, with no upper limit on how large the temporal delay could be. The starting value of the spatial staircase was ±3.25° deviation, yielding a difference in position from the real hand which increased as it moved away from the fixation cross origin. The step size of the staircase was 0.15°, with a maximum possible value set to 4.25°, as any higher value resulted in participants touching outside the edge of the plate, making the discrimination task trivial.

To familiarize themselves with the task and understand how much they could control the virtual hand under nonmanipulated conditions, participants ran 16 trials in which the visual feedback matched their action before starting each block of the Meta-Agency task.

Agency Task

On each trial of the Agency task, participants made only one reaching movement toward the goal (Figure 1d). Unlike in the Meta-Agency task, the online visual feedback of the action in the Agency task could either match the real action or be manipulated to different degrees. After each action, participants used their left hand to provide a subjective agency rating on a standard keyboard by reporting on a scale from 1 to 6 how much they felt they were in control of the action. To ensure that agency ratings did not reflect participants' uncertainty in their decision (similar to their confidence ratings in the Meta-Agency task), we emphasized that their agency ratings are subjective and that we were only interested in the level of control that they experienced regardless of their confidence. We included 120 trials in each condition, which were tested on separate blocks and counterbalanced between participants.

For each condition of the Agency task, we used five levels of magnitude of manipulation (30 trials per level of manipulation). The levels of manipulation were the same for all participants for the temporal (0, 50, 100, 150, and 200 ms) and tactile condition (rotation degrees: 0°, 22.5°, 45°, 67.5°, and 90°). For the spatial condition, we adjusted the values two times. The reason was that, after visually inspecting the spatial staircases from the first two participants on the Meta-Agency task, we realized that the values we initially used in the Agency task (angles: 0°, 0.1°, 0.2°, 0.3°, and 0.4°) were not optimally distributed within the range of values where participants' staircases stabilized. Therefore, we adjusted the range for the following participants so that four had angles measuring 0°, 0.25°, 0.3°, 0.35°, and 0.4° and the remaining 35 had angles measuring 0°, 3°, 3.3°, 3.6°, 3.9°. In all cases, the manipulation magnitudes were preregistered. Similar to the Meta-Agency task, participants completed eight trials prior to each block of the Agency task in which the visual feedback matched their action.

Data Analysis

Data Exclusion

In line with our preregistered plans, we excluded from the Meta-Agency data sets those trials in which the discrimination reaction time was under 0.2 s or above 8 s, trials marked for exclusion by the participants (e.g., error in the discrimination report), and trials where the action time was above 5 s on either interval. We deviated from the preregistered plan and also excluded trials in which the participants touched the wrong plate on any interval. Overall, we excluded a median of 5.97 trials (interquartile range = 3.43–8.51) from each participant. Finally, after visually inspecting the staircases (see Supplemental Material), we decided to deviate from the preregistered plan by removing the first 10 trials from the tactile condition from all the participants to allow the staircases to stabilize, as it is often done in the literature (e.g., Allen et al., 2017; Fleming et al., 2010, 2012). Trial exclusion took place prior to any further data analysis.

Confirmatory Analyses

We fit linear mixed-effect models using the *lme4* package (Bates et al., 2015) in R (Version 4.2.2, R Core Team, 2022).

We measured participants' metacognition of agency by estimating their metacognitive efficiency (Maniscalco & Lau, 2012) with the maximum likelihood estimation method in R using the *metaSDT* package (Craddock, 2021). Only 32 out of the 40 participants had a discrimination accuracy of over 60% in all three conditions. Hence, we ran two different analyses. First, we ran a one-way analysis of variance on these 32 participants to test for differences in the summary measures among conditions, and we ran post hoc pairwise comparisons. To compare d' among the three conditions, we ran a nonparametric Kruskal–Wallis test using the *rstatsix* package (Kassambara, 2023) in R, as the data were not normally distributed, and then we ran post hoc analyses using the Dunn's test and Bonferroni corrections for multiple comparisons. Then, as preregistered, we tested for differences between conditions, using pairwise comparisons with *t* tests and Wilcoxon signed-rank tests (for d' that were not normally distributed) by including all the data from the participants that had discrimination accuracy over 60% in each pair of conditions that entered the comparison (see Supplemental Material). We used the *BayesFactor* package (Morey & Rouder, 2022) to get the Bayes factors for Hypothesis 1 (BF_{10} values) and the *effectsize* package (Ben-Shachar et al., 2020) to estimate partial η^2. We report mean values and standard deviations (M = mean value ± SD).

In a set of exploratory analyses, we ran parametric and nonparametric correlations using the *ggstatsplot* package (Patil, 2021) in R.

Transparency and Openness

This study was preregistered at the Open Science Framework at https://osf.io/ur73j, and any deviations from the preregistered plan are explicitly reported. The raw data, as well as R and MATLAB scripts for the analyses, are freely available at https://osf.io/4tesr.

