Observed non-humanoid robot actions induce vicarious agency when perceived as social actors, not as objects

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Abstract

Robots are rapidly becoming a common aspect of our *physical* environments, but it is unclear under what conditions they can integrate into our *social* world. One prerequisite of such integration may be the perception that robots are agents that act with intention. In two experiments we used a temporal binding paradigm to explore how the implicit sense of agency might be vicariously induced by observing robot actions. In two experiments wherein participants interacted with.a simple non-humanoid toy robot, we found underestimation of the temporal gap between observed robot action and outcome (i.e., temporal binding, an index of the implicit sense of agency; Experiments 1 and 2). Critically however, this was only the case if participants had engaged previously with the robot in a ‘social’ game (Experiment 2). In contrast, binding was weaker for participants who had interacted with the robot on a mechanistic basis. These results are consistent with the notion that even non-humanoid social robots can evoke an implicit sense of vicarious agency, but only in restricted social contexts.

Statement of Relevance

People are increasingly interacting with virtual or robotic agents to achieve work, health, or social goals. However, we know little about what factors make a human-robot interaction feel similar or dissimilar to human-human interactions. We feel a sense of agency when we perform or observe other people making an action – the sense that the action is causing an effect on the world. We measured sense of agency in our human participants by testing how closely in time an observed robotic action occurred relative to the outcome it caused, because we know that typically, actions are misperceived as having occurred closer to their outcome in a way that is thought to help us bind cause and effect in our sensory and motor systems. Therefore, this implies that humans do have a vicarious sense of agency when interacting with acting robots. However, this only occurred if the humans had played a social game with the robot first, and not when the humans had interacted with the robot as a purely mechanical object. This demonstrates the importance of contextualising human-robot interactions when the robots can be represented in our cognitive system as beings that are capable of independent action.

Keywords: Sense of agency, robots, action perception, temporal binding

Observed non-humanoid Robot Actions Induce Vicarious Agency When Perceived as Social Actors, not as Objects

Identifying and interpreting changes to our environment is a core function of the cognitive system. Our own motor system is a frequent cause of environmental changes, but many events are caused by other agents or external events. The motor system monitors action outcomes not only to optimise action control, but also to correctly claim authorship over events in the environment that we caused (Gallagher, 2012). This results in a sense of agency: a recognition of ourselves as agents of goal-directed actions that produce changes in the environment. An accurate sense of agency helps us to distinguish what we are doing from what is happening, including what others around us are doing.

Synofzik et al. (2008) suggested that the sense of agency is comprised of two levels, one of which is an implicit feeling of agency, while the other pertains to the more conscious judgment of agency. According to predictive forward models, the *action prediction* and the *comparison of the predicted consequences to the actual effects* give rise to the causal association that we perceive between our actions and their outcomes. The implicit sense of agency is shown to reflect such causal associations, which can be measured indirectly via tasks whereby voluntary self-made actions and the sensory outcomes are perceived to occur closer together in time (Haggard, 2017). This compression of the time interval between the action and its effect being is referred to as temporal binding, and interestingly, it can be present not only for our own self-made voluntary actions but also for actions that we observe others executing, manifested as a *vicarious* sense of agency*.*

It has been suggested that the vicarious sense of agency that we experience for others’ executed actions involves similar predictive processes as when we execute our own actions (Poonian et al., 2015). Previous research has shown that agency detection for others not only affects but is also affected by cognitive systems including attention, perspective taking and spatial coding (Wiese et al., 2012; Wykowska et al., 2014; Stenzel et al., 2012; Zwickel, 2009). Some have suggested that people predict the intentions, goals and outcomes of others’ actions through the internal representation of the observed action and the activation of the action understanding system (Sato, 2008; Kilner et al., 2007). Such ability to comprehend actions to be related to desires, beliefs and intentions of others is known as adopting the intentional stance (Dennett, 1987; Leslie, 1994). Therefore, the vicarious sense of agency may be related to the degree of intentionality attributed to the other agent, as individuals can attribute intentions to others as well as they do to themselves. This results in the estimates of self-generated actions being comparable to those of the other human-generated actions, perhaps even supporting smooth and effective social interactions between individuals.

While humans have life-long experience in interacting with organic social agents (i.e., other people), interactions with computerised and artificial intelligence systems – whilst increasingly popular in our homes – are still relatively novel. Intuitively, the elements of attribution of intentionality described above do not apply to artefacts or tools that we use to fulfil our goals. For example, when we use a food processor to chop some vegetables, there will likely be no attribution of intentions or desires to the machine. Nonetheless, the distinction between agents and artefacts can become blurred when considering artificially intelligent entities, including social robots. Given the surge in robotic agents in our environments, investigating the conditions and processes through which robotic agents enlist agency attributions normally reserved for other humans becomes important both in theoretical and applied terms.

Previous work has found that the mere presence of a robot in an action context can affect participants’ behaviour, inducing them to follow the robot’s suggestions while undertaking a decision-making task (Shinozawa et al., 2005), or to increase their peri-personal and reaching space to include what is reachable by the robot (Bainbridge et al., 2008). These findings suggest that being in the presence of a robot can alter our decisions and perception, indicating that robots can be treated differently to other artefacts. Robots can also impact human behaviour through their actions. For instance, Kompatisari et al. (2018) showed that participants’ own attention was biased towards the direction of a robot’s gaze, in much the same way that happens in response to human gaze (e.g. Frischen et al., 2007).

