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The sense of agency in human-human vs human-robot joint action

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A R T I C L E I N F O

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A B S T R A C T

Kinesthesis pertains to the perception of moving body parts, while the sense of agency refers to the experience of controlling one's action-effects. Based on previous work, we hypothesized that the sense of agency would decrease in joint action with a robot compared to a human partner. Pairs of participants were jointly manipulating two interconnected haptic devices enabling them to feel each other's forces. Unbeknown to participants, their partner was sometimes replaced by a robot. The sense of agency was assessed using intentional binding, which refers to a contraction of perceived time between an action and its effect for intentional actions, and participants' judgment of their contribution to joint action. Participants judged their contribution as higher when they were initiating action and when they were paired with the robot. By contrast, intentional binding occurred only with a human partner. This outcome supports the hypothesis that human-robot joint action hinders intentional binding.

1. Introduction

Joint actions are observed when different agents coordinate their goals and movements to act together (Pacherie, 2014). Agents can be humans or robots and human-robot joint action has drawn increasing attention in recent years due to the technological progress of automated systems (Sahaï, Pacherie, Grynszpan, & Berberian, 2017). The sense of agency can be defined as one's experience of controlling one's own actions and their effects on one's environment (Haggard & Chambon, 2012). Cognitive sciences have expressed growing interest in joint action for the last two decades and, at the same time, the sense of agency has been extensively studied. Yet, researchers still lack a clear understanding of how the sense of agency operates in joint action. Experimental evidence showed that disambiguating who was responsible for an action was not straightforward when the action was performed jointly with another person (Wegner & Wheatley, 1999). Current accounts of the sense of agency emphasize the contribution of both explicit and implicit mechanisms (Synofzik, Vosgerau, & Newen, 2008). The explicit mechanisms involve high-level cognitive reasoning, while the implicit mechanisms refer to pre-conceptual lower-level processes closely linked to sensorimotor monitoring (Blakemore, Wolpert, & Frith, 2002) and proprioception. Explicit reasoning about one's agency is usually captured by asking participants to judge whether they caused the action-effect (Wegner & Wheatley, 1999). Regarding the implicit sense of agency, researchers commonly rely on phenomena such as Intentional Binding (IB), which refers to a binding effect whereby the perceived time interval between an action and its effect is reduced when the agent acts intentionally to produce the effect (Haggard, 2005; Haggard,

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Clark, & Kalogeras, 2002).

As emphasized by Pacherie (2014), the sense of agency in joint action not only requires predicting and perceiving the effects of one's own actions, but also those of the co-actor's actions and how these effects combine. Pacherie hypothesized that the ability to accurately predict the co-actor's actions associated with a decreased ability to distinguish one's action-effects from those of the co-actor favored a shift from a sense of individual self-agency towards a joint sense of "we-agency". One way to investigate this question is to attribute distinct sequential roles to the co-actors in performing the action. In the study by Capozzi, Becchio, Garbarini, Savazzi, and Pia (2016), participants triggered a tone that served as a go signal for a co-actor's action. Participants' sense of agency as measured by IB was effective for the first tone that was the direct product of their action, but not for the co-actor's action effect. The same pattern of sequential actions was used by Pfister, Obhi, Rieger, and Wenke (2014) who additionally attributed social roles to the two co-actors (leader and follower). They showed that the leader experienced a sense of agency for the follower's action, but not for the tone effect resulting from the follower's action. Notwithstanding, it has been shown that when participants had to judge the loudness of self- and other-generated tones, they experienced sensory attenuation, that is, a reduced perception of loudness intensity, not only for self-generated tones but also for other-generated tones (Weiss, Herwig, & Schütz-Bosbach, 2011). Sensory attenuation has been linked to individuals' sense of agency, yet it seems to follow trends that do not correlate with intentional binding and explicit judgments of agency (Dewey & Knoblich, 2014). Taken together, these results suggest that the sense of agency is manifold. Characterizing the sense of agency may therefore require more than one measure. Unfortunately, the experimental procedures in the above mentioned studies did not allow the examination of the explicit judgement of agency, because each co-actor's degree of control over action was pre-determined by the instructions.

Additionally, analyzing sequential sub-actions performed individually by each co-actor does not enable capturing the sense of agency in simultaneous joint actions. Yet, the latter is very relevant to everyday life experience, as exemplified by the case of two people moving furniture together (Pacherie, 2014). Few studies have addressed the issue of simultaneous joint actions: van der Wel, Sebanz, and Knoblich (2012) designed a task where participants had to pull cords attached on each side of a pole to move it back and forth. This action was performed individually or jointly with another person. They were asked to rate how strongly they had experienced being in control. The authors found that the degree of control that participants reported was similar whether they performed the task alone or with a partner. Obhi and Hall (2011a) conducted two experiments where pairs of participants were instructed to press a spacebar together. In the first experiment, each participant could initiate the press, but if her/his partner was the first to act then she/he had to join in immediately. In the second experiment, the initiator and follower roles of each participant in the pair were assigned beforehand. Results showed that IB occurred whether participants thought they initiated the action or followed their partner's action, thus leading authors to support the "we-agency" hypothesis. In a complementary study, Obhi and Hall (2011b) compared joint action with a human being versus a computer. Participants were paired either with an unseen human confederate or a computer, and had to perform a tapping action that was followed by a tone. They were told that their partner also performed a tapping action that could trigger the tone, but they were actually performing the action alone. IB occurred for the human co-actor but not for the computer, even when the participant believed she/he had initiated the action first. Joint action was nevertheless implemented as a mere belief manipulation in this experiment. It was contingent on top-down processes driven by the verbal instructions provided to participants. To our knowledge, no study has yet investigated bottom-up processes by manipulating the kinesthetic component of joint action, which conceivably plays a major role in the sense of agency. Our goal was to fill in this gap by further investigating joint action with an artificial agent.

