Consciousness and Cognition 124 (2024) 103745

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/yccog

Full Length Article

Metacognition bridges experiences and beliefs in sense of agency

John P. Veillette *, Letitia Ho, Howard C. Nusbaum

Department of Psychology, University of Chicago, 5848 S University Ave, Chicago, Illinois 60637, United States

A R T I C L E I N F O

Keywords:
Agency
Action
Self
Awareness
Metacognition
Beliefs

A B S T R A C T

Cognitive scientists differentiate the "minimal self" – subjective experiences of agency and ownership in our sensorimotor interactions with the world – from declarative beliefs about the self that are sustained over time. However, it remains an open question how individual sensory experiences of agency are integrated into the belief of *being an agent*. We administered a sensorimotor task to measure subjects' (n = 195) propensity to classify stimuli as self-caused and metacognitive monitoring of such judgements, and we compared these behavioral metrics to declarative beliefs about their agency. Subjects who were less sensitive to control cues also reported more negative agency beliefs, though positive beliefs were not clearly correlated with any sensorimotor measure. Importantly, this relationship between first-order sensitivity and declarative beliefs essentially disappears when controlling for metacognitive sensitivity. Results suggest agency beliefs are not related directly to the propensity to make positive agency judgements but are connected through introspective access.

1. Introduction

Sense of agency (SoA) is the feeling or belief that one controls one's own actions and, through those actions, can influence events in the world. We experience a feeling of "I did that" as we intentionally take action. This phenomenological SoA, together with body ownership, has been argued by philosophers, psychologists, and neuroscientists alike to be the most basic building block of a minimal conscious self-awareness (Gallagher, 2000; Tsakiris et al., 2006). However, beyond the "minimal self," SoA is also discussed as a high-level belief about one's level of control incorporated into the "narrative self" that is sustained over time (Dennett, 1993; Gallagher, 2000). An important aspect of this idea is that self-reported beliefs about one's own agency appear to be relatively stable over time, constituting a trait-level phenomenon (Tapal et al., 2017). It is assumed by some that the more elaborated narrative self is, in some way, constructed from our moment-to-moment experience of minimal selfhood, but the operating characteristics of this putative integration have been left vague (Gallagher, 2000). Are sustained beliefs about the self merely the sum of individual experiences, or is there more to the construction of declarative beliefs about one's agency? While it is common for studies in the literature to refer to "the" sense of agency, SoA has been discussed as a heterogenous psychological phenomenon for decades (Charalampaki et al., 2022; David, 2012; Gallagher, 2012; Pacherie, 2007). As such, researchers have employed domain-specific measures to study SoA and related processes at various scales of psychological-behavioral organization, ranging from in-the-moment detection of sensorimotor contingencies to declarative beliefs about one's status as an agent that are sustained over longer periods of time. How measures of SoA across different domains relate to one another remains unclear; indeed, some researchers have argued that the concept of agency as it pertains to the narrative self is totally independent from that of the sensorimotor self (Jenkins, 2001).

* Corresponding author.
E-mail address: johnv@uchicago.edu (J.P. Veillette).

https://doi.org/10.1016/j.concog.2024.103745
Received 8 March 2024; Received in revised form 15 August 2024; Accepted 19 August 2024
Available online 22 August 2024

At a sensorimotor level, humans and other organisms are constantly engaged in a process of distinguishing between self-caused and externally-caused sensory stimuli. A basic expression of this distinction is the neural suppression of predictable sensations resulting from voluntary movement (Frith, 1987). That is, sensations are perceived as self-caused when they are predictable from intended actions and therefore attenuated, but whether one experiences agency over a particular sensation further depends upon other cues such as prospective movement intentions (Frith, 2012; Haggard, 2017) or contextual information (Desantis et al., 2011; Synofzik et al., 2008). In the same manner that detection thresholds vary across participants in a variety of sensory domains (Hirsh & Watson, 1996; Stevens & O'Connell, 1991), the degree to which the sensory consequence of an action must match the predicted consequence before control is reliably detected may vary from subject to subject. One's sensitivity to cues to their own control has been measured using control discrimination tasks, in which subjects identify which of two stimuli they are able to influence with their movements (Wang et al., 2020; Wen & Haggard, 2018, 2020). Eliciting uncertainty ratings about agency judgments during control discrimination tasks also allows one to measure metacognitive sensitivity concerning such judgments. While, depending on a number of contextual factors, judgements of agency may be influenced by metacognitive processes (Chambon et al., 2014), a combination of empirical findings and computational modelling has been used to convincingly argue that agency judgements – once considered inherently metacognitive – need not depend on metacognitive processing (Constant et al., 2022; Wen et al., 2023). Consequently, role of metacognition in the awareness of agency remains a topic of intense debate.

In addition to *whether* one feels agency over an action or outcome (i.e. an agency judgement), one can also discuss phenomenal experiences that either result from or tend to accompany judgements of agency. A basic finding is that, when one experiences agency over an action-outcome pairing (say, a button press with a resulting tone), the perceived time of the action is shifted toward the time of the outcome and vice versa, putatively *intentionally binding* the two into a single event according to the common theoretical interpretation (Haggard et al., 2002). While often used as an implicit measure of agency, the magnitude of the intentional binding effect is typically increased when subjects produce intentional actions but does not depend on explicit consideration of agency per se (Lush et al., 2017). Thus, the measure corresponds to a change in conscious experience that could co-occur with instances of control regardless of whether a subject attends to such instances.

At the level of the narrative self, explicit declarative beliefs about one's SoA can be measured psychometrically using the Sense of Agency Scale (SoAS) (Tapal et al., 2017). Two factors, termed "positive" SoA (SoPA) and "negative" SoA (SoNA) can be derived from subject responses to the scale items. The stability of this factor structure has been confirmed and replicated, and these factors can be differentiated from other related constructs such as self-efficacy beliefs and free will beliefs, and there is high test–retest reliability that can be seen even when separated by months (Hurault et al., 2020; Tapal et al., 2017). Moreover, the measured factors predict obsessive–compulsive symptoms and differ between patients with psychosis and healthy controls, which has suggested that these factors meaningfully, though necessarily crudely, quantify clinically important differences in subjective experience (Kruse et al., 2022; Tapal et al., 2017).

The present study, then, aims to assess the degree to which declarative beliefs about agency are predicted by moment-to-moment agency judgements in our sensorimotor interactions. We use validated online tasks to measure, for each subject, sensitivity to sensory evidence of control during agency judgements and the accuracy of metacognitive monitoring of those judgements (Wang et al., 2020) as well as the magnitude of the intentional binding effect as an index of how deeply inferences of agency affect perceptual awareness (Galang et al., 2021). We then estimate the extent to which individual differences in these indices of moment-to-moment SoA predict beliefs about SoA measured by the SoAS. Our results, accordingly, inform our understanding of how SoA at the sensorimotor level relates to SoA at the level of declarative beliefs.

2. Methods

2.1. Subject recruitment and ethics

200 subjects were recruited online from across the United States using Prolific (prolific.co), the behavioral task was hosted on Pavlovia (pavlovia.org), and all experiment code was written in JavaScript using the jsPsych library (de Leeuw, 2015). Subjects in Prolific's recruitment pool were only allowed to participate if 95 % of their previous submissions on the site had been approved and they were using the Windows operating system. 5 subjects' data were lost due to technical error, resulting in $n = 195$. Subjects' data were excluded from analysis of particular tasks or scales (not removed from analyses of other tasks) if they failed to pass exclusion criteria/attention checks for that task, such as failing an unacceptably high proportion of trivially easy "catch" trials, or if they had partially missing data; that is, exclusion criteria were applied to each task's data separately, and each pairwise statistic comparing measures across tasks used the highest amount of usable data to minimize information loss. Please see task descriptions below for exact exclusion criteria and counts of subjects removed from each task. Subjects were 56.4 % male, with mean age 39.8 (SD=12.7) and a median age of 37.0 years. Sample size was determined arbitrarily.

