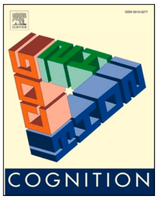
Cognition 267 (2026) 106349

Contents lists available at ScienceDirect

Cognition

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



Minimal conditions for the emergence of a vicarious sense of agency toward artificial agents

Cecilia Roselli [a,b,1], Uma Prashant Navare [a,c,1], Francesca Ciardo [d], Davide De Tommaso [a], Sonja A. Kotz [e,f,2], Agnieszka Wykowska [a,*,2]

[a] Italian Institute of Technology, Social Cognition in Human-Robot Interaction Unit, via Enrico Melen 83, Genoa 16152, Italy
[b] Laboratory of Robotics for the Cognitive and Social Sciences, Department of Human Sciences for Education, University of Milano-Bicocca, via Thomas Mann 8, 20126 Milan, Italy
[c] ETIS IMR 8051, CY Cergy Paris Université, ENSEA, CNRS, F95000 Cergy, France
[d] Department of Psychology, University of Milano-Bicocca, Piazza dell'Ateneo Nuovo 1, 20126 Milan, Italy
[e] Department of Neuropsychology and Psychopharmacology, Faculty of Psychology and Neuroscience, Maastricht University, Universiteitssingel 40, 6200MD Maastricht, the Netherlands
[f] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstrasse 1a, 04103 Leipzig, Germany

ARTICLE INFO

Keywords:
Vicarious sense of agency
Intentional binding
Expectancy
Action outcome
EEG

ABSTRACT

A Sense of Agency (SoA) is the feeling of being in control over own actions and their outcomes. However, people can also experience a "vicarious" SoA over the actions performed by other agents, including artificial agents. The present study aimed to understand the minimal conditions for vicarious SoA toward artificial agents. Specifically, we addressed whether vicarious SoA emerges when people have access only to the action effect (proximal and distal), i.e., when no motor action is executed. In addition, we manipulated the expectancy of the content of the distal effect of the action to check whether the proximal action effect is sufficient for the emergence of the vicarious SoA, or if this effect is due to the learned association between proximal and distal effects. In two experiments, participants performed an Intentional Binding (IB) task, where the IB effect was the behavioural measure of SoA. In the first experiment (Solo), participants judged the onset of self-generated tones, whereas in the second experiment, a new sample of participants judged the onset of tones produced by a computer via an automatically pressed button, i.e., a customized device designed to generate a keypress (proximal action effect) in the absence of an effector executing a keypress (no motor action). In both experiments, participants' neural activity was recorded via electroencephalography (EEG), to examine the N1 and P2 components as neural measures of SoA. Behavioural results across experiments showed that the IB effect always emerged, suggesting that the vicarious IB effect toward an artificial agent emerges when access to the proximal action effect is provided, even in the absence of the action itself. The neural results suggested that while individual (self) SoA seemed to partially rely on motor predictions indexed by the N1, vicarious SoA relies on later, more cognitive (although still predictive) processes indexed by the P2. Overall, these results suggest that individual and vicarious SoA, although behaviourally manifested through a similar IB effect, might – to some extent – rely on different neural mechanisms.

1. Introduction

Our actions bring changes into the environment, which we consciously experience. This experience is known as "Sense of Agency" (SoA). SoA is the feeling of control over one's own actions and subsequent outcomes (Gallagher, 2000), and it is a crucial component of human awareness (Haggard, 2017). Given a SoA, we can discriminate self-generated actions from externally generated ones, recognizing ourselves as "initiators" or "authors" of actions (David, Newen, & Vogeley, 2008). For example, if you are in a dark room and, after a

---

* Corresponding author.
E-mail address: Agnieszka.Wykowska@iit.it (A. Wykowska).

[1] These authors equally share the first authorship.

[2] These authors equally share the senior authorship.

https://doi.org/10.1016/j.cognition.2025.106349
Received 5 May 2025; Received in revised form 13 October 2025; Accepted 16 October 2025

while, you see the room lighting up, you immediately know that this change in the environment is the consequence of your action, as your hand has pressed the light switch. However, the room could light up because of a pre-programmed timer controlling the light switch. In the latter case, you still observe the environment lighting up, but you do not consider yourself the one who caused it. Given this SoA, we can discriminate the "authorship" of events occurring in the environment.

1.1. Theoretical framework

One influential model explaining the emergence of SoA is the *Comparator Model* conceptualized by Frith and colleagues (Frith, Blakemore, & Wolpert, 2000; see also Blakemore, Wolpert, & Frith, 2002). The *Comparator Model* suggests that SoA arises from the representation, at the sensorimotor level, of the causal chain between actions and their *predicted* sensory effects. After a given action has been selected for execution, the corresponding motor commands generate an efference copy, based on which an internal prediction about the sensory outcome of the action is formulated. Then, the predicted outcome is compared to the actual one generated during an action execution. If there is a match between the two, SoA arises (Wolpert, Ghahramani and Jordan, 1995). A consistent body of evidence empirically demonstrated the validity of the Comparator Model, thus confirming the importance of low-level sensorimotor predictive mechanisms in the emergence of SoA (see Sahaï, Pacherie, Grynszpan, & Berberian, 2017 for a review).

The contribution of low-level sensorimotor predictive processes to SoA is also supported by evidence at the neural level (e.g., Waszak, Cardoso-Leite, & Hughes, 2012). In this context, the electroencephalography (EEG)-derived N1 component has been investigated as an index of predictive mechanisms supporting the comparator model (Bäß, Jacobsen, & Schröger, 2008), and thus as a neural measure that may serve as a proxy (and indirect measure of) SoA (Caspar et al., 2020; Caspar, Christensen, Cleeremans, & Haggard, 2016; Poonian, McFadyen, Ogden, & Cunnington, 2015). The N1 is an event-related potential (ERP) that can index early auditory processes; it is also a response to visual and audio-visual stimuli. Thus, it can be described as a sensory ERP, likely independent of modality (Stekelenburg & Vroomen, 2007). Importantly, the N1 is sensitive to the predictability of sensory events (Bendixen, SanMiguel, & Schröger, 2012), and, importantly, to sensorimotor predictability of action outcomes (Bäß et al., 2008; Lange, 2011; Poonian et al., 2015; Sanmiguel, Todd, & Schröger, 2013). For example, N1 amplitude reduction (i.e., N1 suppression) was associated with sensory effects caused by self-generated actions (Aliu, Houde, & Nagarajan, 2009; Hughes, Desantis, & Waszak, 2013; Knolle, Schröger, & Kotz, 2013; Lange, 2011), as well as to self-generated sensory effects that are perceived as predictable rather than unpredictable (Gentsch, Kathmann, & Schütz-Bosbach, 2012; Hughes et al., 2013; Knolle et al., 2013). In effect, N1 suppression in action-effect tasks is thought to arise from a match between predicted and actual sensory outcomes (Aliu et al., 2009; Bäß et al., 2008; Hughes et al., 2013), and thus may represent a mechanism that is related to SoA, in that SoA is also based on predictions formulated within an internal model of actions and their sensory consequences. Furthermore, previous studies have also found concurrent modulations in N1 attenuation and SoA, measured via temporal estimation, further supporting the idea that the N1 may serve as a potential marker of processes that contribute to SoA (Caspar et al., 2016; Caspar et al., 2020; Poonian et al., 2015).

Similarly, the P2 component, i.e., an ERP that occurs immediately after the N1, is associated with the processing of sensory outcomes, and it is sensitive to the sensorimotor predictability of sensory outcomes (Timm, Schönwiesner, Schröger, & SanMiguel, 2016). Specifically, the P2 is suppressed in response to self-generated sounds, as compared to externally generated sounds (Horváth & Burgyán, 2013; Knolle, Schröger, Baess, & Kotz, 2012; Saupe, Widmann, Trujillo-Barreto, & Schröger, 2013; van Elk, Salomon, Kannape, & Blanke, 2014).

Despite the similarities between N1 and P2 components in the context of SoA research, they seem to be functionally dissociable. For example, while N1 suppression is impacted in patients with cerebellar lesions, P2 suppression is not (Knolle et al., 2012). Moreover, N1 and P2 respond differently to certain experimental manipulations. For example, Sanmiguel et al. (2013) found that the N1 suppression varied with different stimulus onset asynchronies (SOA), while the P2 was relatively constant across SOAs. Similarly, van Elk et al. (2014) found that N1 suppression was relatively insensitive to the type of action effector (lower or upper limb), as well as the action-outcome delay, while P2 suppression was sensitive to both these factors. Moreover, Timm et al. (2016) found that a comparable N1 suppression occurred for self-generated actions in two different conditions, i.e., one in which participants experienced SoA, and one in which they did not. This latter effect was due to changing the expected delay between actions and outcomes (Timm et al., 2016). Conversely, when observing P2 activity, the authors found a difference between these conditions, namely, the P2 was less suppressed when participants did not experience SoA (Timm et al., 2016). Therefore, it might be that N1 and P2 reflect two functionally dissociable processes.

Specifically, the N1 might be an *early indicator* of SoA, which depends on processes related to the formation and implementation of a motor plan. Consequently, the sensory suppression indexed by the N1 occurs once the intention to move has been formed, movement preparation starts, and an efferent copy of the motor plan is formed (Timm et al., 2016). Conversely, the P2 might be a *later indicator* of SoA, reflecting processing of action-related sensory outcomes, including the comparison between the predicted and the observed sensory outcomes of an action (Poonian et al., 2015; Timm et al., 2016). Importantly, however, this is not to say that P2 reflects postdictive processes of SoA. P2 most likely still manifests predictive processes, but at a slightly later stage of cognitive elaboration.

1.2. Operationalization of SoA

Experimentally, measures of SoA can be explicit or implicit. Explicit measures involve directly asking participants to rate how much control they perceive over their performed actions and outcomes (Dewey & Knoblich, 2014; Sato, 2009; Wegner & Wheatley, 1999). However, explicit measures might not be optimal, due to potential response biases such as the social desirability bias (Bandura, 2006).

Thus, implicit measures have been postulated as an alternative to measure SoA, with no explicit requests about individuals' agentic experience (Moore, 2016). This might be more ecologically valid if we consider that, in our daily life, we generally feel capable of planning and acting without actively reflecting upon it, i.e., without an explicit judgment of SoA. In this context, behavioural measures such as the Intentional Binding (IB) paradigms can be used to quantify implicit SoA. In their pivotal studies, Haggard and colleagues used the Libet clock method (Libet, 1981) to investigate the perceived time of occurrence of actions and their subsequent outcomes (Haggard, Aschersleben, Gehrke, & Prinz, 2002; Haggard, Clark, & Kalogeras, 2002). Participants were asked to observe a clock with a clock hand rotating and to estimate – with reference to the position of the clock hand – when a given event (i.e., a voluntary action or a sensory outcome, namely an auditory tone) occurred. Haggard, Aschersleben, et al. (2002), Haggard, Clark, and Kalogeras (2002) observed that participants reported a perceptual temporal compression of intervals between self-generated voluntary actions and their sensory (auditory) outcomes. Haggard and colleagues termed this phenomenon the *Intentional Binding (IB) effect.*

However, it is important to note that the IB paradigm based on the Libet clock method suffers from some criticism. For example, the instructions of whether to report the onset or the end of one's movement may affect participants' estimations, as well as the luminance of the clock hand and its size (e.g., Pockett & Miller, 2007). In addition, IB tasks employing the Libet clock method are visually and cognitively demanding, as participants have to continuously follow the clock hand on the screen to provide accurate judgments (Muth, Wirth, & Kunde, 2021). However, the IB paradigm based on the Libet clock methods seems to be a relatively sensitive method to capture implicit SoA (in the form of the IB effect) and more robust than other methods, for example, the interval estimation method (see Tanaka, Matsumoto, Hayashi, Takagi, & Kawabata, 2019, for a more complete overview).

A more theoretical critique might be raised to the IB effect, i.e., it does not capture implicit agency or might also not be related to the subjective experience of agency. Some past evidence (Buehner, 2012; Moore, Lagnado, Deal, & Haggard, 2009) endorsed the IB effect as the result of a mere perceptual attraction between two subsequent events, i.e., an action generating a sensory outcome and the sensory outcome itself. Alternatively, it may be more generally linked to causality rather than agency (Stetson, Cui, Montague, & Eagleman, 2006). For example, Dogge, Schaap, Custers, Wegner, and Aarts (2012) showed that the IB effect also occurs for involuntary actions, when self-causation is implied through instructions. Thus, the claim by Haggard, Aschersleben, et al. (2002), Haggard, Clark, and Kalogeras (2002) that the IB effect occurs only in the case of voluntary (and not involuntary) actions has been challenged. However, there is a consistent body of evidence showing that, whilst it is yet to be fully unravelled, the IB effect supports inferences of agency, as well as inference of agency supports the emergence of the IB effect (Moore & Haggard, 2008; see Moore & Obhi, 2012 for a review).

1.3. *Vicarious SoA*

SoA does not exclusively refer to the sense of control over one's actions and outcomes. In social contexts that humans share with others, a sense of joint-agency can emerge ("the sense that *we* did it"; Pacherie, 2012). However, when people are exposed to actions performed by other agents, SoA may still manifest at the individual level. This is how individual SoA becomes "vicarious" SoA, i.e., the feeling of authorship for others' actions and outcomes (Wegner, Sparrow, & Winerman, 2004). Different from self-SoA, vicarious SoA arises when people know that a given action – and the subsequent change in the environment, i.e., the outcome- is produced by another agent; differently from joint SoA, vicarious SoA may occur over someone else's actions even if no common goal is shared (Sahaï et al., 2017).

Several studies have investigated vicarious SoA, demonstrating that it emerges – in the form of the vicarious IB effect – toward observed voluntary actions of another person (Moore, Teufel, Subramaniam, Davis, & Fletcher, 2013; Pfister, Obhi, Rieger, & Wenke, 2014; Poonian et al., 2015; Poonian & Cunnington, 2013; Wohlschläger, Engbert, & Haggard, 2003; Wohlschläger, Haggard, Gesierich, & Prinz, 2003). When we observe another person acting, predictive mechanisms might link the observed action to our own motor system (Sahaï et al., 2017).

At the neural level, there is evidence showing that tones that participants judged as self-generated elicited a similar N1 amplitude to tones judged to be experimenter-generated, even though they were generated by a computer (Kühn et al., 2011). Although this study did not explicitly target the vicarious SoA phenomenon, it potentially supports the idea that sensorimotor predictive processes are also at play when judging the actions of another agent.

In contrast to Kuhn and colleagues' study (Kühn et al., 2011), Bäß et al. (2008) observed that N1 was attenuated for self-initiated sounds, but not for externally produced ones. However, it should be noted that they asked participants to listen to tones generated by a computer; therefore, the lack of N1 suppression for externally generated sounds could be the consequence of not being preceded by an action event. That said, it is evident that the investigation of the N1 component in the context of self vs. externally generated events (sounds) led to mixed results. In addition, none of these studies directly investigated vicarious SoA, and thus there are no findings clearly describing how the N1 component is modulated in vicarious SoA, and whether it is the same as in self-SoA.