Indeed, robots may even alter the way in which individuals subjectively judge how much control they have over an outcome, i.e., explicit sense of agency. Ciardo et al. (2020) employed an explicit measure of agency in a joint social task (pumping a balloon, which will explode unless one or both agents act to stop it) wherein participants’ co-partner was either another person or a Cozmo robot. They found that when humans perceive robots as intentional agents (or agentic artefacts), a similar decrease in explicit sense of agency was observed in the presence of human interaction partners (Beyer et al., 2018). However, such self-reported measures of agency are limited due to their reliance on retrospectively reflection on their agency judgment after the action outcome (Tsakiris et al., 2005; Wegner & Wheatley, 1999). Implicit measures of agency - such as temporal binding - may provide a very useful window into how co-actors apportion causal responsibility without relying on self-report.

Some very recent work has approached similar research questions to those examined in the present paper. In Sahaï et al. (2023), a temporal binding paradigm was used to measure participants’ sense of agency while working with co-agents. Participants performed a joint Simon Task together with another human, with a servomotor automated artificial system or a full humanoid robot as the co-agent. The authors found that the participants’ mean temporal estimations for self-generated actions were comparable to the mean temporal estimations for other-generated actions during joint actions with another human or with the humanoid robot. Similarly, Navare et al. (2024) aimed to evaluate whether sense of agency occurs in joint action with the humanoid robot iCub and if its emergence is influenced by the perceived intentionality of the robot. Participants engaged in an initial interaction with iCub which encouraged (or did not encourage) the perception that it was an intentional agent. Those exposed the ‘intentional’ iCub evidenced a greater sense of joint agency than those exposed to the ‘non-intentional’ version. Together, these results underscore the importance of attribution of intentionality to the robot in human-robot collaboration (Roselli et al., 2022a).

However, it is important to note that the studies mentioned above employed humanoid robots whose human-like appearance favours the attribution of agency, and they may be more likely to evoke social interactions similar to those of human-human than interactions between human and non-humanoid machines (Wiese et al., 2017; Hu et al., 2018). Roselli et al. (2022b) showed that observing humanoid robots engage in an action produced a vicarious sense of agency and greater inclination towards viewing robots as intentional agents among participants. Non-humanoid robots and other computers or industrial machines are more likely to be viewed mechanistically i.e., using the design stance (Dennett, 1987). Indeed, a systematic review by Thellman et al. (2022) showed that people’s tendency to attribute mental states to robots is influenced by the robot’s characteristics and features, including its behavior, appearance, and identity. Specifically, Thellman et al. (2022) found that there is a *computer < robot < human* pattern in the tendency to attribute mental states, which is moderated by the presence of socially interactive behaviour such as eye gaze or emotional expression. Therefore, attribution of mental states to mechanical objects is highly context dependent. On the one hand, vicarious sense of agency for robots can be facilitated for humanoid robots due to their convergence towards biological motion, allowing participants to create a sensorimotor representation of their actions (Roselli et al., 2022b). On the other hand, Fussell et al. (2008), for example, have shown that people can flexibly deny that a robot has a mind, contradicting their recent attribution of mental states when describing its behaviours. Thus, while a human-like appearance is likely to facilitate the experience of vicarious agency on behalf of humanoid robots, based on the findings of Thellman et al. (2022)’s review, the tendency to attribute mental states to non-human agents is contingent on the presence of socially interactive behaviour. In other words, even non-humanoid robots without human-like features, as long as they produce socially interactive behaviours, can prompt people to attribute mental states to them.

We suspect that the critical factor in determining whether perceivers attribute agency to a robot is the extent to which they are willing to view the robot in *mentalistic* rather than *mechanistic* terms (Ziemke, 2023). Key to this point, and our approach here, research has shown that agency can only be attributed to robots and computer programs when people perceive that the robot can act and manipulate the environment in a goal-directed fashion (Wen & Imamizu, 2022). Absent the belief that the robot is an intentional agent (i.e. it has the ability to plan and act), perceivers may fail to experience a vicarious sense of agency in relation to mechanistic robots (Schellen & Wykowska, 2019, Perez-Osorio & Wykowska, 2019). In the current work, we aim to further explore conditions that may produce a vicarious sense of agency in relation to non-humanoid robots.

Furthermore, despite the importance of adopting an intentional stance for extending agency to robots, little research has yet attempted to manipulate intentional stance toward non-anthropomorphic robotic agents (i.e., those lacking human characteristics). It is worth noting that whilst recent research like Navare et al. (2024) has fostered an initial interaction between participants and iCub, the robot in question was the size of a human child and had humanoid features. In the current study, we aimed to test whether such effects could extend to non-humanoid robots. We used y Cozmo, whose dimension was 18cm x 20cm x 12 cm with no objectively human-like features, and we assessed whether priming social interaction with such a non-humanoid robotic object would suffice for participants to adopt intentionality towards this mechanical object and most importantly, how this would impact the subsequent agency attribution towards the non-anthropomorphic robot. In summary, our second study will examine whether facilitating positive social interactions with a non-humanoid robot induces individuals to adopt the intentional/mentalistic stance rather than the design/mechanistic stance towards the robots, and consequently to experience a vicarious sense of agency in relation to those robots.

**The current study**

Experiment 1 advances the line of human-robot interaction and agency attribution research by directly comparing temporal binding effects elicited by observing the actions of a robotic agent with those produced by oneself or by observing another human’s actions. Using the time interval reproduction task (Humphreys & Buehner, 2010), we tested the hypothesis that if observing a social robot acting in the environment attunes our motor system in the same way that our own or other humans’ actions do, participants will underestimate the time interval between actions and outcomes produced by themselves, another person, or the robot, but not when the outcome follows a computer-generated cue. In this way, we are able to identify whether temporal binding for observed robotic actions falls in line with binding for observed human actions, or observed computer actions. Experiment 2 aimed to investigate whether prior experience interacting with the robot modulates temporal binding effects, and how interactions of different types can affect participants’ tendency to attribute the intentional stance or mechanistic stance to the robots.