All subjects gave written, informed consent before participating. All of the methods performed in the study were in accordance with relevant safety and ethics guidelines for human subject research and were approved by the Social and Behavioral Sciences Institutional Review Board at the University of Chicago (IRB21-1458). This study was not a clinical trial.

2.2. Selection and summary of sensorimotor measures

Since ensuring acceptable stimulus timing for online experiments is inherently difficult, we opted to use only experimental tasks with previously validated JavaScript implementations to obtain agency-related measures in a sensorimotor setting. To limit our own analytic flexibility, and thus avoid biasing results, we initially calculated only – and all of, to avoid selection bias – the measures reported in these previous validation papers. Where we deviate from the original measures (specifically, we use a different measure of metacognitive sensitivity), we report results using the original measure in Supplementary Information.

From the intentional binding paradigm, we report action binding (the amount the perceived timing of an action, i.e. keypress, is shifted toward its sensory consequence) and outcome binding (the amount the perceived time of the sensory consequence is reciprocally shifted toward the precipitating action), as reported in the validation paper for the task implementation (Galang et al., 2021). While *within-subject* differences in these intentional binding effects are frequently used as an implicit measure of SoA (Haggard, 2017), some evidence also suggests that binding strength correlates with the sensitivity of explicit reports of agency to experimental manipulations (Imaizumi & Tanno, 2019). Given, however, that intentional binding is also known to dissociate from explicit agency judgments (Suzuki et al., 2019), the present authors interpret the intentional binding effect at face value; that is, intentional binding effects are interpreted here as a phenomenal experience that often co-occurs with intentional action but it not contingent on subjects making an explicit judgment of agency (Lush et al., 2017, 2019). In addition to action binding and outcome binding, we also report results for a combined intentional binding measure in Supplementary Information.

In the control detection task, we quantify task performance using the control detection threshold (defined as the objective level of control at which subjects can identify that their mouse movements control a sensory stimulus with 75 % accuracy), which reflects subjects' sensitivity to sensorimotor evidence of control. If two subjects encounter the same distribution of sensory evidence of control, the subject with a lower threshold (i.e. the subject with higher control sensitivity) would make positive agency judgments more often. Of course, not all people do encounter the same distribution of evidence of control – someone with a motor deficit, for instance, may simply encounter fewer genuine instances of control – but this measure may be nonetheless thought of as an imperfect proxy for the frequency with which subjects make positive agency judgments based on sensorimotor evidence. This measure was found to have high test–retest reliability in the validation paper associated with the implementation of the control detection task we use (Wang et al., 2020). Additionally, we ask subjects to rate their uncertainty about their agency judgment after each trial, and we quantify the accuracy of their uncertainty judgments – type II error rate – using meta-d'. In an ideal observer under signal detection theory, first order d' (subjects' sensitivity to control in signal-to-noise units) and type II error rates are deterministically related, so meta-d' is defined as the d' one would expect to have produced the observed type II error rates if subjects had complete metacognitive access to the sensory evidence underlying their first order judgment (Fleming & Lau, 2014). Thus, meta-d' is theoretically interpreted as the amount of sensory evidence (again in signal-to-noise units) from their first order judgement to which subjects still have access when reporting their uncertainty; in our case, as we use an adaptive staircase to find subjects' control detection threshold as defined above, meta-d' specifically refers to the amount of sensory evidence of control to which they have metacognitive access at their detection threshold. However, the measure can be more agnostically interpreted as a measure of metacognitive sensitivity, i.e. the precision with which subjects can monitor their own uncertainty.

Further details on the procedures for these two sensorimotor tasks, and the subsequent computation of measures of interest, can be found in their respective sections below.

2.3. Measuring declarative beliefs with the sense of agency scale

Subjects completed the Sense of Agency Scale (SoAS). Since this scale was introduced and first validated by Tapal and colleagues (Tapal et al., 2017), it has become widely used in the literature. Likert scale responses to each of the 13 items on the scale are multiplied by prescribed factor loadings to obtain numerical values for sense of positive agency (SoPA) and sense of negative agency (SoNA), factors which explain separable components of variance in item responses/agency beliefs. While this decomposition may seem unintuitive – i.e., it is unclear why low SoNA should differ from high SoPA – this factor structure has been replicated at least three times in three different languages and populations (Bart et al., 2023; Hurault et al., 2020; Tapal et al., 2017). However, such a dissociation may make sense in light of the view that sense of agency is influenced by both by "positive" prospective cues – such as the ease with which one makes decisions (Sidarus & Haggard, 2016) – as well as "negative" cues such as unexpected sensory feedback (Synofzik et al., 2008).

The test–retest correlations reported by Tapal et al. (2017), measured two months apart, are $r = 0.78$ for SoPA and $r = 0.74$ for SoNA; these correlations may be useful to consider as a point estimate of the potentially explainable variance in scores when considering the effect size estimates we report here. Moreover, this high test–retest reliability lends itself to the interpretation that declarative agency beliefs captured by the scale are sustained over time. However, it is worth noting that while the SoAS is sometimes described in the literature as measuring "trait-level agency," more recent psychometric work has found that sense of agency can be further dissociated into two dimensions: situational – transcending an individual agency judgment but specific to a given context – and dispositional – context independent beliefs about one's own agency – both of which may contribute to subjects' scores on the SoAS (Di Plinio et al., 2024).

Subjects' data were excluded from this task if they only replied with 1′s and 7′s on the Likert scale or gave the same response to every question, indicating lack of honest effort in responding. 21 subjects were excluded on this basis, resulting in $n = 174$.

2.4. Intentional binding task

We use a conventional Libet clock paradigm (Haggard et al., 2002) for measuring the intentional binding. In this task, the subject sees a moving clock hand on each trial, and they are asked at the end of each trial to move the clock hand back to where it was when a "critical event" occurred; this event varies by condition. In the "baseline key" condition, the subject is asked to press a button on their keyboard during the trial (at their leisure but earlier than 8 s into the trial and but after the first rotation of the clock hand has occurred, or the trial restarts); the critical event is the objective time of the keypress. In the "baseline tone" condition, subjects are played an audio tone (at a random time, uniformly distributed throughout the trial), which is the critical event. In the "operant" conditions, the subject presses a key, and their keypress is followed by a tone a constant 0.25 s later. The critical event is the keypress in "operant key" trials and the tone in "operant tone" trials. The measure of intentional binding for each subject was computed separately for the key – "action binding" – and for the tone – "outcome binding" – by subtracting the average misestimation of the event onset (in milliseconds relative to the true event onset) in the baseline condition from that in the operant condition. Thus, these measurements reflect the degree to which perception of the keypress and tone events are shifted toward each other in time when the former is perceived as causing the latter, or intentional binding. Each 2x2 condition (i.e. baseline-tone, operant-tone, etc.) had 40 trials preceded by 5 practice trials, and we used a preexisting jsPsych implementation of the Libet clock paradigm which had already been validated for online use (Galang et al., 2021).

It is common in paradigms that measure intentional binding using a Libet clock paradigm (as opposed to an interval estimation paradigm) to report the perceptual shift corresponding to the action/keypress and outcome/tone separately, as key and tone binding may vary independently and may contain complementary information (Render & Jansen, 2021). In our case, we focus on action and outcome binding simply because the study which validated the JavaScript implementation of the Libet Clock paradigm we used reported both, and we prefer using measures with validated implementations for timing-sensitive experiments (Galang et al., 2021). For analyses of individual differences (see *Data Analysis* below), the sign of the individual subject outcome binding effect was flipped, such that more positive values always mean stronger binding – just as for action binding.