Results

Agency Task

We first examined participants' responses in the embodiment questionnaire and found that participants already experienced both agency and ownership over the virtual hand (ownership score: $M = 1.38 \pm 0.58$; agency score: $M = 1.98 \pm 2.24$; possible range [−3, 3]) after the first 16 trials in which the virtual feedback matched their action. We then examined whether violations of tactile expectations reduce judgments of agency by measuring the relationship between agency ratings and the level of manipulation on each condition. To do so, we split the data into the three different manipulation conditions, z-transformed the magnitude of manipulation per condition (to scale the values by mean-centering to the condition-specific mean and normalizing by the condition-specific), and fit three separate linear mixed-effects models. Henceforth, we use the term "manipulation level" to refer to the ordered magnitude of the manipulation within each condition. This allowed us to align all three conditions on a single axis. Conversely, using the different absolute values of spatial, temporal, or tactile manipulation would not have allowed this.

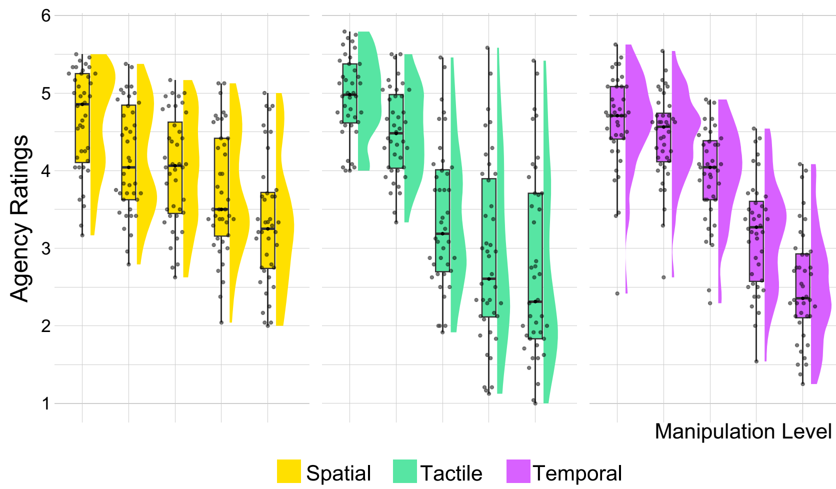
We ran separate models per condition to avoid having a single, overly complex model that would lead to convergence issues in the fitting procedure. We included the magnitude of manipulation as a fixed effect and by-participant random slopes and intercepts (formula: agency ∼ magnitude of manipulation + (magnitude of manipulation | participant)). In line with our preregistered hypothesis, we found a significant negative main effect of the manipulation magnitude on participants' ratings of agency in all three conditions as can be seen in Figure 2, tactile: $F(1, 39) = 99.92$, $p < .001$, $BF_{10} = 1.56 \times 10^9$, $\eta_p^2 = 0.72$, confidence interval (CI) [−1.01, −0.67], temporal: $F(1, 39) = 273.95$, $p < .001$, $BF_{10} = 1.76 \times 10^{16}$, $\eta_p^2 = 0.88$, CI [−0.87, −0.68], spatial: $F(1, 39) = 76.93$, $p < .001$, $BF_{10} = 4.30 \times 10^7$, $\eta_p^2 = 0.66$, CI [−0.49, −0.31]. These results suggest that, similar to violations of temporal and spatial predictions, an incremental mismatch between what participants touched and what they saw on the screen led to an incremental decrease in their agency ratings. This result also confirmed that the tactile stimuli used in our study had the expected influence on participants' agency. Therefore, we could turn to the Meta-Agency task to test the role of tactile information on participants' metacognitive representations of their agency judgments.

Meta-Agency Task

In the Meta-Agency task, participants made relative judgments of agency by comparing two intervals in the amount of control experienced over the virtual hand. The difference in the magnitude of manipulation between the two intervals, and hence the difficulty

Figure 2

Agency Ratings Relative to the Level of Manipulation for Each of the Three Conditions



Note. Each dot corresponds to one participant and condition, the boxplots represent the interquartile range, and the violin plots represent the smoothed distributions of the data. In all conditions, participants rated lower agency with increasing manipulation levels. We use the term "manipulation level" to refer to the ordered magnitude of the manipulation within each condition that could not be compared between conditions (as the manipulated dimension was different). Violations of visuo-tactile predictions resulted in lower judgments of agency, with larger manipulations leading to lower agency ratings, similar to the effect of visuo-proprioceptive (temporal and spatial) predictions. See the online article for the color version of this figure.

