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Working with an Online Artificial Partner Enhances Implicit and Reduces Explicit Sense of Agency

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A B S T R A C T

A “sense of agency” is the feeling that one is the cause of events in the world. The presence of others has been shown to create a diffusion of responsibility and thus reduce individuals’ explicit ratings of control. This notion has recently been conceptualised as “interfered agency”. The current study investigated both explicit and implicit measures of agency in an *interfered agency paradigm*. In two online experiments, we showed that when being induced to feel that they were working with an artificial virtual agent who could potentially act in a shared task, participants felt less control i.e., explicit measure. We also found greater temporal binding (an implicit measure) implying a stronger sense of agency; that is, the opposite pattern of results compared with the explicit measure. Across the two experiments conducted online, we demonstrated that these effects were due to the implied ability for the partner to act and not an effect of social presence per se. We propose that explicit measures of agency reflect the conscious attribution of responsibility, while implicit measures reflect the strength of the representation of the causal links between action and effect. These data reinforce recent theoretical developments in our understanding of the sense of agency and social agency when working with an artificial partner.

1. Introduction

When an individual acts, they generally feel that they are the instigator of that action and the cause of its effect, a phenomenon known as the sense of agency (Haggard et al., 2002a) . The sense of agency allows us to consciously detect the efficacy that we have over our environment and is sufficiently accurate for self-recognition of our actions (Jeannerod, 2003). Research has extensively studied what factors might moderate the sense of agency, such as predictability and outcome valence i.e., the sense of agency is attenuated for predictable negative compared with predictable positive outcomes (Yoshie & Haggard, 2013); or action choices i.e., a greater number of alternative choices is associated with a stronger sense of agency (Barlas & Obhi, 2013). Furthermore, we often encounter situations in which there are other agents whose actions and outcomes could influence ours and vice versa, thus moderating the sense of agency (Zapparoli et al., 2022). In some cases, activities may require two or more individuals who work together to achieve a common goal i.e., joint action (for example, when you and someone else move a heavy sofa to a new location) (Sebanz et al., 2006). We also encounter particular situations when many individuals could act, though only one person need do so in order to achieve an aim. However, if no action is taken, this may affect the outcomes of the task. Such instances are referred to as the ‘diffusion of responsibility’ phenomenon (Bandura et al., 1975; see the “Bystander Effect”; Darley & Latane, 1968). There are multivarious ways that actions (or indeed potential but *withheld* actions) occur in a social scenario (joint action, co-action, social presence etc.) that could

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evoke sense of agency differently. Accordingly, Silver et al. (2021) proposed a framework and taxonomy for social agency. One prominent subset of social agency that reflects the diffusion of responsibility phenomenon is "interfered agency": a situation when a) the agent whom the participants are working with is independent and can act at will; b) there are no joint actions between the agents; and c) the action effects do not affect other agents. For example, in a crowded place during an emergency, each person could call for help, but individuals may refrain from acting because they may assume that someone else has already done so, thereby illustrating interfered agency. We will be focussing on this particular concept of interfered agency in the current research.

Additionally, our research also factors in two more important elements: nature of the other agent and types of sense of agency. First, with the rapid rise in artificial intelligence and virtual reality, we often interact with artificial and virtual agents. Previous research suggests that the nature of the other agent, whether human or artificial, could influence the sense of agency. For example, Sahaï et al. (2019) found that participants exhibited a vicarious sense of agency and co-represented their partner's actions during joint tasks with another human, but not when partnered with a computer. Similarly, Wen and Imamizu (2022) reviewed evidence that in human–machine joint control (e.g., driving automation, surgical assistance, remote machine operation), the sense of agency often decreases compared with solo control or human–human cooperation. That said, despite this growing literature on human–machine interaction, there is very limited research examining how such effects unfold in *interfered agency* contexts. This gap is especially evident when the other agent is a purely virtual artificial agent, and the interaction is minimal or belief-based rather than physically co-acted. Our study addresses this gap by testing whether the mere believed presence of a virtual artificial agent can alter the sense of agency in interfered agency contexts.

Second, sense of agency can be studied using an explicit measure by self-reported feeling of being in control. It can also be studied through an implicit measure, such as the temporal binding effect. This is the phenomenon where a voluntary action is perceived as occurring later in time and its outcome as happening earlier compared with when the action is not intentional or there is no causal relationship between the action and the effect (Haggard, 2017). To date, little research has been done to investigate both implicit and explicit measures using an interfered agency paradigm in the same design. The current research aims to understand how one's implicit and explicit sense of agency play out in a diffused-responsibility context where there is an artificial agent present who may also act independently of one's own action.

1.1. *Interfered agency*

Interfered agency has been studied in the laboratory in some recent studies, notably by Beyer et al. (2017, 2018). In their work, participants were invited to the lab and tested in mixed-gender dyads. The paradigm was designed to evoke diffusion of responsibility: participants were required to press a button to stop a ball rolling down a slope before it crashed off the end. Each participant was told they were performing the task together with their real in-person co-player, seated in an adjoining room and completing the task simultaneously. In reality, the co-player's in-task actions were preprogrammed to ensure standardised partner behaviour across participants. Their results showed that participants reported less control over the outcome when working with their partner, compared with working alone. This suggests that the presence of another agent attenuates the processing of action outcomes, which could then reduce the sense of agency and responsibility. When another person could also act, we are more likely to consider their potential behaviour, which can slow down or complicate our own decision-making processes. The authors propose that consciously deciding whether to act is more difficult when someone else can also intervene than when acting alone. Therefore, the need to mentalise in social contexts can complicate action selection, leading to a reduced sense of agency when one does decide to act (Sidarus & Haggard, 2016).

The work by Beyer et al. (2017, 2018) was conducted with human–human interaction. But a co-actor need not be human to influence one's sense of agency. Ciardo et al. (2018, 2020) replicated the finding from Beyer et al. (2017, 2018) using a physical robot as the other agent with whom participants interacted. In the task, an on-screen balloon inflated in size and had to be stopped before reaching a pin and bursting. Participants could take action to stop the balloon from bursting by tapping a cube. Their results showed that when working with the robot, participants reported lower ratings of control than when acting alone to stop the balloon inflating, similar to the results from the studies from Beyer and colleagues. Furthermore, Ciardo et al. (2020) demonstrated that this effect did not occur when working with a mechanical pump and that comparable results were found when participants worked with the robot as with a human partner. Their results demonstrate that perceived intentionality of a system might be crucial for the application of social agency mechanisms when working with them (see also Pascolini et al. (2025) for the importance of attributing intentionality to a robot in inducing sense of agency). Our approach aims to extend this result further by merely implying the presence of a virtual agent in online experiments; this reduction in explicit agency may not require the physical presence of an agent – human or robotic – but a known ability to perform an action.