In the experiment reported here, pairs of participants were to jointly turn handles that were mechatronically connected to each other: The forces applied on one handle were fed back on the other handle. Unbeknown to the participants, the handles would sometimes be controlled by a robot instead of the co-actor. This procedure enabled us to investigate the bottom-up influence of the kinesthetic component on agency judgment and IB, while maintaining participants' belief that they were interacting with a human partner. The experimental design was inspired by the study of Obhi and Hall (2011a) where pairs of participants cooperated to perform a joint action. Based on the work by Obhi and Hall (2011b), we hypothesized that the sense of agency would decrease in joint action with a robot compared to a human.

2. Method

2.1. Participants

Twenty-six right-handed participants (17 women, mean age 21.73 years [$SD = 3.80$]) were recruited for this experiment. We had estimated the minimum sample size beforehand as being 16, with a power analysis based on data reported by Obhi and Hall (2011a) using the G*Power application (Faul, Erdfelder, Lang, & Buchner, 2007) with a significance threshold set at 0.05 and power at 0.9. Participants were free of any known psychiatric or neurologic symptoms, non-corrected visual or auditory deficits and recent use of any substance that could impede concentration. Participants were grouped in pairs. There were 5 woman-woman pairs, one man-man pair and 7 woman-man pairs. This research was reviewed and approved by an institutional ethics committee. Informed consent was obtained from each participant. One participant had to be excluded, because the debriefing interview suggested that he had some doubts about his partner being a robot (see participant 26 in Table 1 of the Appendix). The analyses were thus based on 25 participants.

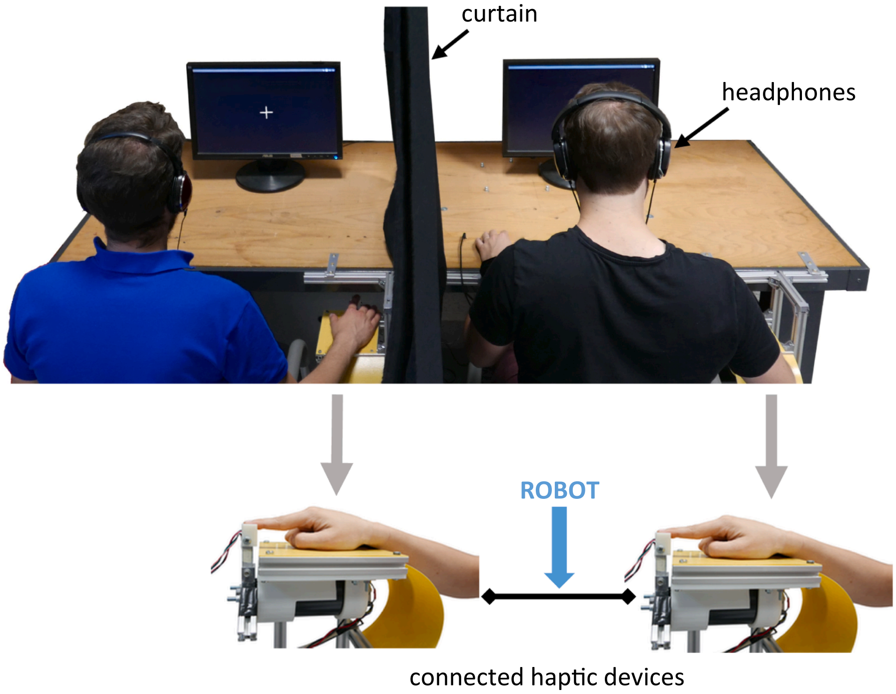


Fig. 1. The experimental setup: Two participants were sitting side by side, separated by a curtain and wearing noise-cancelling headphones. They were manipulating handle haptic devices with their index finger. Each handle could either reproduce the forces applied by their partner on the other handle or be controlled by a robot. Movement and force data were collected by the device.

2.2. Material

The handles were custom-made haptic interfaces that could be manipulated with the index finger. Technical details are described in Roche, Richer, and Saint-Bauzel (2018). The system design was based on prior experimentations involving human-human interaction (Roche & Saint-Bauzel, 2016). Both handles were controlled by the same embedded controller. This controller was a four channel tele-operating controller that was simulating a high stiffness spring damper link as explained in (Roche & Saint-Bauzel, 2018). The sampling rate of the controller was 5 kHz and the teleoperation lag between handles was 0.2 ms. The handles were 80 mm long and could rotate 28.8° leftward or rightward until they bumped into stoppers. Forces applied to the handle could be measured and a tactile receptor was located where participants would place their finger. Each handle could either reproduce the forces applied to the other handle or be controlled by a robot (Fig. 1). The robot was programmed to randomly turn right or left after a random delay between 0 and 3 s. If the participant had started moving the handle before the robot, then the robot would follow her/his lead. If the robot had been the first to move, but the participant exerted forces in the opposite direction above a given threshold of 2 N, then the robot would change direction to follow the participant. This guaranteed safe use for the participant. The threshold was determined based on (Roche & Saint-Bauzel, 2016). The robot simulated human motion using minimum jerk optimization (Flash & Hogan, 1985). Forces in Newton measured by sensors on each handle and the handle orientation in radian were timestamped and recorded for later analysis.