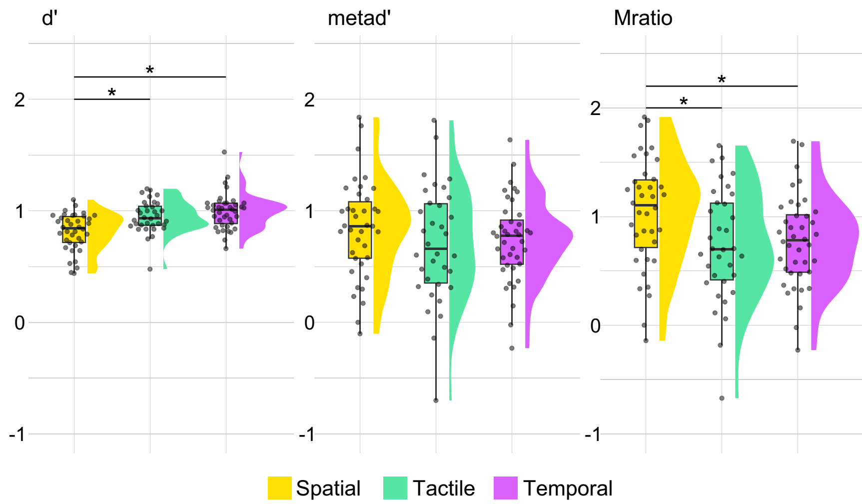
of the discrimination task, was titrated to each participant's ability with an online staircase. Nevertheless, as is common in any analysis of metacognitive performance, we first verified that discrimination performance—measured with d'—was comparable across conditions (Figure 3). We found that d' was significantly different between conditions, $d'_{\text{tactile}} = 0.96 \pm 0.12$; $d'_{\text{spatial}} = 0.81 \pm 0.17$; $d'_{\text{temporal}} = 1.00 \pm 0.16$; $H(2) = 20.42$, $p < .001$, $\eta^2(H) = 0.20$. Post hoc analyses revealed that, despite the condition-specific online staircases, participants were significantly more accurate in selecting the interval in which they were more in control in the tactile compared to the spatial condition ($p < .001$) and in the temporal compared to the spatial condition ($p < .001$). However, the accuracy between the tactile and the temporal conditions was comparable ($p = 1.00$). In short, participants had worse discrimination performance in the spatial condition than in the other two conditions.

Despite the differences in discrimination performance, we found that metacognitive sensitivity measured with Metad' (Figure 3) was not significantly different between conditions, Meta$d'_{\text{tactile}} = 0.73 \pm 0.52$; Meta$d'_{\text{spatial}} = 0.83 \pm 0.42$; Meta$d'_{\text{temporal}} = 0.70 \pm 0.38$; $F(2, 93) = 0.70$, $p = .498$, $\eta^2 = 0.01$, CI [0.00, 1.00], $BF_{10} = 0.17$.

Last and crucially, we compared participants' Mratio across conditions (Figure 3) to test whether participants have better metacognitive efficiency following tactile expectation violations relative to spatial and temporal ones. The results suggest that this is not the case. Mratio was significantly different between conditions, albeit with a small effect size, $\text{Mratio}_{\text{tactile}} = 0.75 \pm 0.53$; $\text{Mratio}_{\text{spatial}} = 1.03 \pm 0.51$; $\text{Mratio}_{\text{temporal}} = 0.73 \pm 0.43$; $F(2, 93) = 3.61$, $p = .031$, $\eta^2 = 0.07$, CI [0.00, 1.00], $BF_{10} = 1.65$. A post hoc analysis showed that Mratio was significantly lower in the temporal condition compared to spatial condition ($p = .055$), while Mratio was indistinguishable between tactile and spatial conditions ($p = .082$) and between tactile and temporal conditions ($p = 1.000$).

The results from the one-way analyses of variance using only the 32 participants were confirmed by the pairwise comparisons we ran including more data sets (see Supplemental Material), except for what we found for the Mratio. According to the pairwise t tests, $\text{Mratio}_{\text{tactile}}$ was indistinguishable from $\text{Mratio}_{\text{temporal}}$ ($\text{Mratio}_{\text{tactile}} = 0.73 \pm 0.52$; $\text{Mratio}_{\text{temporal}} = 0.73 \pm 0.41$), $t(33) = 0.06$, $p = .950$, Cohen's $d = 0.01$, with strong evidence against any differences, $BF_{10} = 0.18$. Also, we found that $\text{Mratio}_{\text{tactile}}$ was consistently lower than $\text{Mratio}_{\text{spatial}}$ ($\text{Mratio}_{\text{tactile}} = 0.75 \pm 0.53$; $\text{Mratio}_{\text{spatial}} = 1.03 \pm 0.51$), $t(31) = 2.45$, $p = .020$, Cohen's $d = 0.43$, $BF_{10} = 2.45$. Finally, $\text{Mratio}_{\text{spatial}}$ was higher than $\text{Mratio}_{\text{temporal}}$ ($\text{Mratio}_{\text{temporal}} = 0.77 \pm 0.43$; $\text{Mratio}_{\text{spatial}} = 1.03 \pm 0.51$), $t(37) = 2.76$, $p = .009$, Cohen's $d = 0.45$, $BF_{10} = 4.53$. Five participants had negative Mratio in some conditions, which indicates that they were often more confident after wrong discrimination decisions than following correct ones. To ensure that these participants' behavior did not drive the effects we saw, we ran the same pairwise comparisons of the behavioral measures between conditions, excluding these participants from the respective comparison. The results held for the comparisons between conditions in d', metad', and Mratio (see Supplemental Material). Taken together, these results argue against any advantage of tactile over temporal or spatial information for participants' metacognition of agency. Instead, the results suggest that spatial manipulations may be especially metacognitively salient relative to both tactile and temporal manipulations. Nevertheless, given the differences we found in discrimination performance, we should interpret these differences in the Mratio with caution, as Mratio has been shown