Subjects' data were excluded from this task if their over- or under- estimation in any one condition was farther than 5 standard deviations from the mean estimation in order to ensure included subjects were not responding randomly. Only 5 subjects were excluded on this basis, indicating decent task compliance overall. The resulting sample size was $n = 190$.

2.5. *Control detection task*

We used Wang and colleagues' jsPsych implementation of the sensorimotor task they introduced and validated (Wang et al., 2020). As with other control detection/discrimination tasks in the literature (Wen & Haggard, 2018, 2020), the task of the subject is to determine which of two moving dots they are able to influence the trajectory of by moving their mouse, while the actual degree of control is low enough to make accurate discrimination challenging. In this way, the task measures perceptual sensitivity to control cues.

Specifically, two moving dots, following independent, pseudorandom trajectories, were presented within separate circles on the screen. The subject could move their cursor to influence the trajectory of one of the two dots (the "target" dot) but were not told which dot they were influencing. The percentage of the target dot's trajectory that the subject could influence ("percent control") was manipulated across trials. Subjects had 4 s to view/influence the dot stimuli during which they could move their mouse as much as they wished, followed by a 0.5 s blank screen before they were asked to identify which dot they thought they were influencing. Subsequently, they were asked to rate their confidence in their answer. A video recording of several trials of this task is available with the online version of Wang et al.'s (2020) paper.

As described by Wang and colleagues, the task begins with 5 practice trials starting at 25 % control (very easy). After the practice trials, the experiment proceeded in two interwoven adaptive staircase procedures by which percent control was adjusted 13 times over 100 trials per staircase, resulting in a total of 200 trials. 15 % of those 200 trials were randomly inserted "catch" trials, in which percent control was always 25 %. Within each staircase, difficulty increased (i.e. true control level decreased) each time subjects got an answer correct and decreased each time they were incorrect. "Reversals" occurred whenever the staircase procedure switched from increasing to decreasing and vice versa. As the goal of the staircase was to hone in on the percent control in which the subject could identify the target dot with 75 % accuracy, the amount of each difficulty increase or decrease following correct or incorrect trials, respectively, were asymmetrically weighted and decreased throughout the task to ensure the procedure asymptoted at 75 % accuracy as described by Wang et al. (2020). (Please refer to Wang and colleagues' (2020) paper for a full description of the staircase procedure.) The average percent control along the last five staircase reversals was taken as the "percent control threshold," which served as our metric for each subject's sensitivity to visual control cues during sensorimotor agency judgements. As pointed out by Wang et al. (2020), the distribution of percent control threshold measurements is highly skewed, so these values were log transformed so as to be closer to normally distributed ("log control threshold"), and the log control threshold was used for analysis.

Moreover, to quantify metacognitive sensitivity, we computed meta-d' by maximum likelihood estimation (Fleming & Lau, 2014), using the *metadpy* Python package. This common measure of metacognitive performance reflects how calibrated subjects' uncertainty judgements are – that is, are they actually wrong more often when they are more uncertain? – while controlling for objective task performance. In addition to this measure, we computed the Type II AUROC metacognition measure described in the validation paper for the control detection task (Wang et al., 2020); main results using this alternative measure of metacognitive sensitivity are reported in Supplementary Information.

Following Wang et al. (2020), subjects' data were excluded from this task if they failed over 40 % of the easy catch trials, indicating they were responding effectively randomly. Moreover, we excluded subjects whose uncertainty ratings scores were significantly *below* chance at predicting incorrect trials with a significance threshold of $p < 0.05$ via a Mann-Whitney test; that is, reported confidence was inversely correlated with success. We interpreted such cases as a misunderstanding of task instructions, such as believing 1 was "most confident" rather than "least confident," whereas subjects with whose certainty ratings were moderately but not significantly below chance were assumed to represent legitimate variance in performance. Subjects were also removed if they always gave the same uncertainty rating, as this prevented the calculation of metacognitive sensitivity measures (and presumably implied lack of effort). One additional subject was removed because their data contained unexplained missing values. Based on these criteria, 13 subjects were excluded, resulting in a sample size of $n = 182$.

2.6. Other self-report measures

We asked subjects to complete two other brief surveys for the purpose of obtaining pilot effect size estimates for future studies. Thus, these scales were never analyzed and results are not reported here, but the raw data are available in our open dataset and may be of use to other researchers. These scales were the Tellegan Absorption Scale (Tellegen & Atkinson, 1981) and the Embodied Sense of Self Scale (Asai et al., 2016).

2.7. Data analysis

All analyses and visualizations were done using Python. Distributions of measurements from the two sensorimotor tasks were visualized using the *DABEST* and *ptitprince* packages (see Fig. 1). Confidence intervals were derived by bootstrap for the Cohen's *d* effect size of intentional binding effects for purposes of replication. Before subsequent analyses of individual differences, all variables were *z*-standardized to facilitate the application of conservative Bayesian priors (see *Bayesian Inference and Multiple Comparisons* below).

In our main analysis, we estimated correlations between each sensorimotor measure (i.e. action binding, outcome binding, log control detection threshold, and meta-d') and each measure of declarative beliefs (SoPA and SoNA). To test whether sensorimotor measures of sense of agency predict declarative beliefs about agency, we correlated each of the sensorimotor measures with both SoPA and with SoNA. All such correlations are estimated and reported, regardless of outcome, to avoid selection bias. We report full Bayesian posteriors for all correlations, which are used for inference (see *Bayesian Inference and Multiple Comparisons* below).

Under the assumptions of signal detection theory, measures of first-order and of metacognitive sensitivity are mathematically guaranteed to be correlated (Galvin et al., 2003); indeed, we did observe a correlation between log control threshold and meta-d' measures in the control detection task (see Fig. 3). Since both performance measures ended up being correlated with SoNA, we used mediation analysis to statistically control for this built-in correlation and ascertain which aspect of performance most directly accounted for their shared correlation with SoNA (see Fig. 2). Posterior distributions for total, direct, and indirect effects were estimated with two linear mediation models – one in which control detection threshold is the mediator, and another in which meta-d' is instead used as the mediator – and shown in Fig. 4.