To evaluate intentional binding, we used two audio signals as action-effects. They were a high-pitched beep (2000 Hz) and a low-pitched beep (1000 Hz) that each lasted 120 ms. A leftward turn of the handle was associated with the high-pitched beep and a rightward turn with the low-pitched beep. Different sound pitches were associated with the leftward and rightward turn to give participants control over the identity of the effect of their action as recommended by Hughes, Desantis, and Waszak (2013). Participants' agency would therefore not only determine the timing of the sound effect, but also its identity.

2.3. Procedure

Pairs of participants sat side-by-side, separated by a curtain, each facing their own computer screen (Fig. 1). Each participant had their own mouse and handle placed on their right side. As a cover story, they were told that they would be jointly manipulating a pair of connected handles and thus led to believe that they were always interacting with a human partner, even when their partner was actually a robot. They wore headsets playing pink noise to prevent them from receiving any sound cue from their partner. The experiment consisted of two training blocks and three experimental blocks separated by short pauses.

2.3.1. Training blocks

Participants performed two training blocks individually. During the first training block, participants gained practice in estimating time intervals. It comprised 30 trials. Each trial started with a message on the screen to request participants' attention. This message was displayed for 500 ms. Then, a white fixation cross over a black background was displayed. Five hundred milliseconds after the fixation cross appeared, participants heard a sequence made of the two above mentioned beeps in their headphones and they had to estimate the time interval separating them. The order of the beeps in the sequence was randomized across trials. The interval duration between the two sounds was a random delay ranging from 300 ms to 1700 ms. Participants had up to 5 s to provide an answer by moving a slider on a horizontal Likert scale. This scale extended from 0 to 2000 ms. Once they validated their answer, participants were shown the correct interval length on another Likert scale that appeared below the one they had used.

The goal of the second training block was to have participants learn the action-effect association between the movement on the handle and the subsequent sound. This block contained 20 trials. To tag the end of the handle turn, a click sound (duration 120 ms) was emitted in the headphones when the handle reached the stopper. As in the previous block, each trial started with a message lasting 500 ms that requested participants' attention. The fixation cross then appeared and the participant had up to three seconds to initiate a turn. The time count before the sound effect was emitted began as soon as the participant reached the stopper. The interval duration between when participants reached the stopper and when the sound was emitted varied randomly between 300 ms and 1700 ms. At the end of the trial, the handle automatically returned to its central position. The next trial began as soon as the receptor located on the handle was able to detect the participant's finger.

2.3.2. Experimental blocks

There were three experimental blocks: a baseline block, a human-human joint action block and a human-robot joint action block. Their order was randomly counterbalanced across participants. The baseline block comprised 40 trials and was similar to the first training block, except that (1) participants were not given any feedback about the correct interval duration, (2) the interval between the two sounds lasted either 700 ms or 1300 ms. A pseudo-random sequence was used to ensure that the number of trials was the same for either interval duration. The human-human and human-robot joint action blocks were the operant conditions and they each contained 120 trials. The only difference between these two blocks was that in the human-human block, the two participants moved the handle together, whereas in the human-robot block, the partner for each of the two participants was the robot. As in the other blocks, the joint action blocks started with a request for attention lasting 500 ms, followed by the fixation cross. Once the fixation cross appeared, participants had up to 3 s to turn the handle. The two participants were asked to cooperate together and equate the number of times they each initiated the move. If their partner initiated the move first, they were instructed to follow her/his lead. For every individual trial, the role (initiator vs follower) of each co-actor was determined a posteriori when analyzing the movements and forces applied on the handles. In each trial, the initiator role was assigned to the first participant to apply a 0.2 N force on her/his handle. This criterion was based on prior experimentations (Roche & Saint-Bauzel, 2016) with the system where it was observed that this value was a threshold discriminating involuntary micro-movements. The beep sound was delivered either 700 ms or 1300 ms after the handle reached the stopper, according to the same pseudo-random procedure as in the baseline block. As in the associative learning block, the high-pitched beep was associated with a leftward turn and the low-pitched beep with a rightward turn. Participants had to estimate the interval duration on a Likert scale ranging from 0 to 2000 ms as in the training block. They also had to rate on a Likert scale how much they thought they had contributed to causing the beep sound by moving a slider on a ruler representing the percentage of their contribution from 0 to 100. The data collected for every trial included participants' estimation of the interval duration, participants' rating of their contribution to the action-effect, the number of times the movement of the handle changed direction and the average of interaction forces applied to the handle (i.e. the sum of interaction forces averaged over the time taken to turn the handle).

2.3.3. Debriefing interview

At the end of the experiment, each of the two co-actors were individually interviewed to verify they believed that they had been interacting with one another during the entire experiment. They were asked the three following questions: (1) "Do you have any comment about the experiment?" (2) "Did you notice a difference between the two blocks where you interacted with your partner?" (3) "In fact, you were interacting with a human partner in one block and with an automated artificial system in the other. Did you realize that?" The answers of the participants were recorded and analyzed by two independent raters. Those raters had to judge whether participants realized that they had been interacting with a robot. If the two raters disagreed, the judgment of a third rater was requested. There was perfect agreement between the two initial raters for 24 participants and, of the two remaining participants, one was excluded. The answers to those questions are listed in Table 1 of the Appendix. Note should be taken that as the second question focused on the comparison between the human and robot partner blocks, the way it was formulated could lead participants to suspect that there actually was a difference between those two blocks. Furthermore, the third question revealed the truth about the manipulation. So participants were likely to reconstruct their experience after these two questions, while answers to the first question could be regarded as more authentic and spontaneous.