Figure 3
Meta-Agency Task Summary Measures



Note. Each dot corresponds to one participant and condition; the boxplots represent the interquartile range. The violin plots represent the smoothed distributions of the data per condition. For the pairwise comparisons, we included only participants with discrimination accuracy over 60% in the two conditions compared. d' = discrimination performance in the Meta-Agency task; metad$'$ = metacognitive sensitivity; Mratio = metacognitive efficiency. See the online article for the color version of this figure.
* $p < .05$.

to depend on d', with higher d' often leading to smaller Mratio values, even when the true metacognitive noise is the same (Guggenmos, 2021) despite the theoretical expectations that it will not (Maniscalco & Lau, 2012).

Correlations Between Measures of Agency

In line with our preregistered plans, we investigated the relationship between the subjective agency ratings and metacognitive judgments of agency. To do so, we first extracted the random slope corresponding to each participant from the condition-specific linear mixed-effects models (see Agency Task above). These slopes for each condition represent how sensitive participants' judgments of agency are to the incremental mismatches between their perceptual predictions and observations. Then, for each condition, we ran nonparametric correlations (because the individual agency slopes were not normally distributed) between the agency slopes and the corresponding Mratio. For all conditions, we found a negative relationship between the two measures (Figure 4), with participants with larger Mratio values (indicating higher metacognitive efficiency) also generally showing steeper agency slopes (indicating higher sensitivity in the magnitude of manipulation). Nevertheless, none of the correlations between these two summary measures was significant in any of the conditions (tactile: $S = 8{,}640$, Spearman's $\rho = -0.32$, $p = .060$, CI [−0.60, 0.03], $n = 34$; spatial: $S = 11{,}216$, Spearman's $\rho = -0.23$, $p = .170$, CI [−0.52, 0.11], $n = 38$; temporal: $S = 11{,}866$, Spearman's $\rho = -0.11$, $p = .490$, CI [−0.42, 0.21], $n = 40$). These results suggest that, while related, agency slope and Mratio do not result from the same underlying processes.

Exploratory Analyses

Correlations Between Sensitivity Across Conditions

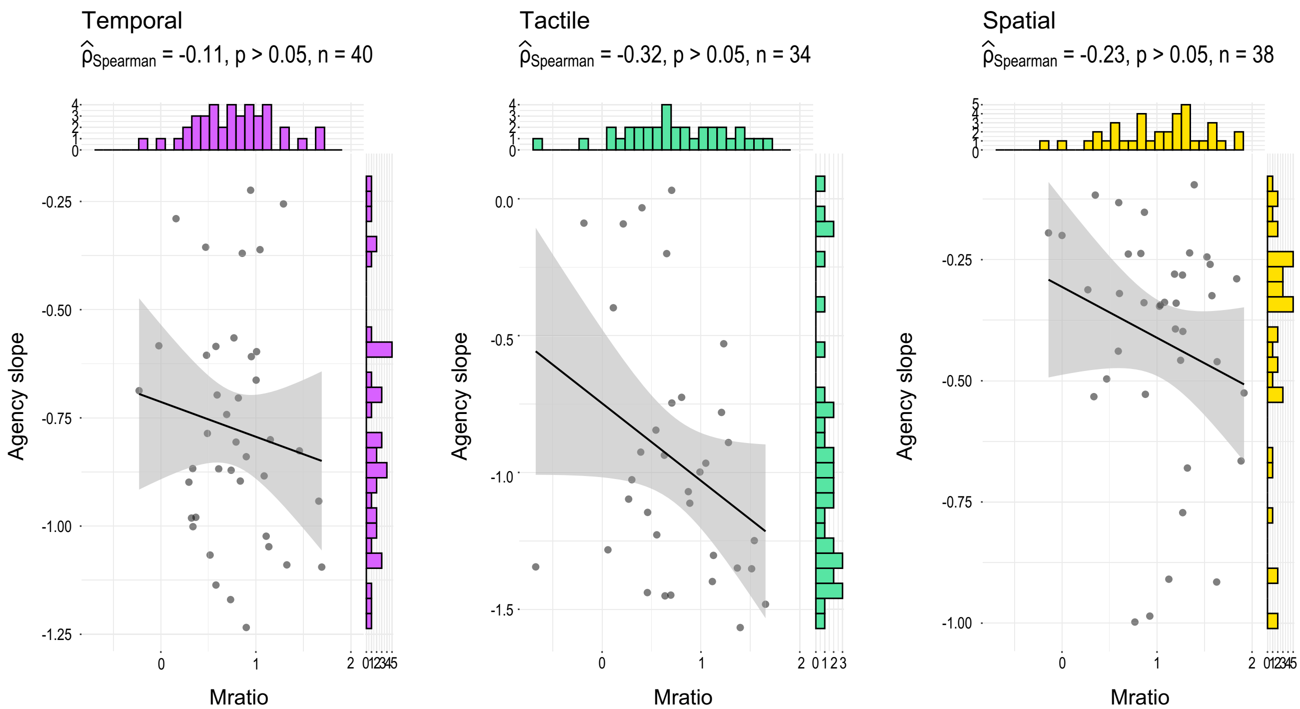
In a set of exploratory analyses, we first tested how the agency measures relate between the different conditions. We found a significant positive correlation only between the slopes of the spatial and temporal conditions (spatial vs. temporal: $S = 7{,}214$, Spearman's $\rho = 0.32$, $p = .042$, CI [0.004, 0.58], $n = 40$; tactile vs. temporal: $S = 7{,}770$, Spearman's $\rho = 0.27$, $p = .091$, CI [−0.05, 0.54], $n = 40$; spatial vs. tactile: $S = 7{,}728$, Spearman's $\rho = 0.28$, $p = .086$, CI [−0.05, 0.55], $n = 40$; Figure 5). Then, we tested for possible correlations between the Mratio values obtained from each condition. We found a significant correlation between the Mratios of only the tactile and the temporal conditions, tactile-temporal: $t(34) = 3.27$, Pearsons's $r = 0.50$, $p = .003$, CI [0.19, 0.72], $BF_{10} = 18.14$, $n = 34$; tactile-spatial: $t(32) = 1.44$, Pearsons's $r = 0.25$, $p = .160$, CI [−0.10, 0.55], $BF_{10} = 0.67$, $n = 32$; spatial–temporal: $t(38) = 1.39$, Pearsons's $r = 0.22$, $p = .170$, CI [−0.10, 0.51], $BF_{10} = 0.59$, $n = 38$; see Figure 5. This correlation between $\text{Mratio}_{\text{tactile}}$ and $\text{Mratio}_{\text{temporal}}$ suggests that temporal and tactile information contribute through similar mechanisms to participants' metacognitive representations of agency.

