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Modulations of one's sense of agency during human–machine interactions: A behavioural study using a full humanoid robot

Aïsha Sahaï[1,2], Emilie Caspar[3], Albert De Beir[4], Ouriel Grynszpan[5], Elisabeth Pacherie[1] and Bruno Berberian[2]

Abstract

Although previous investigations reported a reduced sense of agency when individuals act with traditional machines, little is known about the mechanisms underpinning interactions with human-like automata. The aim of this study was twofold: (1) to investigate the effect of the machine's physical appearance on the individuals' sense of agency and (2) to explore the cognitive mechanisms underlying the individuals' sense of agency when they are engaged in a joint task. Twenty-eight participants performed a joint Simon task together with another human or an automated artificial system as a co-agent. The physical appearance of the automated artificial system was manipulated so that participants could cooperate either with a servomotor or a full humanoid robot during the joint task. Both participants' response times and temporal estimations of action-output delays (i.e., an implicit measure of agency) were collected. Results showed that participants' sense of agency for self- and other-generated actions sharply declined during interactions with the servomotor compared with the human–human interactions. Interestingly, participants' sense of agency for self- and other-generated actions was reinforced when participants interacted with the humanoid robot compared with the servomotor. These results are discussed further.

Keywords

Shared agency; joint Simon task; humanoid robot; servomotor; human–robot interaction; cooperation

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Introduction

The sense of agency refers to the experience of being in control of a voluntary performed action (I. I. Gallagher, 2000; Pacherie, 2007). During the past decades, a significant amount of research examining the sense of agency has been carried out in the context of individual self-generated actions (e.g., Barlas et al., 2018; Haggard et al., 2002; Renes et al., 2015; Sato & Yasuda, 2005; Sidarus & Haggard, 2016; Wen & Haggard, 2020). Thus, it has been pointed out that during self-generated individual actions, individuals' brain actively constructs their sense of agency by using a combination of both internal sensorimotor signals (e.g., feed-forward cues, proprioception, and sensory feedbacks) and circumstantial signals (e.g., intentions, thoughts, and contextual cues) (Moore & Fletcher, 2012; Synofzik et al., 2013).

Yet, in recent years, there has been an increasing interest in understanding the emergence of this sense of agency for cooperative behaviour where actions are intentionally

[1]Département d'Etudes Cognitives, ENS, EHESS, CNRS, PSL Research University, Institut Jean-Nicod, Paris, France
[2]Département Traitement de l'Information et Systèmes, ONERA, The French Aerospace Lab, Salon-de-Provence, France
[3]Department of Experimental Psychology, Social & Moral Brain Lab, Ghent University, Ghent, Belgium
[4]Robotics & Multibody Mechanics Research Group, Vrij Universiteit Brussel (VUB), Bruxelles, Belgium
[5]Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur, LIMSI-CNRS, Université Paris-Sud, Orsay, France

Corresponding author:
Aïsha Sahaï, Département Traitement de l'Information et Systèmes, ONERA, The French Aerospace Lab, BA 701 - FR-13661, Salon-de-Provence, France.
Email: asahai.pro@gmail.com

produced by two persons acting together. Initial results have suggested the possible transformation of the agentive awareness and identity in such a cooperative context, from a sense of individual agency to a sense of joint agency (e.g., Dewey et al., 2014, Bolt et al., 2016; Grynszpan et al., 2019; Jenkins et al., 2021; Le Bars et al., 2020; Obhi & Hall, 2011a; Strother et al., 2010). Indeed, on one hand, it is suggested that during the joint task, both individuals would experience a sense of agency for their own actions and their outcomes (i.e., their individual parts of the joint task), here proposed to be called sense of *self-agency*. Concurrently, on the other hand, both individuals would experience a form of agency for the actions and outcomes generated by their co-agent (i.e., their co-agent's parts of the joint task), here proposed to be called sense of *vicarious agency*. This dual presence of both the sense of *self-agency* and the sense of *vicarious agency* over the partner's contributions during a cooperative task where the self–other distinction remains intact is therefore taken as evidence for the emergence of a form of joint agency, here proposed to be called sense of *shared agency* (Pacherie, 2012; Silver et al., 2021). It is to be noted that different types of joint agency have been highlighted by prior work according to the degree of cooperation between the actors during the joint task (Silver et al., 2021). Hence, Pacherie (2012) and Silver and colleagues (2021) proposed that the sense of joint agency could be regarded as a sense of *we-agency* when the self–other distinction is blurred during the joint task (e.g., Obhi & Hall, 2011a) and rather regarded as a sense of *shared agency* when the self–other distinction remains intact during the joint task. In this study, we will focus on this second form of interaction.

This experience of shared agency during these cooperative joint tasks is an essential aspect of human cooperativeness. Indeed, the development of an agentive experience during a joint task can influence both the objective outcome quality (Babcock & Loewenstein, 1997) and the subjective perception of the outcome quality thereby influencing whether people continue to engage in the joint task (Caruso et al., 2006). Nevertheless, due to the increasing place of automated artificial systems in our daily lives, an important issue remains the emergence of this sense of *shared agency* during interactions that involve artificial partners. Previous work has highlighted individuals' difficulties in developing a sense of *shared agency* during joint tasks with computer co-agents (Obhi & Hall, 2011b; Sahaï et al., 2019). Actually, it has been proposed that these difficulties could stem from humans' inability to simulate or represent the computer-generated actions in their cognitive system (see Sahaï et al., 2017 for a comprehensive review). Indeed, the ability to simulate an observed (or guessed) other-generated action allows the simulation content to be used to predict the consequence of the observed (or guessed) other-generated action, improving implicit action understanding and the experience of being in control as during individual actions (Blakemore & Frith, 2005; Frith et al., 2000; Kilner et al., 2007; Picard & Friston, 2014). At the empirical level, the representation in one's own cognitive system of a co-agent generated actions can be assessed using the joint version of the Simon task (Sebanz et al., 2003). In the standard Simon task, participants had to detect two types of targets with two different response keys. Results showed that their performance decreased when the target appeared in an incongruent location with respect to their response key (Simon & Small, 1969). This occurred because two action representations (i.e., the correct action to perform and the spatially induced automatic activated action) are activated and the participant has to solve the conflict to select the accurate behaviour. By contrast, when participants had to detect only one type of target, there was no effect of location congruency. Intriguingly, during the joint version of the Simon task (Sebanz et al., 2003) in which the double target detection task was distributed across two persons (i.e., each agent was responsible for only one type of target), the interference effect for the incongruent target–response key mapping reappeared.