1.2. *Explicit and implicit measures in interfered agency*

The research reviewed above, investigating what we now term 'interfered agency', all employed subjective explicit self-reports of agency. Such measures are highly valuable and are well-validated. However, implicit measures can provide a complementary approach. One, temporal binding effect (i.e., the compression of perceived time between a voluntary action and its outcome) has been widely used as a measure of the implicit sense of agency (Haggard, 2017; Le Besnerais et al., 2024). It is worth noting that whether temporal binding is an appropriate proxy for the sense of agency remains debated. Evidence from studies on causal event chains without intentional action (e.g., Buehner, 2012; Kirsch et al., 2019) and from findings showing similar binding effects for involuntary and voluntary movements (Suzuki et al., 2019; but see Wiesing & Zimmermann (2024) for contrary findings) suggests that intentionality is not necessary for temporal binding to occur. These results indicate that causality, rather than intention, may be the primary driver of the effect. In relation to time and body perception, it is highlighted that temporal perception in general contributes to the sense of being an agent, suggesting the limits of using temporal binding as a pure measure of intentionality (Ciaunica et al., 2024). Nonetheless, it has been proposed that in voluntary action contexts, temporal binding remains a valid marker of implicit agency, provided that causality between events is carefully controlled (Scott et al., 2022). Comparing an agentic condition with an appropriate non-agentic control condition can reveal a component of binding specifically attributable to intentional action, over and above other factors (Borhani et al., 2017). In the present study, we therefore included a carefully matched control/baseline condition to allow appropriate comparisons of temporal binding effects between conditions. We thus use temporal binding as a proxy for implicit agency while acknowledging its limitations and the ongoing debate.

Importantly, following the two-step account of agency by Synofzik et al. (2008), we distinguish between two related but conceptually distinct aspects: the sense of causing an event (a lower-level, non-conceptual *feeling of agency*, i.e., the background sense of authorship for voluntary actions without explicit reflection) and the sense of being in control (a higher-order *judgment of agency*, i.e., explicit evaluations of control over outcomes). In this framework, temporal binding is taken to capture the lower-level sense of causing an event, whereas explicit self-reports are thought to index the higher-order sense of being in control.

Some studies have found that explicit agency and temporal binding often dissociate (Dewey & Knoblich, 2014; Pfister et al., 2021), reflecting the aforementioned distinctive processes. Explicit measures may reflect judgment of agency that depend on higher-level *meta*-cognitive processes with conscious access to the contextual information retrieved from the events. In contrast, temporal binding may reflect a pre-reflective and low-level feeling of being the author of an action that results from sensorimotor cues and does not rely upon conscious awareness. Furthermore, temporal binding has been shown to increase when presented in a social context (Vogel et al., 2021). These considerations make it challenging to denote whether the social context (Beyer et al. 2017, 2018) and human-robot interactions as observed in (Ciardo et al. 2018, 2020) would influence the implicit sense of agency in the same way that they do to one's explicit judgment of agency. A natural extension of such research is understanding whether the believed presence of another agent, particularly a virtual artificial agent, can affect temporal binding in the same way that it affects explicit agency.

1.3. The current study

Here, we sought to replicate and extend the work of Beyer et al. (2017, 2018) and Ciardo et al. (2018, 2020). Unlike these previous studies, which measured only explicit agency, we also measured temporal binding as an implicit measure of agency. In both experiments, we implemented a task in which a circle could be stopped from inflating by either the participant or another agent, providing a way to study interfered agency effects. Participants either worked alone or they were told they were working together with "Bobby" i.e., the virtual artificial partner who could also act to stop the circle from increasing in size. The behaviour of "Bobby" was in fact preprogrammed. This paradigm aims to modestly evoke some diffusion of responsibility since when working with the agent, one need not necessarily act since "Bobby" might stop the task before the loss of all points. Participants always lost points, but they would lose the most points if no one acted at all to stop the circle. Thus, in this paradigm, the best strategy to avoid the worst outcome (losing the most points) would be to continuously monitor the circle's size and be ready to act as soon as it gained significant scale and to take proactive action to stop the circle from increasing in size. At the end of each trial, we measured both implicit sense of agency via the temporal binding effect as well as explicit agency via self-reported ratings of feeling in control over the outcome of each trial.

With our explicit measure, we hypothesised that we should replicate Ciardo et al., (2018, 2020)'s findings that participants would report a lower feeling of being in control when working with the artificial virtual partner "Bobby" (Experiment 1) compared with working alone, despite the fact that "Bobby" held no physical presence (recall that Ciardo et al. (2018, 2020) used a physically present robot). In Experiment 2, we included a condition where "Bobby" was present but could not act. We predicted that the importance of intentionality in Ciardo et al. (2018, 2020) would be replicated: reduced explicit agency would only be observed when the artificial virtual partner could act but not when "Bobby" was merely present and unable to intervene. Concerning implicit sense of agency, since to our knowledge no studies have measured the temporal binding effect in a similar paradigm, our hypotheses on the magnitude of the temporal binding effect in working alone versus when working with the virtual partner who could also act (not just mere presence) remained open. If our social context manipulations affect different agency-related processes in a similar way, then temporal binding may be modulated in a similar manner to the explicit measures. However, if social context affects the conscious and sensorimotor processing of action in divergent ways as noted has been observed previously in other paradigms, we may find the measures diverge. The current study thus could help contribute to further understanding of the mechanisms driving both implicit and explicit measures of agency by using this subtle manipulation of social context.

Note that we also included the Individual Differences in Anthropomorphism Questionnaire (IDAQ; Waytz et al., 2010) to explore whether individual variation in the tendency to attribute human-like characteristics to non-human agents modulates the impact of the social context manipulation. Higher levels of anthropomorphism might be associated with stronger interference effects on both explicit and implicit measures of agency when participants interacted with the virtual artificial partner.

2. Experiment 1

In this online experiment, we employed similar methodologies as used by Ciardo et al. (2020) and Beyer et al. (2017, 2018) whereby a circle started enlarging in size which should be stopped before turning red. Participants either worked alone, or together with a virtual artificial partner "Bobby" who could also act to stop the circle enlarging, or participants merely observed the circle stop growing automatically. On the screen, the participant was represented by a straight-faced avatar, while the virtual artificial partner

"Bobby" was represented by a smiling avatar (see Fig. 1A). The avatars served as visual representations of self and partner, facilitating participants' sense of embodiment as well as the believability of the virtual artificial partner (Woźniak et al., 2023). "Bobby" was in fact a computer program whose behaviour was pre-determined. All participants took part in the three conditions (Baseline, Alone, Together) and we measured both participants' implicit sense of agency via the interval reproduction paradigm and explicit agency through self-reported ratings.

2.1. Method

2.1.1. Participants

One hundred and forty-two participants (*M*age = 29.50 years, *SD* = 7.45 years, 49 men, 2 non-binary) were recruited from Prolific (https://www.prolific.co) and paid £2.70 for their participation (at a rate of £8 an hour). Ciardo et al. (2020) estimated that the lower sense of control effect due to working with an artificial virtual partner compared to working alone is $d = 0.6$. With our sample size, we have an estimated power of 1 to replicate this result. If the effect is only half as large as what was reported by Ciardo et al., our design still has power of 0.9. Ethical approval for all experiments in this study was granted by the ethics committee at the School of Psychology, University of East Anglia.

2.1.2. Materials

PsychoPy3 (Peirce et al., 2019) was used to create the experiment hosted on Pavlovia.org. The avatar of "Bobby" was a smiling emoji, and participants' own avatar was a straight-faced emoji (see Fig. 1A).