2.4. Data analysis

The data were analyzed using Statistica software. As in the first experiment of Obhi and Hall (2011a), our experimental design did not force roles upon participants during each trial. Indeed, we wanted to investigate joint action in which there was dynamic emergence of an initiator and follower. This would not have been possible had specific roles been assigned to participants in each trial. Yet, the drawback of our design was the possible risk of an imbalance in how participants would share roles. To account for this risk, we included the role (initiator/follower) in the statistical analyses as an adjustment factor. A within-subject analysis of variance (ANOVA) with the partner (human vs robot) and the role of the participant (initiator vs follower) as factors was used for participants' rating of their contribution to the action-effect, the number of times the movement of the handle changed direction and the average of interaction forces applied to the handle. There were two additional factors for participants' estimation of the interval duration: The presence/absence of an action (baseline vs joint action) and the action-effect delay (700 ms vs 1300 ms). One outlier was removed from the dataset of the analysis of intentional binding, because her time estimations were always beyond two standard deviations from the mean of the group. Post-hoc *t*-tests were conducted using Tukey's procedure (Jaccard, Becker, & Wood, 1984), with an a priori alpha value of 0.05. As a preliminary data check, we computed the percentage of left and right turns in the joint action conditions. We conducted an ANOVA for the percentage of turns with partner, role and side (left vs right) as within-subjects factors. It did not yield any significant effect or interaction: $F(1,24) < 10^{-5}$ $p = 1$ for the partner factor, $F(1,24) < 10^{-5}$ $p = 1$ for the role factor, $F(1,24) = 3.20$ $p = 0.09$ for the side factor, $F(1,24) < 10^{-5}$ $p = 1$ for the partner × role interaction, $F(1,24) = 3.04$ $p = 0.09$ for the partner × side interaction, $F(1,24) = 1.03$ $p = 0.32$ for the role × side interaction and $F(1,24) = 1.61$ $p = 0.22$ for the partner × role × side interaction. So the percentage of right and left turns were considered to be matched across conditions. To evaluate whether participants were able to follow the instruction to balance initiator/follower roles between them and their partner during joint action blocks, we computed the percentage of time they initiated joint action. We then applied a paired *t*-test on those percentages to compare the human partner condition with the robot partner condition.

3. Results

3.1. Role sharing within pairs

The percentage of times participants initiated joint action was 50% ($SD = 20.4$) in the human partner condition and 33.8% ($SD = 13.7$) in the robot partner condition. The difference between the two conditions was significant, $t(24) = 3.96$ $p < 0.001$. To check if the imbalance in the number of initiator trials in the robot partner condition could have influenced the subsequent results, we applied a verification procedure whereby the data was re-analyzed after matching the number of trials across conditions, using random selection, on the individual participant level.

3.2. Judgment of agency and intentional binding

Regarding participants' rating of their contribution, the ANOVA indicated a main effect of the partner, $F(1,24) = 12.76$ $p = 0.002$ $\eta^2 = 0.35$, and of the role, $F(1,24) = 67.37$ $p < 0.001$ $\eta^2 = 0.74$ (see Fig. 2). The participants judged their contribution as

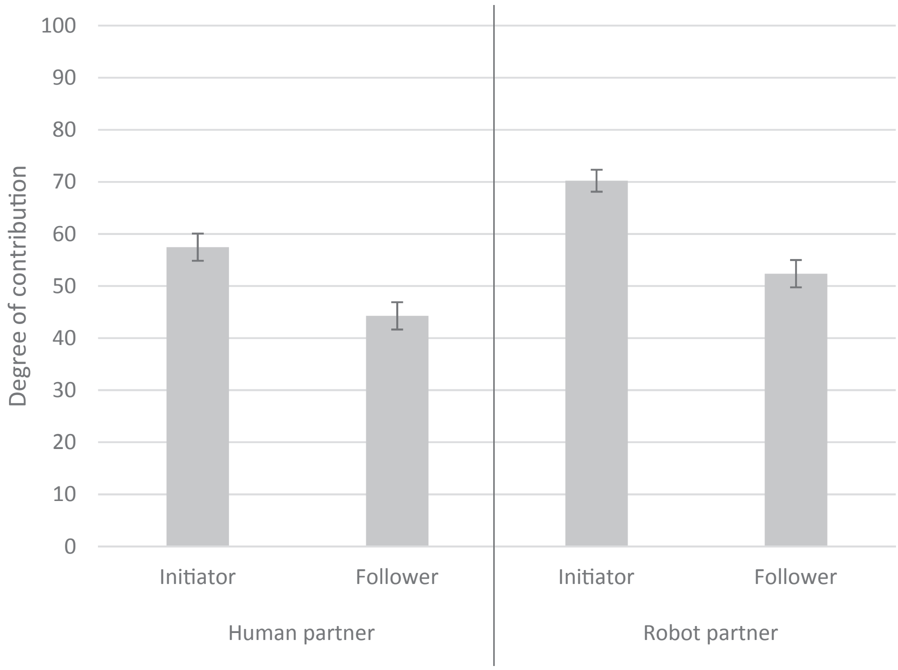


Fig. 2. Judgment of degree of contribution in each condition. Participants rated their contribution as higher when they were partnered with the robot. They also judged that they contributed more when they initiated the action compared to when they followed their partner. Error bars represent the standard error.