Discrimination Decision and Confidence Biases

A two-interval forced choice (2IFC) design, like the one we used, has been suggested to lead to smaller response biases than the equivalent two alternative forced choice discrimination tasks (Green & Swets, 1974; Kingdom & Prins, 2016; Macmillan &

Figure 4

Correlation Analyses Between Measures of Agency: Agency Slope and Mratio



Note. We found no significant correlations between these two measures in any of the conditions. In all panels, each dot corresponds to one participant, the histograms indicate the distribution of data for each measure, the black lines represent the regression line, and the shaded area corresponds to the 95% confidence interval. Mratio = metacognitive efficiency. See the online article for the color version of this figure.

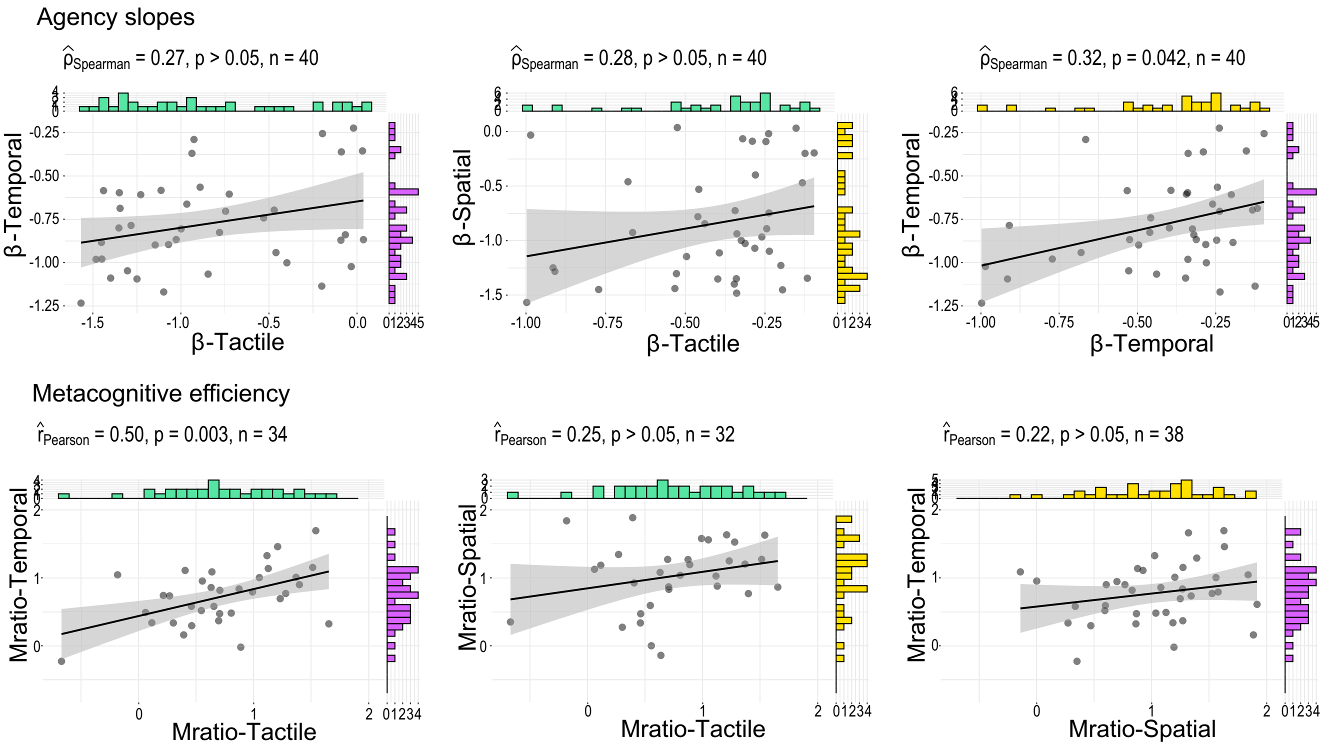
Creelman, 2004), but response biases have still been reported (Yeshurun et al., 2008). We therefore tested for response and confidence biases in all three conditions. First, we obtained participants' decision criteria from the output of the *metaSDT* package, which implements the standard formula to estimate the criterion as: $c = -0.5 \times [z(\text{hit rate}) + z(\text{false alarm})]$, where z is the normal cumulative distribution function. Participants' decision criteria were significantly different from 0 in all three conditions, tactile: $t(33) = 4.82$, $p < .001$, Cohen's $d = 0.82$, $BF_{10} = 729.50$; spatial: $t(37) = 6.10$, $p < .001$, Cohen's $d = 0.98$, $BF_{10} = 3.13 \times 10^4$; temporal: $t(39) = 7.60$, $p < .001$, Cohen's $d = 1.20$, $BF_{10} = 3.79 \times 10^6$. Thus, despite the 2IFC task, participants selected the second interval as the one that they were more in control more often than was presented (in 56% of the tactile trials, 58% of the spatial trials, and 60% of the temporal trials when, in reality, they were in control of the action in the second interval in all three conditions in 49.9% of the trials).