The explicit agency ratings were measured through a 1–100 slider where the far left of the slider had the label "No Control" and the far-right label stated "Full Control". Tones that were used in the temporal binding task were created using the *Sound* class with PTB library in PsychoPy with duration = 150 ms, sample rate = 44100 Hz, bitrate = 16 parameters, these tones were a) 440 Hz tone when participants stopped the circle successfully; b) 131 Hz tone when no one stopped the circle, and it turned red and c) 220 Hz tone when the partner stopped the circle. The circle size was measured in 'height' units of PsychoPy. The initial circle size started at 0.30 circle

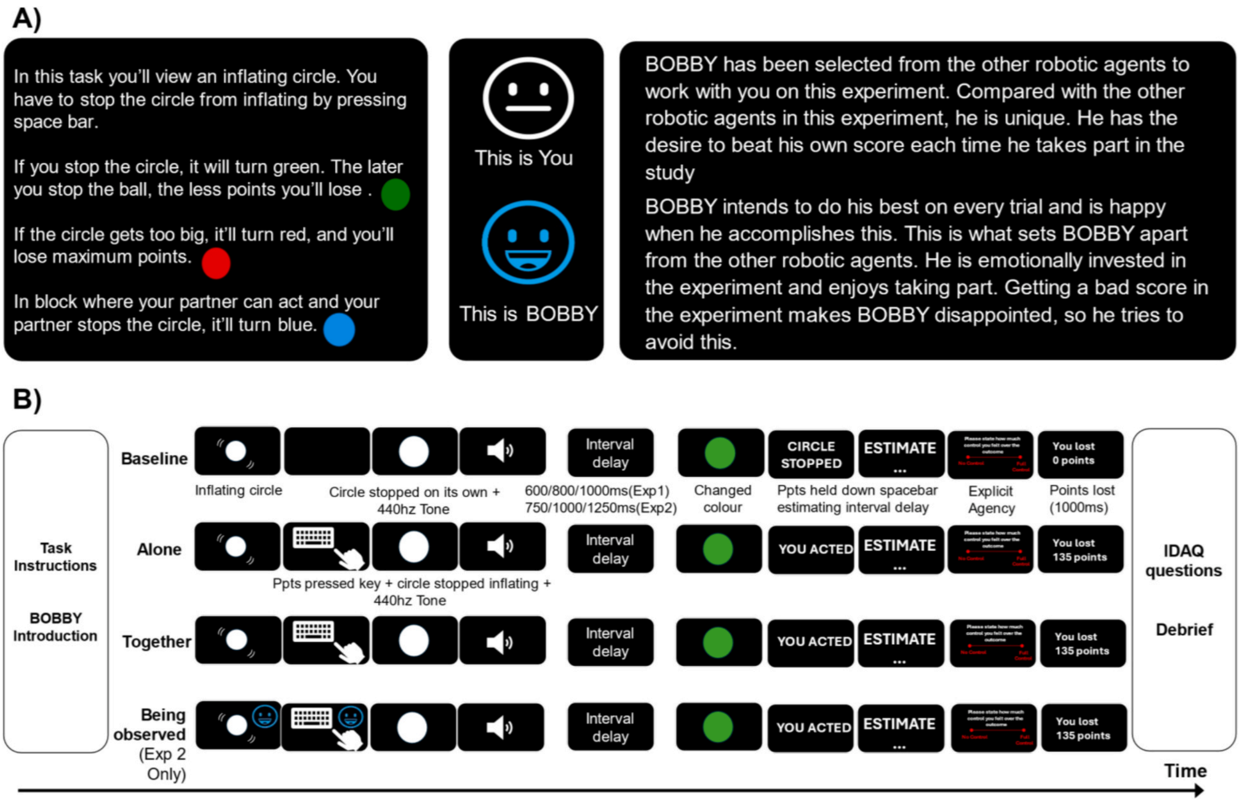

Fig. 1. A) Timeline of avatars and "Bobby" introduction. The figure illustrates the sequence in which participants were introduced to their own avatar and the virtual partner "Bobby," including the texts shown to participants describing Bobby before the experiment began. B) Illustration of the repeated-measure experimental procedure for both Experiment 1 and 2. Note that only Experiment 2 had the Being Observed condition. Trial timeline always shows example of where participants acted. For the interval reproduction task, participants held down space bar to reproduce the interval elasped between the tone and the circle changed its colour. *Note.* Ppts = Participants; Exp1 = Experiment 1; Exp2 = Experiment 2; IDAQ = Individual Differences in Anthropomorphism Questionnaire.

size (i.e., 30 % of the screen height) and its maximum size was 0.80 (i.e., 80 % of the screen height). We also utilised the 30-item Individual Differences in Anthropomorphism Questionnaire (IDAQ) to measure how participants might differ in attributing moral concern, responsibility, trust and social influence towards non-human agents ('To what extent does technology – devices and machines for manufacturing, entertainment, and productive processes (e.g. cars, computers, television sets) – have intentions.' on a 11-point Likert scale where 0 = Not at all; 10 = Very much).

2.1.3. Design

The experiment had a single factor, repeated-measures design, with the three-level independent variable *Partner*: Baseline, Alone and Together; conducted in pseudorandomised blocks using a 3x3 Latin square design to present each order of the sequence across all participants. We measured two dependent variables in the experiment. One was the subjective temporal compression between two events (temporal binding). It is worth noting that in the Alone and Together conditions, the temporal binding scores were only calculated based on trials where the participants had acted. Lower scores reflect stronger temporal binding, which corresponds to a greater implicit sense of agency. The second dependent variable was the explicit rating of agency, measured by asking participants to rate how much control they felt over the outcome on a 1–100 slider. Higher ratings indicate a greater sense of explicit agency reported by the participants. Thus, an increase in implicit agency is reflected by *lower* temporal binding scores, whereas an increase in explicit agency is reflected by *higher* agency ratings.

2.1.4. Procedure

Before the online experiment began, participants gave consent and completed a technical check. They were asked to adjust the volume on their computer speakers to a comfortable listening volume as a repeating tone sounded. Participants then saw the task instructions. They were afterwards introduced to their own avatar and the avatar of their partner who was "Bobby", the virtual artificial partner (see Fig. 1A). The way in which Bobby was introduced and described was to facilitate participants' engagement with Bobby and make it more likely that participants perceived Bobby as an intentional agent (see also Pascolini et al., 2025).

Each block comprised 24 experimental trials preceded by 3 practice trials (72 main trials plus 9 practice trials in total). In the Alone condition, participants would only see their own avatar on the left of the screen. In the Together condition, participants would see their own avatar on the left and their partner's avatar on the right. In the Baseline condition, no avatar was presented as participants were simply observing the circle stopping on its own. Next, a white circle appeared in the centre of the screen (see Fig. 1B). After 1000 ms, the circle began increasing in diameter. The participants were instructed to stop this circle enlarging by pressing space. They were told that the later they stopped the circle, the fewer points they would lose. However, if they stopped the circle too late and the circle turned red, they would lose maximum points. To make the task less predictable, the point at which the circle turned red varied randomly within the last 14 % of the circle enlarging. In the Alone condition, participants worked alone without the possibility of their partner stopping the circle. If participants stopped the circle successfully, a 440hz tone would occur at the time of their keypress. The circle would then turn green after a stimulus onset asynchrony of 600 ms, 800 ms, or 1000 ms. These interval lengths occurred at random and were evenly distributed among blocks so that each interval length was presented to participants 8 times per condition. If participants did not stop the circle, a 131hz tone would occur and the circle would turn red after the same interval periods. In the Together condition, the participants' partner could also act during the trial. "Bobby" was programmed and set to respond on 30 % of trials and only acted if the circle had increased to above 80 % of its maximum size. This threshold was set to align Bobby's behaviour with the task's optimal performance (acting just before the circle turned red so as to lose the least points). If the participant's partner acted, a 220hz tone would be produced and the circle would turn blue after the set interval lengths. In the Baseline condition, participants simply observed the circle stopping on its own. In these trials, the circle stopped itself 100 % of trials and when it stopped, a 440hz tone occurred and the circle's colour turned green. This was to ensure that the Baseline condition matched the trials where the participant successfully acted in the Alone and the Together conditions.