Open Science Statement

In both experiments, details of how sample size was determined, as well as all data exclusions (if any), all manipulations, and all measures are reported. Neither of the studies reported in this article were preregistered, though analyses were carried out in line with our previously published research (Pascolini et al., 2021) and analytic decisions were not altered subsequent to viewing the data. The data have been made available on a permanent third-party repository and can be accessed at https://osf.io/qx24t/?view\_only=3809a077fa4642b0b663d571d1d386c3. The complete questionnaires have also been made available and can be accessed at the same site. Further requests for information or materials can be sent to the corresponding author.

Experiment 1

Participants completed an interval reproduction task under each of four different conditions, each of which featured a different start stimulus (operant, observed human, observed robot, or control/computer-generated) but produced an identical outcome. Participants reproduced the time interval between the start stimulus and the resulting outcome, and temporal binding was assessed using the mean proportional interval reproduction, calculated by dividing the reproduced time interval by the actual time interval for the same trial (in milliseconds).

*Method*

*Participants*

A target sample size of n=32 was determined from a power analysis based on observed effect sizes from our previous work which deployed a similar methodology and research question (Pascolini et al., 2021; *dz* = 0.69; 1–β= 0.95; α= 0.05, n > 30; G\*Power, Faul et al., 2007). Participants (*M*age = 20.03 years, *SD* = 1.60, 21 women) were recruited from the local research participation scheme and received course credit for participation. Participants reported normal or corrected-to-normal vision and hearing. The study was approved by the School of Psychology Research Ethics Committee.

*Materials*

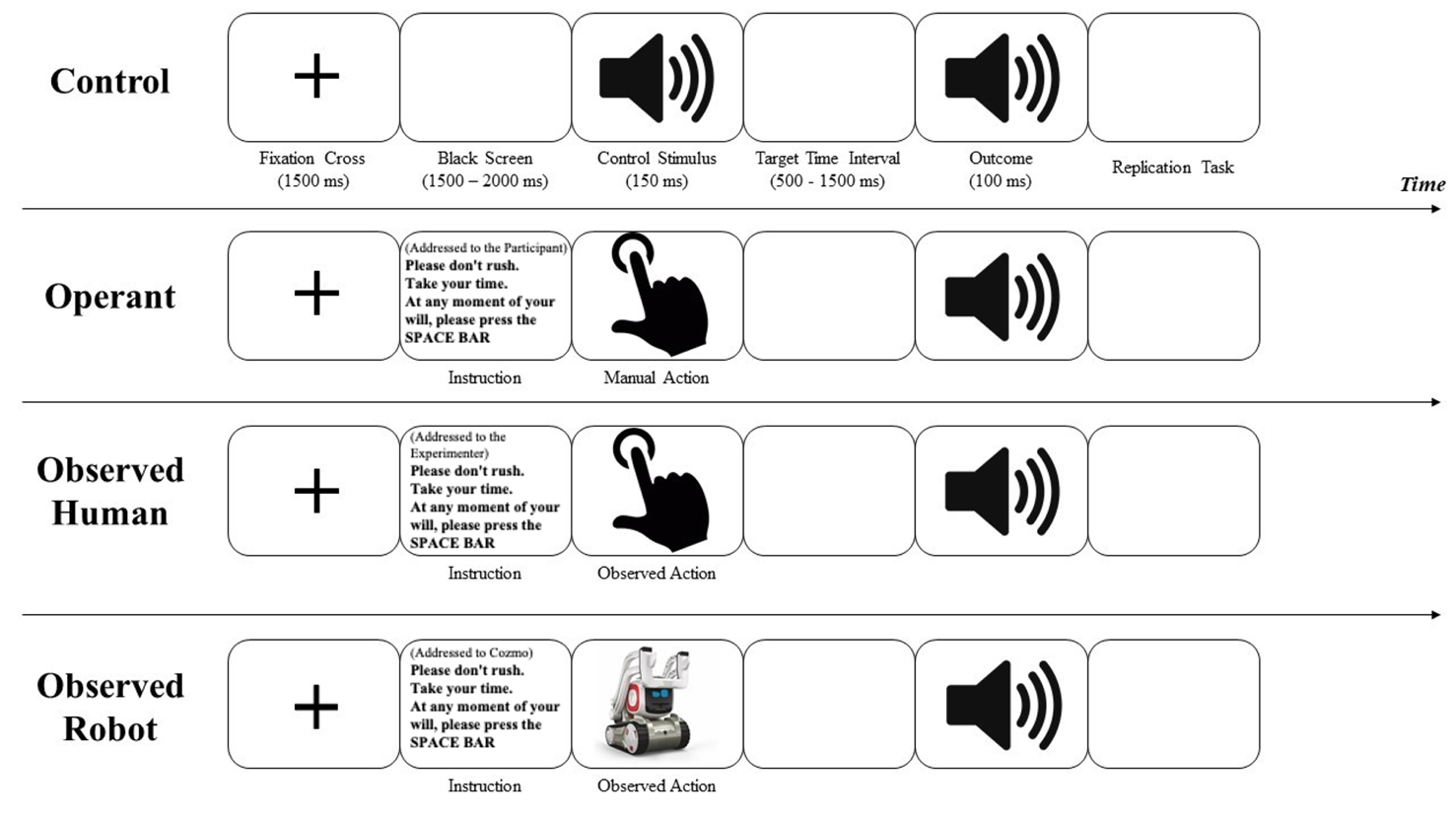
Stimuli included tones: i) Low-pitch (150ms, 440Hz sine wave, sample rate=44100 Hz, bitrate=16), ii) High-pitch (100ms, 1KHz sine wave); created using MATLAB (MathWorks, Natick, MA, USA). The experiment was run using E-prime3.0 (Psychology Software Tools, Inc.). The experimental setting consisted of two adjacent chairs and a table in a dimly lit room. Stimuli were presented on a 24-inch monitor and external speakers, and a standard keyboard to collect participants’ responses. During Observed Human trials, the experimenter sat adjacently on the left of the participants’ position. In the Observed Robot trials, the action was executed by Cozmo. The robot had a non-anthropomorphic appearance: two sets of wheels allowed movement through track connection, while key press actions were enabled by a mobile joint on the front.