Accordingly, previous investigation aimed at examining empirically the possible link between the representation of a co-agent's action and the development of the sense of *shared agency* during a joint Simon task. Indeed, in a previous experiment, Sahaï and colleagues (2019) coupled together a joint Simon target detection task wherein participants' response times (RTs) served as an index of action co-representation (Sebanz et al., 2003 but see Dolk et al., 2011) and an intentional binding (IB) task wherein time estimation served as an implicit measure of participants' sense of agency (Haggard et al., 2002). The IB phenomenon refers to a subjective temporal compression between a voluntary action and its sensory outcome. Importantly, this temporal binding seems to reliably occur in situations in which the participant is an intentional agent, but not with passive movements (Haggard et al., 2002). In the authors' task (Sahaï et al., 2019), participants had to perform the Simon task jointly with a co-agent. They were requested to detect coloured dots (e.g., green dots) that appeared on a screen either on the same side as the accurate response key (e.g., right key) or on the opposite side (e.g., left side), which corresponded to a co-agent's current location. Throughout the task, the co-agent had to alternately detect a different type of dots (e.g., red dots) with a different response key (e.g., left key). The type of co-agent was manipulated so that participants could interact either with another human being or with an unseen computer. Accurate target detections were always followed by an auditory tone after a particular delay. Participants were requested to estimate the delay between the onset of the target detection (that could be either self- or other-generated) and the onset of the subsequent auditory tone. The originality of this joint task consisted in the fact that the two agents performed actions alternately, so that temporal estimations for the other-generated actions only indicated the participants' sense of *vicarious agency* for the co-agent's actions. In fact, in previous studies that focused on individuals' sense of agency during joint actions (e.g., Dewey et al., 2014; Obhi & Hall, 2011a), the participant's action and the co-agent's action were simultaneously performed. As a consequence, this made it difficult to specifically explore the participants' sense of *vicarious agency* for the actions generated by the co-agent excluding their own performance. The results of Sahaï and colleagues (2019)'s study indicated that participants exhibited a stronger sense of agency for their partner-generated actions than for their own self-generated actions during the human–human cooperation, suggesting a loss of sense of *self-agency* in this particular context of joint action. Importantly, participants were able to exhibit a sense of *vicarious agency* for the other-generated action when the co-agent was another human being but not when it was a computer. This paralleled the RTs results demonstrating faster self-generated responses when the target appeared at the same location as the response key in comparison with the opposite location when they were cooperating with another human being but not with a computer. This stimulus–response congruency effect (or social Simon effect, SSE) has been shown to derive from the cognitive interference that occur when two different representations of actions are concurrently activated (Simon & Wolf, 1963). Hence, it could be said that participants co-represented the actions performed by the human co-agent but this ability was impaired for the computer-generated actions.

Given the important role of prediction in both joint action (Sebanz & Knoblich, 2009; Sebanz et al., 2006) and agency development (Sahaï et al., 2017), these difficulties in representing the action of the artificial partner may disturb action understanding and prediction, which may explain the difficulties in developing the sense of *shared agency* when interacting with a computer co-agent. Moreover, recent neurophysiological investigations have underlined that the sense of *shared agency* exhibited by two human individuals during a joint task was correlated with inter-brain synchronisation (Shiraishi & Shimada, 2021). Yet, this cerebral activity has been shown to be decreased during human–computer cooperation (Hu et al., 2018), suggesting that individuals were unable to neurally bind with the computer, as well as a lack of engagement (Schilbach et al., 2013) with this type of machine.

Nevertheless, the large variety of automated artificial systems facing us, with varying complexities from single-unit levers as well as desktop computers to full human-like machines, must be taken into consideration. More in detail, little is known about the specific contribution of the external appearance of the machine in the alteration of the sense of *shared agency* during human–machine interactions. Yet, there is evidence that during a joint task, anthropomorphised robots, in contrast to traditional machines, can elicit the representation of the machine-generated actions in the human brain. Indeed, human-like appearance favours the attribution of an intentional agency to robots and evokes attitudes similar to those governing human social interactions (Wiese et al., 2017). For instance, studies in neuroimaging have shown that, under certain constraints (the human-like appearance, notably), the neural mechanisms involved in action understanding are activated for both human–robot and human–human interactions (H. L. Gallagher et al., 2002; Krach et al., 2008; Saygin et al., 2012; Takahashi et al., 2014; Wang & Quadflieg, 2015). Moreover, it has been shown that during hand-over interactions between a human and a robotic arm, the predictability of the robotic arm motions for the human was strongly dependent on the automaton's motion laws and physical appearance (Glasauer et al., 2010). Indeed, the authors showed that when the robotic arm was handing on a cube to the human seated in front of it, the human's RTs to grasp the cube were faster when the robot assumed human-like kinematics in comparison with a trapezoidal joint velocity (i.e., a typical robotic motion), meaning that individuals were able to better predict the observed human-like movement endpoints. Interestingly, the effect of the kinematic profile on the RTs was modulated by the external appearance of the robot: when the robotic arm had a humanoid appearance, its human partner had faster RTs than when the robotic arm had an industrial appearance, suggesting a better motion prediction. Moreover, the human's RTs tended to be faster when the robotic arm had a typical robotic motion profile but a humanoid appearance than when the robotic arm had a human-like kinematic but an industrial appearance. Finally, previous work on social robotics investigated the human ability to represent actions that have been performed by a humanoid robot in one's cognitive system (Stenzel et al., 2012). In the study by Stenzel and colleagues (2012), the participants were sitting next to a full humanoid robot described either as an intelligent and active agent or as a passive machine acting in a deterministic way. The participants had to detect one type of target (e.g., a white square) that could appear on the left or the right side of a screen. The task of the robot was to detect another type of target (e.g., a white diamond) on the same screen. Interestingly, the authors found an SSE in the participants' RTs when the robot was introduced as a human-like robot who can actively act but not when the robot was introduced as a deterministic machine. Hence, this finding pointed out that representation of machine-generated actions could also occur during a joint task with a humanoid robot provided that the robot was considered as an active partner. Possibly, to envisage the other as similar as oneself is needed to map their actions into one's own cognitive system during a joint task. Therefore, the first objective of the current study consisted in investigating the impact of an artificial system's physical appearance (i.e., human-like or not) on both individuals' sense of *self-agency* and *vicarious* *agency* using a paradigm that allows the measurement of action representation.

In addition, the second objective of the current study was to investigate the underlying cognitive mechanisms of the modulation of the sense of *self-agency* towards an experience of a sense of *shared agency* during a joint task with a machine. Indeed, it has been established that individuals could build a sense of "we-ness" during human–human joint tasks (Crivelli & Balconi, 2010; Dewey et al., 2014; Obhi & Hall, 2011a). Moreover, previous work has highlighted that egocentric sensory predictions were less involved in the construction of the agentive experience during joint action, with respect with individual actions. For example, some authors reported that individuals had a general bias towards claiming more explicit control than they objectively had over a performed joint action (Dewey et al., 2014; van der Wel et al., 2012), indicating a modulation of the *self-agency* experience during human–human joint actions. However, whether such a new "we-identity" is constructed during human–robot interactions remains unclear as most of the study have focused on actions that have been generated by a computer (Obhi & Hall, 2011b; Sahaï et al., 2019) or by low-level robotics (Grynszpan et al., 2019).