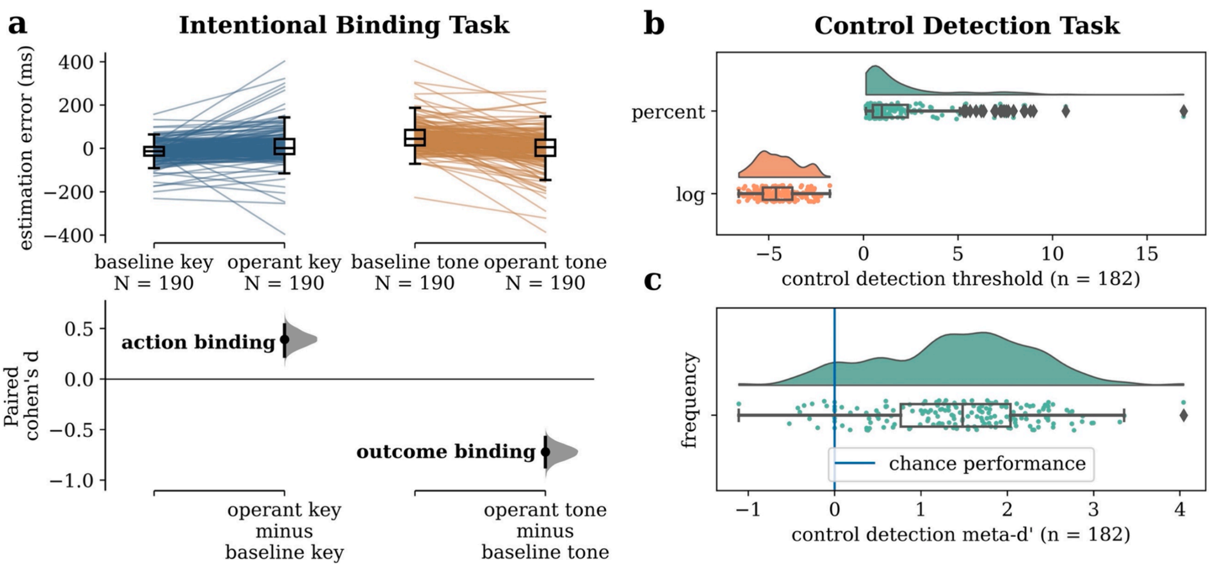

Fig. 1. Distributions of sensorimotor, behavioral measures. (a) Each subjects' mean estimates of the timing of keypress and tone events relative to the true event times in the intentional binding task in each condition are shown on top, with bootstrapped distributions and 95 % confidence intervals of the Cohen's *d* effect size for group-level intentional binding effects on bottom. (b and c) Raincloud plots of control detection threshold (in both percent and log scale), measuring sensitivity to control cues, and meta-d', measuring metacognitive ability. Box component of raincloud plots shows the median and quantiles, while whiskers show the extent of the distribution excluding extreme points (for visualization only). (b) Extreme points (those that fall more than 1.5 the interquartile range from the closest quartile are marked with diamonds; those same points are no longer extreme once log scaled.

2.8. Bayesian inference and multiple comparisons

The aim of a Bayesian data analysis is usually to estimate the probability of some unobserved parameters given the data, using Bayes' rule: P(parameter|data) = P(data|parameter)P(parameters)/P(data). The 95 % "highest density interval" (HDI) or credible interval is often reported for each parameter, which is interpreted as reflecting a 95 % posterior belief that the parameter lies within that interval. (This is in contrast to a frequentist confidence interval, which is defined by a long term coverage rate over many repetitions of the whole study procedure – i.e. "If I compute such intervals on a very large number of repeated samples, 95 % of them will cover the true parameter" – rather than probability that any given CI encompasses the true parameter.) It is typical, then, to interpret the data as showing evidence for a non-zero effect if the 95 % HDI does not cover zero (or whatever the "null" effect size would be).

Since the denominator P(data) of Bayes' rule is normally intractable to compute analytically, but is conveniently known to be constant, modern Bayesian inference leverages the relative information in the numerator P(parameter|data)P(parameter) to draw samples from the posterior distribution, and the 95 % HDI is approximated with an interval that contains 95 % of these samples. Thus, for each parameter/model we estimate, we draw 10,000 posterior samples across 2 sampling chains using the no-U-turn sampler in Python's *PyMC* package.

If one uses "flat," uninformative priors P(parameter) in a Bayesian analysis, the HDI will end up being equivalent to a frequentist confidence interval, since P(data|parameter)P(parameter) will be proportional to P(data|parameter), the ordinary likelihood function. However, this is actually an undesirable effect, since many of the advantages of the Bayesian approach will be lost. Instead, if one sets "weakly informative" priors which rule out unreasonably large effect sizes a priori but are symmetric about zero to avoid biasing the analysis to show a non-zero effect, then effect size estimation is usually improved while heavily attenuating familywise error rate inflation due to multiple comparisons. For instance, if one z-normalizes their data before analysis (as we do here) and uses Normal(0, 1) (i.e. unit variance) priors for the linear relationship between two variables, then the familywise error rate inflation as the number of comparisons increases is empirically negligible, and parameter estimates are remain quite well calibrated (Gelman & Tuerlinckx, 2000). Intuitively, where the frequentist approach to dealing with multiple comparisons is to effectively increase the width of all confidence intervals while keeping point estimates constant, the Bayesian approach is no shift the whole HDI toward zero. So for all of our analyses, we used a Normal(0, 1) prior for population means and regression coefficients, an Exponential(1) prior for variance/noise terms, and an LKJ(eta = 2) prior for correlations – all priors which will shrink effect estimates and their HDIs toward zero.

For readers who are uncomfortable with the Bayesian approach to multiple comparisons correction (or who simply wish the see the results of an analysis approach with which they are more familiar), we also provide raw and false-discovery-rate (FDR) corrected p-values (using a Benjamini-Hochberg FDR correction with $\alpha = 0.05$) for the frequentist correlation corresponding to each of our Bayesian correlations in our results table, though they are not discussed in-text.

3. Results

We observe distributions of behavioral effects consistent with the prior work from which our sensorimotor tasks (intentional binding and control detection) were taken (Galang et al., 2021; Wang et al., 2020). We replicate the previously reported intentional binding standardized effect sizes for both key (d = 0.39, 95 % CI [0.23, 0.54]) and tone (d = -0.72, 95 % CI [-0.87, −0.58]),

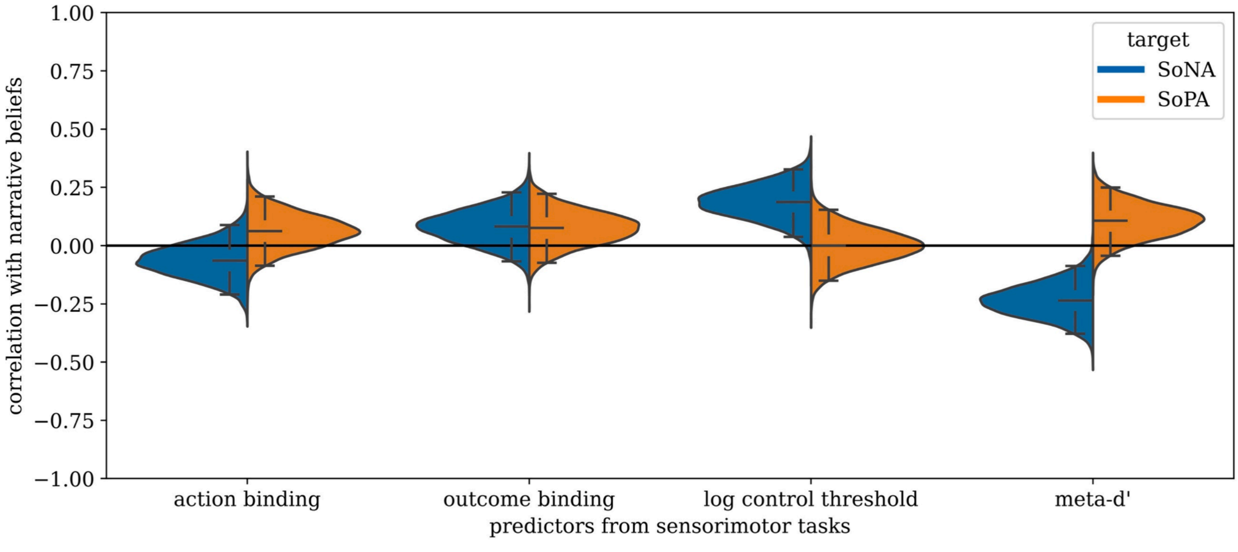

Fig. 2. Posterior distributions of correlations between sensorimotor, behavioral measures and agency beliefs. Behavioral measures are as in Fig. 1. Agency beliefs, measured by the Sense of Agency Scale, are subdivided into sense of positive agency (SoPA) and negative agency (SoNA). Whiskers overlaid atop the violin plots extend to the 2.5 % and 97.5 % quantiles of the posterior distributions, representing 95 % credible intervals.