Furthermore, the P2 component was investigated in the context of self- vs. externally generated events and SoA. Previous evidence showed that self-generated tones elicit a suppressed P2, as compared to externally generated tones (Horváth & Burgyán, 2013; Knolle et al., 2012; Saupe et al., 2013; van Elk et al., 2014). Moreover, Bolt & Loehr (2021) found that when two people produced a sequence of tones together, the P2 was more suppressed for self-generated tones than other-generated tones. However, to our knowledge, few, if any, studies have investigated P2 suppression specifically in the context of vicarious SoA. Thus, the effects of self vs. vicarious SoA on P2 modulation remain to be examined.

1.4. *Mechanisms underlying vicarious SoA toward humans and nonhuman agents*

Given that self-SoA relies on predictive mechanisms related to motor control (Frith et al., 2000), it is plausible that in vicarious SoA toward other humans the same predictive mechanisms are involved (Moore et al., 2013; Pfister et al., 2014; Poonian et al., 2015; Poonian & Cunnington, 2013; Wohlschläger, Engbert, & Haggard, 2003; Wohlschläger, Haggard, et al., 2003). In fact, due to the same sensorimotor repertoire shared by humans, individuals likely form a representation of the motor control mechanisms of others when observing them in action. This would be supported by the human action perception (Adolphs, 2009; Sahaï et al., 2017) or the mirror neuron systems (Gallese et al., 1996; Rizzolatti & Craighero, 2004).

Interestingly, vicarious SoA is not unique to observing actions performed by other humans but seems to also emerge when observing actions performed by artificial agents, such as robots. Khalighinejad, Bahrami, Caspar, and Haggard (2016) performed an IB study in which participants observed actions initiated either by a human agent or by a human-shaped robotic hand. Participants' task was to report the time of occurrence of tone outcomes generated by either action. Results showed that vicarious SoA, in form of a vicarious IB effect, similarly emerged for actions initiated by another human and by the robotic hand. More recently, Roselli, Ciardo, and Wykowska (2022) showed that vicarious SoA toward the non-anthropomorphic robot Cozmo (Anki Robotics) can occur if the robot performs a physical action. In follow-up studies (Roselli, Ciardo, De Tommaso, & Wykowska, 2022; Roselli, Ciardo, De Tommaso, & Wykowska, 2025), the authors showed that the humanoid robot iCub (Metta et al., 2010) elicited a robust vicarious IB effect. Navare, Ciardo, Kompatsiari, De Tommaso, and Wykowska (2024) showed – with the same humanoid robot iCub – that a sense of joint agency (SoJA) emerged in a joint human-robot action task. SoJA is a similar phenomenon to vicarious SoA and occurs when one experiences SoA over actions of their partner, in the same way as over one's own actions, independent of who is actually producing the action. This is due to two partners forming a team, and as such, representing their actions (and the action consequences) jointly.

1.5. *Minimal requirements for vicarious SoA – the role of proximal and distal effects*

There is little evidence in the literature addressing the distinction between proximal (e.g., the auditory and tactile information related to the keypress) and distal action effects (the goal of the action) and their contribution to self-SoA (Metcalfe, Eich, & Miele, 2013). Specifically, they both seem to contribute to self-SoA; however, they exhibit different profiles. While the proximal action-related information can be considered as a diagnostic cue for SoA, as it indicates the match between one's intentions and actions (and internal monitoring of intentions is necessary for SoA), the distal action effect can be largely monitored also using information that is external to the agent. Consequently, it is not a diagnostic cue – although it is mainly used by people to make agency judgments (Metcalfe et al., 2013).

With this in mind, it remains to be answered what role proximal and distal action effects play in vicarious SoA toward artificial agents. Vicarious SoA arises for physical actions performed by embodied robots, but not for disembodied computers (Obhi & Hall, 2011; see Limerick, Coyle, & Moore, 2014 for a review) or "disembodied" actions, such as digital commands, of a robot (Roselli, Ciardo, & Wykowska, 2022). Therefore, it is of interest which mechanisms underlie the emergence of vicarious SoA. It is not clear what the minimal requirements for the action perception system are, and for vicarious SoA to emerge, especially in the case of nonhuman agents. When humans observe an entire action sequence performed by another human, they have access to the action execution itself (movement trajectory, kinematics, etc.), the proximal action effects (the auditory and visual information related to the action, for example, a keypress, as well as the movement of the finger to press the key), and the distal action effects (the goal of the actions, e.g., tone or light being turned on). Therefore, it remains to be addressed whether the observer needs to have access to all this information of the other's motor plan (and thus, predictive processes that are at play) to experience vicarious SoA.

In fact, human-like characteristics of motion (e.g., kinematics) significantly affect people's ability to predict a course of action, namely, human-like movements represent a perceptual advantage for predictive processes (Stadler, Springer, Parkinson, et al., 2012). And those, according to the Comparator Model (Frith et al., 2000), are crucial for SoA. Glasauer, Huber, Basili, Knoll, and Brandt (2010) were among the first to demonstrate the importance of the human-likeness of robot movements. They showed that during handover interactions, involving a human agent and a robotic arm, characteristics such as an arm's motion law and its physical appearance were significantly modulating the perception of the robotic arm, as they were influencing the predictability (and thus the understanding) of its action goals. Specifically, when the robotic arm was handing over an object to the human participants seated in front of it, participants' reaction times to grasp the object were faster when the robotic arm displayed human-like kinematics as compared to when it moved following a trapezoidal joint velocity profile (i.e., machine-like kinematics). In other words, participants were better able to predict the movements of the robotic arm when they were human-like than when they were machine-like (Glasauer et al., 2010). Notably, this effect was modulated by the physical appearance of the robot, in such a way that faster reaction times were the consequence of human-like appearance, whereas machine-like appearance (i.e., industrial robot system) led to slower reaction times (Glasauer et al., 2010). Therefore, it is not surprising that with the humanoid robot iCub, whose finger movements (leading to a button press) highly resemble human movements, Roselli and colleagues (Roselli et al., 2025; Roselli, Ciardo, De Tommaso, & Wykowska, 2022) observed a robust vicarious IB effect.

However, it might also be that the action outcome (action goal) is a sufficient trigger for the activation of predictive mechanisms related to one's motor control. In fact, according to the ideomotor theory of action planning (e.g., Greenwald, 1970; Hommel et al., 2001; James, 1890; Prinz, 1990, 1997), humans plan actions in terms of action goals (sensory outcomes of planned actions), rather than through representation of minute details of motor programs. Through lifelong experience with the generation of various movements and observations of sensory consequences of those movements, humans learn the action-outcome associations and thus can select (and plan) the action that best matches the desired action outcome. In line with this reasoning, the action outcomes are the key to the activation of motor plans that lead to those actions. This might be sufficient to activate the represented motor plan, and vicarious SoA to emerge. Should that be the case, then one should observe vicarious SoA also in cases when observers have access only to distal action effects (action goals) and not to action execution.

However, Roselli, Ciardo, and Wykowska (2022) showed that when a physically embodied robot produced a tone by executing a digital command sent via Bluetooth, vicarious SoA did not occur. In contrast, when the same action outcome was generated via a physical action, vicarious SoA occurred even if the effector of the robot was not human-like (i.e., a lift instead of a hand-shaped effector). These results suggest that vicarious SoA toward artificial agents occurs when people can represent the physical action of the observed agent. However, it remains to be addressed, which of these components are crucial for vicarious SoA to occur. Roselli, Ciardo, and Wykowska (2022) showed that access to the distal action effect alone is not sufficient for vicarious SoA, as an action generated digitally did not elicit the effect. The remaining question is whether providing the observer with slightly more information than just distal action would be sufficient for vicarious SoA to occur. By "slightly more information" we refer to information about the proximal effects of an action (the button press itself).

2. Aim of the study

This study aimed to examine the minimal requirements for vicarious SoA to occur in relation to artificial agents. Past evidence demonstrated that observing a human-like action, executed by an embodied artificial agent (a robot), elicits vicarious SoA in a Libet clock task (Khalighinejad et al., 2016; Roselli, Ciardo, De Tommaso, & Wykowska, 2022), whereas having access to only the distal sensory effects of an action (action goals) does not (Roselli, Ciardo, & Wykowska, 2022). Thus, with this study, we addressed whether providing participants access to only the proximal effect of action (keypress) in the absence of motor action execution would be sufficient for vicarious SoA to occur.

Should this be the case, then it would demonstrate that when observing events generated by an artificial agent, the proximal *action effect* is sufficient for activating sensorimotor action representations, which, in turn, activate vicarious SoA. Importantly, the proximal action effects might not be necessarily equivalent to action goals. Returning to the light example – a person presses the light switch to turn on the light (action goal). In this context, the proximal action effects of pressing the light switch are the sound of the click of the switch and the haptic feedback of the finger.

We designed (in collaboration with the Electronic Design Laboratory of the Italian Institute of Technology, Genoa, Italy) a device (a button) – hereafter named "ghost button" (GB) - that allows observers to access proximal action effects, i.e., keypress, generated by a disembodied artificial agent (a computer) in the absence of a motor action execution. The ghost button was programmed in such a way that, when the computer sent the command, the GB mechanically lowered down, as if there was an invisible hand pushing it down (see Fig. 1 for illustration; and Supplementary Materials, section SM.1, for a detailed technical description of the ghost button).

Participants performed an IB task, estimating the time of occurrence of the outcome (tone) generated by the ghost button in a Libet-like clock task. We chose the Libet-like clock task, despite some critique of the methods (cf. Introduction Section) to be in line with previous literature on vicarious SoA (e.g., Khalighinejad et al., 2016; Roselli et al., 2022,b).

Furthermore, given that the present study focused on the vicarious SoA, rather than individual SoA, we needed to use the implicit measures of SoA (despite their limitations), rather than explicit judgments of control. Asking participants a question of the type "how much control did you feel over the outcome of the action performed by the Ghost Button?" would be a very strange question to ask when another agent performs the action. It seems that the explicit judgment of control does not apply to the case of vicarious SoA: to the best of our knowledge, there is no evidence in literature showing the use of explicit measures to measure vicarious SoA, which is better assessed by both implicit (Wohlschläger, Haggard, et al., 2003) and neurophysiological measures such as ERPs (Poonian et al., 2015).

In addition to the IB task, we employed EEG measurements to understand whether the information provided to participants about the action of the GB activates mechanisms related to the predictions involved in motor planning (manifested through N1 effects), or rather slightly later, in higher-level cognitive processes linked to SoA and perhaps the comparison between predicted and observed action

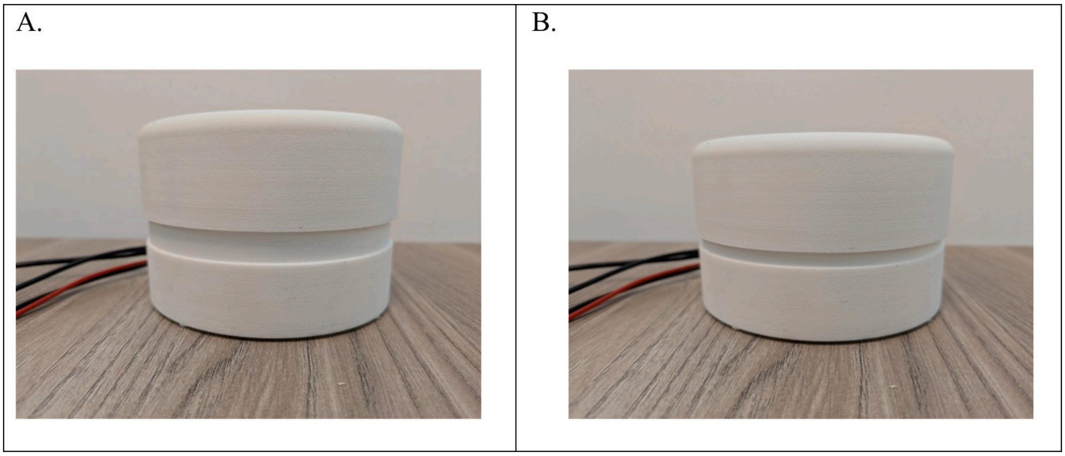


Fig. 1. Ghost button in the state of not being pressed (A) and the same button “pressed” (B).

outcomes (manifested by P2 effects).

To test whether the observed vicarious IB effect (if observed) indeed reflects vicarious SoA and is due to the activation of a sensorimotor representation of an action, rather than simply reflecting the learned association between proximal and distal effects, we manipulated the predictability (expectancy) of the *content* of the distal effect. We reasoned that if access to a proximal action effect is sufficient for vicarious SoA to emerge, then the learned association between action and tone outcome *content* should not be crucial, namely the comparable vicarious IB effects should be observed for both expected and less expected tones. On the other hand, if the observed effect was to reflect learned associations between proximal and distal action effects (rather than the vicarious SoA), then disrupting such learned associations, should eliminate (or at least attenuate) the effect.

To address this, we introduced an experimental manipulation of expectancy (in content) of the distal action effect. Participants were exposed to a learned association of the proximal-distal chain of action effects in 70 % of trials, while in 30 % of trials, they would experience the same proximal action effect (keypress) but a different distal effect (different tone pitch).[3] If the expectancy of the learned association between proximal and distal action effects does not affect the vicarious IB effect, then this means that the effect reflects the vicarious SoA (and is not based on learned associations between proximal and distal action effects).

Regarding EEG, we used this measure to understand the specific mechanisms involved in the vicarious SoA (should this be observed behaviourally). We reasoned that if the N1 in response to tones generated following the GB “action” relative to baseline (no action) was reduced (a difference henceforth called the N1 suppression), this would indicate that the effect is due to sensorimotor prediction involved in a lower-level, pre-reflective generation of a motor plan (Timm et al., 2016). Conversely, not observing differential N1 effects would mean that the behavioural vicarious SoA (if observed) might be due to other (perhaps later) cognitive processes. Moreover, based on previous studies showing that N1 response to self-generated tones is sensitive to the predictability of content outcomes (Baess et al., 2011; Hughes et al., 2013), we hypothesized that the N1 response might be smaller for predictable than unpredictable tones, independent of the IB effect.

On the other hand, if we were to observe a P2 suppression effect, this would mean that the behavioural vicarious IB effect reflects (also) later sensory processes, perhaps related to the comparison of expected and observed action effects. Important to note is that this would not mean that the P2 reflects postdictive processes of SoA, as this response shows during a relatively early processing stage. We suggest that P2 would still indicate predictive, but more cognitively elaborated and later (rather than early sensory) processes.

In sum, the aims of the current study were to:

1) Understand the minimal conditions under which vicarious SoA toward artificial agents occurs, namely whether the proximal action effects are sufficient to trigger vicarious IB effect;
2) Examine – with the use of the EEG – if vicarious SoA (if observed) is based on predictive mechanisms related to the motor plan (N1 effect) or is rather related to higher level cognitive processes involved perhaps in the comparison between observed and predicted action outcome (P2 effect, Timm et al., 2016).
3) Confirm – using expectancy manipulation – that the IB effect (if observed) is due to vicarious SoA rather than the learned association between the proximal and distal action effects.