We then tested for potential biases in participants' confidence. We fit a linear mixed-effect model that included condition, manipulated interval, interval selected, and scaled magnitude of manipulation as main effects, along with the interaction between the condition, manipulated interval, the interval selected, and with by-participant random intercept (formula: confidence ∼ condition × interval-manipulated × interval-selected + manipulation magnitude + (1 | participant)). Frequentist statistics revealed a significant three-way interaction between the condition, manipulated interval, and interval selected, $F(1, 12672) = 3.23$; $p = .039$ (see Figure 6), albeit with a small effect size ($\eta_p^2 = 0.0005$). While Bayesian hypothesis testing, using the *bayestestR* package (Makowski et al., 2019), revealed evidence against an effect of the three-way interaction term ($BF_{10} = 0.002$), frequentist and Bayesian statistics point toward different conclusions, but we honored our preregistered plans to interpret both. We therefore ran post hoc tests, using the *emmeans* package (Lenth, 2023) in R, to tease it apart (reported in detail in the Supplemental Material). These revealed that participants were more confident when they were correct. Additionally, participants tended to report higher confidence when they selected the second interval, in all conditions when this response was incorrect, and only in the tactile and temporal conditions, for both correct and incorrect responses. We also found a significant main effect of manipulation magnitude, $F(1, 12671) = 140.30$; $p < .001$; $BF_{10} = 1.88 \times 10^{28}$; $\eta_p^2 = 0.01$. The latter indicates that a larger level of manipulation resulted in higher confidence ratings.

Given that we also found a response bias (participants selected the second interval more often), we also measured participants' metacognitive efficiency by fitting the data using response-specific Meta*d* models (Maniscalco & Lau, 2014). We found no significant differences in participants' Mratio for selecting the first or the second interval in any conditions (see Supplemental Material). Therefore, the results from the confirmatory analysis hold despite participants' biases.

Figure 5

Correlation Analyses of Different Measures of Agency Sensitivity Between the Pairs of Conditions



Note. Significant correlations were found between agency slope$_{temporal}$ and agency slope$_{spatial}$ and between Mratio$_{tactile}$ and Mratio$_{temporal}$. In all panels, each dot corresponds to one participant, the histograms indicate the distribution of data for each condition, the black lines represent the regression line, and the shaded area corresponds to the 95% confidence interval. Mratio = metacognitive efficiency. See the online article for the color version of this figure.