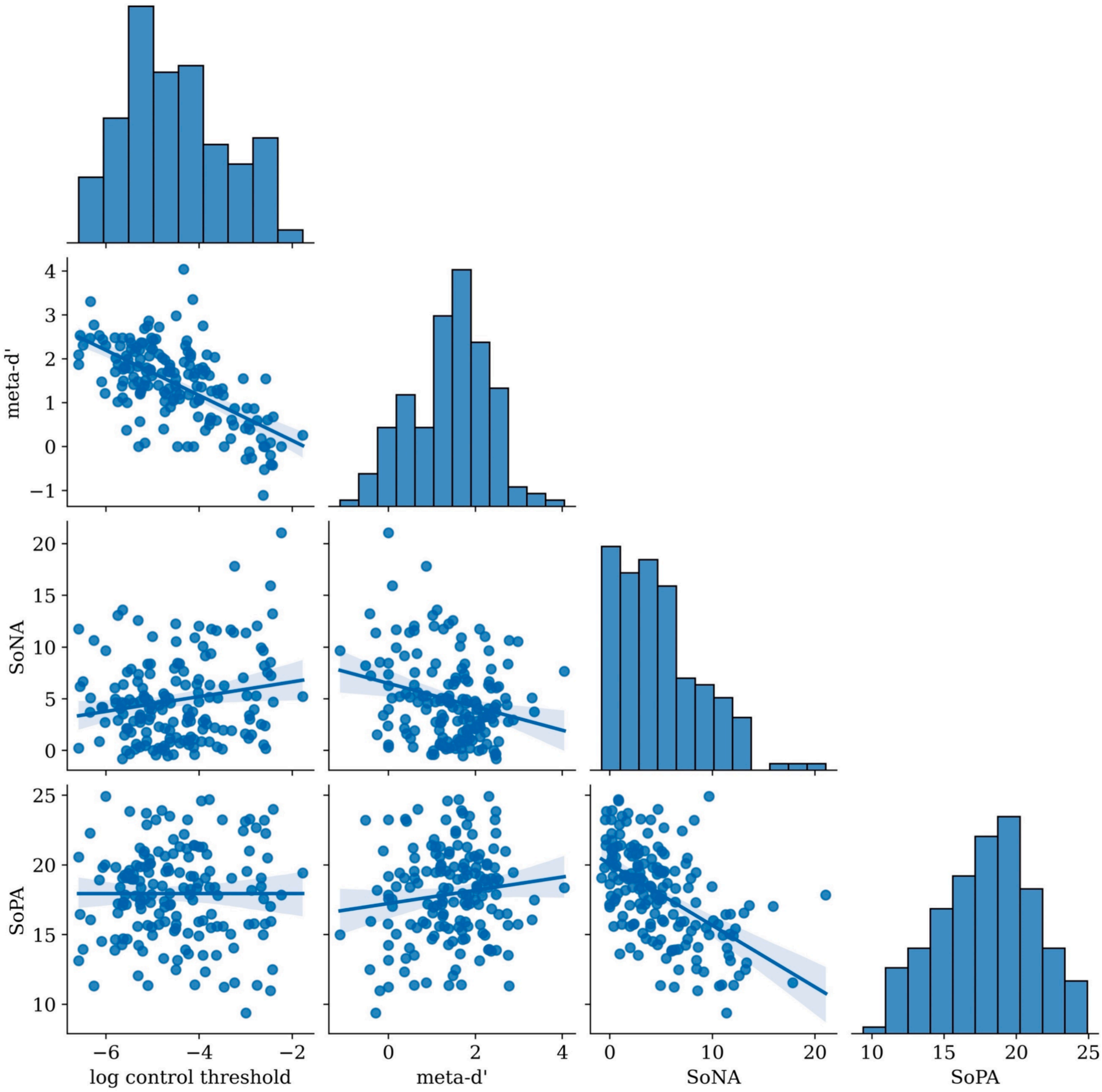

Fig. 3. Joint distributions of control cue sensitivity, metacognitive performance, and sense of negative agency. Histograms for each variable are shown on the diagonal, raw data with best-fit linear regression lines and 95 % confidence bands are shown off the diagonal. Data are shown in their original scale for visualization only.

corresponding to absolute effect sizes of 27.85 ms (95 % CI: [17.68, 39.25]) and −57.89 ms (95 % CI: [-71.27, −46.57]), respectively. In comparison, the *meta*-analytic effect sizes for the intentional binding effect are $d = 0.45$ and $d = -0.73$ for action (key) and outcome (tone) binding, respectively (Tanaka et al., 2019). In other words, we obtained effect size estimates consistent with "gold standard" in-lab measurements. Additionally, the distributions of percent control threshold and metacognitive sensitivity we observe in the control detection task are similar in shape and in mean (percent control threshold = 2.07, 95 % CI: [1.74, 2.50]) to those obtained by Wang and colleagues in their original validation of the task (Wang et al., 2020). Meta-d' measurements had mean 1.41 (95 % CI: [1.27, 1.54]). Observed distributions of behavioral measurements of interest are visualized in Fig. 1. The distribution of Type II AUROC, the metacognition measure used by Wang et al. (2020) instead of meta-d', is also visualized in Supplementary Fig. 1.

Bayesian posterior distributions for Pearson correlations between potential sensorimotor predictors and measures of declarative beliefs are shown in Fig. 2, with summary statistics in Table 1. We find evidence of a positive correlation between log control detection threshold and negative agency beliefs (r = 0.186, 95 % HDI: [0.043, 0.337]). That is, those who are less sensitive to control cues report having less agency. Moreover, we find evidence of a negative correlation between metacognitive ability (meta-d') and SoNA (r = -0.235, 95 % HDI: [-0.378, −0.087]). That is, those with better metacognitive ability for agency judgements report feeling less negative agency overall. We do not find sufficient evidence to draw a conclusion as to whether intentional binding magnitudes predict beliefs about agency, but we report 95 % "highest density intervals" (HDIs, i.e. Bayesian credible intervals) in Table 1 which place upper