3. Study design

3.1. Solo experiment

Before running the GB experiment, we conducted a Solo experiment (in which participants performed the task alone) to check if our implementation of the IB task works, and what impact (if any) the expectancy of the action distal effect (tone) has on SoA. To manipulate the expectancy of tone outcomes, we first asked participants to perform a short familiarization session, in which they were asked to judge the occurrence of a tone. Notably, the tone could be either preceded by their button press (Operant block) or not. In the latter case, the tone was randomly played during the rotation of the clock hand with no action (no button press) preceding it (Baseline block). During this phase, participants learned the association between their actions and the subsequent tone outcome.

Afterwards, during the IB task in 70 % of trials, participants were presented with the tone they learned to associate with their action (expected outcomes), whereas they were presented with a different tone in the remaining 30 % of trials (thus, a less expected tone). This was made for both Operant and Baseline blocks, with the only difference that in the Operant blocks the tone (being expected or less expected) was generated by participants’ actions, namely the keypress, whereas in the Baseline block the tone (being expected or less expected) was not preceded by any action.

Additionally, in both blocks (Baseline and Operant), we manipulated expectancy only in terms of content. It would mean that the difference

---

[3] Note, however, that we did not manipulate predictability in the *temporal* expectation, namely the action-tone interval (as in previous studies which manipulated the temporal predictability of the delay duration; e.g., Haggard et al., 2002b; Ruess et al., 2018).

between expected and less expected outcomes was in the tone pitch (low vs. high pitch tone), and not in the timing of its occurrence.

During the completion of the IB task, participants' neural activity was recorded via electroencephalography (EEG), to target neural correlates of SoA, namely the auditory N1 and P2 (Timm et al., 2016).

3.2. GB experiment

A new sample of participants performed the same IB task as in the Solo experiment, but this time, in the Operant block, the ghost button (GB) executed the keypress instead of the participants themselves. Comparable to the Solo experiment, before the IB task, participants performed a familiarization session in which they learned to associate the actions of the GB and the subsequent tone outcome. Then, as in the Solo experiment, during the IB task, the tone outcome they learned to be associated with the keypress GB (i.e., the expected outcome) was presented in the 70 % of trials, whereas in the 30 % of trials participants were presented with a different tone from the one they learned to associate with the keypress of the GB (i.e., the less expected outcome).

In both experiments, and in line with previous evidence (Haggard, Clark, & Kalogeras, 2002), for self-generated tone outcomes (i.e., Solo experiment), we expected to replicate the IB effect at the behavioural level. For tone outcomes generated by the GB (GB experiment), we reasoned that if proximal effects of an action are a sufficient trigger for activating simulation of the representation of an action, then we should also observe a vicarious IB effect.

Regarding the ERPs, in line with previous evidence (Bäß et al., 2008; Knolle et al., 2012), we hypothesized that for the self-generated actions, N1, and potentially the P2, would be more suppressed in the Operant block, as compared to the Baseline (i.e., suppression of self-generated tones), thus mirroring the IB results. Moreover, we hypothesized that the expectancy of the tone might also affect the N1 amplitude, such that the N1 would have larger amplitude for less expected than expected tones, in line with the classical literature on predictability affecting the N1 component (as in Gentsch et al., 2012; Hughes et al., 2013; Knolle et al., 2013). This effect could be independent of the agency manipulation.

For the experiment with GB manipulation, we reasoned that a N1 suppression effect would indicate that early predictive processes related to a (simulated) motor plan underlie the vicarious IB effect (if observed). A P2 suppression effect, on the other hand, would suggest that the vicarious IB effect (if observed) is related to higher-level cognitive processes involved in SoA.

4. Solo experiment (self-generated tones)

4.1. Materials and methods

4.1.1. Participants

Forty participants were recruited to take part in the Solo Experiment ($M_{\text{Age}} = 28$, $SD_{\text{Age}} = 5.7$, 17 males, 23 females, 37 right-handed, 3 left-handed). All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. They all gave written informed consent, and the study was conducted with the approval of the local Ethical Committee (Comitato Etico Regione Liguria, registry number IIT_INSTANCE 049REG2017), and the ethical standards of the 2013 Declaration of Helsinki. The sample size was estimated based on a priori power analysis, using G * Power v.3.1.9.7 (Erdfelder, Faul, & Buchner, 1996). We estimated that, to perform a within-subjects Repeated Measures ANOVA, a sample size of $N = 35$ was needed for sufficient power ($\beta = 0.95$) to detect a small-medium effect size (Cohen's $d = 0.25$; α (two-tailed) $= 0.05$). We recruited five more participants to account for possible exclusions of some of the datasets. All participants were paid 35 euros for their participation; at the end of the experimental session, they were all debriefed about the purpose of the experiment.

4.1.2. Experimental apparatus

The experimental setup comprised a workstation equipped with a 27′ screen to display the IB task; one Logitech button for participants to perform the keypress; one QWERTY keyboard to type the temporal estimate; one workstation equipped with one 21′ screen for the EEG recording, and one set of speakers. The IB task was programmed and presented using Psychopy v2021.2.0 (Peirce, 2007). EEG data were recorded using Ag-AgCL electrodes from a 64 electrodes system, following the International 10–20 layout (ActiCap, Brain Products, GmbH, Munich, Germany). Data were referenced online to Fz. The EEG signal was amplified with a BrainAmp amplifier (Brain Products, GmbH), digitized at 500 Hz sampling rate, and recorded. No filters were applied during EEG recording. Electrodes impedances were kept below 10 K for the entire duration of the experiment.

4.1.3. Procedure

The experiment was conceived as a 2 (Block: Baseline, Operant) x 2 (Outcome Expectancy: Expected, Less Expected) within-subjects design. Participants were seated approximately 70 cm from the computer screen and asked to perform the IB task. Specifically, participants' task was to estimate the time of occurrence of the critical event, namely the tone outcome. At the beginning of each trial, a black fixation dot appeared on the screen for 100 ms, followed by a static image of a clock with a red clock hand for 500 ms. The clock was marked with 12 conventional minute intervals (5, 10, 15, etc.) to help participants give as accurate time estimates as possible. The initial clock position was random. Afterward, the clock hand started rotating clockwise, with ten full rotations for each trial. Each rotation took 2560 ms to complete, as in the original study of Haggard, Aschersleben, et al. (2002). The clock hand stopped rotating at a random time between 1500 and 2500 ms after the occurrence of the critical event, i.e., the tone outcome caused by the computer's action. During the experimental session, participants performed three blocks: Operant Tone, Baseline Tone, and Baseline Action block. The Baseline Action Block was introduced for the correction of motor-related neural activity in the Operant Block trials, but it was not used for the calculation of the IB effect. The presentation of the Operant Tone and Baseline Tone block was fully randomized, whereas the Baseline Action block was always performed at the end of the experimental session. In the Operant Tone block, participants were instructed to wait until the end of the first full rotation of the clock hand; subsequently, they were asked to act, i.e., to execute the keypress at the time of their choosing (i.e., when they "felt" to do it). The keypress produced a sensory outcome, namely a tone beep, after a fixed interval of 250 ms. Conversely, in the Baseline Tone block participants did not execute any action, and the tone beep was randomly played during the rotation of the clock hand (within a predefined time window of 2560–8000 ms). In both blocks, participants' task was to estimate the time of occurrence of the tone outcomes. Finally, participants performed a Baseline Action block, in which participants were asked to perform a keypress at the time of their choosing- with no following tone thereafter.

As we also sought to investigate whether, and how, the expectancy of the content of the tone outcomes affected SoA, in both tone blocks (Operant, Baseline) the presentation of the type of tone outcomes was manipulated according to a 70/30 ratio. Before the IB task participants performed a short familiarization phase, in which they practiced the task and learned the association between their actions and the following tone outcome (high-pitch tone: 800 Hz, 100 ms duration). Afterwards, when performing the Operant and Baseline blocks, in 70 % of trials (140 trials) participants were exposed to the tone outcome that, from the practice session, they learned to expect as the outcome of their self-generated actions (Expected Outcome: high-pitch tone, 800 Hz, 100 ms duration). Conversely, in the remaining 30 % of trials (60 trials), participants were exposed to a different tone outcome they did not expect to occur, as in the practice phase it was never presented as a possible outcome of their action (Less expected Outcome: low-pitch tone, 400 Hz, 100 ms duration). Within each block, the presentation of expected vs. less expected tone outcomes was completely randomized. The task comprised 470 trials in total. Both Operant Tone and Baseline Tone block comprised 200 trials each, whereas the Baseline Action comprised 60 trials. Finally, the practice familiarization session comprised 10 trials, and it was always administered before the task. In this session, the same association between participants' actions and a given tone outcome was presented. For the entire duration of the task, participants' neural activity was recorded via EEG.

4.2. Data preprocessing

4.2.1. Judgment Errors and IB effect

Three participants were excluded from preprocessing due to the experiment crashing, and thus no data were saved, resulting in a sample size of $N = 37$. Subsequently, for each trial, we calculated the Judgment Error (JE), namely the “minute” difference between the position of the clock hand reported by participants and its actual position when the critical event (i.e., self-generated tone outcomes) occurred. Then, the minute differences were transformed into millisecond differences (minute JEs x 2560/60). For each combination of Block (Operant, Baseline), and Outcome (Expected, Less Expected) we calculated their means and standard deviations (SDs). JEs that deviated more than ±2.5 SD from the participants' mean in each combination were considered outliers and removed from further analysis (2.8 % of the total number of trials). Following outliers' removal, the data of two participants was excluded due to a low number of remaining trials (≤ 25 in one or more combinations of Block (Operant, Baseline) and Outcome (Expected, Less Expected)). It resulted in a final sample size of $N = 35$.

Please note that the IB effect for tone outcomes (i.e., Tone IB effect) is observed as less positive JEs in The Operant block as compared to the Baseline block (Ruess, Thomaschke, Haering, et al., 2018; Roselli, Ciardo, & Wykowska, 2022). The greater the difference in JEs between Operant and Baseline, the stronger the Tone IB effect (and thus SoA).

4.2.2. N1 and P2 ERPs

Data from five participants were excluded because they were removed from behavioural data. Furthermore, the data of another participant was excluded due to poor EEG signal quality throughout the whole experimental session, resulting in a final sample size of $N = 34$. Then, participants' neural EEG data were pre-processed and analysed using MATLAB v. R2020b (The MathWorks Inc, 2022), as well as EEGLAB (Delorme & Makeig, 2004) and FieldTrip toolboxes (Oostenveld, Fries, Maris, & Schoffelen, 2011).

First, data were re-referenced to the average of all electrodes, and Fz was added back to the channel matrix. Then, data were down sampled to 250 Hz, and band-pass filtered between 0.1 and 40 Hz. Then, data were segmented in epochs (−200; 3500 ms) to make the subsequent processing step easier. A baseline correction from −100 to 0 ms was applied to the epochs. Epochs with prominent artifacts (e.g., muscle noise) were removed through visual inspection, as were bad channels. On average, we removed 28.05 epochs per participant (SD = 23.08), and 0.23 channels per participant (SD = 0.78). Following the visual inspection, data were re-referenced to the average of all electrodes. Independent component analysis (ICA) was applied to the data to further remove artifacts related to eye blinks or eye movements, and other artifacts (i.e., muscle noise). On average, we removed 18.32 ICs per participant (SD = 8.00). Following artifacts' removal via ICA, the removed channels were spatially interpolated, and data were re-referenced to the mastoids (TP9/TP10). Finally, data were separated into four types of segments (Operant Tone Expected; Baseline Tone Expected; Operant Tone Less Expected; Baseline Tone Less Expected).

For further statistical analysis, both the N1 and P2 amplitude were extracted. The N1 amplitude was defined as the mean amplitude in the time window [peak amplitude ±50 ms], where the peak was defined as the minimum amplitude in the time window [60 to 160 ms], for each subject, outcome, block, and channel. The P2 amplitude was defined as the mean amplitude in the time window [peak±50 ms], where the peak was defined as the maximum amplitude in the time window [170 to 240 ms], for each subject, outcome, and block condition.

4.3. Statistical analysis

4.3.1. Judgment Errors and IB effect

As the dependent variable, JEs were submitted to a 2 × 2 Repeated Measures ANOVA in JASP 0.14.1.0 (2020), with Block (Operant, Baseline) and Outcome Expectancy (Expected, Less Expected) as the within-subject factors. The threshold for the level of significance was set at $p < 0.05$; η^2 is reported as an index of the effect size.

4.3.2. ERPs

Data were analysed in RStudio. For both N1 and P2, amplitudes were pooled across the channels Cz, C3 and C4. Pooled data were then submitted to a 2 (Block: Operant, Baseline) x 2 (Outcome: Expected, Less Expected) Repeated Measures ANOVA. Significant effects were investigated further with paired sample *t*-tests. The threshold for the level of significance was set at $p < 0.05$; all *p*-values were FDR (False Discovery Rate) corrected for multiple comparisons were appropriate. The η^2 is reported as an index of the effect size for the ANOVA and the Cohen's d is reported for the t-tests.

4.4. Results

4.4.1. Judgment Errors and IB effect

Results showed a significant main effect of Block [$F_{(1, 34)} = 33.43$, $p < 0.001$, $\eta^2 = 0.49$], with underestimated JEs in Operant as compared to Baseline block [$t = 5.78$, SE = 18.1, $p < 0.001$, Cohen's d = 0.98; ($M_{Operant} = -95$ ms, $SE_{Operant} = 14.13$; $M_{Baseline} = 9.6$ ms; $SE_{Baseline} = 14.13$)] (Fig. 2).

Furthermore, the main effect of Outcome Expectancy emerged as significant [$F_{(1, 34)} = 31.97$, $p < 0.001$, $\eta^2 = 0.005$], with underestimated JEs (further from the actual timing of the tone, thus less accurate) when the tone outcome was expected as compared to when it was less expected (in this case, participants were closer to the actual timing, and thus more accurate) [$t = -5.66$, SE = 1.85, $p < 0.001$, Cohen's d = −0.96; ($M_{Expected} = -47.94$ ms, $SE_{Expected} = 10.89$; $M_{Less\ Expected} = -37.46$ ms; $SE_{Less\ Expected} = 10.89$)] (Fig. 3). However, the two-way interaction between Block (Operant, Baseline) and Outcome Expectancy (Expected, Less Expected) did not emerge as significant [$F_{(1, 34)} = 0.1$, $p = 0.75$, $\eta^2 < 0.0001$].

4.4.2. ERPs

4.4.2.1. N1.

Results of the 2 × 2 ANOVA showed a significant main effect of Block [$F_{(1,33)} = 12.52$, $p = 0.001$, $\eta^2 = 0.06$] (Fig. 4), and of Outcome Expectancy [$F_{(1, 33)} = 39.28$, $p = 0.0000004$, $\eta^2 = 0.04$] (Fig. 5). There was no significant interaction [$F_{(1, 33)} = 0.05$, $p = 0.82$, $\eta^2 = 0.00002$]. The N1 was less negative (i.e., smaller absolute amplitude) in the Operant block, compared to the Baseline block ($M_{Operant} = -3.20$, $SD_{Operant} = 2.48$; $M_{Baseline} = -4.68$, $SD_{Baseline} = 3.16$), indicating sensory suppression. Regarding Outcome Expectancy, the N1 was less negative (i.e., smaller absolute amplitude) when the tone outcome was expected as compared to when it was less expected ($M_{Expected} = -3.32$, $SD_{Expected} = 2.32$; $M_{Less\ Expected} = -4.56$, $SD_{Less\ Expected} = 2.92$), paralleling the behavioural results.