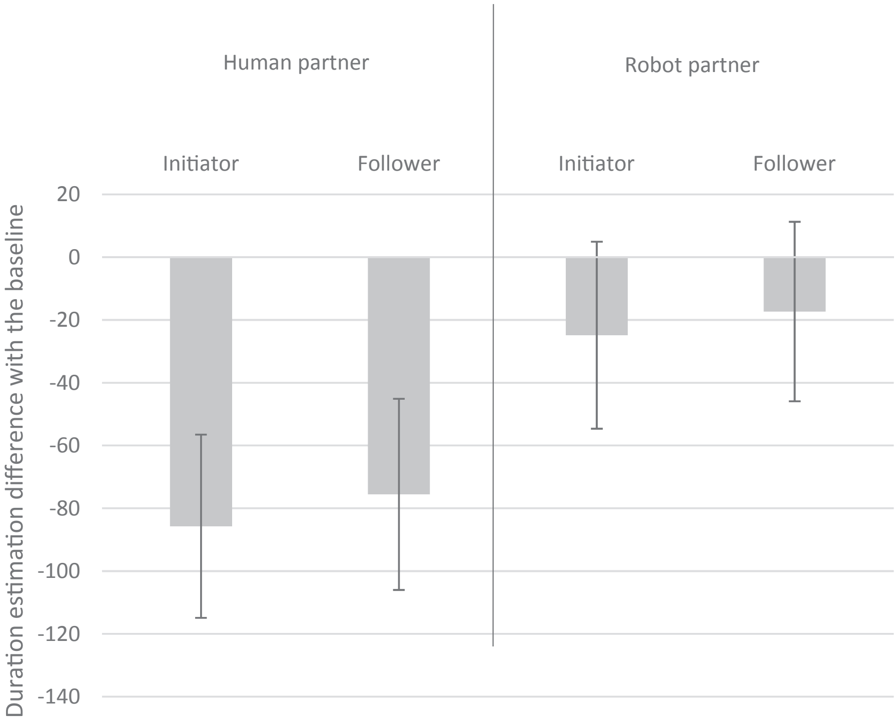


Fig. 3. The difference in interval duration estimation between each condition and the baseline. Interval duration estimations were significantly larger than the baseline only when the partner was human. There were no differences whether the participant was initiator or follower. Error bars represent the standard error.

significantly higher when they were partnered with the robot [*mean* = 61.3 *SD* = 2.0] than with a human being [*mean* = 50.9 *SD* = 2.3]. They also judged they contributed significantly more when they were initiators [*mean* = 63.8 *SD* = 1.9] than followers [*mean* = 48.3 *SD* = 1.8].

The same pattern of results was found when we applied the verification procedure: There was main effect of the partner, $F(1,24) = 6.58$ $p = 0.017$ $\eta^2 = 0.22$, and of the role, $F(1,24) = 8.86$ $p = 0.007$ $\eta^2 = 0.27$.

The intentional binding effect was assessed by analyzing participants' estimation of interval duration. The ANOVA yielded a main effect of the partner factor, $F(1,23) = 8.27$ $p = 0.009$ $\eta^2 = 0.26$, a main effect of the delay factor, $F(1,23) = 241.89$ $p < 0.0001$ $\eta^2 = 0.91$, an interaction between the action and partner factors, $F(1,23) = 8.27$ $p = 0.009$ $\eta^2 = 0.26$, and an interaction between the action and delay factors, $F(1,23) = 105.43$ $p < 0.0001$ $\eta^2 = 0.82$. There was no other main effect or interaction, including for the role factor, $F(1,23) = 0.30$ $p = 0.59$, and the interaction between the action, partner and role factors, $F(1,23) = 0.22$ $p = 0.64$.

The estimations of duration were higher for the 1300 ms delay [*mean* = 1117 *SD* = 113] than for the 700 ms delay [*mean* = 738 *SD* = 71]. Participants estimated the interval duration as longer when they were paired with the robot [*mean* = 943 *SD* = 74] than with another human being [*mean* = 911 *SD* = 82]. Regarding the interaction between the action and partner factors, post-hoc tests showed a significant difference between the joint action condition and the baseline only for the human partner ($p = 0.001$) and not for the robot partner ($p > 0.98$) [human-human joint action: *mean* = 877 *SD* = 127; human-robot joint action: *mean* = 940 *SD* = 101; baseline: *mean* = 946 *SD* = 83] (see Fig. 3). Concerning the interaction between the action and delay factors, post-hoc tests revealed that estimations of duration were significantly lower in the joint action condition compared to the baseline when the delay was 1300 ms ($p < 0.001$) [joint action: *mean* = 1005 *SD* = 137; baseline: *mean* = 1230 *SD* = 134] and that they were significantly higher than the baseline when the delay was 700 ms ($p < 0.001$) [joint action: *mean* = 813 *SD* = 101; baseline: *mean* = 663 *SD* = 98]. Estimations of duration for the 1300 ms delay were nevertheless significantly higher than those for the 700 ms delay even in the joint action condition ($p < 0.001$). In other words, in the joint action condition, estimations of duration for the 700 ms and 1300 ms delays were closer to the middle of the scale while remaining significantly different.