In this context, the aim of the current study was two-fold: (1) to investigate the effect of the robot's physical appearance on the individuals' sense of *self-agency* and *vicarious agency* and (2) to explore the cognitive mechanisms underlying the sense of *shared agency* when individuals are engaged in a joint task with a machine. We ran a modified version of Sahaï and colleagues' (2019) paradigm. In the current study, the type of co-agent was manipulated so that the participants could perform the task jointly with another human, a full humanoid robot, or a servomotor. All accurate target detection triggered an auditory tone after a certain delay. We investigated the participants' sense of agency for the individual parts of the joint task: the sense of agency over the participant's *own part* of the joint task (here called sense of *self-agency*), and the sense of agency over their *partner's part* of the joint task (here called sense of *vicarious agency*). Particularly, the participants had to estimate the temporal delay between the onset of the target detection (either self- or other-generated) and the onset of the tone. This measure served as an implicit measure of participants' sense of agency (IB phenomenon, Haggard et al., 2002). We hypothesised that the more similar to the participants the co-agent would be, the stronger the participants' sense of *vicarious agency* would be, mainly due to their ability to better simulate and predict their co-agent's actions and outcomes. We also hypothesised a shift from a sense of *self-agency* to a sense of *shared agency* with the human and human-like co-agents but not with the servomotor due to the foreseeable construction of the "we-identity" with the first two agents.

Method

Ethic statement

This study was approved by the institutional ethical research committee of the Université libre de Bruxelles (Belgium, N° 008/2016). The investigation was carried out in accordance with the Declaration of Helsinki and all participants provided their written informed consent before starting the experiment. All participants were assigned a number to ensure the anonymity of the data.

Participants

Participants were recruited through social medias. Twenty-eight healthy adults volunteered to take part in the experiment (22 women, 24 right-handed, mean age 23.61 years, *SD*: 3.52 years). Two power analyses tested for repeated measures and within-factors analysis of variance (ANOVA) were run using G*Power application (Faul et al., 2007) to estimate the minimal required sample size to highlight differences on participants' RTs and temporal interval estimations. The significance threshold was set at $\alpha = .05$ and the power at $1 - \beta = .90$ for both power analyses. Based on the parameters reported in the previous study by Sahaï and colleagues (2019), the first power analysis revealed that a sample of nine participants was needed to exhibit an SSE on participants' RTs when considering three types of Co-agent (Human, Human-like, Servomotor), two levels of Congruency (Congruent, Incongruent), and an effect size defined by partial $\eta^2 = .42$ (SSn = 3200.03 and SSd = 4484.45). Moreover, because the authors' study did not report any significant Co-agent × Congruency × Agent interaction on participants' temporal estimations in their previous investigation, an a priori medium effect size defined by partial $\eta^2 = .09$ was considered in the second power analysis. In this later analysis, we found that a sample size of 21 participants was needed to exhibit differences on participants' temporal estimations when considering three types of Co-agent (Human, Human-like, Servomotor), two levels of Congruency (Congruent, Incongruent), and two levels of Agent (Self, Other). Therefore, the minimal required sample size in the current study consisted of a sample of 21 participants. A little over participants were finally tested to compensate for potential data loss. All participants had normal or corrected-to-normal vision. None of them had prior knowledge about the purpose of the experiment. Participants were paid €30 for their participation in the experiment.

Materials and stimuli

Two desktop computers were used to allow pairs of participants to run the experiment in parallel.

Visual stimuli consisted of three dots of 0.5 cm diameter: a white dot, a blue dot, and a yellow dot. An auditory

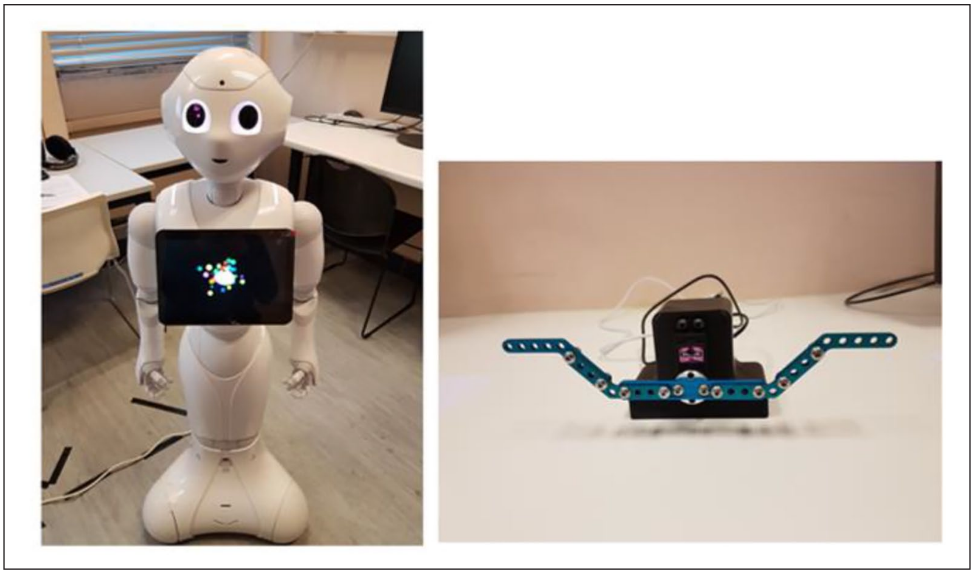

Figure 1. The humanoid robot and the servomotor used as co-agents during the experiment.

tone (1,000 Hz and 200 ms duration), presented via a headphone, was used during the experiment as a sensory consequence of the agent's key presses for measuring IB. Moreover, the use of headphones made it possible to mask the sound naturally generated by the co-agent's actions (e.g., the sound outputted from the effector in motion or from the key presses).

The type of co-agent participants interacted with was manipulated using a within-participants design so that participants successively interacted with another human, a full humanoid robot named Pepper, and a servomotor in a counterbalanced order (see Figure 1 for pictures of the two robots). Robots such as Pepper belong to a class of robots designed to engage people at an interpersonal and socio-affective level (Breazeal et al., 2008), and are called social robots (see Fong et al., 2003 for a discussion of the concept of social robot). However, in order to control prior belief or expectations about the robots, neither Pepper nor the servomotor interacted with the participants before the testing phase. Hence, both machines were already powered up and placed at the suitable location when participants entered in the testing room. Participants were told that they would have to perform a joint task with different co-agents, without being introduced to each other. During the task, Pepper's key presses were performed with the help of its fist, and the servomotor's key presses were performed according to a toggle mechanism of a pivoting bar.

When the humanoid robot or the servomotor performed key presses, their RTs were randomly taken from a normal distribution computed from the mean and standard deviation of naïve participants' RTs during a previous similar experiment (Sahaï, et al., 2019). Hence, the co-agents' RTs to detect the target were similar in all experimental conditions, that is to say, when the co-agent was another human, a humanoid robot, and a servomotor.

Stimuli presentation and robot-generated actions were controlled using PsychoPy software (2_PY3 version).