4.4.2.2. P2.

Results of the 2 × 2 ANOVA showed a significant main effect of Block [$F_{(1, 33)} = 12.27$, $p = 0 = 0.001$, $\eta^2 = 0.10$], but no main effect of Outcome Expectancy [$F_{(1, 33)} = 1.34$, $p = 0.26$, $\eta^2 = 0.002$]. The ANOVA also showed a significant interaction [$F_{(1, 33)} = 18.98$, $p = 0.0001$, $\eta^2 = 0.02$] (Figs. 6–8). Follow-up *t*-tests to check the main effect of Block for each level of Outcome Expectancy showed that the P2 was

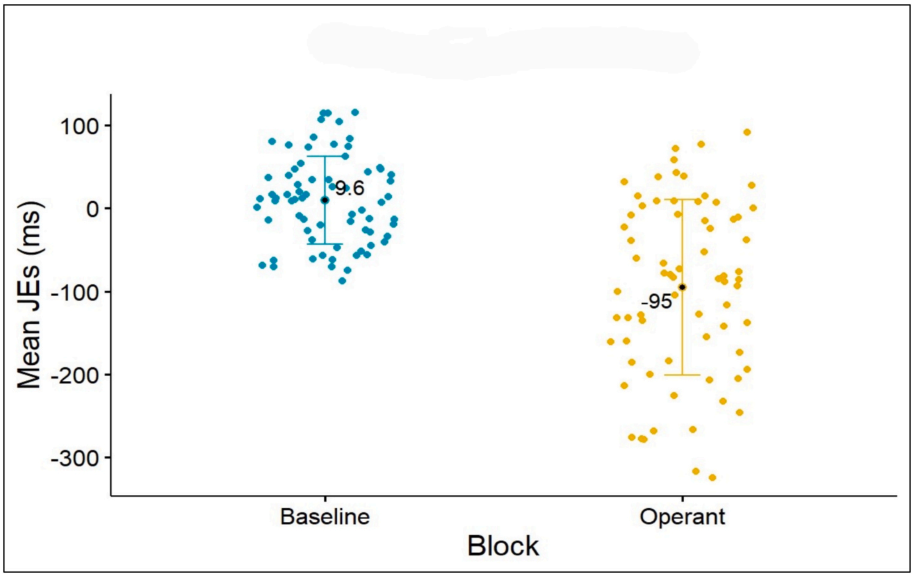


Fig. 2. Mean Judgment Errors (Mean JEs, in ms) plotted as a function of Block (Baseline, Operant). Coloured dots represent individual means, whereas black dots (with numbers) represent the mean values for each block. Errors bars represent standard errors.

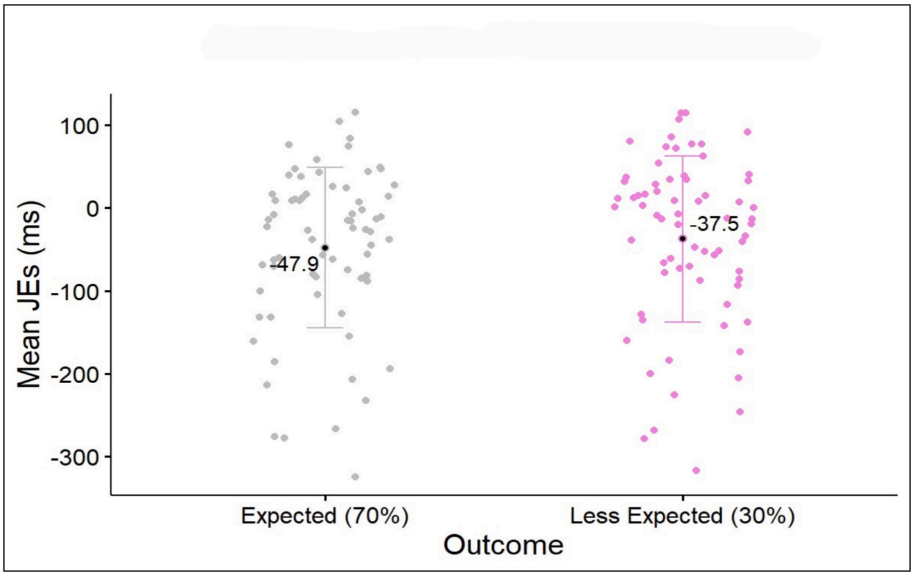


Fig. 3. Mean Judgment Errors (Mean JEs, in ms) plotted as a function of Outcome (Expected, Less Expected). Coloured dots represent individual means, whereas black dots (with numbers) represent the mean values for each type of outcome. Error bars represent standard errors.

significantly smaller in the operant blocks compared to the baseline blocks for less expected tones (Baseline-Operant: $t_{(34)} = 3.93$, $p_{FDR} = 0.0008$, Cohen's $d = 0.67$) and expected tones (Baseline-Operant: $t_{(33)} = 2.59$, $p_{FDR} = 0.01$, Cohen's $d = 0.44$). However, the magnitude of the effect was slightly larger for less expected tones as compared to expected tones.

4.5. Discussion of the solo experiment

The aim of the experiment was twofold. First, we intended to check whether our implementation of the IB task works, namely, whether it elicits the IB effect both behaviourally and at the neural level. Second, we aimed to investigate whether, and how, the expectancy of a specific content of an action outcome affects behavioural and neural manifestations of SoA. To these aims, participants performed the IB task by judging the occurrence of self-generated tones (and thus we focused on individual implicit SoA).

Behavioural results showed a main effect of block (operant vs. baseline), namely, the Tone IB effect always emerged for self-generated outcomes. In other words, participants always exhibited implicit SoA over tones when they were outcomes of their actions, regardless of whether they were expected or less expected. These findings demonstrate that our implementation of the IB task worked as predicted, based on past literature (Haggard, Aschersleben, et al., 2002). The expectancy manipulation (expected vs. less expected content of the action outcomes, namely the specific pitch of the tones), affected judgment errors, showing that participants' estimations were more accurate for less expected compared to expected tone outcomes. This might have been due to more accurate processing of the less expected outcomes, which might have elicited higher alertness and thereby more attentional focus on the stimulus. Although in our experiment the main effect of expectancy was observed only in relation to judgment errors and not in relation to the IB

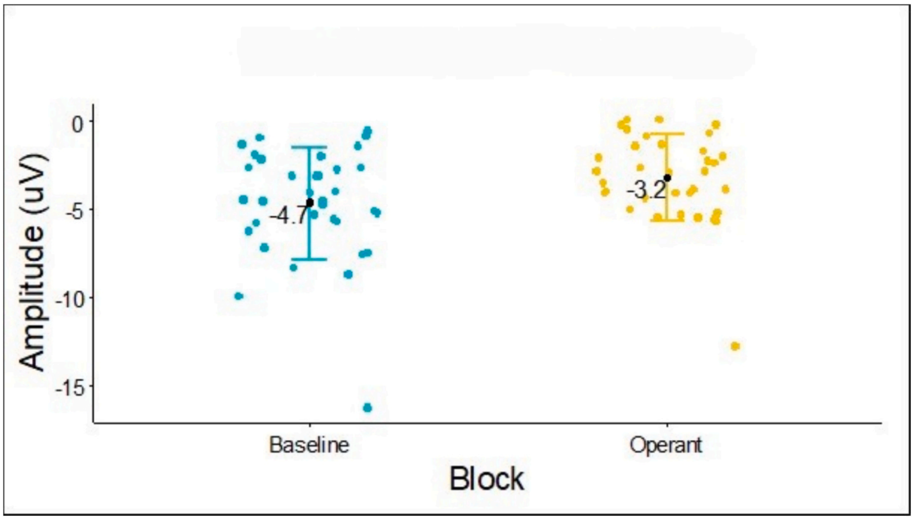


Fig. 4. Mean N1 amplitude, averaged across the electrode Cz, C3, and C4, plotted as a function of Block (Baseline, Operant). Coloured dots represent individual means, block dots represent group means, and error bars represent the standard deviation.

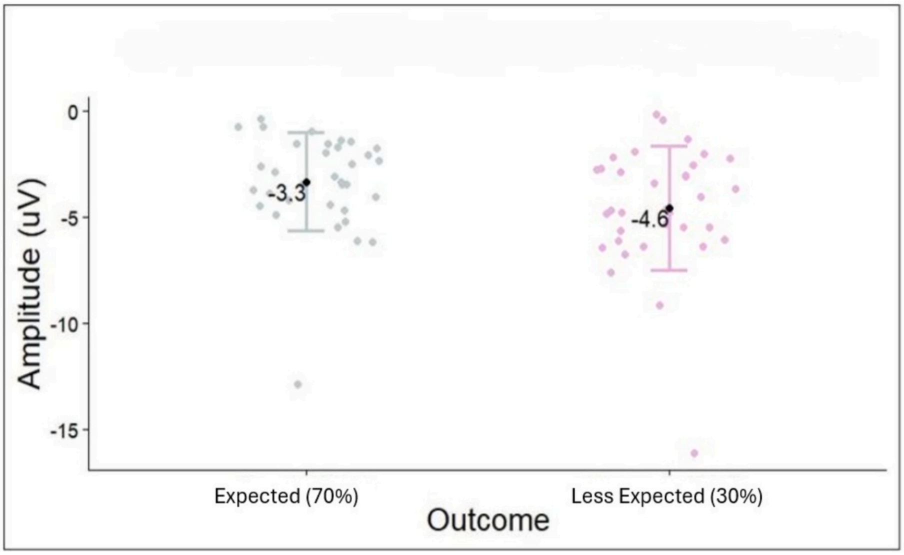


Fig. 5. Mean N1 amplitude, averaged across the electrode Cz, C3, and C4, plotted as a function of Outcome Expectancy (Expected, Less Expected).

effect, it is worth noting that it seems in contrast with past evidence showing different results, i.e., the IB effect was not modulated by the expectancy of the tone (e.g., Desantis, Hughes, & Waszak, 2012). Indeed, in Desantis et al.'s (2012) study, the onset of the tone outcome (regardless of its identity) was fixed to 400 ms after the participants' action onset. In our version of the IB task, however, the action-tone interval was fixed to 250 ms. It is an important methodological detail, since there is past evidence showing that the time course of the IB effect may change as a function of the temporal predictability of the delay duration (e.g., Haggard, Clark, & Kalogeras, 2002; Ruess et al., 2017; Ruess et al., 2018). Therefore, it might be that also expectancy in the content of the event is modulated differently according to the time course of the action-tone delay.

Moreover, this interpretation (higher accuracy for less expected outcomes) is also supported by the neural evidence, as manifested by a higher amplitude of N1 for less expected outcomes, relative to those that were expected, see paragraph below. However, the lack of the two-way interaction between Block (Operant, Baseline) and Outcome Expectancy (Expected, Less Expected) suggests that the IB effect was comparable across types of tone outcomes. This (lack of) effect was important for the Solo experiment, because it suggests that the expectancy of the content of the action outcome – at least in the way we manipulated it - does not affect the self-IB effect (individual SoA). Therefore, should we observe in the main experiment any modulation of the vicarious IB effect related to expectancy, it might suggest that this modulation is related to the learned associations between proximal and distal action effects, in the case of action consequences observed for another (artificial) agent. On the other hand, not observing a modulation of the IB effect by expectancy would manifest the vicarious IB effect and would demonstrate that observable proximal action effects are sufficient for eliciting the vicarious SoA. At the neural level, results of the Solo experiment showed that both Block Type and Outcome Expectancy affected N1 amplitude, though there was no interaction between the two. Specifically, the N1 was more suppressed in the Operant block as compared to the Baseline block, regardless of the expectancy of the tone, indicating vicarious SoA. Moreover, expected tones elicited a smaller N1 amplitude as compared to less expected tones, regardless of the block. These results are in line with our initial hypotheses, as well as with the pattern of IB effects, and they support the idea that the N1 can both index processes related to SoA and is also sensitive to expectancy manipulations (Bendixen et al., 2012;

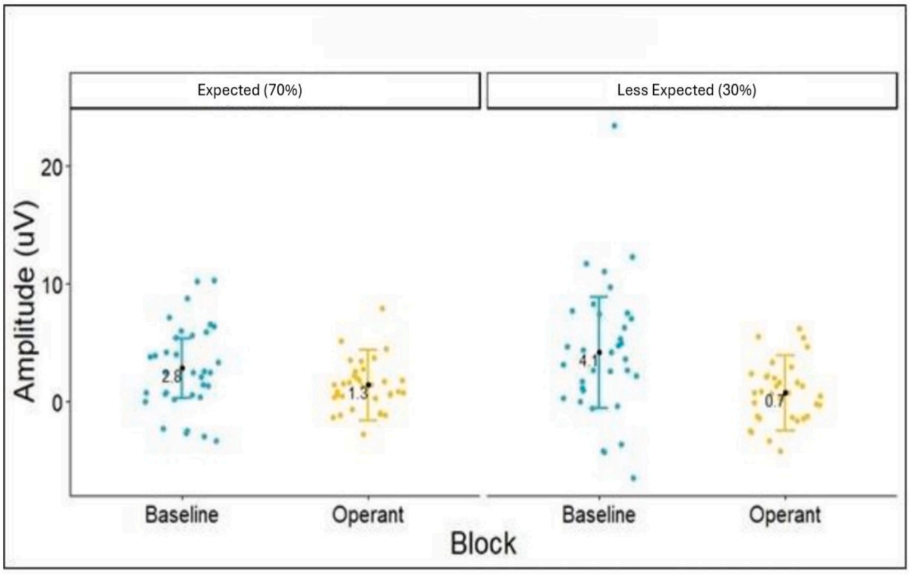


Fig. 6. Mean P2 amplitude averaged across the electrode Cz, C3, and C4, and Outcome Expectancy (Expected, Less Expected). Coloured dots represent individual means, block dots represent group means, and error bars represent the standard deviation.

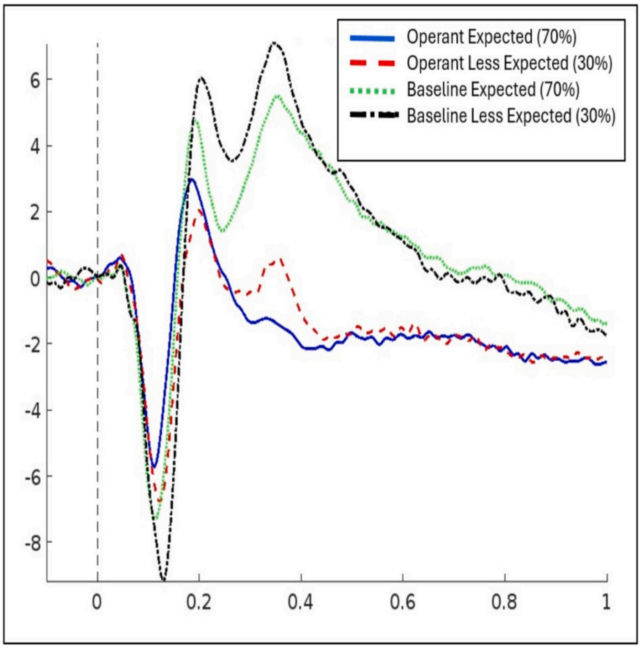


Fig. 7. ERP waveforms for each combination of Block (Baseline, Operant) and Outcome (Expected, Less Expected), averaged across the electrode Cz, C3, and C4 (left).