Participants were then told how many points they had lost (displayed for 1000 ms). Afterwards, irrespective of whether the participant acted, the partner acted, or neither acted, participants were presented with a screen that stated who acted. Participants were then presented with a screen stating "estimate…" and were asked to estimate the time between the tone occurring and the shape changing colour by holding down the spacebar for the same amount of time that they thought had elapsed from when they had heard the tone to when the circle changed its colour. On trials with estimates < 100 ms, an instruction screen was displayed to remind them of the task that participants must hold down the space bar rather than merely press it. After the temporal estimation, participants were asked to rate how much control they felt they had over the outcome. After the main experiment finished, participants were brought to a brief survey that asked demographic questions, the Individual Differences in Anthropomorphism Questionnaire (IDAQ), and the debriefing sheet.

2.2. Results

Note that the data were analysed with both frequentist and Bayesian statistics so as to provide complementary statistical evidence using conventions whereby $1/3 < BF_{10} < 3$ implies that the data are similarly likely under the H_1 and H_0. A $BF_{10} < 1/3$ or > 3 is interpreted as supporting H_0 and H_1, respectively (Dienes, 2011). All BFs were computed using SPSS v.31 with the exception of Bayesian linear regression analyses being computed using R package *rstanarm.*

2.2.1. Exclusion criteria and manipulation Checks

To control rate of change of the circle expansion, only participants running a 60 Hz refresh rate screen were retained (13 participants excluded). Trials where temporal estimations were more than 3*SD*s from an individual subject's mean across all experimental conditions or were less than 100 ms were removed from analysis (4 % of total trials). Trials where the participants did not act in the Alone and Together conditions were then removed (18 % of total trials). Finally, 6 participants were removed from the analysis because they acted on fewer than 8 trials in either the Alone or Together conditions. This criterion removed participants who failed to respond in at least two-thirds of the total trials. Since the experiments were conducted online, this helps ensure that the analysis reflects participants who appropriately engaged with the task. Therefore, 123 participants remained for analysis.

As this is, to our knowledge, a rare example of an interval estimation task conducted online, we wanted to confirm overall estimates scaled with the veridical interval, supported by a one-way repeated measures ANOVA $F(2, 244) = 39.21$, MSE = 0.19, $p < 0.001$, $\eta_p^2 = 0.243$, $BF_{10} > 1000$. Participants' interval estimations increased as the stimulus-onset-asynchrony increased from 600 ms ($M = 740$ ms, $SD = 290$ ms), 800 ms ($M = 770$ ms, $SD = 280$ ms) and 1000 ms ($M = 820$ ms, $SD = 300$ ms) (smallest $t(123) = 4.30$, all $ps < 0.001$, all $BF_{10}s \geq 250$).

2.2.2. *Temporal binding*

For each of the remaining participants, mean proportional interval reproduction was calculated by dividing the reproduced time interval by the actual time interval. Scores equal to 1 indicate perfect reproduction, scores greater than 1 indicate overestimation, and scores less than 1 indicate underestimation (i.e., temporal binding). (Pascolini et al., 2021; Stephenson et al., 2018; Imaizumi & Tanno, 2019). Temporal binding scores in the Alone and Together conditions were based only on trials where participants acted.

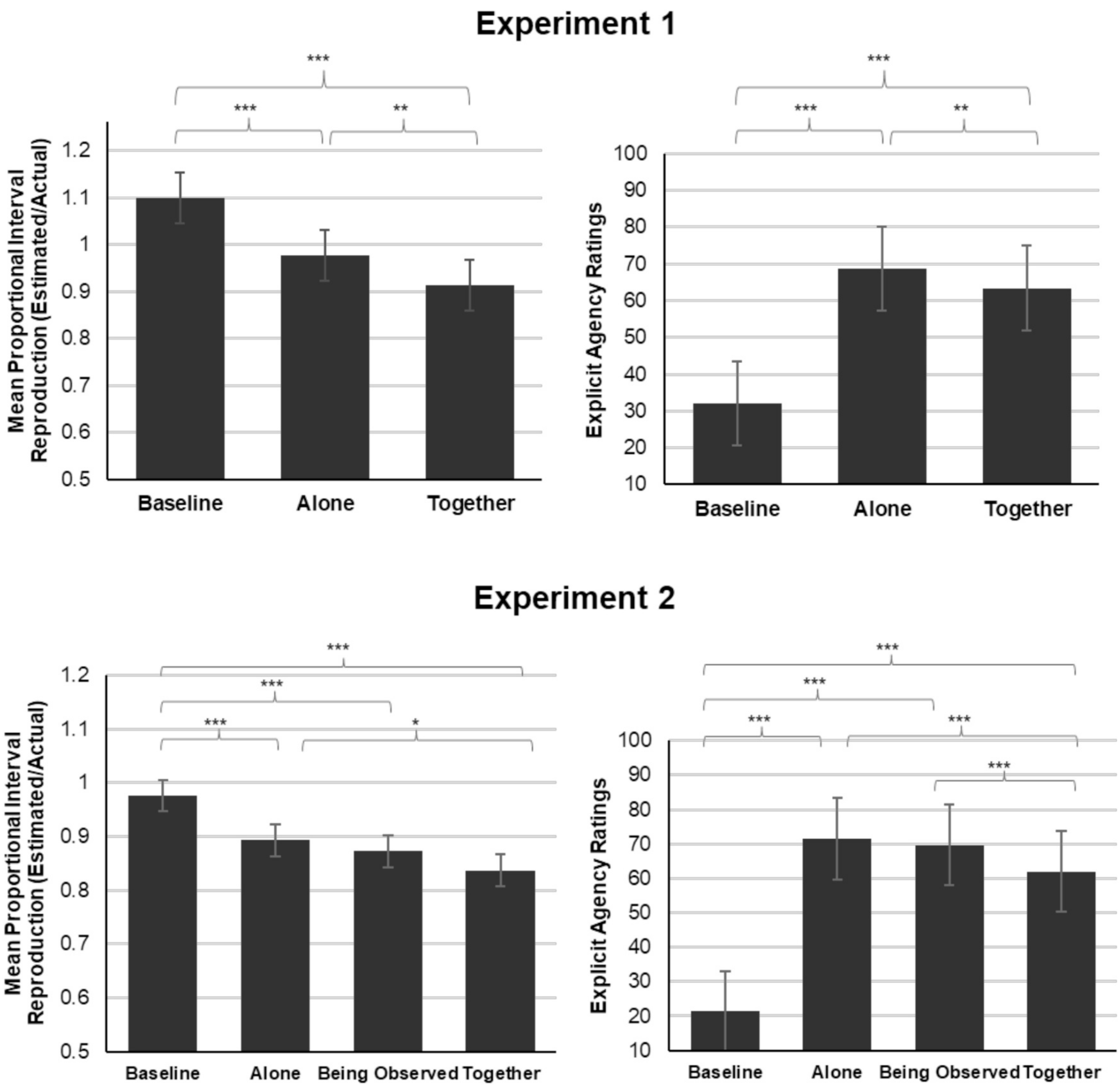

Fig. 2. Results for Experiments 1 and 2. Graphs on the left illustrate the mean proportional interval reproduction (Estimated/Actual) (i.e., temporal binding). Graphs on the right show explicit agency ratings. Error bars represent standard errors. Statistically significant differences within an experiment and measure have been denoted with asterisks on the graphs with ***$p < 0.001$, **$p < 0.01$ and *$p < 0.05$.