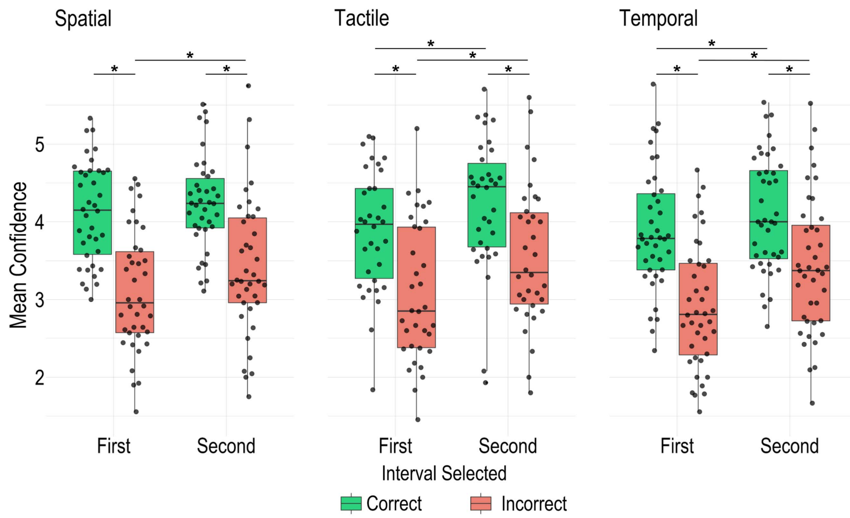
Discussion

This article delved into the role of tactile information in explicit agency judgments and their metacognitive representations. Importantly, we used an ecologically valid task that aimed to create mismatches between visuo-tactile predictions and expectations by exploiting the natural process of interacting with the world through our sense of touch.

In line with the predictions of the comparator model, numerous studies have established that when there is a temporal (David et al., 2016; Farrer et al., 2008; Leube et al., 2003; Sato & Yasuda, 2005) or spatial (David et al., 2007; Farrer et al., 2003; Penton et al., 2022; Ritterband-Rosenbaum et al., 2014) mismatch between the action one performs and the visual feedback one perceives, the sense of agency diminishes. As previous studies have done, we relied here on mismatches between expected and perceived action consequences, but critically, we included mismatches in tactile predictions and experimental methods that in principle and theoretically allow for a comparison of different modalities, unlike absolute agency ratings (due to their susceptibility to overall report biases; Wang et al., 2020). In our study, participants moved their hand toward a target textured surface, and we manipulated the visual representation of their moving hand and the tactile stimuli they interacted with, allowing us to study their embodied sense of agency (Christensen & Grünbaum, 2017; Kalckert & Ehrsson, 2012; Wen, 2019). In two separate tasks (Agency and Meta-Agency), we measured subjective judgments and metacognitive representations of agency and studied the relationships between them. Briefly put, participants' responses in the Agency task revealed that violations of tactile predictions reduce the reported sense of agency, much like violations of temporal and spatial predictions in the visual domain. Additionally, participants' responses in the Meta-Agency task revealed that their metacognitive access to representations of (loss of) agency was above chance, in line with previous studies (Krugwasser et al., 2019, 2022; Penton et al., 2022; Stern et al., 2020; Wang et al., 2020; Wen et al., 2023). Finally, comparing participants' two kinds of ratings (agency and confidence in agency discrimination) suggested that the two measures might differ, also in agreement with previous work (Constant et al., 2022). We will now elaborate on these three findings.

In our Agency task, we saw that tactile information plays a role in subjective agency ratings. This finding complements recent accounts highlighting the significance of tactile information in guiding motor control (Moscatelli et al., 2019) and the sense of agency (Bergström et al., 2022; Bergström-Lehtovirta et al., 2018; Cornelio Martinez et al., 2017; Coyle et al., 2012; Driller et al., 2023; Falcone et al., 2022; Zhao et al., 2016). In our task, both the movement and the outcome were tightly linked to participants' body. The goal of the motor task was to touch a surface with a certain textured orientation. While performing the action, participants could monitor their hand movement by comparing proprioceptive and visual information and evaluate whether they achieved their goal by comparing tactile

Figure 6
Mean Confidence Ratings



Note. Mean confidence ratings split according to the interval participants selected as the one in which they had more control and the accuracy of that decision for all three conditions. Each dot corresponds to one participant, and the boxplots represent the interquartile range. We found a three-way interaction effect on confidence between the condition, manipulated interval, and interval selected. We present the most relevant results from post hoc pairwise comparisons between the factors while adjusting for multiple comparisons using the Bonferroni correction. The figure illustrates the effects reported in the text: Participants were more confident when they were correct. In the tactile and temporal conditions, participants were more confident when they selected the second interval regardless of their accuracy. In the spatial condition, this was only true when participants wrongly selected the second interval. See the online article for the color version of this figure.
* $p < .05$.

and visual information. Arguably, therefore, the Agency task required judgments about embodied feelings of agency (over the movement or the outcome)—more so than other studies on external agency. In these studies, participants perform an action (e.g., pressing a button) followed by an outcome distal to the body (e.g., a tone following button presses), and agency is measured, implicitly or explicitly, over the distal outcomes associated with the action (Christensen & Grünbaum, 2017; Wen, 2019). Therefore, our design and the tactile stimuli allow one to bridge embodied and external agency, which have thus far been studied in separation. This is important, following the discussion in the literature on the role of forward models in embodied and external agency (Dogge et al., 2019) and particularly whether the comparator model can adequately explain sense of agency for both actions tightly linked to the body and those actions with consequences in the environment (for a discussion on the limitations of the comparator model, see e.g., Christensen & Grünbaum, 2018; Dogge et al., 2019). Therefore, our motor task can be further developed to include an external outcome (e.g., adding a distal outcome, like a sound, after participants touch the plate). This would allow one to test whether the same forward models used to make predictions about the sensory consequences of an action tightly linked to the body (for embodied agency) are responsible for predictions that go beyond the body (for external agency).