Sanmiguel et al., 2013). The larger N1 amplitude for less expected outcomes was presumably due to the alerting effect of those outcomes. In fact, N1 is sensitive not only to expectancy but also to the alerting nature of stimuli (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006). Therefore, in our study, the less expected action outcomes might have elicited a stronger neural response, and, thereby, a larger amplitude of the N1. This supports our above interpretation of the IB expectancy effect: the less expected outcomes elicited alerting response of the brain, which, in turn, increased performance (accuracy in the temporal judgments). However, most importantly for the purposes of our study, similar to the IB effect, the N1 suppression in the Operant block, relative to the Baseline block, showed that the IB manipulation worked as expected. The fact that we did not find an interaction between suppression and expectancy confirms the pattern of the behavioural data and shows that the (content) expectancy manipulation did not affect self-SoA.

Regarding P2, results showed a main effect of Block, but not of Outcome Expectancy. We also found a significant interaction between Block and Outcome Expectancy. Further investigation of the Block effect revealed that the P2 was suppressed in the Operant block, relative to the Baseline block for both expected and less expected tones, though the magnitude of this difference was larger for less expected tones. Thus, even though the magnitude of the effect differed between the expectancy conditions, the pattern of P2 suppression (related to SoA) was similar. The larger effect in the less expected outcome condition might be due to higher inter-participant variability in this condition, as indicated by the larger standard deviations (Fig. 6). Therefore, this interaction effect should be interpreted with caution. Overall, we can state that the modulation of individual SoA by expectancy (as manipulated in our study) seems to be rather minimal.

5. GB experiment (ghost-button generated tones)

5.1. Materials and methods

5.1.1. Participants

Forty-three participants were recruited to take part in the GB experiment 1(M Age = 24.53, SD Age = 3.55, 23 males, 20 females, 34 right-handed, 9 left-handed). All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. As for the Solo experiment, we estimated the sample size based on a priori power analysis, using G * Power v.3.1.9.7 (Erdfelder et al., 1996). We estimated that, to perform a within-subjects Repeated Measures ANOVA, a sample size of $N = 35$ was needed for sufficient power ($\beta = 0.95$) to detect a small-medium effect size (Cohen's d = 0.25; α (two-tailed) = 0.05). We tested forty-three participants to account for the possible need to exclude participants from further analyses.

The study was conducted with the approval of the local Ethical Committee (Comitato Etico Regione Liguria, registry number IIT_INSTANCE 049REG2017), and the ethical standards in the 2013 Declaration of Helsinki. Before the experiment, all participants provided written informed consent, and they were all paid 35 euros for their participation. At the end of the experiment, they were all debriefed about the

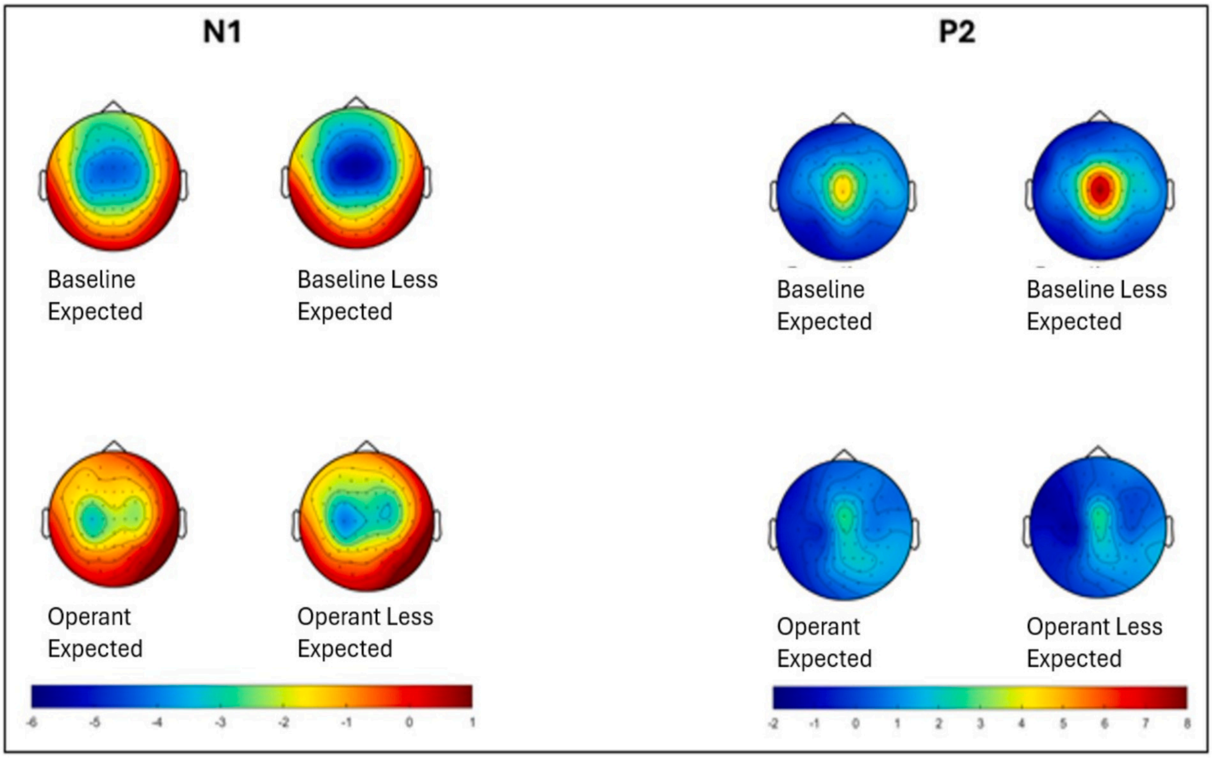


Fig. 8. Scalp activity in each combination of Block (Baseline, Operant) and Outcome (Expected, Less Expected), corresponding to the approximate time window of the N1 (50 to 150 milliseconds, left) and P2 (180 to 280 milliseconds, right). These approximate time windows for the N1 and P2 are based on estimates of their timing from the literature (e.g., Paiva et al., 2016), for the purpose of visualization.

purpose of the experiment.

5.1.2. Experimental apparatus

The experimental setup comprised a workstation equipped with a 27′ screen to display the IB task; the Ghost button (GB) for the computer to perform the keypress; one Logitech button for participants to perform the keypress; one QWERTY keyboard to type the response; one workstation equipped with one 21′ screen for the EEG recording, and one set of speakers. The IB task was programmed and presented using Psychopy v2021.2.0 (Peirce, 2007). Regarding the EEG apparatus, the same system and same settings have been used as in the Solo experiment.

5.1.3. Procedure

The experimental setup, procedure, and trial sequence, as well as conditions, were identical to the Solo experiment, except that participants judged the outcome (tone) of the Ghost button's "action", instead of acting (keypress) themselves (and thus generating the tones themselves in the operant condition). Participants estimated the occurrence of the tone generated by the Ghost button (Operant block) or occurring without any preceding action (Baseline block). As in the Solo experiment, this (GB) experiment was conceived as a 2 (Block: Baseline, Operant) X 2 (Outcome Expectancy: Expected, Less Expected) within-subjects design.

As in the Solo experiment, participants performed three blocks: Operant, Baseline, and Baseline Action block. In the Operant block, participants were instructed to observe the Ghost button acting. They were told that the Ghost Button always waited for one full rotation before acting, as in the Solo experiment and Haggard and colleagues' study (Haggard, Clark, & Kalogeras, 2002). After this first full rotation, the Ghost button was programmed to act at a random time, within a predefined time window (2600–8000 ms). After the Ghost button lowered down (performed the action), a sensory outcome, in the form of an auditory tone beep, occurred. The tone outcome always occurred after a fixed time, namely 250 ms after the keypress that was performed through the Ghost button. Then, participants were asked to report the time of occurrence of the tone outcome.

In the Baseline block, the Ghost button did not act, and the tone outcome was randomly played during the rotation of the clock hand (within the same predefined time window: 2600–8000 ms). Participants' task was simply to judge the occurrence of the tone. Finally, in the Baseline Action block, the Ghost button acted as in the Operant block, with the only difference being that it did not produce any tone outcome; therefore, the participants' task was to judge the occurrence of the Ghost button keypress. Notably, as in the Solo experiment, the Baseline Action block served only the purpose of being used for the correction of overlapping components elicited by the Ghost button when it acted. For example, it produced some noise that could be "subtracted" from the conditions of interest (Operant block).

We also manipulated the content expectancy of the tone outcome. Participants first performed a practice session of ten trials. The mapping between the tone pitch and the agent was counterbalanced across participants. Therefore, for half of the sample, participants judged the occurrence of a certain tone outcome (High-pitch tone: 800 Hz, 100 ms duration) of Ghost button's action. In the other half of the trials, participants were asked to perform a voluntary keypress, which was followed by a different tone outcome (Low-pitch tone: 400 Hz, 100 ms duration). Notably, for the other half of the sample, the tone pitch-agent mapping was reversed so that, in half of the trials, the outcome of the Ghost Button action was the low-pitch tone, whereas in the other half of the trials, the outcome of participants' action was the high-pitch tone. In both cases, this was done so that participants could learn the association between the actions generated by the Ghost button and a given outcome.

Afterward, during the IB task, in both tone blocks (Operant, Baseline), in 70 % of trials (140 trials), participants were exposed to the "expected" tone outcome, namely the tone that in the preceding practice session they learned to associate with the action of the Ghost button. Conversely, in the remaining 30 % of trials (60 trials), participants were exposed to the " less expected" outcome, namely the tone that they did not expect to hear as a consequence of the Ghost button's actions, as in the preceding practice session, it was associated with their self-generated actions. Within each block, the presentation of expected (70 %) vs. less expected tone outcomes (30 %) was randomized.

The mapping between the tone pitch (High: 800 Hz, Low: 400 Hz) and the expectancy (expected, less expected) was counterbalanced across participants. In other words, for half of the participants, the high-pitch tone was presented as the outcome of Ghost button-generated actions, whereas the low-pitch tone was presented as the outcome of self-generated actions. Conversely, for the other half of the participants, the high-pitch tone was the outcome of self-generated actions, and the low-pitch tone was the outcome of the actions generated by the Ghost button.

The task comprised 470 trials in total (200 trials for the Operant and the Baseline Tone blocks, respectively; 60 trials for the Baseline Action block; 10 trials for the practice session). For the entire duration of the task, participants' neural signal was recorded via EEG.

5.2. Data preprocessing

5.2.1. Behavioural (Judgment Errors)

One participant was excluded from preprocessing due to the experiment repeatedly crashing, which did not allow to save the data. Thus, the sample size was $N = 42$. Subsequently, for each trial, we calculated the Judgment Error (JE) in the same way as in the Solo experiment. For each combination of Block (Operant, Baseline) and Outcome Expectancy (Expected, Less Expected), we calculated their means and standard deviations (SDs). JEs that deviated more than ±2.5 SD from participants' mean in each combination were considered outliers and removed from further analysis (2.9 % of the total number of trials). Following outliers' removal, the data of another participant were excluded due to a low number of remaining trials ($\leq$25 in one or more combinations of Block and Outcome Expectancy). This resulted in a final sample size of $N = 41$.

5.2.2. EEG

Participants' neural EEG data were pre-processed and analysed in the same manner and with the same software as in the Solo experiment. The data of five participants in total were excluded from further analysis. As in behavioural analysis, the data of one participant were excluded due to the experiment repeatedly crashing (see above). The data of the remaining four participants were excluded because their ICA decompositions resulted in over 75 % of non-brain related ICs, meaning that the data could not be properly cleaned with our pre-processing pipeline. As a result, we obtained a final sample size of $N = 38$.

On average, due to artifact rejection procedures (muscle artifacts, visual inspection), we removed 35.42 (SD = 26.14) epochs per participant, and 2.97 (SD = 3.77) channels per participant. Following visual inspection, ICA was applied (as in the Solo experiment) and we removed 19.61 (SD = 7.71) ICs per participant. The epochs in the Operant Tone blocks, in which the Ghost Button produced a tone outcome (expected or less expected) were subsequently corrected for overlapping components, generated by the movements of the Ghost button. This was done by subtracting the average activity in the Baseline Action block (in which the Ghost button simply pressed without producing any tone outcome), from the average ERPs in the Operant blocks, for each participant. The Baseline Action data were pre-processed in the same manner as the data of the tone-related blocks (Operant, Baseline).

For further statistical analysis, both N1 and P2 amplitude were extracted. The N1 amplitude was defined as the mean amplitude in the time window [peak amplitude ±50 ms], where the peak was defined as the minimum amplitude in the time window [60 to 160 ms], for each participant, variable (Block and Outcome Expectancy) and channel condition. The P2 amplitude was defined as the mean amplitude in the time window [peak amplitude ±50 ms], where the peak was defined as the minimum amplitude in the time window [170 to 240 ms], for each participant, variable (Block and Outcome Expectancy) and channel condition.

5.3. Statistical analysis

All data (both behavioural and ERPs) have been subjected to statistical analysis in the same manner as in the Solo experiment.

5.4. Results

5.4.1. Behavioural (Judgment Errors)

Results showed a significant main effect of Block [$F_{(1, 40)} = 16.19$, $p < 0.001$, $\eta^2 = 0.29$], with underestimated JEs in Operant as compared to Baseline block [$t = 4.02$, SE = 21.9, $p < 0.001$, Cohen's d = 0.63; $M_{\text{Operant}} = -101.5$ ms, $SE_{\text{Operant}} = 15.8$; $M_{\text{Baseline}} = -13.5$ ms, $SE_{\text{Baseline}} = 15.8$] (Fig. 9), indicating a vicarious IB effect. Neither the main effect of Outcome Expectancy emerged as significant [$F_{(1, 40)} = 0.07$, $p = 0.79$, $\eta^2 = 0.001$], nor the two-way interaction between Block (Operant, Baseline), and Outcome Expectancy (Expected, Less Expected) [$F_{(1, 40)} = 2.38$, $p = 0.13$, $\eta^2 = 0.0001$].

5.4.2. EEG

5.4.2.1. N1. Results showed neither a significant main effect of Block [$F_{(1, 37)} = 3.14$, $p = 0.08$, η2 = 0.03] (Fig. 10), nor Outcome Expectancy [$F_{(1, 37)} = 1.16$, $p = 0.29$, η2 = 0.0009] (Fig. 11). Furthermore, there was no significant interaction between the two [$F_{(1, 37)} = 0.004$, $p = 0.95$, η2 = 0.0000009].

5.4.2.2. P2. Results of the 2 × 2 ANOVA showed a significant main effect of Block [$F_{(1, 37)} = 5.34$, $p = 0.027$, $\eta^2 = 0.06$] (Figs. 12–14). There was neither a significant effect Outcome Expectancy [$F_{(1, 37)} = 3.09$, $p = 0.09$, $\eta^2 = 0.002$] nor a significant interaction between the two [$F_{(1, 37)} = 2.28$, $p = 0.14$, $\eta^2 = 0.001$]. The P2 amplitude was smaller in the operant condition as compared to the baseline conditions ($M_{\text{Operant}} = -0.57$, $SD_{\text{Operant}} = 4.76$; $M_{\text{Baseline}} = -1.71$, $SD_{\text{Baseline}} = 3.84$).