*Design*

The experiment had a single factor repeated measures design with four levels: Operant, Observed Human, Observed Robot, and Control presented in pseudorandomised blocks using a modified 4x4 Latin square design to was presented in each order of the sequence across participants (ABCD, DCBA, BDAC, CADB) . The dependent measure was the mean proportional interval reproduction, derived by dividing the reproduced time interval by the actual time interval for the same trial (milliseconds) (Stephenson et al., 2018; Pascolini et al., 2021). Therefore, scores equal to 1 indicated perfect accuracy, whereas scores greater than 1 were over-reproductions and scores lower than 1 represented under-reproductions i.e., the subjective temporal compression indicative of the temporal binding effect. Both proportional interval reproduction and absolute reproduction errors have been used to measure temporal binding; we elected to use the proportional measure in this work because it is less sensitive to the duration of the interval, which was not of particular interest in this study (Imaizumi & Tanno, 2019; Silver et al, 2025). This aligns with the use of proportional measures in the time perception literature because it is not confounded with the absolute duration (where perception errors are positively correlated with duration; see Guay & Salmoni, 1988; Mioni et al, 2014; Riemer & Wolbers, 2020

*Procedure*

Each block comprised 30 experimental trials preceded by 5 practice trials. Control trials began with a white fixation cross in the centre of the screen (1500ms) followed by a low-pitch tone through the left speaker after a delay of 1500-2000ms (varying randomly). After the target time interval (randomised between 500-1500ms) a high-pitch tone was presented through the right speaker. Participants reproduced the duration of the interval between the tones by pressing and holding down the SPACE key for the same amount of time. Participants then pressed the ‘N’ key to begin the next trial (see Figure 1).



*Figure 1.* Trial procedure for the four conditions in Experiment 1. Each trial lasted 5s-7s.

In Operant trials, participants were instructed that after the fixation cross disappeared, they should press the space bar at any moment of their choosing. This released, after a variable time interval (randomized between 500 and 1500ms) a high-pitch tone (100ms, 1 kHz) through the right speaker only. Participants then reproduced the interval as above. In the Observed Human condition, participants watched the experimenter performing the action.

In the Observed Robot condition, Cozmo was placed at the centre of the keyboard, in reach of the space bar. The trial procedure was identical to the Observed Human condition, with the only difference being the agent executing the action. Cozmo’s actions were remotely controlled by the experimenter positioned outside the room. Participants were given no specific information about how Cozmo was executing. The experimenter waited outside the laboratory in all conditions, except for the Observed Human condition.

*Results*

The following exclusion criteria were applied, consistently with our previous studies involving the same methodology (Pascolini et al., 2021): participants not producing reproductions covarying monotonically with veridical intervals (i.e., *r* < 0.4; see Caspar et al., 2016), trials with reproductions < 100ms, and trials with reproductions +/- 3SD from participant mean). This resulted in one participant and 0.96% of total trials removed. Shapiro-Wilk tests performed on mean proportion reproduction for each condition showed that the Observed Robot condition held a non-normal distribution: *W*(30) = 0.911, *p* = .016, while other conditions reported *p* > .05 (Figure 2).

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*Figure 2***.**Frequencies histograms for the four conditions in Experiment 1 based on data from all participants (n=32). The X-axis represents values of the mean proportional interval reproduction (calculated as the reproduced time interval (in milliseconds) divided by the veridical interval (in milliseconds) for each trial (i.e., estimated/actual)). The Y-axis indicates the number of participants with a given proportional interval reproduction value.

Because of the non-normality of the distribution of scores in the Observed Robot condition (described above), a non-parametric analysis was performed on median scores. A Friedman test showed a statistically significant effect of condition, *χ2*(3) = 32.15, *p* < .001 (see Figure 3). Planned contrasts using Wilcoxon signed-rank tests showed significant differences between the Control and the Observed Robot conditions (*Z* = -2.09, *p* = .037,   
*ES* = 0.37), between Observed Robot and Observed Human (*Z* = -2.48, *p* = .013, *ES* = 0.45), and between Observed Human and Operant conditions (*Z* = -2.83, *p* = .005, *ES* = 0.52).