Procedure

Once arrived in the experimental room, participants were asked to give their informed and written consent before to take part in the experiment. Participants and their co-agent were seated on each side of a screen. They had to detect, as quickly and as accurately as possible, coloured dots that appeared either on the left or the right side of a central fixation cross. Participants' co-agent could be another naïve participant, a full humanoid robot, or a servomotor (see Figure 2). During the human–human interactions, the participant and his or her co-agent were matched both by gender and handiness.

Each trial started with a fixation cross that appeared at the centre of the screen for 500 ms followed by the immediate apparition of the target dot. According to the colour of the target dot (either blue or yellow), the participants or their co-agent (i.e., the other human, the humanoid robot, or the servomotor) had at most 1,000 ms to press their assigned response key (e.g., left or right key, counterbalanced across participants) otherwise an error message appeared, and the trial was cancelled. Participants were informed of the onset of their own action and those of their co-agent in real-time with the help of the presentation of a white dot (with the same size as the target dot) that was displayed above the target dot for a duration of 200 ms. Participants were required to look at the computer screen throughout the experiment and not to look at the actions performed by their co-agents. Each correct target detection was followed by an auditory tone presented after the key press at one of two possible stimulus onset asynchronies (SOA) of 400 or 1,200 ms, randomly

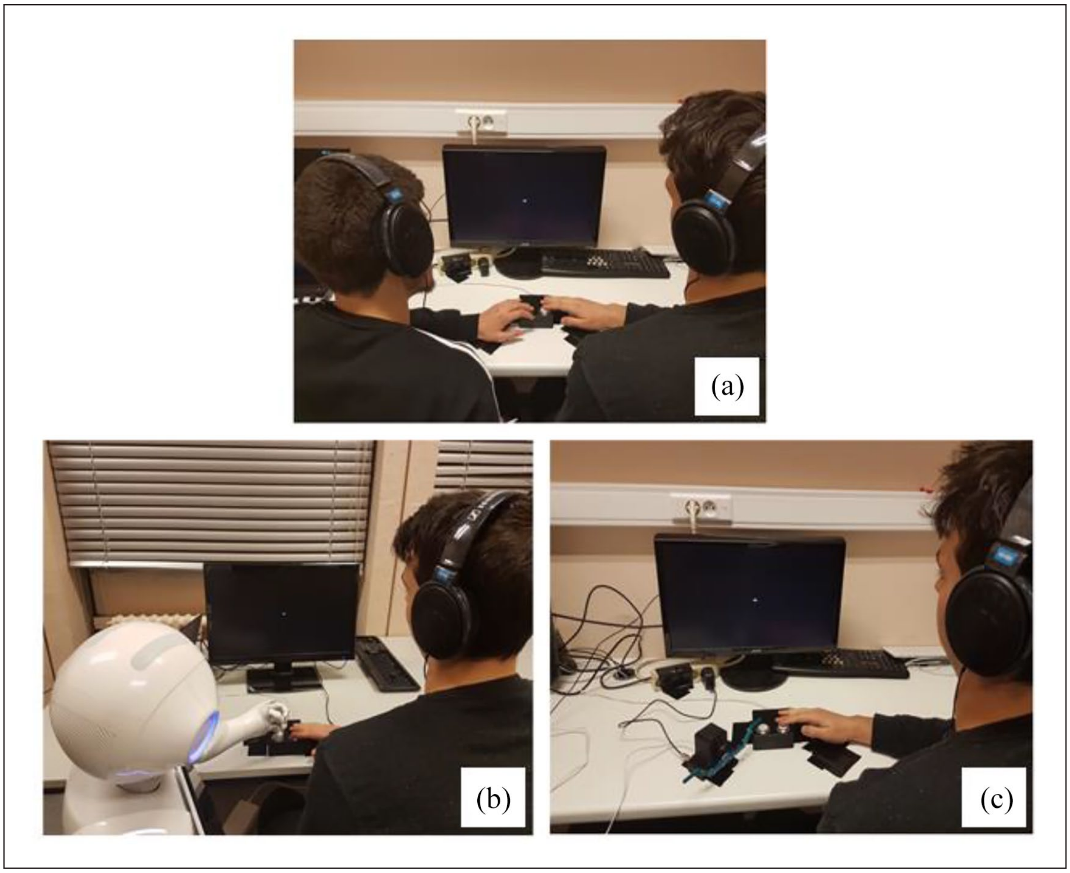

Figure 2. The experimental display of the experiment when the participants performed the joint task with (a) another human, (b) the humanoid robot, and (c) the servomotor.

selected. However, participants were told that this delay was totally random and that it could vary between 100 ms and 2,000 ms. After the presentation of the auditory tone, participants had to write on a sheet of paper the perceived duration between the onset of the target detection (self- or other-generated, indicated by the white dot appearing on the target) and the onset of the auditory tone (see Figure 3 for a summary). The sheet of paper consisted of several empty rows, each corresponding to a specific trial of the experiment. Participants were requested to report the temporal estimation for the corresponding trial in the accurate row. These time interval estimations served as an implicit measure of the participants' sense of agency (Haggard et al., 2002). Moreover, at each change of partner, participants were trained at the beginning of the block to estimate and report their perceived duration of the action-tone intervals. During this training, they were presented with two different colours dots that appeared sequentially with a random time interval comprised between 100 ms and 2,000 ms. Participant were told to write on a sheet of paper the perceived duration of this interval in milliseconds. Then, participants were given a feedback with the correct delay that appeared on the screen to accurately recalibrate their internal clock. This training session consisted of 25 trials. Thereafter, participants performed 16 trials of the forthcoming experimental condition as training. The aim of this training was to familiarise participants with the task so that they would associate their key presses with the subsequent auditory tone.

The mappings between the colour of the target dot (e.g., blue or yellow) and the accurate response key that was associated with (e.g., left or right key) were counterbalanced across participants but stayed constant throughout all the experiment for a given participant. For the participants' trials, every trial was coded as "Congruent" when the target appeared on the side of the participant's response key, and as "Incongruent" when the target appeared on the opposite side of the participant's response key. Moreover, for the co-agent's trials, every trial was coded as "Congruent" when the target appeared on the side of the partner's response key, and as "Incongruent" when the target appeared on the opposite side of the partner's response key. Participants completed a total of 720 trials (3 Co-agents [Human, Humanoid robot, Servomotor] ×2 agents (Self, Other) × 2 Congruency levels (Congruent, Incongruent) × 2 delays (400, 1,200) × 30 trials).