5.5. Discussion of the GB experiment

The GB experiment aimed to investigate the minimal conditions for the emergence of vicarious SoA, and whether access to the proximal effects is sufficient for the vicarious IB effect toward an artificial agent. More specifically, we addressed the question of whether an artificial agent elicits the sensorimotor representation of an action, and thereby vicarious SoA (as manifested by the vicarious IB effect), in the absence of action execution. In addition, we manipulated the expectancy of the content of the distal effect of the action, to check whether the vicarious IB effect (if observed) is indeed related to the vicarious SoA rather than to the learned association between the proximal and the distal action effects. Based on the results from the Solo experiment, we knew that the outcome expectancy (in the way we manipulated it) affected accuracy in the temporal judgments, but did not modulate the IB effect (the individual SoA).

Therefore, should we observe an interaction between Block and Outcome Expectancy on either behaviour or neural markers in the GB experiment, it might suggest that those effects are due to the learned association between two sensory outcomes of an action (the proximal and distal effects) of the observed agent. On the other hand, a lack of modulatory effect of expectancy over the IB effect would demonstrate that the effect is due to vicarious IB.

The behavioural results showed a robust IB effect, which was not modulated by the expectancy of the distal action effect (tone). This shows that the occurrence of the proximal action effect (button press) was sufficient to elicit sensorimotor representation of that action, and thereby, to elicit the vicarious IB effect. Some past studies that investigated temporal estimation between two external events (for example,

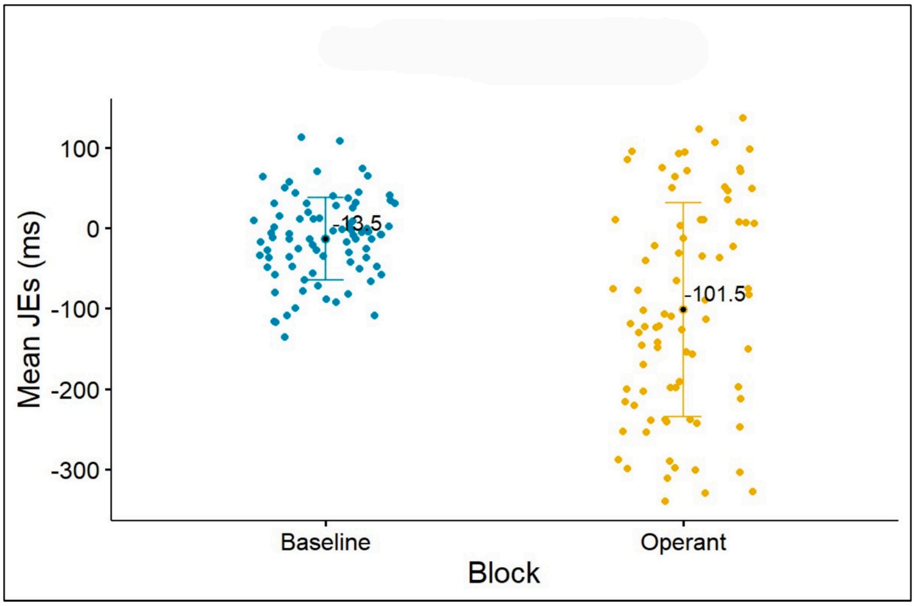


Fig. 9. Mean Judgment Errors (JEs, in ms) plotted as a function of Block (Baseline, Operant). Coloured dots represent individual means, whereas black dots represent group means. Errors bars represent standard errors.

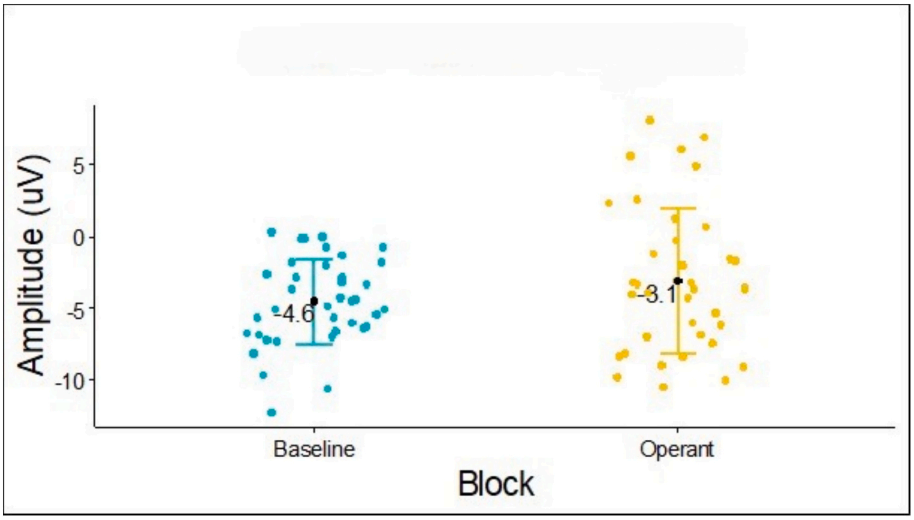


Fig. 10. Mean N1 amplitude, averaged across the electrodes Cz, C3, and C4, plotted as a function of Block (Baseline, Operant). Coloured dots represent individual means, whereas black dots represent group means. Error bars represent standard deviations.

two auditory stimuli) show robust temporal repulsion between these external events, even when one causes the other (Antusch, Custers, Marien, & Aarts, 2020, 2021). Thus, it is important that that we did observe a vicarious IB effect for the Ghost Button (compression rather than a repulsion effect), as this further supports the idea that, in the case of our study, the effect is due to vicarious SoA, rather than mere causal link between two external events.

Interestingly, in contrast to the results of the Solo experiment for self-generated action outcomes, no effect of expectancy on JEs emerged. This might mean that the less expected action outcomes might elicit an alerting effect that improves performance only for self-generated actions.

The neural results did not parallel the pattern of results observed for self-generated actions, in that the N1 component was not modulated by whether the tone occurred as a consequence of GB's "action" or without it (Baseline block). In other words, we did not observe an N1 suppression effect for the GB. Thus, the pattern of N1 results did not mirror the pattern of IB results. These results suggest that the vicarious IB effect might *not* rely on "early", lower-level processes involved in the formation of a motor plan, to which N1 suppression is sensitive. Instead, the vicarious IB effect might rely on "later", higher-level cognitive processes involved in comparison of predicted and observed action effects (Timm et al., 2016). Indeed, the P2 was modulated by the type of block (Operant vs. Baseline) and thus showed a signature of vicarious SoA. Furthermore, P2 mirrored the pattern of behavioural results. In line with our interpretation of the P2 pattern of the Solo experiment, as well as previous work suggesting the P2 is sensitive to higher-level processes (Timm et al., 2016), we suggest that the present pattern of ERP results indicate that the vicarious IB effect toward an artificial agent relies on later cognitive processes.

In addition, counter to our expectations (but in line with JEs results), the N1 amplitude was not sensitive to the content expectancy of the tone. This is somewhat surprising, given that N1 is in general sensitive to expectancy manipulations. However, perhaps the impact of expectancy

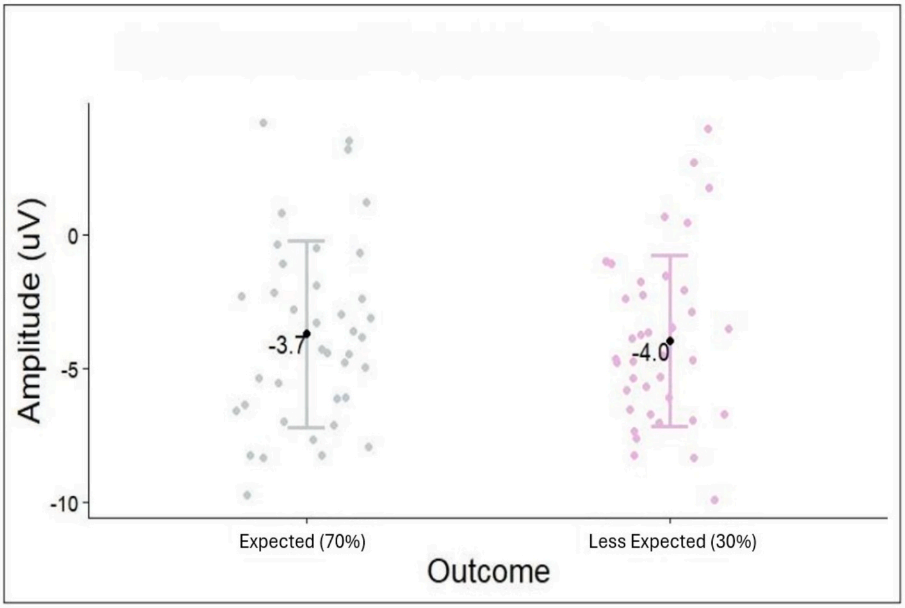


Fig. 11. Mean N1 amplitude, averaged across the electrodes Cz, C3, and C4, plotted as a function of Outcome Expectancy (Expected, Less Expected). Coloured dots represent individual means, whereas black dots represent group means. Error bars represent standard deviations.

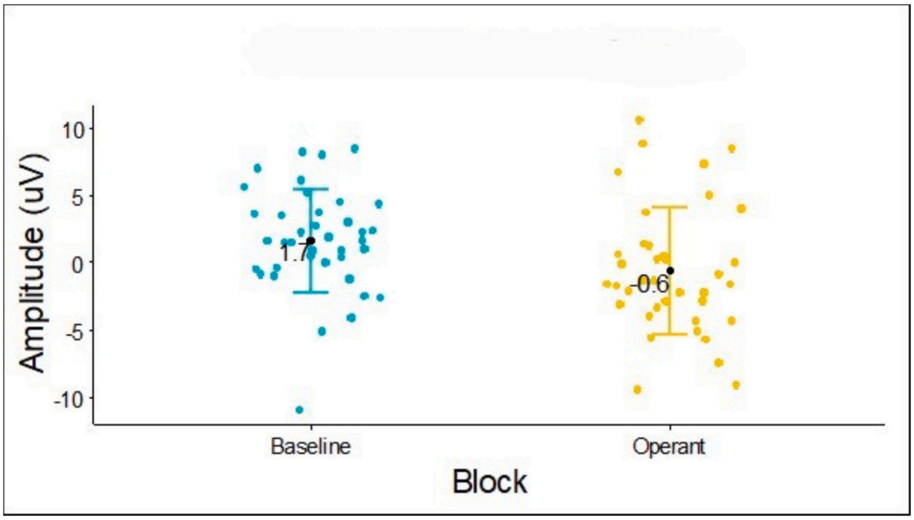


Fig. 12. Mean P2 amplitude, averaged across the electrodes Cz, C3, and C4, plotted as a function of Block (Baseline, Operant). Coloured dots represent individual means; black dots represent group means; error bars represent standard deviations.

on the N1 component, as observed in our Solo experiment, and as reported in literature (Bendixen et al., 2012; Sanmiguel et al., 2013), might be due solely to cases of self-generated action outcomes. As this lack of expectancy effect also parallels the lack of effect in the IB measure, it seems plausible that less expected stimuli elicit an early alerting reaction of the brain only for self-performed actions and their sensory outcomes. Indeed, in standard oddball paradigms, the reaction of the brain is slightly later (either manifested through mismatch negativity (Näätänen, Paavilainen, Rinne, & Alho, 2007) for auditory unexpected stimuli or through P300 for visual oddballs (Sutton, Braren, Zubin, & John, 1965). Interestingly, the expectancy effect in the Solo effect was observed early even in the baseline trials (thus when no action was performed). It might be that the self-action condition context sensitized the brain to expectancy (and thus early responses) more than observing consequences of another agent's actions (as in the case of the GB experiment).

Regarding the effect of expectancy on the P2, there was no difference in the P2 suppression effect between predictable and unpredictable tone, mirroring the pattern of IB and N1 results as expected.

Together, these results suggest that indeed, the proximal effects of an action are sufficient to elicit the vicarious IB effect, but that effect might not be due to lower-level predictive processes related to the formation of a motor plan, but rather due to later (higher level) cognitive processes involved perhaps in the comparison between observed and expected action outcomes.

Finally, in the present experiment, none of the variables (IB effect, N1 or P2) were affected by the expectancy modulation. Therefore, it is rather implausible that the observed IB effect is related to the learned associations between proximal and distal action effects.

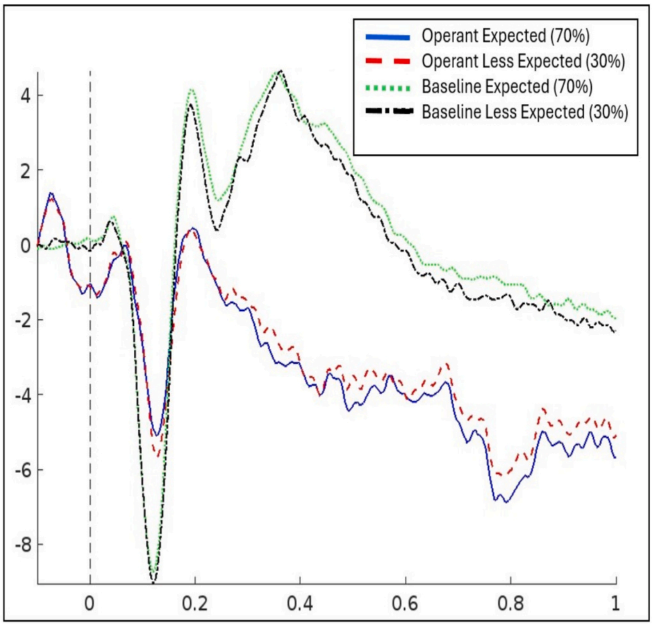


Fig. 13. ERP waveforms for each combination of Block (Operant, Baseline) and Outcome Expectancy (Expected, Less Expected), averaged across the electrodes Cz, C3, and C4. It should be noted that, despite the procedure applied to correct for overlapping components, overlapping components noise stemming from the sound made by the Ghost button is still present in the Operant blocks.

6. General discussion

The present study aimed to understand the minimal conditions needed for vicarious SoA toward artificial agents to occur. Past research has shown that disembodied (digital) computer actions do not elicit vicarious SoA (Limerick et al., 2014; Obhi & Hall, 2011; Sahaï et al., 2017). On the other hand, embodied robots that perform a physical action execution do evoke a vicarious SoA (Roselli, Ciardo, & Wykowska, 2022), and when they have a human-like shape and motor repertoire, the effect is quite robust (Roselli et al., 2025; Roselli, Ciardo, De Tommaso, & Wykowska, 2022). Interestingly, the same robot that can evoke the vicarious SoA when performing a physical action can eliminate the effect when the action is performed in a non-physical (but rather digital) manner (Roselli, Ciardo, & Wykowska, 2022). Therefore, it seems that observing a physical action is a prerequisite for vicarious SoA to occur, as only a physical action might activate a sensorimotor representation of the observer's actions, based on which the vicarious SoA might occur. However, according to ideomotor theories, one activates action plans, not based on representing the action execution per se, but rather based on the action outcomes and goals. With this in mind, we asked the question of whether the vicarious SoA could be observed when observers have access only to the action effects (proximal and distal) and not to the action execution per se.