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*Figure 3****.*** *Boxplot comparing the proportional interval reproductions across the four conditions in Experiment 1. Central lines within each box represent the medians, with top and bottom boundaries of each reflecting the 1st and 3rd quartile. The line endpoints depict the minimum and maximum values of the distributions.*

*Discussion*

This experiment replicated the temporal binding effect, whereby participants produced significant underestimations of the temporal gap between an action and an outcome that they had caused (Operant) compared with two non-caused events (Control). This effect is thought to relate to the ascription of self-agency over the outcomes of one’s actions. However, like other authors (Poonian & Cunnington, 2013; Pascolini et al., 2021; Strother et al., 2010; Wohlschläger et al., 2003), we also found reliable temporal binding for observed actions by another human (the experimenter). This replicates previous findings and may imply a shared or social agency, or the engagement of a more general causality detection process (Buehner & Humphreys, 2009). We also discovered temporal binding for observed robotic actions: the temporal gap between action and outcome caused by Cozmo was also under-estimated. While interesting in its own right, a feature of the data pattern in this latter condition – a bimodal distribution (see Observed Robot Frequencies Histogram, Figure 1) – was striking in that one mode comprised participants who produced binding at a level comparable to that seen in the observed human condition, whilst the other mode included participants who were much more accurate (similar to accuracy levels in the control condition). This pattern gives rise to an opportunity to explore whether the mechanism underpinning the temporal binding effect from robot actions is general or mentalistic in nature (see also Manera et al., 2014).

Experiment 2

Following the bimodal distribution of the Observed Robot condition in Experiment 1, we hypothesised that some participants spontaneously approached that condition with an Intentional Stance (i.e., they perceived Cozmo as a potentially intentional agent: Dennett, 1989), and others with a Design or Physical stance (i.e., they perceived Cozmo as a physical, non-intentional agent). This would be consistent with Roselli et al’s (2022) finding that intentionality ratings predicted the extent to which participants exhibited vicarious agency for Cozmo’s actions. We speculated that those who imbued the robot with anthropomorphised characteristics showed temporal binding (as they would when observing a human agent), and those that did not generated accurate interval interactions (as they did when indicating the interval between two computer-generated tones). To test this hypothesis, in Experiment 2, we introduced a manipulation wherein participants interacted with Cozmo in different ways prior to the temporal binding tasks. This was designed to encourage some participants to see Cozmo as an independent playful character and other participants to see Cozmo as a programmable mechanistic device. We expected to replicate the temporal binding effects for self-generated and observed human actions, as well as for observed robot actions – but only when an intentional stance was taken toward the robot. Such a finding would be consistent with the hypothesis that mentalistic attribution is necessary for temporal binding. Importantly, this would also imply that temporal binding in this context reflects vicarious agency ascription rather than simple registration of a causal association.

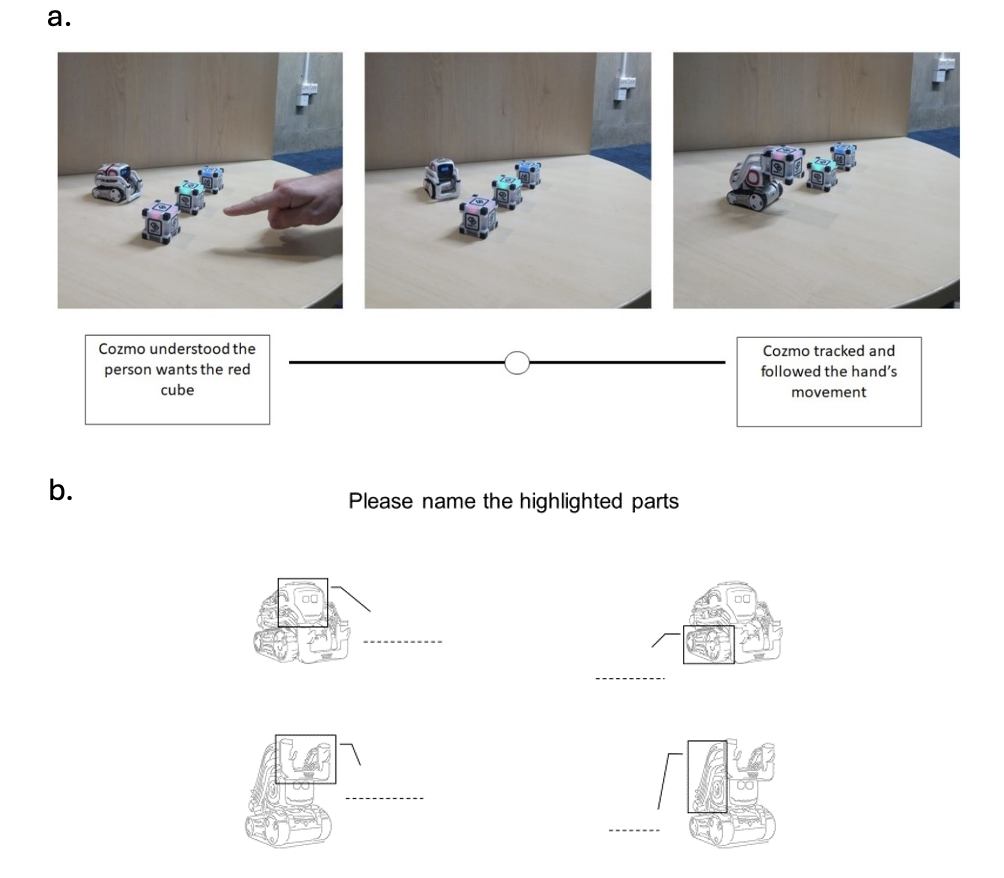
*Method*

*Participants*

A power analysis determined a target sample size of 112 (56 per group). This was based on power required to detect the same effect size observed between Control and the Observed Human in Pascolini et al. (2021): *dz* = 0.88;1–β = 0.95; α = .05, which indicated a minimum n=54 (27 per between-subjects condition). This was doubled to account for the hypothesis regarding the interaction term (following Simonsohn, 2014, and Blake & Gangestad, 2020). Thus 56 participants were randomly allocated to the Mechanistic group (*M*age = 20.1 years, *SD* = 3.28, 46 women), and 56 in the Mentalistic group (*M*age = 19.8 years, *SD* = 2.05, 45 women).