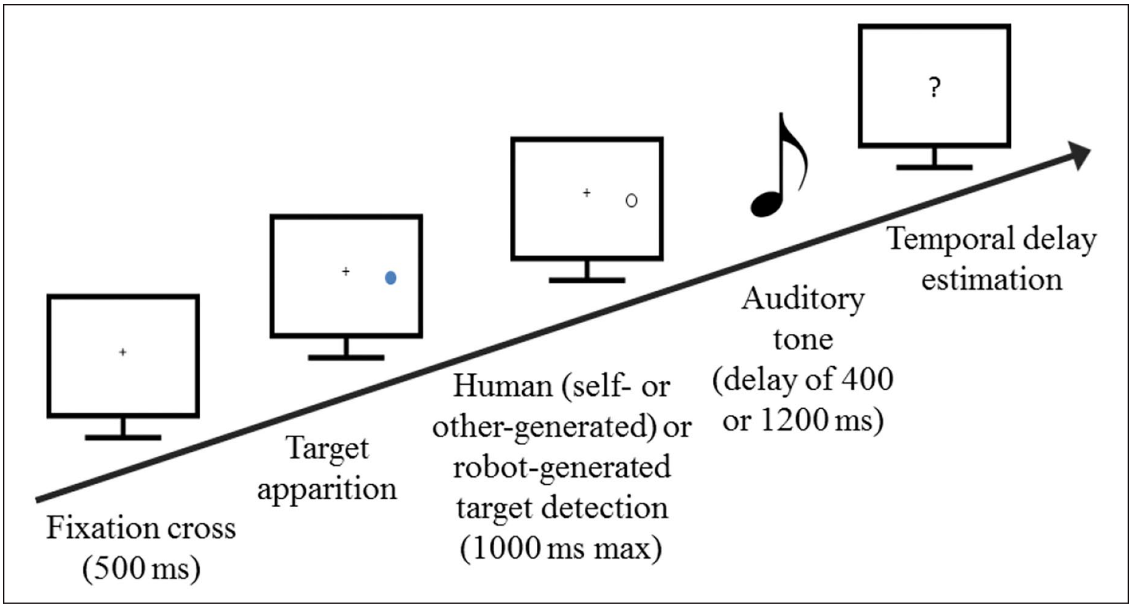

Figure 3. A trial timeline. The trial started with a fixation cross that appeared for 500 ms. Then, the target dot (either blue- or yellow- coloured) appeared. According to the colour of the target, participants or their co-agents had to detect the target by pressing a specific key (either the left or the right key) within a time window of 1,000 ms. Every target detection was signalled by the target becoming white-coloured. An auditory tone was generated at one of the two possible a SOA (either 400 ms or 1,200 ms) following the target detection. Participant had to report the perceived temporal delay between the onset of the target detection (self- or other-generated) and the onset of the tone.

Data analyses

Our first dependent measure was the participants' mean target detection RT. Our second dependent measure was the participants' mean perceived action-tone temporal interval. To distinguish the participants' trials from the co-agent's trials, the participants' trials were labelled "*Self* trials," and the co-agents' trials were labelled "*Other* trials." Statistical analyses were performed with R software (3.3.1 version). Extreme values (i.e., the values that were below or above 2 standard deviations from the mean) of the participants' RTs were excluded from further analyses in order to eliminate outliers and allow for robust statistical analyses. These rejections represented 7% of the raw data. Previous work using the Simon task has already used a similar approach in the pre-processing of the RTs (Sahaï, et al., 2019; Wylie et al., 2010). The significance level was set at $\alpha = .05$. In addition, post-hoc comparisons were made using the false discovery rate (FDR) correction (Benjamini & Hochberg, 1995).

RT analyses

This analysis was based exclusively on the data gathered in the conditions wherein participants performed an action (i.e., the *Self* trials). An ANOVA was computed on the participants' mean RTs with Co-agent (Human, Pepper, Servomotor) and Congruency (Congruent, Incongruent) as within-factors, and Hand (Dominant, Non-dominant) as a between-factor. The Hand factor was included in the ANOVA because some studies reported that handiness asymmetries could impact the stimulus-response congruency effect (Rubichi & Nicoletti, 2006; Seibold et al., 2016). Note should be taken that the Target (blue dot, yellow dot) factor was not included in the ANOVA because the stimulus-response congruency effect does not rely on the target identity (i.e., its colour) but rather on the congruency between the location of the target and the location of the response key. Finally, the delay (400 or 1,200) factor was irrelevant for this analysis as the auditory tone was produced after the participants' response and therefore could not influence their RTs.

Temporal interval estimations analyses

The so-called IB phenomenon was used as an implicit measure of the sense of agency. This phenomenon refers to the individuals' illusory temporal attraction between the onset of a generated action (e.g., a key press) and the onset of its sensory consequence (e.g., a tone) which occurs only when the action has been intentionally triggered (Haggard et al., 2002). IB is known as a robust implicit measure of sense of agency (for a review, see Moore & Fletcher, 2012).

An ANOVA was computed on the participants' mean temporal estimations with Co-agent (Human, Pepper, Servomotor) and Congruency (Congruent, Incongruent) as within-factors and Agent (Self, Other) as a between-factor. The Congruency factor was included in the ANOVA to

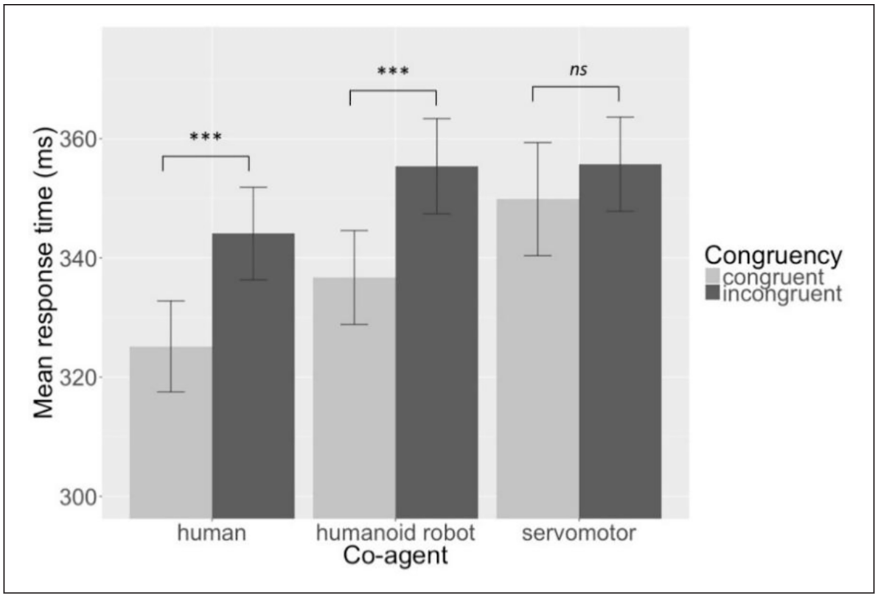

Figure 4. The Congruency × Co-agent interaction on the participants' mean response times in the joint Simon task according to the type of Co-agent. Error bars represent standard errors. All tests were two-tailed. *** corresponds to a *p* value $< .001$.

investigate foreseeable effects of the conflictual action selection context (e.g., on incongruent trials) (Sidarus & Haggard, 2016) on the participants' mean temporal estimations. The action-tone delay (400 or 1,200 ms) was not included in the ANOVA as a separate factor. Indeed, the participants' temporal estimations for both delays were averaged as we were interested in the way the social context could influence the temporal interval estimations, rather than the influence of different temporal interval lengths on the reported temporal estimations. In the current study, the variations in interval lengths were made to avoid a predictability bias.