A one-way repeated-measures ANOVA with *Partner* (Baseline v. Alone v. Together) as the factor showed a significant effect on the mean proportional interval reproduction, $F(2, 244) = 25.51$, MSE = 1.10, $p < 0.001$, $\eta_p^2 = 0.173$, $BF_{10} > 1000$.

Paired t-tests showed that participants' proportional interval reproduction scores were significantly lower in the Together condition ($M = 0.91$, $SD = 0.36$) and the Alone condition ($M = 0.98$, $SD = 0.39$) compared with the Baseline condition ($M = 1.10$, $SD = 0.44$), $t(122) = -6.54$, $p < 0.001$, $d = 0.59$, $BF_{10} > 1000$; and $t(122) = -4.52$, $p < 0.001$, $d = 0.41$, $BF_{10} > 1000$ respectively (Fig. 2). This confirms that the temporal binding effect was replicated in this online experiment (Humphreys & Buehner, 2010; Haggard et al., 2002b).

Furthermore, the proportional interval reproduction scores were also significantly smaller in the Together condition compared with the Alone condition: $t(122) = -2.69$, $p = 0.008$, $d = 0.24$, $BF_{10} = 2.31$, with the Bayes factor suggesting anecdotal evidence (Fig. 2). This means that there was stronger temporal binding in the Together than the Alone condition, implying stronger implicit sense of agency in the Together condition than when participants were working alone.

2.2.3. Explicit agency ratings

A one-way repeated measures ANOVA was conducted to examine the effect of *Partner* (Baseline v. Alone v. Together) on the explicit agency and the effect was significant $F(2, 244) = 91.37$, 48185.80, $p < 0.001$, $\eta_p^2 = 0.428$, $BF_{10} > 1000$.

Paired t-tests showed that participants rated their control in the Baseline condition lower ($M = 32.07$, $SD = 32.23$) than both the Alone ($M = 68.66$, $SD = 26.35$, $t(122) = -10.23$, $p < 0.001$, $d = 0.92$, $BF_{10} > 1000$) and Together ($M = 63.45$, $SD = 23.26$, $t(122) = -9.85$, $p < 0.001$, $d = 0.88$, $BF_{10} > 1000$) conditions (Fig. 2).

Participants' agency ratings were also lower in the Together condition compared with the Alone condition, $t(122) = -3.12$, $p = 0.002$, $d = 0.28$, $BF_{10} = 7.52$ (strong evidence). This implies that, consistent with Beyer et al, participants felt less control in the Together condition compared with the Alone or Baseline conditions (akin to diffusion of responsibility). However, the temporal binding effect in the Together condition exhibited the reverse pattern.

2.2.4. Further analyses

We further explored whether there was a relationship between agency when acting with a virtual artificial partner and the degree to which participants imbued "Bobby" with mentalistic capabilities. However, we found no correlations between IDAQ scores (Waytz et al., 2010) and explicit agency ratings $r(121) = -0.04$, $p = 0.680$, $BF_{10} = 0.07$; or between IDAQ and temporal binding, $r(121) = 0.05$, $p = 0.591$, $BF_{10} = 0.07$.

We also conducted analyses on the percentage of times the participants acted and found that participants acted significantly more often in the Alone condition ($M = 82.47$ %, SD = 15.49 %) compared with when working with "Bobby" ($M = 68.35$ %, $SD = 13.04$ %, $t(122) = 10.60$, $p < 0.001$, $d = 0.95$, $BF_{10} > 1000$). However, to further assess whether the percentage of times acted would influence agency ratings in the Alone and Together conditions, we conducted a multiple regression analysis with interaction terms between Condition (Alone v. Together) and percentage of times acted as predictors on explicit agency ratings. The overall model was not statistically significant, $F(2, 243) = 1.83$, $p = 0.162$. Neither the number of times acted in the Alone condition ($\beta = 0.08$, $p = 0.436$) nor in the Together condition ($\beta = 0.01$, $p = 0.934$) were significant predictors of agency ratings. We also conducted Bayesian linear regression analyses in addition to the frequentist regressions. Note that all Bayesian regression analyses reported in the study were conducted using the R package *rstanarm* for Bayesian applied regression modelling (Muth et al., 2018). A Bayesian linear regression with similar predictors above also showed that neither predictor had a meaningful effect (Together: posterior mean = 0.0, Alone: posterior mean = 0.1, all 95 % CIs overlapped 0.0), with excellent convergence (Rhat = 1.0, n_eff > 3700).

Likewise, we conducted a multiple regression with similar predictors but with the temporal binding effect as the dependent variable. We found similar results that the model was not significant $F(2, 243) = 0.79$, $p = 0.454$, $R^2 = 0.006$ and both percentage of times acted in Alone condition ($\beta = 0.0002$, $p = 0.875$) and in Together condition ($\beta = -0.0006$, $p = 0.756$) did not significantly predict the magnitude of temporal binding. A Bayesian linear regression confirmed these results: posterior means were effectively zero with a narrow 95 % CI, and MCMC diagnostics indicated excellent convergence (Rhat = 1.0, n_eff > 4000), indicating that variation in number of times acted did not meaningfully influence temporal binding. Together, these findings indicate that we found no meaningful evidence that the percentage of times participants acted influenced either explicit or implicit measures of agency in this experiment.

2.3. Discussion

In this experiment, we examined how social context influences both explicit and implicit measures of agency. Building on the work of Beyer et al. (2017, 2018) and Ciardo et al. (2018, 2020), we used a task in which participants attempted to stop a circle from enlarging to avoid losing points with three conditions: participants either acted alone, worked with a virtual partner ("Bobby") who could also intervene, or observed the circle stopping automatically. Like these previous studies, we found that participants' agency ratings were lower when working with their partner compared with working alone. As expected, explicit agency ratings were lowest in the Baseline condition, where they were told to observe their partner performing the task and could not stop the circle themselves. These results suggest that explicit agency is reduced when working with a partner and is lowest when participants cannot control the outcome of an event. With the implicit measure of agency, we found that participants underestimated their temporal reproductions in the Together condition more strongly compared with the Alone condition. This suggests that participants' implicit agency was in fact stronger when working with a partner. Implicit and explicit measures of the sense of agency do not always correlate and are often seen to dissociate (Dewey & Knoblich 2014; Pfister et al., 2021).