*Materials*

The same materials were used as in Experiment 1, with the following additions. Two questionnaires were developed to assess both participants’ tendency to adopt either a design or intentional stance, and their propensity to anthropomorphise Cozmo. The first questionnaire was based on the InStance measure (Marchesi et al., 2019) wherein five scenarios were created, depicting Cozmo interacting with objects and/or humans over three images (1080x920px). Accompanying each scenario were two descriptions: One explained Cozmo’s actions invoking the design stance (i.e., Mechanistic), the other invoked the intentional stance (i.e., Mentalistic). These descriptors appeared the left or right of the screen randomly. Participants responded on a 100-point slider to indicate the extent to which their interpretation fit either explanation, with lower scores reflecting a stronger design stance. The anthropomorphism questionnaire was designed with a sketch of Cozmo, with empty labels linked to four of its physical features (see Figure 4). Further, participants’ tendency to attribute mentalising skills to themselves, the human experimenter, the computer, and the robot were measured with the 10-item Mind Attribution Scale (e.g., ‘(Target) is capable of doing things on purpose’ rated from 1 (strongly disagree) to 9 (strongly agree); Kozak, et al., 2006).

*Figure 4***.** a) Example InStance questionnaire item: Participants moved the slider towards the description they found more plausible, h) Anthropomorphism questionnaire: Participants label Cozmo’s ‘body’ parts*.*

*Design*

The design from Experiment 1 was adopted, with the addition of Interaction Priming as a between-subjects factor with groups in either the Mechanistic or Mentalistic condition, hence a 2x4 mixed design. We also collected measures of anthropomorphism to be analysed in relation to temporal binding.

*Procedure*

Each participant was first primed with a similar interaction with Cozmo. Participants in the Mechanistic group could see the Experimenter controlling Cozmo, whilst for those in the Mentalistic group Cozmo’s actions were programmed to appear autonomous. The interaction format was a ‘keep-away’ game; Over the course of 10 turns at the game lasting approximately five minutes, participants were asked to slowly slide a cube towards Cozmo positioned ready to tap the cube with its manipulandum. Participants aimed to approach as close as possible and quickly retreat before the robot could tap it. Participants gained (known-to-be inconsequential) points for Cozmo misses and lost points for Cozmo hits. Hence, a successful tap from Cozmo would have meant a point lost for the participants, while a miss would have meant a point gained. In the Mentalistic group Cozmo displayed a brief emotional animation (cheerful or disappointment) according to its win/loss performance. Each priming interaction consisted of ten trials. Participants were given no specific information about how Cozmo was executing actions (i.e., whether by remote control, a programmed sequence or spontaneously).

Next, participants completed the same four temporal binding tasks as described in Experiment 1, with two exceptions. First, whereas in Experiment 1 the experimenter remained outside of the room during the Observed Robot condition (with no specification of how the robot was acting, rendering its level of agency ambiguous), in this experiment we endeavoured to explicitly disambiguate the robot’s agency or lack thereof. As such, while the Experimenter controlled the robot in both groups, he did so either in full view of participants (Mechanistic condition) or from outside of the room (Mentalistic condition, and similarly to Experiment 1). Secondly, at the end of each experimental block, participants completed the Mind Attribution Scale, adapted to refer to the specific agent that acted in that block (i.e., themselves, the experimenter, Cozmo, or experimental apparatus). Finally, participants completed the InStance and anthropomorphism questionnaires.

*Results*

The same exclusion criteria of Experiment 1 were applied, and this led to seven participants being excluded (two from Mechanistic, five from Mentalistic) and the removal of 102 (1.59%; Mechanistic) and 107 (1.59%) trials. Mean proportional interval reproductions were calculated for each participant for each condition; none violated the normality assumption. A mixed ANOVA was conducted on proportional interval reproduction scores (Greenhouse-Geisser correction applied where required) and showed a significant main effect of Agent, *F*(2.4, 244.5) = 62.1, *p* < .001, *ηp2*=.38, and a significant interaction effect between Agent and Interaction Priming, *F*(2.4, 244.5) = 6.05, *p* <.001, *ηp2* = .057, The main effect of Priming was not significant, *F*(1, 102) = 0.03, *p* = .87, *ηp2* < .01 (see Figure 5).

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*Figure 5***.** Boxplot comparing the proportional interval reproductions across conditions in Experiment 2. Central lines within each box represent the medians, with top and bottom boundaries of each reflecting the 1st and 3rd quartile. The line endpoints depict the minimum and maximum values of the distributions.

Determining the source of the interaction, independent t-tests showed a significant group difference only in the Observed Robot condition: *t*(102) = 2.60, *p* = .011, *dz* = 0.62 because temporal binding was stronger for Observed Robot actions in the Mentalistic group than in the Mechanistic group. Further, within the Mechanistic condition, paired t-tests revealed that the Observe Robot and Control conditions were statistically equivalent (*t*(53) = 0.26, *p* = .80), as were the Observe Human and Operant conditions *(t(*53) = 1.20, *p*= .24). Bayesian paired-sample t-tests were conducted to confirm whether there was indeed the absence of difference between the Observe Robot – Control conditions; and between the Observe Human – Operant conditions using a diffuse prior. Both Bayesian t-tests showed that the Bayes factors were BF₀₁ = 9.068 and BF₀₁ = 4.680 (Bayes factor BF₀₁: Null v. alternative hypothesis), respectively and these results indicate substantial evidence in favour of the null hypothesis over the alternative.