Results

RTs

We aimed to examine the occurrence of the SSE during a joint task with regard to the nature of the co-agent (Human, Humanoid robot, Servomotor). We assessed the normality of the RTs distributions of the differences between the congruent trials and the incongruent trials, separately for each type of co-agent, using the Shapiro–Wilk test. The analyses showed that none of the RTs distributions deviated from normality (all $W > 0.90$ and all $p > .10$). Hence, a 3 × 2 × 2 ANOVA with Co-agent (Human, Humanoid robot, Servomotor) and Congruency (Congruent, Incongruent) as within factors and Hand (Dominant, Non-dominant) as a between factor was computed. A significant main effect of Congruency was found on the participants' mean RTs, indicating longer participants' mean RTs on Incongruent trials compared with Congruent trials ($F(1,26) = 43.98, p < .001$, partial $\eta^2 = .63$). Moreover, there was no significant main effect of Co-agent ($F(2,52) = 1.90, p = .16$, partial $\eta^2 = .07$) or Hand ($F(1,26) = .04, p = .85$, partial $\eta^2 = .001$) on the participants' mean RTs. However, a significant interaction between Congruency and Co-agent was found ($F(2,52) = 6.53, p = .003$, partial $\eta^2 = .20$, Figure 4) on the participants' mean RTs. Other interactions did not reach significance (all $ps > .05$).

Post hoc comparisons investigating the Congruency × Co-agent interaction revealed that the participants' mean RTs on Incongruent trials were significantly longer than the participants' mean RTs on Congruent trials when the Co-agent was a Human (respectively, 344.08 ms (95% CI = [328.87; 359.30]) and 325.16 ms (95% CI = [310.21; 340.10]), $pFDR < .001$, Cohen's $d = .32$) and a Humanoid robot (respectively, 355.39 ms (95% CI = [339.75; 371.03]) and 336.72 ms (95% CI = [321.31; 352.13]), $pFDR < .001$, Cohen's $d = .26$) but not when the Co-agent was the Servomotor (respectively, 355.71 ms (95% CI = [340.21; 371.21]) and 349.86 ms (95% CI = [331.29; 368.44]), $pFDR = .12$, Cohen's $d = .11$. Hence, the SSE was observed both when the participants performed the task with another human and with the humanoid robot. On the contrary, no SSE was observed when the participants interacted with the servomotor.

Temporal interval estimations

We aimed to examine the influence of the social context and the target congruency on the participant's perceived temporal interval estimations between the onset of a performed action, either self- or other-generated, and the onset of a subsequent auditory tone. A 3 × 2 × 2 ANOVA

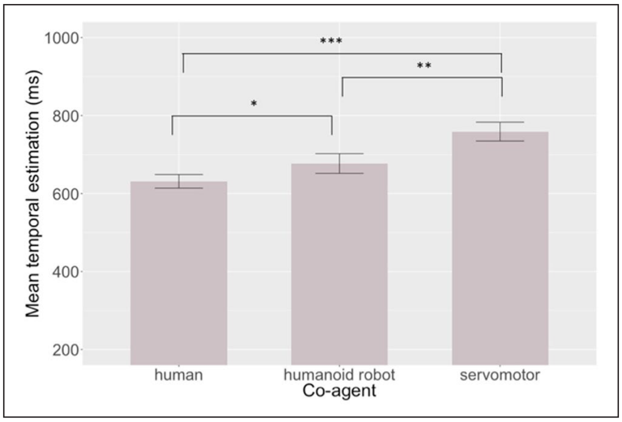

Figure 5. The main effect of Co-agent. Error bars represent standard errors. All tests were two-tailed. * corresponds to a *p* value < .05, ** corresponds to a *p* value < .01, and *** corresponds to a *p* value < .001.

with Co-agent (Human, Pepper, Servomotor), Congruency (Congruent, Incongruent), and Agent (Self, Other) as within-factors. A significant main effect of Co-agent ($F(2,54) = 5.36$, $p=.008$, partial $\eta^2=.17$, see Figure 5) was found on the participants' mean temporal estimations. This main effect indicated that the participants' mean temporal estimations were shorter during the joint task with another human compared with the humanoid robot, respectively, 631.42 ms (95% CI = [563.13; 699.71]) and 676.92 ms (95% CI = [578.00; 775.85]), *pFDR* = .03, Cohen's $d=.44$, and with the servomotor 758.89 ms (95% CI = [664.22; 853.56]), *pFDR* < .001, Cohen's $d=.64$. In addition, the participants' mean temporal estimations were shorter during the joint task with the humanoid robot compared with the Servomotor (*pFDR* = .001, Cohen's $d=.57$). Furthermore, no significant main effect of Congruency, $F(1,27) = 3.48$, $p=.07$, partial $\eta^2=.11$, or Agent, $F(1,27)=.64$, $p=.43$, partial $\eta^2=.02$, was found on the participants' mean temporal estimations. However, a significant Congruency × Agent × Co-agent interaction was found on the participants' mean temporal estimations (*HFe* = .78, $p=.02$, partial $\eta^2=.15$, see Figure 6).

Post hoc comparisons investigating the Congruency × Agent × Co-agent interaction revealed that during Congruent trials, the participants' mean temporal estimations did not differ between the Self and the Other trials when the Co-agent was another human, respectively 633.50 ms (95% CI = [573.90; 693.09]) and 634.30 ms (95% CI = [554.84; 713.77]), *pFDR* = .97, Cohen's $d=.01$, the humanoid robot, respectively, 678.50 ms (95% CI = [586.00; 771.00]) and 679.28 ms (95% CI = [574.86; 783.70]), *pFDR* = .97, Cohen's $d=.01$, and the Servomotor, respectively, 735.49 ms (95% CI = [640.80; 830.17]) and 732.26 ms (95% CI = [632.06; 832.45]), *pFDR* = .90, Cohen's $d=.02$. However, during the Incongruent trials, a significant difference indicated that the participants' mean temporal estimations were longer during the Self trials compared with the Other trials when the Co-agent was the Servomotor, respectively, 832.62 ms (95% CI = [745.65; 919.59]) and 735.18 ms (95% CI = [639.03; 831.34]), *pFDR* = .02, Cohen's $d=.48$. By contrast, the participants' mean temporal estimations during the Incongruent trials did not differ between the Self trials and the Other trials when the Co-agent was another human, respectively, 635.28 ms (95% CI = [571.47; 699.09]) and 622.59 ms (95% CI = [550.33; 694.84]), *pFDR* = .45, Cohen's $d=.14$, or the humanoid robot, respectively, 660.05 ms (95% CI = [567.37; 752.72]) and 689.87 ms (95% CI = [579.79; 799.95]), *pFDR* = .23, Cohen's $d=.23$. Hence, the results indicated that the participants' mean temporal estimations were modulated by the nature of the Agent (Self, Other) only during the interactions with the servomotor, on the incongruent trials.