To address this question, we used an adapted version of the Intentional Binding (IB) paradigm based on the Libet clock method (Haggard, Aschersleben, et al., 2002; Haggard, Clark, & Kalogeras, 2002), since the IB effect might be considered as a proxy measure of implicit SoA (Moore & Obhi, 2012). Specifically, we focused on the Tone IB effect, namely, the IB effect that emerges when the critical event that participants judge is the sensory tone outcome produced by their actions. It is an important detail, considering the existence of the Action IB effect, which emerges when the critical event to judge is the action (rather than its outcome as in the Tone IB case), and the fact that the two IB effects might be driven (at least partially) by different mechanism, according to the type of the critical event (Wolpe, Haggard, Siebner, & Rowe, 2013). Notably, the same dissociation also seems to occur in the context of vicarious SoA toward others, namely with artificial agents (Roselli, Ciardo, & Wykowska, 2022). We decided to use only the tone as the critical event to judge, due to the use of the Libet clock manipulation. The tone allows for simultaneous observation of the clock hand and listening to the tone event. Therefore, it does not require participants to switch attentional focus from the action event generated by another agent to the clock presented on a screen. Note that, unlike in self-produced actions, to

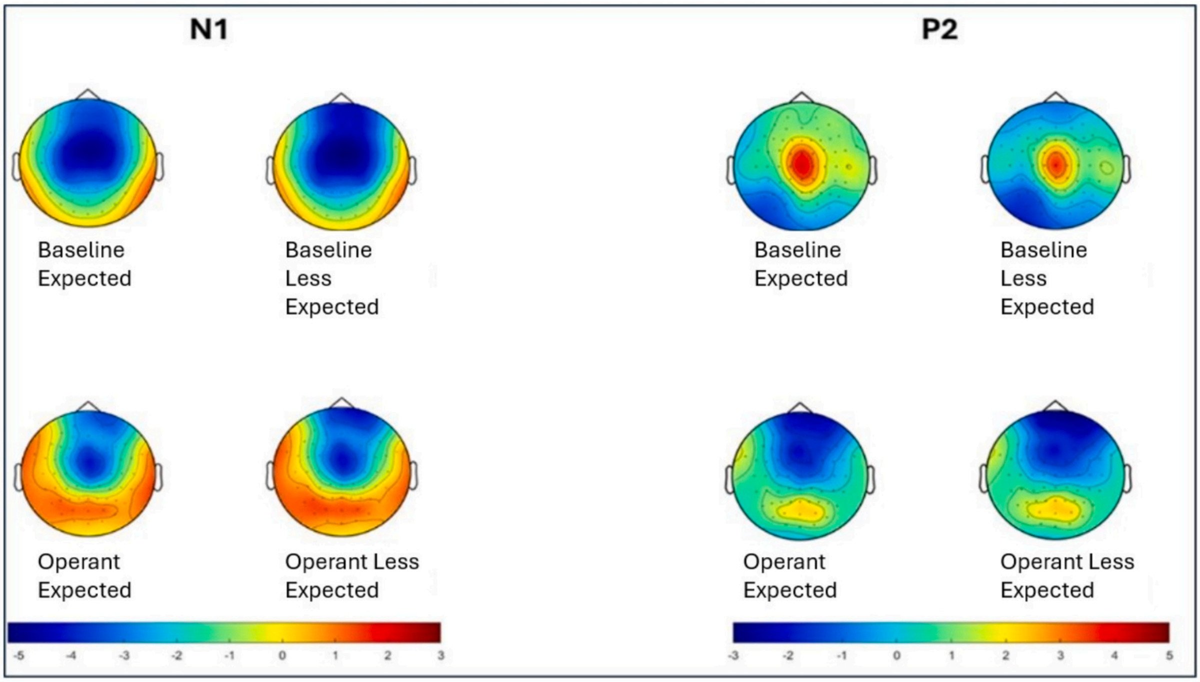


Fig. 14. Scalp activity in each combination of both Block (Baseline, Operant) and Outcome Expectancy (Expected, Less Expected), corresponding to the approximate time window of the N1 (50 to 150 ms, to the left), and P2 (180 to 280 ms, to the right). These approximate time windows for the N1 and P2 are based on estimates of their timing from the literature (e.g., Paiva et al., 2016), for the purpose of visualization.

make a judgment about the action produced by another agent (in our case, the ghost button), participants presumably need to look at the agent's effector, and then look at the clock. This might create distorted temporal judgment. By using the tone, we were able to circumvent this issue. However, as our experiment required participants to judge only the tone event, our results and potential interpretations exclusively refer to the Tone IB effect as a proxy measure for both self- (if participants performed the actions) and vicarious SoA (if the Ghost Button performed the action).

In the context of our experiments, we designed a special device – the "Ghost button"- which produced a key press without any effector pressing the key. Thus, observers had access to the proximal action effects (the keypress) but not to the action execution. Participants performed an IB task where they judged the temporal occurrence of the tone outcome of the ghost button press. In both the first (Solo) and second (GB) experiments, as previously outlined, we manipulated the tone expectancy not in terms of temporal predictability (action-tone delay) but in terms of content (expected vs. less expected tone pitch).

Our results showed that observing such disembodied actions accompanied by embodied proximal action effects (button press) elicited the vicarious IB effect for the distal action effects (tones). The manipulation of content expectancy of the distal action effects showed that this effect was not due to the learned association between proximal and distal action effects. Instead, the effect appears to be related to the vicarious SoA. However, the lack of effect related to SoA on the N1 component, but a perfect correspondence between IB and P2 amplitude results, suggests that the vicarious IB effect for artificial agents may not be due to early predictive processes related to the formation of a motor plan but rather to later cognitive processes, perhaps related to the comparison between observed and expected action outcome. This would indicate that access to the proximal action effect might be sufficient to elicit a vicarious SoA, but not necessarily through activation of a motor plan for said action. Rather, the proximal action effect might be sufficient for observers to activate a higher-level representation of the action plan, allowing them to integrate the proximal action effect into a temporal judgment about the distal action effect. Importantly to note, however, such judgment is not based on simple associations between proximal and distal sensory effects, as the expectancy of the distal effect did not affect the IB effect. Rather, it is due to later (and more cognitive) processes underlying agency judgments.

Our pattern of results is in line with a recent study which found that when observing another person pressing a button, the observers' N1 was not suppressed, compared to externally generated tones that were not preceded by actions, though the P2 was attenuated for observed action-generated tones as compared to externally generated tones (Ghio, Egan, & Bellebaum, 2021). Furthermore, another study found that the N1 amplitude did not differ between active conditions, in which participants caused a tone to occur by *withholding* a button press, i.e., participants were agents in the *absence* of motor action, and a passive condition, in which participants did not cause a tone to occur, but were simply informed whether a tone would occur, though they did find differences between these conditions in the P2 (Han, Jack, Hughes, Elijah, & Whitford, 2021). The authors posited that for N1 suppression in response to a sensory outcome, it is necessary to have access to one's own motor action, and thus potentially also a motor plan, closely preceding the outcome and that SoA, or being the author of the outcome in the absence of action, by itself, may not be sufficient. Moreover, these results further suggest that the N1 and P2 might be dissociable and that the P2 may be more closely related to SoA.

Finally, Timm et al. (2016), found that N1 suppression occurred for self-generated sounds, even in conditions in which participants reported an illusory lack of SoA, while the P2 was sensitive to participants' experience of SoA, further supporting the idea that the P2 is linked to the experience of SoA, while the N1 may be linked to the activation of a motor plan.

Overall, these results suggest that the P2 might be a better marker of (vicarious) SoA, than the N1. Conversely, for individual (self) SoA, N1 shows the sensory suppression effect related to self-generated actions and their outcomes (Solo experiment of the present study). Thus, while the individual IB effect seems to (at least partially) rely on early predictive processes related to the formation of a motor plan, vicarious SoA relies more on later cognitive processes, presumably related to the comparison of predicted and actual sensory outcomes.

6.1. Limitations and future directions

This study has several limitations that can be considered for future research. First, and foremost, the use of the IB effect as a measure of SoA has been criticised in literature, as discussed in the Introduction Section. Similarly, the N1 might not be a direct measure of SoA, but only a proxy of mechanisms related to SoA. Therefore, in future research it would be worthwhile to examine the questions related to the vicarious sense of agency toward artificial agents with more direct (and perhaps explicit) measures of SoA. However, those would need to be still conceived, as the standard way of collecting explicit judgments (e.g., "how much control did you feel over the action outcome?") cannot apply to the case of vicarious SoA. Second, in our experiments, the training sessions differed slightly between the two experiments. While in the first (Solo) experiment, the less expected tone never appeared in the training session, in the second (GB) experiment, it was associated with the action generated by the participant. This was made because, in Experiment 1, our idea was to have a completely "solo" experiment. Therefore, we designed the study in such a way that participants were presented with the tone they learned to associate with their action (expected outcomes), whereas they were presented with a different tone in the remaining 30 % of trials (thus, a less expected tone). We reasoned that the "expected" tone should be related to the main agent. Thus, in the Solo experiment, there was an expected Self, and a non-Self (meaning "no one", which was then unexpected for the self). In the Ghost Button experiment, however, there are two agents: the participant and the Ghost Button. Thus, there was the self (participant) tone and the Ghost Button tone. However, as the Ghost Button was the main agent in this experiment, the aim was to have an expected tone for the Ghost Button, and an unexpected tone for the Ghost Button (which was related to the participant, who in this experiment was the "other agent").

Although it is unlikely that those 10 trials of the training session would affect the effects occurring during the experiment consisting of 460 trials (note that the expectancy was also manipulated by means of frequency of occurrence of a given tone during the experiment), future studies might consider a more balanced design of the training. Finally, it remains to be further examined why, in our study, an alerting reaction of the brain to less expected stimuli occurred only for self-generated actions.

7. Conclusions

The current study aimed at:

1) understanding the minimal conditions for vicarious SoA for artificial agents to occur, namely whether the proximal action effects are sufficient to trigger vicarious IB effect: indeed, the current study showed that access to the proximal action effects is sufficient to elicit vicarious SoA;
2) examine, with the use of the EEG, if vicarious SoA (if observed) is based on predictive mechanisms related to the motor plan or rather to later cognitive processes involved in SoA: our results showed that the vicarious SoA elicited by a disembodied artificial agent with a physical proximal action effect presumably relies on later, higher-level cognitive processes, rather than early predictive processes related to a the formation of a lower level motor plan;
3) confirm – using expectancy manipulation – that the vicarious SoA (if observed) is due to the vicarious SOA rather than the learned

association between the proximal and distal action effect: indeed, the fact that expectancy did not alter the vicarious IB effect confirmed that this effect toward a disembodied agent was likely due to vicarious SoA rather than learned associations between proximal and distal sensory action effects.

Overall, these results provide insights into the mechanisms of vicarious SoA toward artificial agents demonstrating that artificial agents can evoke vicarious SoA as long as proximal action effects are observable. However, the underlying neural mechanisms might slightly differ with respect to SoA over one's own individual actions, as the vicarious SoA seems to rely on later cognitive mechanisms rather than early sensorimotor processes related to the formation of a motor plan.

CRediT authorship contribution statement

Cecilia Roselli: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Uma Prashant Navare:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Francesca Ciardo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Davide De Tommaso:** Writing – review & editing, Writing – original draft, Software. **Sonja A. Kotz:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Agnieszka Wykowska:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Funding

This work has received support from the European Research Council under the European Union's Horizon 2020 Research and Innovation Program, ERC Starting Grant, G.A. number: ERC-2016-StG-715058, awarded to AW. The content of this paper is the sole responsibility of the authors. The European Commission or its services cannot be held responsible for any use that may be made of the information it contains.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

The authors would like to thank Marco Crepaldi and Davide Dellepiane for their precious help in the design and development of the Ghost button. Furthermore, the authors would like to thank Federico Rospo for his help in data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106349.

Data availability

A video of the Ghost Button, and datasets used for analyses, are publicly available at the corresponding repository on the Open Science Framework (OSF) platform, at the following link: https://osf.io/c79hv/

References

Adolphs, R. (2009). The social brain: neural basis of social knowledge. *Annual review of psychology, 60*(1), 693–716. https://doi.org/10.1146/annurev.psych.60.110707.163514

Aliu, S. O., Houde, J. F., & Nagarajan, S. S. (2009). Motor-induced suppression of the auditory cortex. *Journal of Cognitive Neuroscience, 21*(4), 791–802. https://doi.org/10.1162/jocn.2009.21055

Antusch, S., Custers, R., Marien, H., & Aarts, H. (2020). Intentionality and temporal binding: Do causality beliefs increase the perceived temporal attraction between events? *Consciousness and Cognition, 77*, Article 102835. https://doi.org/10.1016/j.concog.2019.102835

Antusch, S., Custers, R., Marien, H., & Aarts, H. (2021). Studying the sense of agency in the absence of motor movement: an investigation into temporal binding of tactile sensations and auditory effects. *Experimental Brain Research, 239*(6), 1795–1806. https://doi.org/10.1007/s00221-021-06087-8

Baess, P., Horváth, J., Jacobsen, T., & Schröger, E. (2011). Selective suppression of self-initiated sounds in an auditory stream: An ERP study. *Psychophysiology, 48*(9), 1276–1283. https://doi.org/10.1111/j.1469-8986.2011.01196.x

Bandura, A. (2006). Toward a psychology of human agency. *Perspectives on. Psychological Science, 1*(2), 164–180. https://doi.org/10.1111/j.1745-6916.2006.00011.x

Bäß, P., Jacobsen, T., & Schröger, E. (2008). Suppression of the auditory N1 event-related potential component with unpredictable self-initiated tones: evidence for internal forward models with dynamic stimulation. *International Journal of Psychophysiology, 70*(2), 137–143. https://doi.org/10.1016/j.ijpsycho.2008.06.005

Bendixen, A., SanMiguel, I., & Schröger, E. (2012). Early electrophysiological indicators for predictive processing in audition: a review. *International Journal of Psychophysiology, 83*(2), 120–131. https://doi.org/10.1016/j.ijpsycho.2011.08.003

Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (2002). Abnormalities in the awareness of action. *Trends in Cognitive Sciences, 6*(6), 237–242. https://doi.org/10.1016/S1364-6613(02)01907-1

Bolt, N. K., & Loehr, J. D. (2021). Sensory attenuation of the auditory P2 differentiates self-from partner-produced sounds during joint action. *Journal of Cognitive Neuroscience, 33*(11), 2297–2310. https://doi.org/10.1162/jocn_a_01760

Buehner, M. J. (2012). Understanding the past, predicting the future: Causation, not intentional action, is the root of temporal binding. *Psychological Science, 23*(12), 1490–1497. https://doi.org/10.1177/0956797612444612

Caspar, E. A., Christensen, J. F., Cleeremans, A., & Haggard, P. (2016). Coercion changes the sense of agency in the human brain. *Current Biology, 26*(5), 585–592. https://doi.org/10.1016/j.cub.2015.12.067