The significant main effects and interactions were the same when applying the verification procedure on estimations of duration: We found a main effect of the partner, $F(1,24) = 5.09$ $p = 0.033$ $\eta^2 = 0.17$, a main effect of delay, $F(1,24) = 227.41$ $p < 0.0001$ $\eta^2 = 0.90$, an interaction between the partner and action factors, $F(1,23) = 5.09$ $p = 0.033$ $\eta^2 = 0.17$, and an interaction between the action and delay factors, $F(1,23) = 112.25$ $p < 0.0001$ $\eta^2 = 0.82$.

3.3. Movement data

The data for the average of interaction forces did not conform to the assumption of normality due to a floor effect, so we applied a

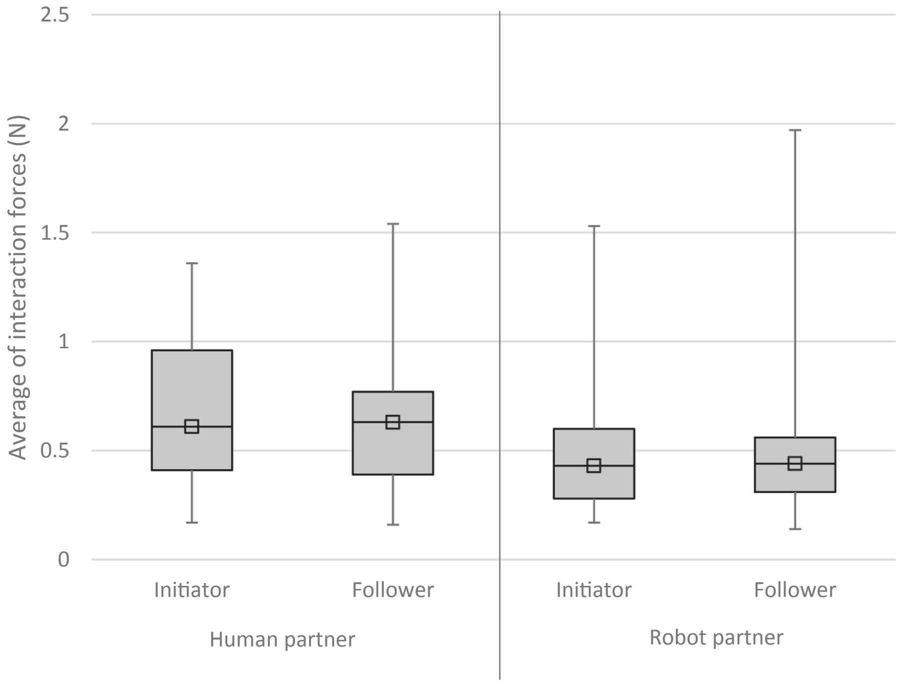


Fig. 4. Average of Interaction Forces applied by the participants. As the data were not normally distributed, boxplots were used to display the medians, the interquartile intervals and range of values in each condition. Participants applied more forces when the partner was human. When initiating action, they also applied more forces.

Box Cox transformation (Sakia, 1992) that yielded a normal distribution. The ANOVA for this variable showed a main effect of the partner, $F(1,24) = 9.51$ $p = 0.005$ $\eta^2 = 0.28$, and a main effect of role, $F(1,24) = 4.68$ $p = 0.04$ $\eta^2 = 0.16$. The average of interaction forces was significantly higher with the human partner [*mean* = 0.66 N *SD* = 0.06 N] than with the robot partner [*mean* = 0.50 N *SD* = 0.07 N]. It was also significantly higher when the participant was the initiator [*mean* = 0.60 N *SD* = 0.05 N] than when she/he was the follower [*mean* = 0.56 N *SD* = 0.06 N]. There was no interaction between the partner and role factors. Fig. 4 shows boxplots of the data.

Once again, we found the same pattern of results when the verification procedure was applied on the average of interaction forces: A main effect of partner, $F(1,24) = 8.33$ $p = 0.008$ $\eta^2 = 0.26$, and a main effect of role, $F(1,24) = 5.56$ $p = 0.027$ $\eta^2 = 0.19$.

For the number of direction changes, we had to remove an outlier whose data was beyond two standard deviations from the mean to conform to the assumption of normality. The ANOVA yielded a main effect of the partner, $F(1,23) = 1231.99$ $p < 0.0001$ $\eta^2 = 0.98$ (Fig. 5). There were significantly more direction changes with the human partner [*mean* = 1.66 SD = 0.05] than with the robot [mean = 0.14 SD = 0.02].

The verification procedure showed the same pattern of results, that is, a main effect of partner for the number of direction changes, $F(1,23) = 187.08$ $p < 0.0001$ $\eta^2 = 0.89$.

Fig. 6 shows exemplar plots of the movement trajectories to provide readers with visual illustrations of the differences between the human-human and human-robot conditions. The plot in the human-human condition was zoomed at the point of time when the pair of participants started to move in a specific direction. This zoom shows how one co-actor initiated the move, waited for the other to catch up, was overtaken by the latter, had to catch up and so forth. Then, they eventually decided to change direction and moved together in the opposite direction from the one they had started with.