We found that metacognitive efficiency (Mratio) was comparable between the temporal and tactile conditions and that metacognitive efficiency correlated positively between the tactile and temporal conditions. Together, these results suggest that tactile information contributes to the experience of agency in a comparable manner and, perhaps through similar mechanisms, as visuo-temporal information does. While relatively straightforward to control experimentally, visuo-temporal manipulations have recently been criticized on conceptual grounds. Wen (2019) argued that temporal delays might not have the expected effect on participants' agency because, for instance, a delay in feedback may impair participants' ability to monitor and continuously correct a movement. On the other hand, tactile manipulations that tackle an embodied component of our actions do not suffer from this conceptual limitation. Hence, given the apparent practical equivalence to temporal manipulations that we reported here, we speculatively argue that they might be a promising alternative for experimental manipulations.

Interpretation of Mratio Differences Between Conditions

We found that Mratios for visuo-tactile and visuo-temporal violations were consistently lower than visuospatial ones, implying noisier metacognitive representations. Two nonexclusive explanations can account for this result. First, it is possible that this is caused by an estimation error. Despite the online adaptive staircases, discrimination performance (d') was consistently lower in the spatial condition than in the other two conditions. Mratio is, in theory, independent of discrimination performance (Maniscalco & Lau, 2012), but in practice, a dependency exists (Guggenmos, 2021; Rausch et al., 2023).

Because Mratio increases slightly with decreasing d', this could explain (partially, at least) both the consistently higher Mratio values in the spatial condition and the absence of correlations with Mratio in the other conditions. Therefore, we interpret this difference with caution. Notwithstanding this potentially more parsimonious explanation, previous studies have shown that participants tend to recognize temporally manipulated visual feedback to be a delayed version of their movements (Farrer et al., 2008) and more often attribute temporally manipulated visual feedback to themselves than spatially manipulated visual feedback (Stern et al., 2020; but see Krugwasser et al., 2019). Additionally, we note a limitation of our design: In cases where the visuospatial manipulation was large enough, participants could have felt the edge of the plate but seen their fingers touching only the plate. We aimed to avoid this situation by setting a maximum to the spatial staircase of exactly the radius of the plate, but this may not have been enough. Hence, in these trials, participants would have had both spatial and tactile information to guide their judgments. We expect this to have affected judgments in both tasks, so it calls for caution against strongly interpreting an advantage of visuospatial manipulations.

2IFC Metacognitive Paradigms to Study Agency

Recently studies have shifted away from simple agency ratings and have instead incorporated agency judgments in metacognitive tasks (Krugwasser et al., 2019, 2022; Penton et al., 2022; Stern et al., 2020; Wang et al., 2020; Wen et al., 2023). This aims to explicitly quantify the uncertainty in participants' judgments, thereby providing a bias-free measure of participants' agency representations. While attractive, this approach entails two potential limitations. First, as we saw in our study, response and confidence biases are still present—overall, we found decision and confidence biases in all three conditions as participants tended to select the second interval as the one in which they felt more in control and to report higher confidence when they did. Additionally and more conceptually, in line with a recent study showing that agency judgments do not rely on the same computations as confidence ratings do (Constant et al., 2022), we found in our exploratory analysis a negative but nonsignificant relationship between the subjective and metacognitive representations of agency in all three conditions. Therefore, care should be taken before simply replacing agency judgments with 2IFC confidence tasks in the study of agency.

Conclusion

This study shows that action related tactile predictions, like the better studied (temporal and spatial) visuo-proprioceptive predictions, contribute to participants' subjective agency ratings and their metacognitive representations. Moving forward, our experimental design can be further developed to address, for example, how different types of predictions computationally combine to create a unified experience of agency.

Context of the Research

The interplay between touch and our sense of agency has been highly overlooked despite the importance of touch in our daily lives: from interacting and exploring physical objects in the world around us to social interactions and communication. With this project, we aimed to address this interplay. We devised a tactile stimulus that can become, as we found, an ideal candidate for creating ecologically valid experimental setups in a tightly controlled and graded fashion, where the successful interaction with the tactile stimulus determines the outcome and whether a goal was reached.

Constraints on Generality

In our study, we recruited healthy young adults. We see no reason to question the generality of our findings to other healthy participants. However, given the diminished agency typically reported in several neurological conditions, like anarchic hand syndrome, alien hand syndrome, utilization behavior (Moore & Fletcher, 2012), and movement disorders, like Parkinson's disease, Gilles de la Tourette syndrome, corticobasal syndrome, and functional movement disorders (Seghezzi et al., 2021), our results might differ for these populations.

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