In contrast, the Observe Human and Operant conditions both evidenced significantly stronger binding than both the Observe Robot and Control conditions (smallest *t*(53) = 7.76, *p* < .001). Within the Mentalistic condition, paired t-tests indicated that the Operant and Observed Human conditions produced equivalent binding (*t*(50) = 0.34, *p* = .74; Bayesian paired t-test result also indicated substantial evidence in favour of the null hypothesis: BF₀₁ = 8.622) and were both stronger than the Observed Robot condition (smaller *t*(49) = 3.15, p = .003). All three of those conditions produced stronger binding than the Control condition (smallest *t*(49) = 4.17, *p* < .001).

*Interaction Priming Effects on Mental Representation of Cozmo*

To assess the extent to which participants attributed mental states as a function of which agent was performing the action in each priming group, a mixed ANOVA was conducted on the scores for the Mind Attribution Scale[[1]](#footnote-2). This showed significant main effects of Agent: *F*(1.65, 169.9) = 692.7, *p* < .001, *ηp2* = .87 and of Interaction Priming, *F*(1, 103) = 23.1, *p* < .001, *ηp2*  = .18, as well as a significant interaction, *F*(1.65, 169.9) = 17.8, *p* < .001, *ηp2* = .15. A series of independent samples t-tests found a significant effect of Interaction Priming only in the Observed Robot condition, *t*(90.2) = 6.14, *p* < .001, *dz*=1.20) due to higher mind attribution scores for the Mentalistic than the Mechanistic group (see Table 1), while all other comparisons were non-significant, largest *t*(103) = 1.20, *p* = .23), supporting the efficacy of the priming manipulation. Similarly, Interaction Priming had a significant effect on InStance questionnaire scores *t*(103) = 7.16, *p* < .001, *dz* = 1.40.

**Table 1*.*** Mind Attribution, Intentional Stance and Anthropomorphism scores (mean (standard error)) as a function of Interaction Priming - Experiment 2. Note that lower scores on the Intentional Stance Scale reflect a stronger intentional stance/weaker design stance.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Mind Attribution Scale | | | | Intentional Stance | Anthropo-morphism |
|  | Control | Operant | Observed Human | Observed Robot |  |  |
| Mechanistic | 2.83  (0.15) | 8.27  (0.11) | 8.29  (0.10) | 2.31  (0.19) | 75.90  (2.15) | 0.35  (0.03) |
| Mentalistic | 3.12  (0.19) | 8.35  (0.11) | 8.28  (0.12) | 4.32  (0.27) | 47.22  (3.38) | 0.65  (0.03) |

The anthropomorphism score was calculated by first coding each label participants assigned to either a human or mechanistic category. Words associated with human features (e.g., face, hands, legs) were operationalised as ‘1’, while words associated with mechanistic features (e.g., screen, grabber, wheels) were operationalised as ‘0’. Ambiguous words, valid for both the human and mechanistic domain (e.g., arm) were always considered as mechanistic. The final anthropomorphism score was calculated by averaging values on all labels for each participant. The final score ranged from 0 to 1, with higher values representative of greater anthropomorphism tendency. An independent samples t-test found higher anthropomorphism scores for the Mentalistic than Mechanistic groups, *t*(103) = 7.32, *p* < .001, *dz*=1.44.

*Exploratory Mediation Analysis*

Because the interaction priming manipulation had parallel effects on both explicit measures of perceived intentionality and implicit measures of agency, we decided to test the theoretical proposition that intentional stance is a critical determinant of sense of agency. To do so, we conducted a mediation analysis in which interaction priming was a between-subjects factor, temporal binding in the Cozmo condition was the dependent variable, and the three explicit measures (Mind Attribution Scale in the Cozmo condition, InStance Questionnaire, and Anthropomorphism Questionnaire) were entered as mediating variables (see Figure 6).

The analysis indicated that the effect of interaction priming was fully mediated by scores on the InStance measure (indirect effect *b* = -0.210, *z* = -2.835, *p* = .005; direct effect *b* = -0.002, *z* = -0.013, *p* = .989). Neither Anthropomorphism (*b* = -0.063, *z* = -0.864, *p* = .005, *p* = .388) nor Mind Attribution (*b* = 0.025, *z* = 0.457, *p* = .648) scores emerged as significant mediators.

A diagram of a flowchart

Description automatically generated

*Figure 6.* Mediation model – Experiment 2

*Discussion*

Experiment 2 replicated Experiment 1 by showing temporal binding for operant and observed human actions compared with the control condition. However, the extent to which temporal binding emerged for the observed robot condition was contingent on our manipulation of intentional stance. Participants in the Mechanistic group showed no temporal binding (implying little implicit agency was induced), equivalent to the Control condition. In contrast, those in the Mentalistic group reliably underestimated the time elapsed between Cozmo’s actions and their outcomes, similar to the Observed Human condition. We interpret this in line with our hypothesis that priming participants with different (mentalistic vs mechanistic) stances toward Cozmo led to different attributions about the agentic capacities of Cozmo. This interpretation was supported by the manipulation checks that showed that participants in the Mentalistic (v. Mechanistic) condition reported greater mind attribution to the robot, scored higher on our anthropomorphism measure, and were more likely to adopt an intentional (v. design) stance towards Cozmo. However, only the last of these explicit measures mediated the effects of interaction priming.