Discussion

The aim of this study was to investigate (1) the effect of the robot's physical appearance on the individuals' sense of *self-agency* and *vicarious agency* and (2) to explore the cognitive mechanisms underlying the sense of shared agency when individuals they are engaged in a joint task with a machine. Participants were requested to perform a joint Simon task with a co-agent that could be either another human, or a machine. The machine appearance was manipulated so that it could be a full humanoid robot or a servomotor. Every accurate target detection (self- or other-generated) triggered an auditory tone after a certain delay. The participants had to report the perceived delay between the onset of the target detection and the onset of the auditory tone, which served as an implicit measure of the participants' sense of agency (Haggard et al., 2002).

With regard to the effect of the impact of the robot's physical appearance on the individuals' experience of agency, our results revealed that overall, the participants reported shorter mean action-tone temporal intervals during the joint task with the other human compared with the humanoid robot, and shorter temporal estimations during the joint task with the humanoid robot compared with the servomotor. This finding suggested an increased overall experience of agency during the joint task with the humanoid robot relative to the servomotor. Furthermore, our experiment provided additional evidence bearing on a debated issue in the literature, namely, whether one's sense of agency is specific for one's own action or not. In the current research, we demonstrated that the experienced sense of agency was not specific to one's own actions, and that a form of vicarious agency was possible during a joint task. Importantly, our findings also revealed that the humanoid appearance of a machine could impact the development of the individuals' sense of *shared agency* during human-machine interactions. Indeed, participants' overall experience of agency was at its maximum

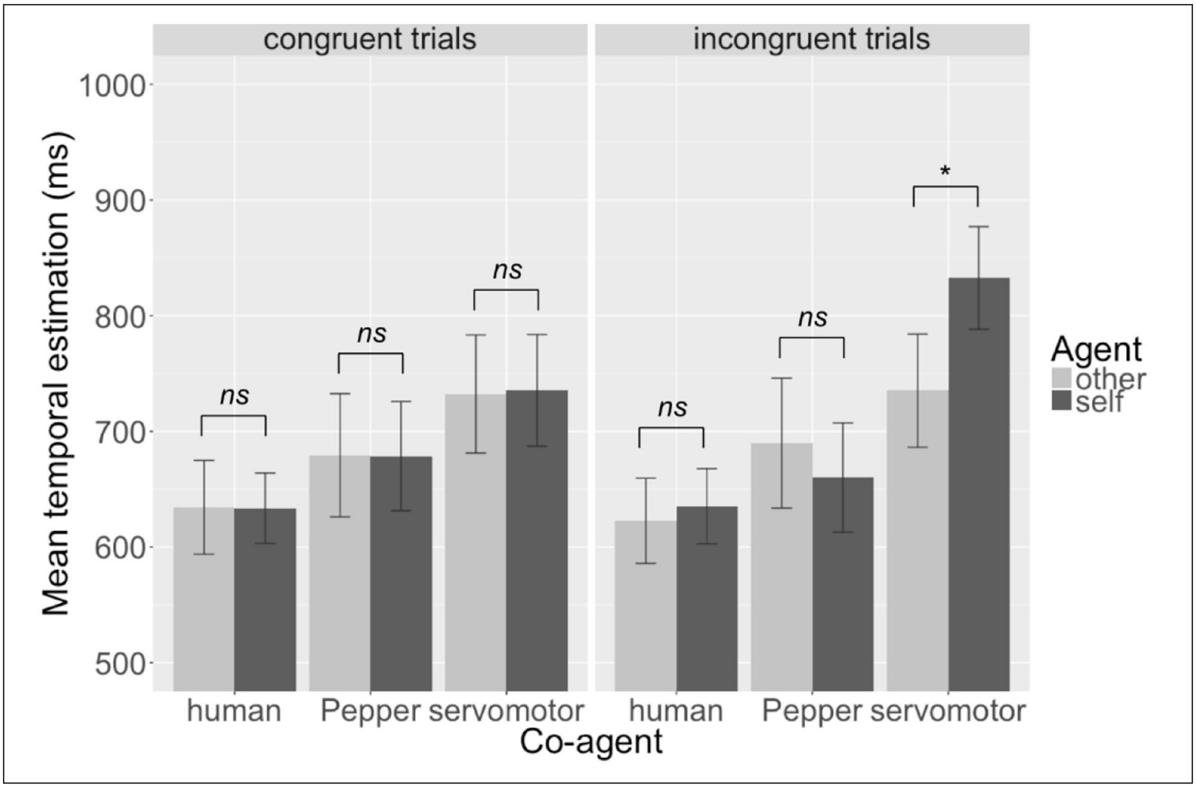

Figure 6. The Congruency × Agent × Co-agent interaction. Error bars represent standard errors. All tests were two-tailed. * corresponds to a p value $< .05$.

during the human–human interactions and sharply declined during the human-servomotor interactions while an intermediate level was found during the interactions with the humanoid robot. At the same time, we found that the participants' mean temporal estimations for the self-generated actions were not different to the mean temporal estimations for other-generated actions during the joint actions with the other human and with the humanoid robot, suggesting the emergence of a sense of *shared agency* in the both cases. As matters stand, it is difficult to explain why distinct experiences of agency were found for the self-generated actions and the other-generated actions during the joint task with the human co-agent in Sahaï and colleagues' (2019) study whereas no differences were observed in the present study using a similar paradigm. Interestingly, distinct temporal estimations were found for the self-generated actions and for the other-generated actions during the joint task when the co-agent was the servomotor on incongruent trials, meaning that no shared experience of agency (or *shared agency*) occurred with this type of machine when the task difficulty increased. Seemingly, it could be speculated that the similarity with the humanoid robot led participants to treat the machine as a potential social partner (Fogg, 2003), echoing Searle's (1983) contention that recognising the other as similar to oneself and as a potential agent is a prerequisite to engaging in a collaborative activity (Searle, 1983). This ability to search for social boundaries has been demonstrated to be present very early in life, which made human individuals profoundly social (Ciaunica et al., 2021; Fotopoulou & Tsakiris, 2017). Because human-like robots are known to elicit empathic behaviours in humans as opposed to non-human-like robots (Kwak et al., 2013; Riek et al., 2009; Slater et al., 2006; but see also "uncanny valley" phenomenon, Misselhorn, 2009 and empathic behaviour with minimal humanity cues, Vaes et al., 2016), it is conceivable to think that participants were more likely to create similarity boundaries with the humanoid robot compared with the servomotor (de Vignemont & Singer, 2006). Indeed, a linear relation has been observed between the degree of anthropomorphism of robots and the activation of brain areas involved in the processing of others' minds (Krach et al., 2008).