3. Experiment 2

In our second experiment, we aimed to replicate Experiment 1 to confirm the general pattern of findings with a few lines of inquiry. First, we amended the stimulus-onset-asynchrony after the participant stopped the circle to 750 ms, 1000 ms, 1250 m because in Experiment 1, participants were rather inaccurate in reproducing the interval when it was at 600 ms in the Baseline condition ($M_{\text{estimated}} = 740$ ms, $SD = 290$ ms). Second, we wanted to test if the temporal binding effect was enhanced only when the virtual and artificial partner could also act; or whether their mere implied presence might be sufficient to induce the enhanced binding effect as observed in Experiment 1. To do so, we added an extra condition called Being Observed. In this condition, participants acted alone but they were told that "Bobby" would be observing them. Therefore, in this experiment, all participants took part in the same task as before to stop the circle from enlarging with four conditions: Baseline, Alone, Being Observed, and Together.

3.1. Method

3.1.1. Participants

One hundred and ten participants (Mage = 30.87, $SD = 6.66$, 32 men) were recruited from Prolific (https://www.prolific.co) and paid £2.70 for their participation (at a rate of £8 /hour).

3.1.2. Materials

The materials were identical to those used in Experiment 1, with one modification that in the additional Being Observed condition, the avatar of "Bobby" was displayed in the top-right corner of the screen (see Fig. 1B).

3.1.3. Design

The design of this experiment was based on Experiment 1. The difference in this Experiment 2 was that we added the Being Observed condition. Therefore, we had a single factor repeated-measures design with the independent variable of *Partner* (Baseline, Alone, Being Observed, Together) and the blocks were also pseudorandomised using the 4x4 Latin square approach. The dependent variables for each condition were the proportional reproduction errors and explicit agency ratings.

3.1.4. Procedure

The procedure for this experiment was largely the same as Experiment 1. The main change was the additional inclusion of the Being Observed condition, wherein participants acted alone but they were told that "Bobby" would be observing them as they performed the task. To reinforce this idea, the avatar of "Bobby" was shown in the top right of the screen while the circle was increasing in size. The avatar disappeared after the participant stopped the circle.

Another change was the interval delays between the tone and the circle changing colour. In Experiment 1, these delays were 600 ms, 800 ms, and 1000 ms, and they were adjusted to 750 ms, 1000 ms, and 1250 ms in the current experiment. Participants performed each condition in blocks. Participants completed 96 main trials plus 12 practice trials in total, with 3 practice trials for each condition and 24 trials for each condition in the main experiment.

3.2. Results

3.2.1. Exclusion Criteria and manipulation Checks

The same exclusion criteria that were used in Experiment 1 were applied here. One participant was excluded from the analysis as they contributed fewer than 8 trials in any condition, indicating insufficient engagement with the task. Seven participants were removed as they did not use a 60*hz* monitor. Therefore, 102 participants remained for analysis. Like in Experiment 1, a repeated-measures ANOVA revealed a significant effect of temporal gap on interval estimations ($F(2, 202) = 52.02$, MSE = 0.51, $p < 0.001$, $\eta_p^2 = 0.40$, $BF_{10} > 1000$). Paired t-tests indicated that interval estimations were progressively longer as the stimulus-onset-asynchrony increased: 750 ms ($M = 810$ ms, $SD = 350$ ms), 1000 ms ($M = 880$ ms, $SD = 360$ ms), and 1250 ms ($M = 950$ ms, $SD = 370$ ms) (smallest $t(101) = 4.85$, all $ps < 0.001$, all BF_{10}s > 1000).

3.2.2. Temporal binding

A one-way repeated-measures ANOVA was conducted to examine the effect of *Partner* (Baseline, Alone, Being Observed, Together) on the mean proportional reproductions and the results suggested that there was a significant main effect of *Partner* ($F(3, 303) = 15.66$, MSE = 0.36, $p < 0.001$, $\eta_p^2 = 0.134$, $BF_{10} > 1000$).

Paired t-tests were conducted, and we found no significant difference between the Alone ($M = 0.89$, $SD = 0.40$) and Being Observed condition ($M = 0.87$, $SD = 0.38$) ($t(101) = 1.43$, $p = 0.156$, $d = 0.14$, $BF_{10} = 0.15$ i.e., substantial evidence supporting H_0) but a significant difference between the Alone and the Together conditions ($M = 0.84$, $SD = 0.36$) ($t(101) = 2.87$, $p = 0.005$, $d = 0.28$). For the Alone vs. Together contrast, which was measured in the same way across both experiments, accumulated evidence resulted in a $BF_{10} = 3$, indicating support for the difference. Lastly, no significant difference was found between the Being Observed and Together conditions: $t(101) = 1.15$, $p = 0.202$, $d = 0.20$, $BF_{10} = 0.33$ supporting H_0 (Fig. 2).

3.2.3. Explicit agency ratings

A one-way repeated measures ANOVA was conducted, showing a significant main effect of *Partner* on the explicit ratings of agency,

$F(3, 303) = 144.89$, MSE = 56697.49, $p < 0.001$, $\eta_p^2 = 0.589$, $BF_{10} > 1000$.

We conducted paired t-tests and found that there was no significant difference in agency ratings between the Alone ($M = 71.56$, $SD = 26.12$) and Being Observed conditions ($M = 69.74$, $SD = 25.68$) ($t(101) = 1.32$, $p = 0.190$, $d = 0.13$, $BF_{10} = 0.19$ supporting H_0). For the Alone vs. Together ($M = 61.98$, $SD = 23.61$) contrast of explicit agency, which was measured similarly across both experiments, cumulative evidence yielded $BF_{10} > 1000$ ($t(101) = 6.10$, $p < 0.001$, $d = 0.58$). Finally, participants rated their agency lower in the Together condition compared with the Being Observed condition. $t(101) = -4.34$, $p < 0.001$, $d = -0.43$, $BF_{10} = 500$ (see Fig. 2).

3.2.4. Further analyses

Similar to Experiment 1, we also conducted analyses to examine the effect of *Partner* (Alone, Together, Being Observed) on the percentage of times the participants acted. Results of a one-way ANOVA showed that there was a significant main effect of *Partner* ($F(2, 202) = 19.03$, MSE = 0.138, $p < 0.001$, $\eta_p^2 = 0.233$, $BF_{10} > 1000$). Follow up paired t-tests suggested that participants did not act more in the Being Observed ($M = 83.06$ %, $SD = 11.18$ %) compared to the Alone condition ($M = 82.52$ %, SD = 12.49 %, $t(101) = 0.44$, $p = 0.66$, $d = 0.04$, $BF_{10} = 0.08$) but participants acted significantly more often in Alone and Being Observed conditions compared with when working with "Bobby" ($M = 65.57$ %, $SD = 16.42$ %, smallest $t(101) = 11.20$, $p < 0.001$, $d = 1.11$, $BF_{10} > 1000$).

Like Experiment 1, we also assessed whether the number of times acted would influence explicit agency ratings in Alone, Being Observed and Together conditions, thus a multiple regression analysis was conducted with Condition × number of times acted i.e., their interaction terms as predictors. The overall model was statistically significant, $F(5, 300) = 3.76$, $p = 0.002$, but explained only a small proportion of the variance in agency ratings ($R^2 = 0.059$). Neither the interaction effects between the percentage of times acted with conditions (Alone: $\beta = 0.24$, $p = 0.234$; Being Observed: $\beta = 0.31$, $p = 0.301$; Together: $\beta = 0.02$, $p = 0.946$) were significant predictors of agency ratings. A Bayesian linear regression with similar predictors also showed no meaningful effect of any predictor. Posterior means were near zero for Together (mean = -0.1) and Alone (mean = 0.0) and modest for Being Observed (mean = 0.4), with all 95 % CIs overlapping zero. MCMC diagnostics indicated excellent convergence (Rhat = 1.0, n_eff > 3000).