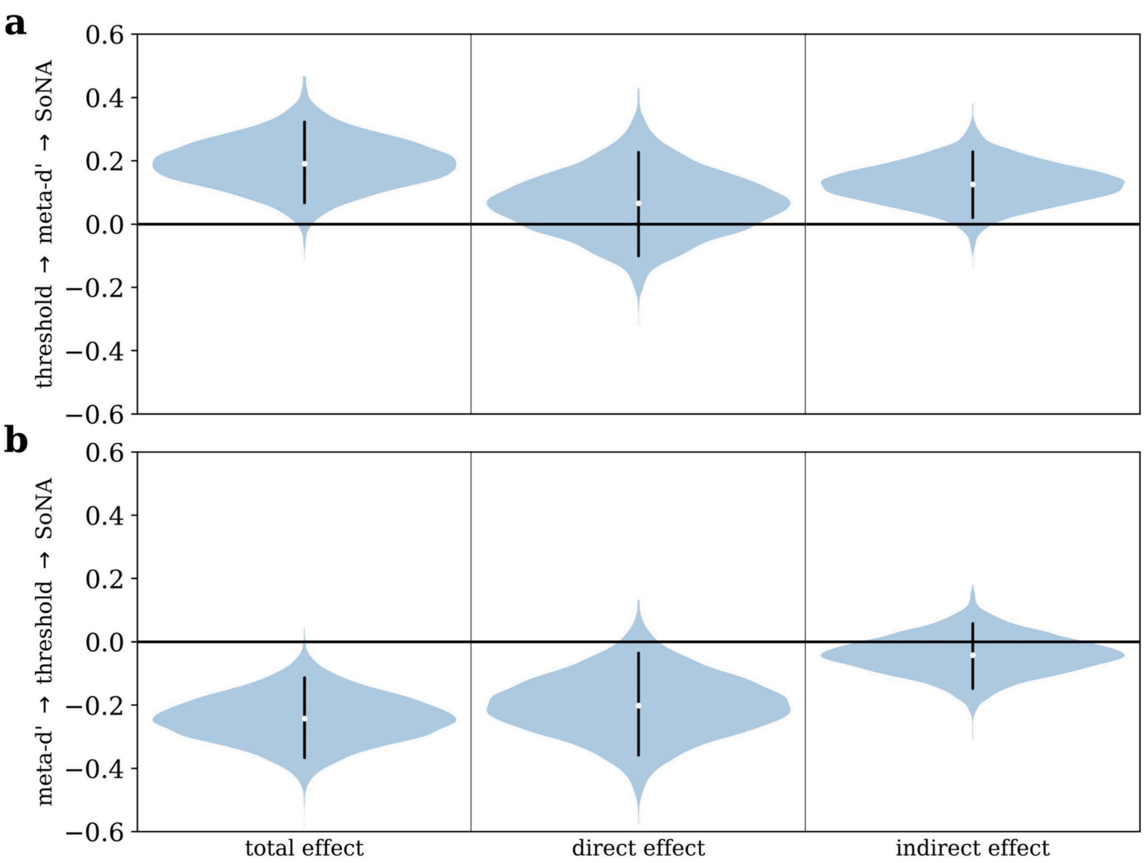

Fig. 4. Posterior distributions for mediations analyses. (a) Posterior distributions and 95 % HDIs for estimated effects of control detection threshold on negative agency beliefs (SoNA) with metacognition (meta-d') as a mediator. We find evidence for an indirect effect mediated by metacognition, but not of a direct effect. (b) Estimated effects of metacognition on SoNA with control detection threshold as a mediator. We find evidence for a direct effect of metacognition on negative agency beliefs, but not of an indirect effect. All variables (log control threshold, meta-d', and SoNA) were standardized before mediation analysis, so the regression coefficient estimates are on roughly the same scale as the correlations visualized in Fig. 2.

Table 1

Posterior summary statistics for correlations behavioral measures and agency beliefs. Summary statistics include posterior mean (expected value), lower edge of 95 % highest density interval (HDI), upper edge of 95 % HDI, posterior probability effect size is negative, probability effect size is positive, and R-hat: a measure of the convergence of the posterior sampling procedure that is optimal at R-hat = 1. We also include raw and FDR-corrected *p*-values for the corresponding frequentist correlations; multiple comparisons correction also accounts for the additional measures reported in Supplementary Table 1.

Predictor	Target	Mean	Lower HDI	Upper HDI	Prob. Neg.	Prob. Pos.	R-hat	p-val. (raw)	p-val. (FDR)
action binding	**SoPA**	0.063	−0.086	0.211	0.207	0.793	1.000	0.407	0.407
action binding	**SoNA**	−0.063	−0.207	0.090	0.798	0.202	1.000	0.400	0.407
outcome binding	**SoPA**	0.075	−0.070	0.225	0.157	0.843	1.000	0.315	0.394
outcome binding	**SoNA**	0.081	−0.069	0.225	0.146	0.854	1.000	0.280	0.394
log control thres.	**SoPA**	0.001	−0.154	0.150	0.498	0.502	1.000	0.997	0.831
log control thres.	**SoNA**	0.186	0.043	0.337	0.008	**0.992**	1.000	0.014	0.045
meta-d'	**SoPA**	0.106	−0.045	0.332	0.081	0.919	1.000	0.164	0.338
meta-d'	**SoNA**	−0.235	−0.378	−0.087	**0.999**	0.001	1.000	0.002	0.009

bounds on how large such an effect could plausibly be based on our data.

While we found that control sensitivity (log control detection threshold) and metacognitive performance (meta-d') both correlate with SoNA separately, visualizing the joint distributions of the three measurements as in Fig. 3 reveals a clear correlation between log control threshold and meta-d' of r = -0.622 (95 % HDI [-0.708, −0.521]) between the two measures. This finding motivated a mediation analysis to determine whether this correlation between behavioral predictors confounded our estimate of their correlations with SoNA.

In a mediation model in which log control threshold is a predictor and meta-d' a potential mediator, we find evidence that the total effect of control sensitivity on negative agency beliefs (beta = 0.190, 95 % HDI: [0.037, 0.340]) can be explained in part by an indirect effect mediated by metacognition (beta = 0.130, 95 % HDI: [0.003, 0.250]), but we do not find sufficient evidence of any direct effect (beta = 0.066, 95 % HDI: [-0.120, 0.260]). In contrast, when we use metacognition as a predictor and control threshold as a mediator, we find that the total effect of metacognitive ability on negative agency beliefs (beta = -0.240, 95 % HDI: [-0.390, −0.090]) can be explained by a direct effect (beta = -0.200, 95 % HDI: [-0.390, −0.006]), and we do not find evidence of an indirect effect (beta = -0.042, 95 % HDI: [-0.160, 0.084]). Taken together, we can conclude with high probability that metacognition mediates the relationship between control detection threshold and negative agency beliefs; conversely, there is an effect of metacognitive ability on negative agency beliefs that is not mediated by the control detection threshold (see Fig. 4).

While we model control sensitivity as affecting agency beliefs, please note our analysis does not rule out the possibility that causality may flow in the reverse direction as well, which would generate an identical partial correlation matrix (Rigoni et al., 2011). Our mediation analysis simply constrains the possibility space of causal structures relating control sensitivity and agency beliefs (with whatever directionality) to those that are mediated by metacognition.

4. Discussion

Agency judgements (or self-vs-other judgements in general) do not only occur at the sensorimotor level, nor is there a clear boundary between experiences of individual agency judgments and declarative beliefs. Sense of agency (SoA) has been studied at many levels of abstraction (e.g. mental, social, etc.), and recent controversies have cast doubt on the notion that a common cognitive or neural substrate can account for agency judgements across all these scales (Charalampaki et al., 2022; David, 2012; Gallagher, 2012; Pacherie, 2007). Indeed, the neural predictors of agency judgements appear to meaningfully differ even between different types of sensorimotor judgements, such as those concerning muscle movements (Veillette et al., 2023) and downstream outcomes (Timm et al., 2016). If asked, however, most people might say that the “I” to which they attribute actions and consequences does not differ across these domains; this unity of self-as-agent in experience seems to contradict the heterogenous cognitive and neural mechanisms that account for SoA across levels of abstraction. While our results are indeed consistent with the view that subjects' sensitivity to their own control in the sensorimotor domain is not congruent with their declarative beliefs about agency, we do find evidence of a surprising relationship between the two.

While it would be intuitive to theorize that those who experience agency more frequently in their moment-to-moment agency judgements will report higher SoA when asked about their beliefs about their own agency – as a matter of statistical learning – what we find instead is more nuanced. While the intuitive correlation between (in)sensitivity to control cues (i.e. control detection threshold) and sense of negative agency (SoNA) does appear to exist, this effect was mediated primarily by metacognitive accuracy (i.e. meta-d', see *Methods*) about such agency judgements – that is, the accuracy with which one monitors uncertainty about agency judgements. In other words, we do not find evidence of a direct relationship between sensitivity to control cues and declarative agency beliefs but of an indirect relationship mediated by metacognition. While sensitivity to control and metacognitive accuracy are correlated in the present study, this need not be the case in all situations; evidence suggests agency judgements can be made without recruiting metacognitive resources (Constant et al., 2022). In such cases, however, metacognition may still play a role in determining how individual experiences of agency are integrated into a persistent self-concept.