General discussion

This research investigated whether observing actions performed by a social robot (Cozmo by Anki) leads participants to experience a subjective time compression towards the outcomes of those actions. In two experiments, data showed that observing robotic actions produced a temporal binding effect, and also provided evidence that higher-level mechanisms may be involved (Ciardo et al., 2018; Roselli et al, 2019). When participants received no information about the robot, and thus they were free to interpret its actions according to any spontaneously-emerging beliefs (Experiment 1), their performance in an interval reproduction task was distributed bimodally. This result implied that some participants did experience temporal compression (just as they did for human-generated actions), while others were accurately replicating the time intervals between robotic actions and their outcomes (just as they replicated the interval between two computer-generated tones). This implied that some participants perceived the robot as agents and others did not. Such findings are in line with the notion that there are two contradictory attitudes which people can hold towards robots ‘(a) a willingness to interact with social robots as real people or animals; and (b) a recognition that they are mechanical artifacts’ (p.1, Clark & Fischer, 2022).

In Experiment 2, the prior beliefs participants had about the robot were systematically manipulated, priming participants with a mechanistic or mentalistic interaction with the robot. The aim of the study was to polarize the pre-existing attitude participants had towards the robot, inducing them to see it either as a machine controlled by the experimenter or as a spontaneous agent, even if the robots are non-humanoid. Participants in the Mentalistic group produced a reliable temporal binding effect, whereas those in the Mechanistic group showed no differences between the Observed Robot and Control condition. These findings suggest that agency detection and mentalising processes are deeply interconnected, but dissociable. Temporal binding is not generated for every action observed, but rather is influenced by top-down mechanisms that use information about the agent performing the action. This sheds light on the findings from Experiment 1 suggesting that if that information is not available, prior beliefs may fill that gap such that some participants did respond to non-humanoid Cozmo robots in ways similar to their response to another human, while others responded to Cozmo in ways similar to their response to a non-agentic computer.

Experiment 2 further showed that our manipulation of intentional stance also produced differences in explicit theory of mind measures. More specifically, participants who experienced non-humanoid Cozmo as a spontaneous agent more readily attributed mental states, and were more likely to both explain its behaviour as a result of mental activities, and to refer to its components in human terms compared to those in the Mechanistic group. Together with the temporal binding data, this evidence suggests the sense of agency is related to anthropomorphism and theory of mind. This is consistent with the models proposed by Castelli et al. (2000) and Iacoboni et al. (200), who suggested that anthropomorphism mechanisms rely on the same cognitive processes involved in the attribution of intentions. Our study highlights the evidence that the robots need not to exhibit humanoid physical entities with great human-likeness for agency to be attributed. Rather, priming participants to perceive Cozmo as an intentional social agent was sufficient to produce the vicarious sense of agency that people normally experience when observing the actions of other humans.

Finally, these studies provide further evidence relating to the interpretation of temporal binding. We found that mere action observation is not sufficient to achieve reliable time compression. Instead, explicit knowledge about the observed agent’s mental states is also needed. These data would fit a theoretical model in which action observation and mentalising converge to generate subjective time compression. Accordingly, action observation mechanisms could account for implicit and low-level mechanisms, while mentalising processes are dedicated to explicit and higher-level social cues. How these mechanisms interact to influence both implicit and explicit sense of agency warrants further investigation, but our finding that intentional stance fully mediated priming effects on temporal binding (see also Roselli et al., 2022a) suggests explicit intentionality beliefs may guide the operation of predictive mechanisms in action observation.

It is worth noting that the current study focusses on the vicarious sense of agency. this contrasts with other relevant research which also manipulated socially interactive behaviour with a robotic agent (Navare et al., 2024). In that research (which also differs from the work reported here in that it involved humanoid robots), they investigated joint agency in a social context. The fundamental difference in vicarious agency and joint agency is that the latter requires cooperative and joint effort from both participating agents, whereas vicarious agency could be induced in the absence of a joint task and by merely observing the other agent perform actions (Silver et al., 2021). That said, it can be argued that these two types of agency are not entirely unrelated because both require an attribution of intentionality to the other agent. That is, without attributing mental states to the robotic agent, neither joint agency (Sahaï et al., 2023; Navare et al., 2024) nor vicarious agency towards the robotic agent (the present study) would emerge. Whilst this research aims at bridging the gap by demonstrating that prior social interaction with a non-humanoid robot can lead to vicarious agency, even in the absence of direct cooperation, it is beyond the scope of the study to establish conclusively whether either joint agency and vicarious agency can be assumed when the other is present. Future research could incorporate both types of sense of agency in one study to examine whether, in the context of human and non-humanoid robot interaction, one type of agency could occur without another. To conclude, our findings provide new evidence about the capacity for humans to interact with non-humanoid robots as intentional agents. Alongside findings from others (Hortensius et al., 2018; Navare et al, 2024; Roselli et al, 2022ab; Wang & Quadflieg, 2015) these results pave the way for considering how robots might integrate into our social environments, filling roles typically reserved for other humans.

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**Author Contributions**

LP, APB, and NAW conceived the study. All authors designed the experiments. LP created the materials, collected and analysed the data. LP, AHL, APB, and NAW interpreted the data. LP drafted the manuscript. All authors provided critical revisions and approved the final version of the manuscript for submission.

**Data Availability**

Raw data has been made public to comply with open science practices. All files can be accessed at [https://osf.io/qx24t/?view\_only=3809a077fa4642b0b663d571d1d386c3]. This study was not preregistered.

**Conflicts of Interest**

Authors declare no conflict of interest for this project.

1. The Mind Attribution Scale consists of three factors: Emotion, Intention and Cognition. We conducted a further analysis in which subscale (Intention, Emotion, Cognition) is entered along with Target (Control, Operant, Human, Robot) as repeated-measures factor with Interaction Priming as a between-subjects factor. This analysis produced no significant effects involving the subscale factor, indicating that the effects of Target and Priming were equivalent across all three subscales [↑](#footnote-ref-2)