Similarly, a multiple regression with the same predictors but with the temporal binding effect as the dependent variable was also analysed. Results showed that the model was non-significant, $F(5, 300) = 1.20$, $p = 0.309$, $R^2 = 0.020$, and there were no significant interaction effects between Condition and the number of times acted on the magnitude of temporal binding (Alone: $\beta = 0.24$, $p = 0.234$; Being Observed: $\beta = 0.31$, $p = 0.301$; Together: $\beta = 0.02$, $p = 0.946$. The Bayesian linear regression also showed no evidence for any effect. Posterior means for all predictors were effectively zero (mean = 0.0; 95 % CIs overlapped 0.0), and all MCMC diagnostics indicated excellent convergence, Rhat = 1.0, n_eff > 3700. Thus, the frequency with which participants acted did not significantly moderate the relationship between condition and explicit or implicit agency. Together with the explicit agency findings, these results suggest that the percentage of times participants acted had minimal impact on either implicit or explicit measures of agency in this experiment.

3.3. Discussion

Compared to Experiment 1, we replicated both diverging effects of explicit and implicit agency. Regarding explicit agency, participants reported more control when working alone compared with working with "Bobby". We also found that participants rated similar feelings of control when working alone and when "Bobby" was observing but could not act. Furthermore, agency ratings were lower in the Together condition compared with the Being Observed condition. This would suggest that the presence of a partner was not sufficient to influence participants' explicit judgment of agency and only when the partner could act should explicit agency be decreased.

With implicit agency, temporal binding was significantly greater in the Together condition than in Alone condition, like in Experiment 1. Additionally, this experiment showed that temporal binding did not appear meaningfully different when the partner was merely present (Being Observed). Such results suggested that the increase in implicit agency was contingent on the virtual artificial "Bobby" being able to act rather than simply being present. Altogether, these findings reinforce the diverging effects observed across measures: explicit agency decreased and implicit agency increased when working with the virtual partner. Both effects were not driven solely by the mere presence of the partner but were instead contingent on the partner being able to act during the task (Zajonc, 1965).

4. Exploratory analysis: Repeated-measures MANOVA with both explicit and implicit measures as outcome variables

Throughout the study, the temporal binding effect and explicit agency ratings have been tested separately and we observed opposite patterns of these outcomes across conditions. However, we have not conducted direct comparisons of how different conditions influenced the two dependent variables (explicit and implicit agency). That is, the opposite patterns of increased temporal binding v. decreased explicit agency when working with the virtual artificial partner compared with alone was not formally tested. As a result, we conducted repeated-measure MANOVAs for both experiments with two independent variables *Partner* (Baseline, Alone, Together in Experiment 1; Baseline, Alone, Together, Being Observed in Experiment 2) and *Measure* (Implicit, Explicit) on two dependent variables (temporal binding effect and explicit agency rating).

Across both experiments, the multivariate tests revealed robust main effects of *Partner* (Experiment 1: Pillai's Trace = 0.467, $F(2, 121) = 52.98$, $p < 0.001$, $\eta p^2 = 0.47$; Experiment 2: Pillai's Trace = 0.661, $F(3, 99) = 64.34$, $p < 0.001$, $\eta p^2 = 0.66$) and *Measure* (Experiment 1: Pillai's Trace = 0.878, $F(1, 122) = 881.69$, $p < 0.001$, $\eta p^2 = 0.88$; Experiment 2: Pillai's Trace = 0.891, $F(1, 101) = 823.55$, $p < 0.001$, $\eta p^2 = 0.89$). Notably, both analyses showed significant *Partner* × *Measure* interactions (Experiment 1: Pillai's Trace = 0.470, $F(2, 121) = 53.75$, $p < 0.001$, $\eta p^2 = 0.47$; Experiment 2: Pillai's Trace = 0.662, $F(3, 99) = 64.55$, $p < 0.001$, $\eta p^2 = 0.66$), confirming that the effects of condition indeed differed for implicit and explicit measures. Follow-up univariate tests yielded patterns consistent with those already reported in the main analyses of each experiment, and thus are not repeated in full here.

This analysis suggests that explicit and implicit measures were indeed affected in opposite directions by the experimental manipulation, though note that we do not directly test whether the magnitude of change differs between the two types of measure. That is, because the two measures are on different scales, we are not making claims about whether the increase in implicit agency was significantly greater than the decrease in explicit agency, etc. Rather, we merely show that the manipulation (working with a virtual partner) had opposite effects on implicit and explicit agency measures. Further research is needed to investigate the generality of this dissociation and the contexts in which such divergent patterns are most pronounced.

5. General Discussion

5.1. Summary of the current study

This study investigated how both the implicit and explicit aspects of the sense of agency could be modulated by the presence of a virtual artificial agent who was also capable of acting. Notably, we manipulated participants' belief that the virtual artificial agent "Bobby" could act to stop the circle from inflating, but the behaviours of "Bobby" were in fact pre-programmed. "Bobby" was presented as an avatar, as were the participants, which made it more believable that Bobby was an agent capable of acting and allowed participants to experience control through their own avatar (Woźniak et al., 2023). Regarding explicit agency, in Experiment 1, we found that participants reported lower feelings of control when working with the virtual artificial partner compared to when working alone. Experiment 2 showed that while agency ratings were lower in the Together condition compared with the Alone condition, there was no difference between the Alone condition and the Being Observed (i.e., when the partner was only observing the participants but could not interfere) condition. Moreover, agency ratings were lower in the Together condition compared with the Being Observed condition, this would suggest that the presence of a partner was not sufficient to produce this effect.

Meanwhile, with implicit agency, temporal binding was greater when participants worked together with the virtual artificial partner compared with working alone in Experiment 1. In Experiment 2, a similar pattern was observed: temporal binding appeared stronger when participants worked with a virtual artificial partner who could act and stop the circle from enlarging, whereas when the partner was merely observing and could not intervene, temporal binding did not show a clear increase. This pattern suggests that the mere presence of the artificial agent may not be sufficient to modulate implicit agency. We did not observe significant correlations between IDAQ scores and either the explicit or implicit measures of agency, suggesting that individual differences in anthropomorphism as measured by this scale were not clearly associated with the social interference effects in the current experiments.

5.2. Explicit agency

Explicit agency, measured by participants' ratings of control, was reduced in the presence of a partner, aligning with prior studies (Beyer et al., 2017; Ciardo et al., 2020). We replicated the behavioural findings and showed that participants reported feeling less control over the outcome when working with the virtual artificial partner compared with working alone, even when participants' ability to act remained constant in both circumstances, that is, participants could always take the same action at will to stop the circle. The mere presence of the partner did not appear sufficient to produce this effect; explicit agency was primarily attenuated when the partner could independently act and intervene. Considering the model from Beyer and colleagues, our findings related to explicit agency are consistent with the notion that an individual's sense of personal responsibility is divided by other agents being present but only if the others can also act. The reduction in explicit agency originates from the ability of other people to act independently, increasing the uncertainty about possible scenarios. This in turn interferes with mentalising processes that deciding to take action or not is more challenging when the others could intervene compared with working alone. Ultimately, such conflict in action selection creates the diffusion of responsibility when the individuals reflect on how much control they feel (Beyer et al., 2017).