We do not find convincing evidence for a correlation between intentional binding measurements and either measurement of SoA beliefs. An advantage of Bayesian analyses is that they sometimes allow one to interpret null findings (i.e. when the HDI is narrow around an effect size of zero); however, since some of our 95 % HDIs comfortably contain correlations as large as 0.2 (see Table 1), we also cannot rule out substantial, non-zero correlations in this case. Interestingly, previous work has suggested that the magnitude of intentional binding predicts free will beliefs (Aarts & van den Bos, 2011) and, conversely, that free will beliefs affect motor preparatory neural activity (Rigoni et al., 2011). Given that free will beliefs are correlated with the intentional binding effect, one might expect that agency beliefs would be as well – as beliefs in one's own causal power intuitively seem to be a special case of the belief that people have causal power in general. SoA beliefs, which pertain specifically to one's own ability to exert control over the world, do however vary independently of free will beliefs (Tapal et al., 2017). One possibility which may explain this difference is that free will beliefs are more related to phenomenal correlates of agency (i.e. how it *feels* to produce actions/outcomes), as reflected in intentional binding, rather than whether or not actions are believed to be self-caused. This distinction could be a fruitful subject for future study.

Moreover, we did not find compelling evidence that any sensorimotor metric predicted positive SoA (SoPA), only SoNA. This finding (or lack thereof) makes sense in light of existing theory, as interruptions of normal sensorimotor control become salient intrusions in conscious experience, but the routine flow from action to outcome naturally falls into the background (Synofzik et al., 2008). However, another possibility is that SoPA items on the SoAS showed worst internal reliability (Cronbach's alpha = 0.651, 95 % CI: [0.562, 0.727]) than did SoNA (Cronbach's alpha = 0.838, 95 % CI: [0.797, 0.872]); in other words, SoPA scores could have just been noisier, allowing a true correlation to evade detection. We present more detailed analyses of the SoAS as a measurement instrument in Supplementary Information.

It is important to note some limitations on the inferences we can draw from the present data. Obviously, we did not measure all possible behavioral indices of agency experience at either the sensorimotor or the narrative level; indeed, no single study can. Consequently, we cannot rule out a direct effect of control sensitivity or some other index that would affect the frequency of positive agency judgements on SoA beliefs. Not all such relationships, if they exist, are necessarily mediated by metacognition. Of particular note, the sensorimotor tasks used here primarily reflect the action-to-outcome part of the intention-action-outcome chain, while prospective cues that are known to influence SoA seem to arise from the intention/selection process itself (Haggard, 2017). Moreover, our correlation estimates fall far below the test–retest correlation of the Sense of Agency scale (Tapal et al., 2017), suggesting that there is still much meaningful variance in agency beliefs left to be explained – in all likelihood by factors that are not to be found at the sensorimotor level. Moreover, while the mediation analysis was necessary to tease apart the contributions of first order and of metacognitive sensitivity to predicting agency beliefs, as these two variables were mutually confounding, this analysis was not preplanned; it would be beneficial for future research to replicate these findings in a new sample.

Further, the extent to which the observed correlations are explained by a causal effect of sensorimotor experience on beliefs, rather than of beliefs on sensorimotor experience, remains unclear, as mediation analyses (or any correlational analysis) cannot distinguish between those two causal models, which would give rise to identical partial correlation matrices (Fiedler et al., 2011). In other words, while we can say with some certainty that the observed relationship between control sensitivity and agency beliefs is through metacognition, these data alone cannot tell us whether moment-to-moment agency is driving beliefs or if beliefs influence moment-to-moment agency. In the former direction, a likely interpretation is that only sensory evidence of control to which one has metacognitive access – rather than all the sensory evidence that affects the first order decision – is ultimately incorporated into agency beliefs; this is consistent with the interpretation of the meta-d' measure under signal detection theory as described in Methods (Fleming & Lau, 2014). Conversely, we have more trouble imagining a mechanism by which agency beliefs could impinge upon first order agency judgments in a manner that is mediated by metacognitive sensitivity, as metacognitive reflection/introspection in principle occurs after those first order judgements. Thus, the present authors favor an interpretation in which sensorimotor-level experiences are integrated into declarative beliefs contingent upon metacognitive access, but we want to make clear that is a theoretic interpretation of the data rather than a fact implied by the data themselves.

However, our results clearly show that a (surprisingly) substantial portion of the individual differences in self-agency beliefs are concretely related to the perception of volitional action in a sensorimotor setting, and that the observed relationship is mediated by metacognition. We interpret our findings as pointing toward a model of SoA in which moment-to-moment experiences of agency are aggregated into beliefs contingent upon having metacognitive access to the evidence of control that resulted in those experiences (though we cannot rule out, from our data, the possibility that beliefs instead or also impact agency judgments through metacognition). Recent evidence has suggested that first order agency judgements may not always recruit metacognitive resources, leaving the role of metacognition in the experience of agency unclear (Constant et al., 2022). The present study suggests it may serve a critical function in incorporating experiences of agency into narrative beliefs.

Funding

J.P.V. was supported by the United States National Science Foundation GRFP DGE 1746045 and a Neubauer Family Distinguished Doctoral Fellowship. This study was supported by the United States National Science Foundation BCS 2024923 awarded to H.C.N.

CRediT authorship contribution statement

John P. Veillette: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Letitia Ho:** Writing – review & editing, Software, Investigation, Data curation. **Howard C. Nusbaum:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All code for both the experiment (https://doi.org/10.5281/zenodo.8173285) and the analysis (https://doi.org/10.5281/zenodo.8173282) is permanently archived on Zenodo. Deidentified raw data is available on the Open Science Framework (https://osf.io/753c2/) and is organized roughly according to the Brain Imaging Data Structure specifications for behavioral data to facilitate easy navigation.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2024.103745.

References

Aarts, H., & van den Bos, K. (2011). On the foundations of beliefs in free will: Intentional binding and unconscious priming in self-agency. *Psychological Science, 22*(4), 532–537. https://doi.org/10.1177/0956797611399294

Asai, T., Kanayama, N., Imaizumi, S., Koyama, S., & Kaganoi, S. (2016). Development of Embodied Sense of Self Scale (ESSS): Exploring everyday experiences induced by anomalous self-representation. *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.01005

Bart, V. K. E., Wenke, D., & Rieger, M. (2023). A German translation and validation of the sense of agency scale. *Frontiers in Psychology, 14*, 1199648. https://doi.org/10.3389/fpsyg.2023.1199648

Chambon, V., Filevich, E., & Haggard, P. (2014). What is the Human Sense of Agency, and is it Metacognitive? In S. M. Fleming & C. D. Frith (Eds.), *The Cognitive Neuroscience of Metacognition* (pp. 321–342). Springer. Doi: 10.1007/978-3-642-45190-4_14.

Charalampaki, A., Ninija Karabanov, A., Ritterband-Rosenbaum, A., Bo Nielsen, J., Roman Siebner, H., & Schram Christensen, M. (2022). Sense of agency as synecdoche: Multiple neurobiological mechanisms may underlie the phenomenon summarized as sense of agency. *Consciousness and Cognition, 101*, Article 103307. https://doi.org/10.1016/j.concog.2022.103307

Constant, M., Salomon, R., & Filevich, E. (2022). Judgments of agency are affected by sensory noise without recruiting metacognitive processing. *eLife, 11*, Article e72356. https://doi.org/10.7554/eLife.72356

David, N. (2012). New frontiers in the neuroscience of the sense of agency. *Frontiers in Human Neuroscience, 6*. https://doi.org/10.3389/fnhum.2012.00161

Dennett, D. (1993). *Consciousness explained*. Penguin uk.