Caspar, E. A., Lo Bue, S., De Saldanha, M., da Gama, P. A., Haggard, P., & Cleeremans, A. (2020). The effect of military training on the sense of agency and outcome processing. *Nature Communications, 11*(1), 4366. https://doi.org/10.1038/s41467-020-18152-x

Correa, Á., Lupiáñez, J., Madrid, E., & Tudela, P. (2006). Temporal attention enhances early visual processing: A review and new evidence from event-related potentials. *Brain Research, 1076*(1), 116–128. https://doi.org/10.1016/j.brainres.2005.11.074

David, N., Newen, A., & Vogeley, K. (2008). The "sense of agency" and its underlying cognitive and neural mechanisms. *Consciousness and Cognition, 17*(2), 523–534. https://doi.org/10.1016/j.concog.2008.03.004

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Desantis, A., Hughes, G., & Waszak, F. (2012). Intentional binding is driven by the mere presence of an action and not by motor prediction. *PLoS One, 7*(1), Article e29557. https://doi.org/10.1371/journal.pone.0029557

Dewey, J. A., & Knoblich, G. (2014). Do implicit and explicit measures of the sense of agency measure the same thing? *PloS one, 9*(10), Article e110118. https://doi.org/10.1371/journal.pone.0110118

Dogge, M., Schaap, M., Custers, R., Wegner, D. M., & Aarts, H. (2012). When moving without volition: Implied self-causation enhances binding strength between involuntary actions and effects. *Consciousness and Cognition, 21*(1), 501–506. https://doi.org/10.1016/j.concog.2011.10.014

van Elk, M., Salomon, R., Kannape, O., & Blanke, O. (2014). Suppression of the N1 auditory evoked potential for sounds generated by the upper and lower limbs. *Biological Psychology, 102*, 108–117. https://doi.org/10.1016/j.biopsycho.2014.06.007

Erdfelder, E., Faul, F., & Buchner, A. (1996). GPOWER: A general power analysis program. *Behavior Research Methods, Instruments, & Computers, 28*, 1–11. https://doi.org/10.3758/BF03203630

Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 355*(1404), 1771–1788. https://doi.org/10.1098/rstb.2000.0734

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

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*(2), 593–609. https://doi.org/10.1093/brain/119.2.593

Gentsch, A., Kathmann, N., & Schütz-Bosbach, S. (2012). Reliability of sensory predictions determines the experience of self-agency. *Behavioural Brain Research, 228*(2), 415–422. https://doi.org/10.1016/j.bbr.2011.12.029

Ghio, M., Egan, S., & Bellebaum, C. (2021). Similarities and differences between performers and observers in processing auditory action consequences: Evidence from simultaneous EEG acquisition. *Journal of Cognitive Neuroscience, 33*(4), 683–694. https://doi.org/10.1162/jocn_a_01671

Glasauer, S., Huber, M., Basili, P., Knoll, A., & Brandt, T. (2010, September). Interacting in time and space: Investigating human-human and human-robot joint action. In *19th international symposium in robot and human interactive communication* (pp. 252–257). IEEE. https://doi.org/10.1109/ROMAN.2010.5598638.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. *Psychological Review, 77*(2), 73. https://doi.org/10.1037/h0028689

Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience, 18* (4), 196–207. https://doi.org/10.1038/nrn.2017.14

Haggard, P., Aschersleben, G., Gehrke, J., & Prinz, W. (2002). Action, binding and awareness. In *Common mechanisms in perception and action* (pp. 266–285). Oxford University Press.

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*(4), 382–385. https://doi.org/10.1038/nn827

Han, N., Jack, B. N., Hughes, G., Elijah, R. B., & Whitford, T. J. (2021). Sensory attenuation in the absence of movement: Differentiating motor action from sense of agency. *Cortex, 141*, 436–448. https://doi.org/10.1016/j.cortex.2021.04.010

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849–878. https://doi.org/10.1017/S0140525X01000103

Horváth, J., & Burgyán, A. (2013). No evidence for peripheral mechanism attenuating auditory ERPs to self-induced tones. *Psychophysiology, 50*(6), 563–569. https://doi.org/10.1111/psyp.12041

Hughes, G., Desantis, A., & Waszak, F. (2013). Attenuation of auditory N 1 results from identity-specific action-effect prediction. *European Journal of Neuroscience, 37*(7), 1152–1158. https://doi.org/10.1111/ejn.12120

James, W. (1890). The principles of. *Psychology, 2*, 94.

Khalighinejad, N., Bahrami, B., Caspar, E. A., & Haggard, P. (2016). Social transmission of experience of agency: An experimental study. *Frontiers in Psychology, 7*, 1315. https://doi.org/10.3389/fpsyg.2016.01315

Knolle, F., Schröger, E., Baess, P., & Kotz, S. A. (2012). The cerebellum generates motor-to-auditory predictions: ERP lesion evidence. *Journal of Cognitive Neuroscience, 24*(3), 698–706. https://doi.org/10.1162/jocn_a_00167

Knolle, F., Schröger, E., & Kotz, S. A. (2013). Prediction errors in self-and externally-generated deviants. *Biological Psychology, 92*(2), 410–416. https://doi.org/10.1016/j.biopsycho.2012.11.017

Kühn, S., Nenchev, I., Haggard, P., Brass, M., Gallinat, J., & Voss, M. (2011). Whodunnit? Electrophysiological correlates of agency judgements. *PLoS One, 6*(12), Article e28657. https://doi.org/10.1371/journal.pone.0028657

Lange, K. (2011). The reduced N1 to self-generated tones: An effect of temporal predictability? *Psychophysiology, 48*(8), 1088–1095. https://doi.org/10.1111/j.1469-8986.2010.01174.x

Libet, B. (1981). The experimental evidence for subjective referral of a sensory experience backwards in time: Reply to PS Churchland. *Philosophy of Science, 48*(2), 182–197. https://doi.org/10.1086/288990

Limerick, H., Coyle, D., & Moore, J. W. (2014). The experience of agency in human-computer interactions: a review. *Frontiers in Human Neuroscience, 8*, 643. https://doi.org/10.3389/fnhum.2014.00643

Metcalfe, J., Eich, T. S., & Miele, D. B. (2013). Metacognition of agency: proximal action and distal outcome. *Experimental Brain Research, 229*, 485–496. https://doi.org/10.1007/s00221-012-3371-6

Metta, G., Natale, L., Nori, F., Sandini, G., Vernon, D., Fadiga, L., … Montesano, L. (2010). The iCub humanoid robot: An open-systems platform for research in cognitive development. *Neural Networks, 23*(8–9), 1125–1134. https://doi.org/10.1016/j.neunet.2010.08.010

Moore, J., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition, 17*(1), 136–144. https://doi.org/10.1016/j.concog.2006.12.004

Moore, J. W. (2016). What is the sense of agency and why does it matter? *Frontiers in Psychology, 7*, 1272. https://doi.org/10.3389/fpsyg.2016.01272

Moore, J. W., Lagnado, D., Deal, D. C., & Haggard, P. (2009). Feelings of control: Contingency determines experience of action. *Cognition, 110*(2), 279–283. https://doi.org/10.1016/j.cognition.2008.11.006

Moore, J. W., & Obhi, S. S. (2012). Intentional binding and the sense of agency: a review. *Consciousness and Cognition, 21*(1), 546–561. https://doi.org/10.1016/j.concog.2011.12.002

Moore, J. W., Teufel, C., Subramaniam, N., Davis, G., & Fletcher, P. C. (2013). Attribution of intentional causation influences the perception of observed movements: behavioral evidence and neural correlates. *Frontiers in Psychology, 4*, 23. https://doi.org/10.3389/fpsyg.2013.00023

Muth, F. V., Wirth, R., & Kunde, W. (2021). Temporal binding past the Libet clock: Testing design factors for an auditory timer. *Behavior Research Methods, 53*(3), 1322–1341. https://doi.org/10.3758/s13428-020-01474-5

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology, 118*(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026

Navare, U. P., Ciardo, F., Kompatsiari, K., De Tommaso, D., & Wykowska, A. (2024). When performing actions with robots, attribution of intentionality affects the sense of joint agency. *Science Robotics, 9*, Article eadj3665. https://doi.org/10.1126/scirobotics.adj366

Obhi, S. S., & Hall, P. (2011). Sense of agency in joint action: Influence of human and computer co-actors. *Experimental Brain Research, 211*, 663–670. https://doi.org/10.1007/s00221-011-2662-7

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, 2011*(1), Article 156869. https://doi.org/10.1155/2011/156869

Pacherie, E. (2012). *14 the phenomenology of joint action: Self-agency versus joint agency. Joint attention: New developments in psychology, philosophy of mind, and social neuroscience* (p. 343).

Paiva, T. O., Almeida, P. R., Ferreira-Santos, F., Vieira, J. B., Silveira, C., Chaves, P. L., … Marques-Teixeira, J. (2016). Similar sound intensity dependence of the N1 and P2 components of the auditory ERP: Averaged and single trial evidence. *Clinical Neurophysiology, 127*(1), 499–508. https://doi.org/10.1016/j.clinph.2015.06.016

Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods, 162*(1–2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Pfister, R., Obhi, S. S., Rieger, M., & Wenke, D. (2014). Action and perception in social contexts: intentional binding for social action effects. *Frontiers in Human Neuroscience, 8*, 667. https://doi.org/10.3389/fnhum.2014.00667

Pockett, S., & Miller, A. (2007). The rotating spot method of timing subjective events. *Consciousness and Cognition, 16*(2), 241–254. https://doi.org/10.1016/j.concog.2006.09.002

Poonian, S. K., & Cunnington, R. (2013). Intentional binding in self-made and observed actions. *Experimental Brain Research, 229*, 419–427. https://doi.org/10.1007/s00221-013-3505-5

Poonian, S. K., McFadyen, J., Ogden, J., & Cunnington, R. (2015). Implicit agency in observed actions: evidence for N1 suppression of tones caused by self-made and observed actions. *Journal of Cognitive Neuroscience, 27*(4), 752–764. https://doi.org/10.1162/jocn_a_00745

Prinz, W. (1990). A Common Coding Approach to Perception and Action. In O. Neumann, & W. Prinz (Eds.), *Relationships Between Perception and Action*. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-75348-0_7.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*(2), 129–154. https://doi.org/10.1080/713752551

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci., 27* (1), 169–192. https://doi.org/10.1146/annurev.neuro.27.070203.144230

Roselli, C., Ciardo, F., De Tommaso, D., & Wykowska, A. (2022). Human-likeness and attribution of intentionality predict vicarious sense of agency over humanoid robot actions. *Scientific Reports, 12*(1), Article 13845. https://doi.org/10.1038/s41598-022-18151-6

Roselli, C., Ciardo, F., De Tommaso, D., & Wykowska, A. (2025). Does perceived voluntariness of others' actions induce vicarious sense of agency? Evidence from human-robot interaction. *Consciousness and Cognition, 130*, Article 103835. https://doi.org/10.1016/j.concog.2025.103835

Roselli, C., Ciardo, F., & Wykowska, A. (2022). Intentions with actions: The role of intentionality attribution on the vicarious sense of agency in Human–Robot interaction. *Quarterly Journal of Experimental Psychology, 75*(4), 616–632. https://doi.org/10.1177/17470218211042003

Ruess, M., Thomaschke, R., Haering, C., et al. (2018). Intentional binding of two effects. *Psychological Research, 82*, 1102–1112. https://doi.org/10.1007/s00426-017-0892-4

Ruess, M., Thomaschke, R., & Kiesel, A. (2017). The time course of intentional binding. *Attention, Perception, & Psychophysics, 79*(4), 1123–1131. https://doi.org/10.3758/s13414-017-1292-y

Sahaï, A., Pacherie, E., Grynszpan, O., & Berberian, B. (2017). Predictive mechanisms are not involved the same way during human-human vs. human-machine interactions: A review. *Frontiers in Neurorobotics, 11*, 52. https://doi.org/10.3389/fnbot.2017.00052

Sanmiguel, I., Todd, J., & Schröger, E. (2013). Sensory suppression effects to self-initiated sounds reflect the attenuation of the unspecific N 1 component of the auditory ERP. *Psychophysiology, 50*(4), 334–343. https://doi.org/10.1111/psyp.12024

Sato, A. (2009). Both motor prediction and conceptual congruency between preview and action-effect contribute to explicit judgment of agency. *Cognition, 110*(1), 74–83. https://doi.org/10.1016/j.cognition.2008.10.011

Saupe, K., Widmann, A., Trujillo-Barreto, N. J., & Schröger, E. (2013). Sensorial suppression of self-generated sounds and its dependence on attention. *International Journal of Psychophysiology, 90*(3), 300–310. https://doi.org/10.1016/j.ijpsycho.2013.09.006

Stadler, W., Springer, A., Parkinson, J., et al. (2012). Movement kinematics affect action prediction: comparing human to non-human point-light actions. *Psychological Research, 76*, 395–406. https://doi.org/10.1007/s00426-012-0431-2

Stekelenburg, J. J., & Vroomen, J. (2007). Neural correlates of multisensory integration of ecologically valid audiovisual events. *Journal of Cognitive Neuroscience, 19*(12), 1964–1973. https://doi.org/10.1162/jocn.2007.19.12.1964

Stetson, C., Cui, X., Montague, P. R., & Eagleman, D. M. (2006). Motor-sensory recalibration leads to an illusory reversal of action and sensation. *Neuron, 51*(5), 651–659. https://doi.org/10.1016/j.neuron.2006.08.006

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. *Science, 150*(3700), 1187–1188. https://doi.org/10.1126/science.150.3700.1187

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

The MathWorks Inc. (2022). *MATLAB version: 9.13.0 (R2022b)*. Natick, Massachusetts: The MathWorks Inc. https://www.mathworks.com.

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

Waszak, F., Cardoso-Leite, P., & Hughes, G. (2012). Action effect anticipation: neurophysiological basis and functional consequences. *Neuroscience & Biobehavioral Reviews, 36*(2), 943–959. https://doi.org/10.1016/j.neubiorev.2011.11.004

Wegner, D. M., Sparrow, B., & Winerman, L. (2004). Vicarious agency: experiencing control over the movements of others. *Journal of Personality and Social Psychology, 86*(6), 838. https://doi.org/10.1037/0022-3514.86.6.838

Wegner, D. M., & Wheatley, T. (1999). Apparent mental causation: Sources of the experience of will. *American psychologist, 54*(7), 480. https://doi.org/10.1037/0003-066X.54.7.480

Wohlschläger, A., Engbert, K., & Haggard, P. (2003). Intentionality as a constituting condition for the own self—and other selves. *Consciousness and Cognition, 12*(4), 708–716. https://doi.org/10.1016/S1053-8100(03)00083-7

Wohlschläger, A., Haggard, P., Gesierich, B., & Prinz, W. (2003). The perceived onset time of self-and other-generated actions. *Psychological Science, 14*(6), 586–591. https://doi.org/10.1046/j.0956-7976.2003.psci_1469.x

Wolpe, N., Haggard, P., Siebner, H. R., & Rowe, J. B. (2013). Cue integration and the perception of action in intentional binding. *Experimental Brain Research, 229*, 467–474. https://doi.org/10.1007/s00221-013-3419-2

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 269*(5232), 1880–1882. https://doi.org/10.1126/science.7569931