Consistently, the participants' RTs were also modulated by the human-like features of the co-agent. Indeed, we found an SSE with longer RTs on the incongruent trials compared with the congruent trials only when participants performed the joint Simon task with another human and with the humanoid robot. By contrast, this effect disappeared during the joint task with the non-human like machine (i.e., the servomotor). Supporting this, previous studies using a joint Simon paradigm have shown no SSE on participants' RTs when they partnered with non-biological agents (Sahaï et al., 2019; Tsai et al., 2008, 2011). Yet, some studies nevertheless observed an SSE when sharing a Simon task with a non-human agent (Dolk et al., 2011, 2013; Puffe et al., 2017; Stenzel & Liepelt, 2016). A possible reason for explaining such a discrepancy may relate to the agents' belief regarding the partner. Indeed, previous work emphasised that agents' beliefs on the origin of the robotic behaviour could influence the outcome on a variety of behavioural and neuroimaging tasks (Hortensius & Cross, 2018; Stenzel et al., 2012; Wykowska et al., 2016). For example, Stenzel and collaborators (2012) showed that the SSE reappeared when an intentional stance towards the machine was encouraged, that is, when the robot was described as an active and intelligent agent, and suggest that ascribing agency to the co-actor (i.e., perceiving the co-actor as being the initiator of the action effect) is critical to observe the SSE (Stenzel et al., 2014). In the current study, even if it was not explicitly pointing out during task instructions, it is possible that having the participants interact with agents of a different nature had unconsciously led them to focus on the intentional aspect of the agents. Interestingly, the participants' RTs revealed that the SSE did not differ in amplitude when the participants performed the task with another human and with the humanoid robot. This suggested that the biological nature of the co-agent *per se* was not what influenced the SSE, but rather the ability to consider the co-agent as a social partner as it is the case with robots such as Pepper.

Finally, our findings support the existence of differences in the processing of the sense of *self-agency* and the processing of the sense of *shared agency* during a joint task. On one hand, it has been proposed that the individuals' sense of *self-agency* was informed by the dynamic integration of both internal motor cues and contextual cues, with typically more weight given to the motor cues (Moore & Fletcher, 2012; Synofzik et al., 2013). In addition, some authors pointed out that when action selection was easy (e.g., on congruent trials), the participants' sense of *self-agency* was stronger compared with a conflictual action selection context (e.g., on incongruent trials) (Sidarus & Haggard, 2016). On the other hand, in the current study, no Congruency effect was observed on the participants' mean action-tone temporal estimations neither for the self- or the other-generated actions when participants partnered with another human or with the humanoid robot, that is to say, when a sense of *shared agency* was experienced. By contrast, the Congruency did have an effect on the participants' mean action-tone temporal estimations for the self-generated actions when the sense of *shared agency* was not present anymore, that is to say, when the participants partnered with the servomotor. Taken together, this suggested that the fluency of action selection had a weaker role in the construction of the sense of *shared agency* than in the sense of *self-agency*. Consequently, it could be tentatively suggested that the weight of the egocentric internal cues linked to decision fluency was weakened when the individuals involved in the joint task were not considered as separate entities but holistically within a shared "we-identity." Unlike individual actions, during a joint task, the modulations in the individuals' sense of agency may be prominently dependent on contextual cues, even if internal motor cues are available. This corroborates previous investigations that showed that the experience of agency exhibited during joint actions, which were performed simultaneously by the agents involved in the task, was not based on egocentric predictions but depended on the degree of control exhibited by the whole team (Dewey et al., 2014; van der Wel et al., 2015). Hence, the current study provided additional evidence in the context of a joint task where the actions were performed alternately by the two agents involved in the shared task. Finally, the question of whether similar results would have been observed with an explicit measurement of one's sense of agency could be raised. However, explicit measurement of the individuals' sense of agency has been shown to be mostly influenced by contextual cues such as prior thoughts, for example (Synofzik et al., 2008). Yet, in the current study, the author of the generated key press was clearly identified given the colour of the target so that the participants' self-reported explicit judgement of agency would not have differed from the instructions induced by the joint Simon task.

Eventually, some limitations of our work must nonetheless be acknowledged. First, note should be taken that during the experiment, the co-agent's effector was not hidden by a physical separation. Hence, even though participants were given the explicit instruction to look at the screen and not at the actions performed by the co-agent, peripheral vision might have allowed them to discern their co-agent's actions. Consequently, it was not possible in the current research to distinguish between the contribution of the low-level processing of the social visual cues and the contribution of higher-order socio-cognitive processes. Second, because our experiment did not include a baseline condition (e.g., an experimental condition wherein the participants would have to estimate the action-tone temporal delays triggered by a computer program), it is difficult to know whether the lower level of agency found in the joint task with the servomotor was a floor effect or already an increment of agency. Yet, recent findings emphasised variations in the sense of *vicarious agency* exhibited by individuals during a joint task with a non-human-like robot, according to the level of embodiment of the machine-generated action (Roselli et al., 2021). More specifically, it has been shown that when participants were performing a joint task with a robot that performed a physically perceivable action (e.g., executing a key press with the help of a limb, which triggered an auditory tone), they were able to experience a sense of *vicarious agency* over the robot's generated outcome. Conversely, when the robot's action was known but unperceivable and digitised (e.g., sending a Bluetooth command made noticeable with a visual signal, which triggered an auditory tone), the participants did not demonstrate a sense of *vicarious agency* for the robot's generated outcome anymore. Hence, it could be possible that the lower level of agency observed during the joint task with the servomotor in the current study did not imply a total absence of agency. Nonetheless, it could be said that the similarity of the humanoid robot appearance with the participants seemed to boost the participants' sense of *shared agency* during the joint task, in comparison to the non-anthropomorphised machine. Finally, another limitation of the study was that the robot co-agents did not have the same physical size. Indeed, while the humanoid robot was the size of a child, the servomotor was only about 10 cm tall. Hence, it is difficult to evaluate the part of the exogenous salience of the co-agent related to its size, and that related to the human-like embodiment in our results on the representation of other-generated actions and on the sense of agency.

In conclusion, the findings of this research showed that automation technology design could significantly change the individuals' agentive experience. Remarkably, human-like machines helped to mitigate the reported negative aspects induced by traditional automated systems in the individuals' experience of agency (Obhi & Hall, 2011b; Sahaï et al., 2019). Indeed, the participants' sense of agency was reinforced during the joint task with the humanoid robot compared with the traditional machine, leading even to the construction of a sense of *shared agency* during the interaction with the human-like automata. Importantly, it must be said that the experience of agency is highly flexible and other factors could also influence how individuals develop a sense of *shared agency* with a robot, such as the duration of collaboration, the participants' intentional stance towards the robots (Barlas, 2019; Ciardo et al., 2020), and the robot behaviour predictability (Bolt & Loehr, 2017). Considering both the impact of the individuals' sense of agency on their capacity to engage in cooperative joint tasks (Babcock & Loewenstein, 1997; Caruso et al., 2006),) and the inexorable drive towards more automation, such findings must be taken into consideration for the successful design of new automated systems.

Declaration of conflicting interests

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ORCID iD

Aïsha Sahaï https://orcid.org/0000-0001-9571-1363

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