5.3. Implicit agency

To explain the enhanced implicit agency in the Together condition compared with when participants were working alone or merely being observed, the mechanism could lie at the level of action choice. In the paradigm, participants had more action options in the Together condition than the Alone condition: when alone, participants had no choice but to act in order to stop the worst possible outcome i.e., the circle turning red; whereas in the Together trials working with "Bobby", participants could choose to 1) not to act at all and defer to their robotic partner to stop the circle or 2) to take action and stop the circle from enlarging themselves. This is consistent with prior research showing that action choice has been shown to enhance the temporal binding effect (Haggard, 2017; Barlas & Obhi, 2013). Participants thus may have experienced heightened implicit agency because they proactively chose to take the initiative to stop the circle from enlarging when they might have instead chosen to defer to their partner. In this way, choosing to not let the partner act and take the more effortful option to stop the circle themselves resulted in greater implicit agency.

Additionally, as mentioned, implicit agency was not modulated by the mere presence of the virtual artificial agent. If temporal binding relates this pre-reflective sense of agency (i.e., the general sense of authorship when causing something to happen), then one would expect that the mere implied presence of another agent would not interfere with that process. In the Being Observed condition, the agent remained the sole possible source of producing the action because the virtual artificial agent could not contribute in any way. Thus, implicit agency might be modulated only when the other agent could act. From this perspective, the increase in temporal binding when working with another partner could reflect a heightened need to maintain a clear sense of self in such situations, distinguishing 'my' actions from those of the partner.

Overall, the role of implicit agency could be related to the low-level, automatic monitoring of self-generated action as distinct from those of other agents. That is, the increase in temporal binding when working with a partner could reflect a heightened sense of agency to ensure our own actions are distinguishable from others; this is particularly important in these diffused-responsibility circumstances. In contrast, the mere presence of a non-acting agent provides no such challenge and therefore elicits no modulation of implicit agency. Taken together, this suggests that implicit agency can indeed be modulated by social cues, but only when those cues have the potential to interfere with the action outcomes. When no such interference is possible, implicit agency remains stable and robust.

5.4. Diverging but complimentary roles of implicit and explicit agency

Based on the findings across the two experiments, we argue that the formation and transition of the explicit and implicit aspects of agency take place in parallel, thus complimenting each other because one taps into the conscious inference while the other reflects processes that are not consciously registered (Moore et al., 2012; Imaizumi & Tanno, 2019; Moore, 2016; Dewey & Knoblich, 2014). In the interfered agency paradigm, up until the point of action execution, participants are likely to continually engage mentalising processes to predict whether the other agent might act (Beyer et al., 2017, Beyer et al., 2018). Engaging these higher-order processes might then result in action dysfluency through interference. This decision dysfluency presents distributed responsibility (Beyer et al., 2017). These cognitively demanding conscious processes thus affect explicit agency ratings.

Meanwhile, self-other distinction and the availability of action choices are managed by subconscious processes, so participants are not consciously deliberating about them. These processes give rise to the heightened implicit sense of agency in the Together condition, as the sensorimotor system enhances the action-outcome attribution, binding the action and its outcome towards each other even more so than when individuals are alone (Haggard & Clark, 2003, Novembre et al., 2016). One beneficial consequence of this implicit system is to support agency attribution in a resource-efficient way. Thus, while some processes are captured by conscious explicit agency, others are spontaneously registered via the implicit system, affording the construction of a fuller picture of agency establishment whatever dynamics a situation may demand (Synofzik et al., 2013).

5.5. Cognitive load and multisensory integration

It is worth considering the potential roles of cognitive load and multisensory integration in our findings. Given the task structure whereby the participants had to mentalise about the partner's potential actions and increased action choices (withholding or initiating actions), it is possible that this imposes substantial cognitive load on the participants in the together condition. Whilst cognitive load could indeed influence temporal perception (Block et al., 2010), prior work has shown that increased cognitive load decreases temporal binding (Howard et al., 2016), whereas in our study we observe the opposite pattern. Thus, increased cognitive load might not easily explain our findings.

Regarding the multisensory integration as the possible mechanism, the brain combines information from different sensory modalities such as vision and auditory, weighted by their reliability, so that signals from the same event (e.g., seeing and hearing hands clapped together) are integrated (Klaffehn et al., 2021; Zimmermann et al., 2016). This allows an action and its effect to be perceived as a single unified event, which can give rise to temporal binding. Whilst it is possible that compared with the baseline condition (where participants were merely observing the circle enlarging and stopping itself), in the Alone and Together conditions, temporal binding arose when participants acted because acting involves motor preparation, and the mere presence of body movements influence temporal perception (Gutzeit et al., 2023). However, we found that temporal binding was stronger in the Together condition compared with the Alone condition, whilst both of these conditions involved similar auditory and visual modalities and that participants voluntarily initiated action. Thus, multisensory integration might not explain fully the observed differences in temporal binding between the Alone and Together condition. Therefore, the observed differences in the study are unlikely to be driven by these factors and instead reflect modulations of agency in response to social contexts.

5.6. The role of social manipulations in studying agency

The cognitive architecture comprised of both implicit and explicit aspects supporting agency seems sensitive to minor social manipulations (implied mere presence of an artificial agent). When studying agency in non-social contexts, the formation of agency might be relatively straightforward: participants' actions and outcomes are self-contained. Introducing another agent adds complexity. Participants must now consciously monitor and predict the other's potential actions, generating action dysfluency and distributed responsibility captured by explicit ratings. Meanwhile, the implicit system continues to track self-generated action-outcome contingencies without conscious awareness. By amplifying situations in which these systems can diverge, social manipulations make it possible to observe their complementary yet dissociable roles which would otherwise be difficult in non-social settings (De Felice et al., 2023). Thus, examining how agency adapts to the presence and behaviour of others offers critical insight into its flexible and context-sensitive nature.

6. Conclusion

Understanding how others, particularly virtual artificial agents, influence our sense of agency is important in human–machine interaction. Previous work suggests that social presence of a human or robot can reduce explicit control through diffusion of responsibility, but its impact on implicit agency is less clear. In two experiments, we observed that explicit agency tended to decrease, while implicit agency tended to increase when participants worked with a virtual artificial partner compared with working alone. Importantly, these patterns were not observed for the mere presence of the partner; that is, the modulation of agency appeared contingent on the partner being able to act rather than simply being present. We interpret these diverging effects of implicit and explicit agency as reflecting the fact that they tapped into different but complimentary processes. Implicit agency may allow us to identify which alternative action options to choose from and underline the self-other distinction at the sensorimotor level; while explicit agency may help us reflect on how we attribute responsibility in this particular diffused-responsibility context, thereby enabling a full picture of agency formation and transformation. Our action system co-evolved with the emergence of social cognition to support human interaction; it is thus important to note how subtle social manipulations can help uncover the mechanisms underpinning our sense of agency.

CRediT authorship contribution statement

Anh H. Le: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Thomas Burke:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrew P. Bayliss:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2025.103962.

Data availability

I have shared the link to the data in Author Statement attached file

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