4. Discussion

The present experiment showed a dissociation between the explicit agency judgment and the implicit IB measure. Dewey and Knoblich (2014) had previously reported a lack of correlation between these measures, but without specifying what differences there were between the underlying cognitive mechanisms that these measures tapped into. Our experimental design created a contrast between what participants were drawn to believe about their partner and her/his true nature. Except for one participant who was excluded, the change in kinesthetic/tactile reafferences yielded by the robot did not prompt them to revise their belief in the cover story when they were debriefed. Despite being unaware that their partner had changed, participants judged their contribution to the action-effect as higher when they were paired with the robot, while IB occurred only with the human partner and not the robot. This suggests that agency judgments and IB were attuned to the kinesthetic/tactile reafferences rather than to participants' belief, and that they varied in opposite directions. Such an interpretation is in line with the idea that IB is more closely linked to sensorimotor processes than agency judgments that are also influenced by contextual cues and reflective thinking (Synofzik et al., 2008). The

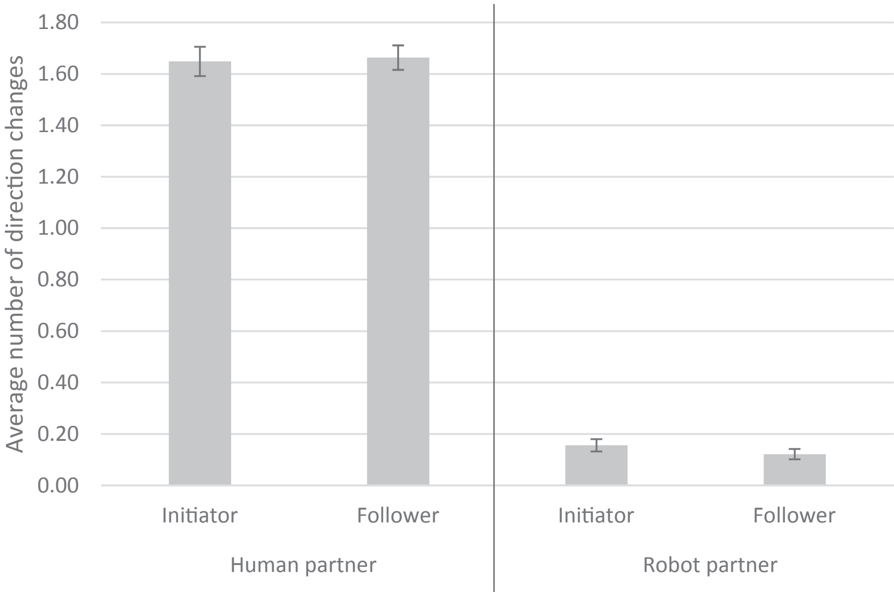


Fig. 5. The average number of direction changes in each condition. Participants changed the direction of movement more often when the partner was human. Error bars represent standard errors.

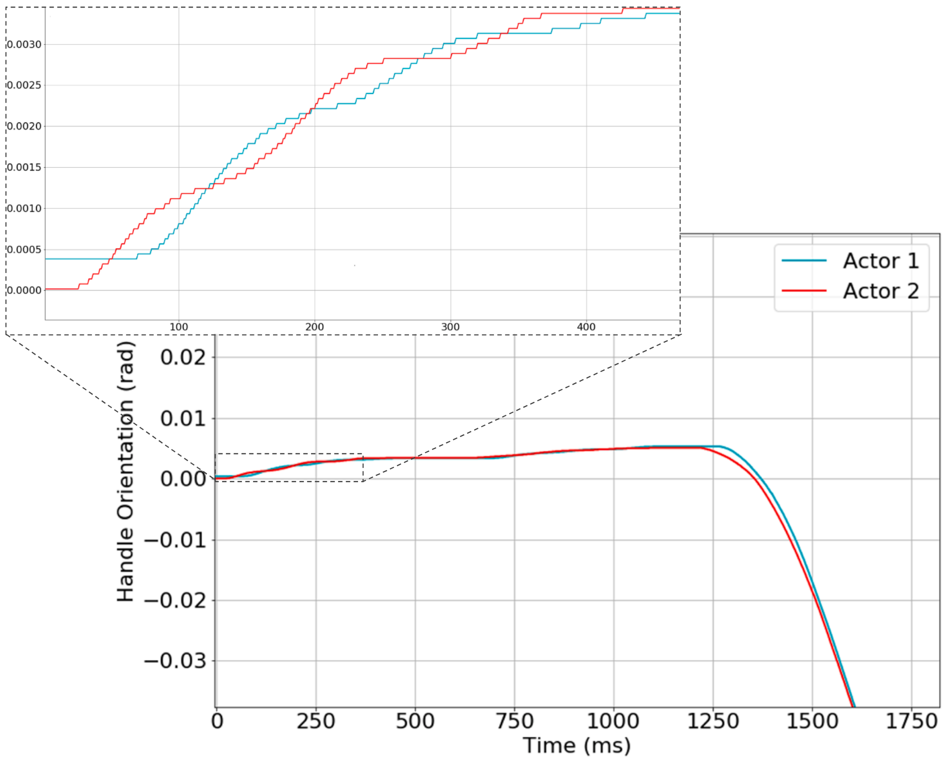
estimation of interval duration used to assess IB was significantly higher for the longer delay than the shorter one, which lends support to participants' compliance with the task. Participants' tendency to rate time intervals differently in the joint action condition compared to the baseline may be explained by the graphical interface of the Likert scale. Indeed, when the Likert scale was displayed on the screen, the cursor was initially placed in the middle of the scale. As the task demands were higher in the joint action condition compared to the baseline, which was similar to the training block, participants may have tended to hesitate more in the joint action condition due to increased workload and not move the cursor as far from its initial position than in the baseline condition. This would explain why ratings were closer to the middle of the scale in the joint action condition. Notwithstanding, the delay was not an effect of interest in the present study and was merely used as an adjustment factor in the analysis.