Desantis, A., Roussel, C., & Waszak, F. (2011). On the influence of causal beliefs on the feeling of agency. *Consciousness and Cognition, 20*(4), 1211–1220. https://doi.org/10.1016/j.concog.2011.02.012

Di Plinio, S., Arnò, S., & Ebisch, S. J. H. (2024). The state-trait sense of self inventory: A psychometric study of self-experience and its relation to psychosis-like manifestations. *Consciousness and Cognition, 118*, Article 103634. https://doi.org/10.1016/j.concog.2024.103634

Fiedler, K., Schott, M., & Meiser, T. (2011). What mediation analysis can (not) do. *Journal of Experimental Social Psychology, 47*(6), 1231–1236. https://doi.org/10.1016/j.jesp.2011.05.007

Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00443

Frith, C. (1987). The positive and negative symptoms of schizophrenia reflect impairments in the perception and initiation of action. *Psychological Medicine, 17*(3), 631–648. https://doi.org/10.1017/S0033291700025873

Frith, C. (2012). Explaining delusions of control: The comparator model 20 years on. *Consciousness and Cognition, 21*(1), 52–54. https://doi.org/10.1016/j.concog.2011.06.010

Galang, C. M., Malik, R., Kinley, I., & Obhi, S. S. (2021). Studying sense of agency online: Can intentional binding be observed in uncontrolled online settings? *Consciousness and Cognition, 95*, Article 103217. https://doi.org/10.1016/j.concog.2021.103217

Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences, 4*(1), 14–21. https://doi.org/10.1016/S1364-6613(99)01417-5

Gallagher, S. (2012). Multiple aspects in the sense of agency. *New Ideas in Psychology, 30*(1), 15–31.

Galvin, S. J., Podd, J. V., Drga, V., & Whitmore, J. (2003). Type 2 tasks in the theory of signal detectability: Discrimination between correct and incorrect decisions. *Psychonomic Bulletin & Review, 10*(4), 843–876. https://doi.org/10.3758/BF03196546

Gelman, A., & Tuerlinckx, F. (2000). Type S error rates for classical and Bayesian single and multiple comparison procedures. *Computational Statistics, 15*(3), 373–390. https://doi.org/10.1007/s001800000040

Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience, 18*(4), Article 4. https://doi.org/10.1038/nrn.2017.14

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*(4), Article 4. https://doi.org/10.1038/nn827

Hirsh, I. J., & Watson, C. S. (1996). Auditory psychophysics and perception. *Annual Review of Psychology, 47*(1), 461–484.

Hurault, J.-C., Broc, G., Crône, L., Tedesco, A., & Brunel, L. (2020). Measuring the sense of agency: A French adaptation and validation of the Sense of Agency Scale (F-SoAS). *Frontiers in Psychology*, 11. https://doi.org/10.3389/fpsyg.2020.584145

Imaizumi, S., & Tanno, Y. (2019). Intentional binding coincides with explicit sense of agency. *Consciousness and Cognition, 67*, 1–15. https://doi.org/10.1016/j.concog.2018.11.005

Jenkins, A. H. (2001). Individuality in cultural context: The case for psychological agency. *Theory & Psychology, 11*(3), 347–362. https://doi.org/10.1177/0959354301113004

Kruse, E., Lesh, T., Board, S., Carter, C., & Joiner, W. (2022). P588. Exploring the neural correlates of sense of agency deficits in psychosis: A DTI study. *Biological Psychiatry, 91*(9), S327–S328. https://doi.org/10.1016/j.biopsych.2022.02.825

Lush, P., Caspar, E. A., Cleeremans, A., Haggard, P., De Saldanha, M., da Gama, P. A., & Dienes, Z. (2017). The power of suggestion: Posthypnotically induced changes in the temporal binding of intentional action outcomes. *Psychological Science, 28*(5), 661–669. https://doi.org/10.1177/0956797616687015

Lush, P., Roseboom, W., Cleeremans, A., Scott, R. B., Seth, A. K., & Dienes, Z. (2019). Intentional binding as Bayesian cue combination: Testing predictions with trait individual differences. *Journal of Experimental Psychology: Human Perception and Performance, 45*(9), 1206.

Pacherie, E. (2007). The sense of control and the sense of agency. *Psyche, 13*(1), 1–30.

Render, A., & Jansen, P. (2021). Influence of arousal on intentional binding: Impaired action binding, intact outcome binding. *Attention, Perception, & Psychophysics, 83*(1), 103–113. https://doi.org/10.3758/s13414-020-02105-z

Rigoni, D., Kühn, S., Sartori, G., & Brass, M. (2011). Inducing disbelief in free will alters brain correlates of preconscious motor preparation: The brain minds whether we believe in free will or not. *Psychological Science, 22*(5), 613–618. https://doi.org/10.1177/0956797611405680

Sidarus, N., & Haggard, P. (2016). Difficult action decisions reduce the sense of agency: A study using the Eriksen flanker task. *Acta Psychologica, 166*, 1–11. https://doi.org/10.1016/j.actpsy.2016.03.003

Stevens, D. A., & O'Connell, R. J. (1991). Individual differences in thresholds and quality reports of human subjects to various odors. *Chemical Senses, 16*(1), 57–67. https://doi.org/10.1093/chemse/16.1.57

Suzuki, K., Lush, P., Seth, A. K., & Roseboom, W. (2019). Intentional binding without intentional action. *Psychological Science, 30*(6), 842–853. https://doi.org/10.1177/0956797619842191

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition, 17*(1), 219–239. https://doi.org/10.1016/j.concog.2007.03.010

Tanaka, T., Matsumoto, T., Hayashi, S., Takagi, S., & Kawabata, H. (2019). What makes action and outcome temporally close to each other: A systematic review and meta-analysis of temporal binding. *Timing & Time Perception, 7*(3), 189–218. https://doi.org/10.1163/22134468-20191150

Tapal, A., Oren, E., Dar, R., & Eitam, B. (2017). The sense of agency scale: A measure of consciously perceived control over one's mind, body, and the immediate environment. *Frontiers in Psychology, 8*.

Tellegen, A., & Atkinson, G. (1981). Tellegen absorption scale. *Journal of Abnormal Psychology*. https://doi.org/10.1037/t14465-000

Timm, J., Schönwiesner, M., Schröger, E., & SanMiguel, I. (2016). Sensory suppression of brain responses to self-generated sounds is observed with and without the perception of agency. *Cortex, 80*, 5–20. https://doi.org/10.1016/j.cortex.2016.03.018

Tsakiris, M., Prabhu, G., & Haggard, P. (2006). Having a body versus moving your body: How agency structures body-ownership. *Consciousness and Cognition, 15*(2), 423–432. https://doi.org/10.1016/j.concog.2005.09.004

Veillette, J. P., Lopes, P., & Nusbaum, H. C. (2023). *Temporal Dynamics of Brain Activity Predicting Illusory Agency over Involuntary Movements* (p. 2023.05.06.539706). bioRxiv. Doi: 10.1101/2023.05.06.539706.

Wang, S., Rajananda, S., Lau, H., & Knotts, J. D. (2020). New measures of agency from an adaptive sensorimotor task. *Plos One, 15*(12), Article e0244113. https://doi.org/10.1371/journal.pone.0244113

Wen, W., Charles, L., & Haggard, P. (2023). Metacognition and sense of agency. *Cognition, 241*, Article 105622. https://doi.org/10.1016/j.cognition.2023.105622

Wen, W., & Haggard, P. (2018). Control changes the way we look at the world. *Journal of Cognitive Neuroscience, 30*(4), 603–619. https://doi.org/10.1162/jocn_a_01226

Wen, W., & Haggard, P. (2020). Prediction error and regularity detection underlie two dissociable mechanisms for computing the sense of agency. *Cognition, 195*, Article 104074. https://doi.org/10.1016/j.cognition.2019.104074