The lack of IB when participants performed joint actions with the robot brings additional evidence supporting the previous report by Obhi and Hall (2011b). In their study, however, participants did not feel their partner's action and merely received a feedback about who had acted first once the action-effect had occurred. The joint action with a computer was created by a belief manipulation and participants were actually performing an action alone. The approach of Obhi and Hall (2011b) was therefore purely top-down. By contrast, participants in our experiment believed they were acting with another human while in fact it was a robot that controlled the handle. We thus opted for a bottom-up approach where kinesthetic and tactile sensory reafferences were the only source of information about the change of partner. We nevertheless ended up with the same outcome as Obhi and Hall (2011b) that human-machine joint action suppresses IB.

At the explicit level, participants' agency judgment was also higher when they initiated joint action than when they followed it, whereas there was no such difference for IB. This dissociation between agency judgment and IB in joint action had also been pointed out by Obhi and Hall (2011a), although a limitation of their study was that their apparatus could not discriminate who had indeed initiated the action, and thus they could not ascertain that agency judgment reliably identified the initiator and follower. Our study shows that participants had a clear perception of whether they had initiated or followed the joint action and that IB was unaffected by who was the initiator. Hence, the "we-agency" hypothesis that posits a joint sense of agency for the two co-actors is consistent with our results for IB, but not for agency judgement. The "we-agency" construct should thus be regarded as relevant for the implicit level of the sense of agency, but not to the explicit level.

This dissociation between participants' agency judgment and IB brings about new insight regarding the notion of IB. First, our results suggest a weaker link between IB and the sense of agency than commonly reported in individual actions (Haggard, 2005). Indeed, IB decreased with the robot partner, even though participants were still producing action-effects and that their judgment of agency was actually higher than with the human partner. In addition, the initiator/follower roles endorsed by participants had an observable influence on participants' judgment of agency but not on IB. Second, the IB effect occurred only when participants were paired with a human being. Somehow, the underlying neurocognitive processes associated with IB were sensitive to the presence of the robot even though participants did not know about its existence.

Furthermore, when paired with the robot, participants did not display IB even when they initiated action and they initiated action less often. Although they received instructions to do so, participants had difficulties in balancing the initiator role with the robot partner. The nature of the partner thus influenced IB and turn-taking abilities. Although the robot could perform goal directed actions that simulated human movements, it did not have the ability to form an intention based on anything else than a randomly generated command. Neither was it endued with the ability to communicate its intention by using its movements. By contrast, recent research



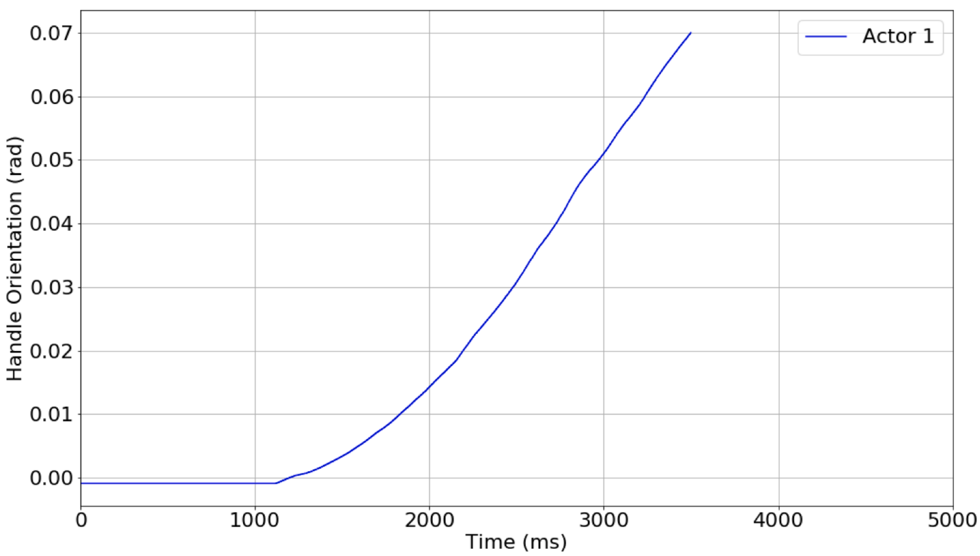


Fig. 6. Trajectories of the handles during a trial where the Y-axis represents the angle orientation. Positive angles are rightward turns. Top: a human-human trial where actor 2 was the initiator. The handles were first turned rightwards and eventually leftwards. The beginning of the joint action was zoomed. This zoom shows how actor 2 started to turn rightward, and then waited for actor 1; actor 1 overtook actor 2, who had to catch up and so forth. Eventually, the two co-actors changed direction and turned leftward together until they reached the stopper. Bottom: a human-robot trial where the human participant was the initiator (as the robot partner controlled the same handle as her/him, only one trajectory was represented). The handle was turned rightwards and did not change direction.

suggests that human being are able to convey information on their intention using body language during joint action (Gaziv, Noy, Liron, & Alon, 2017; Noy, Dekel, & Alon, 2011). We thus tentatively suggest that IB relies on mechanisms that detect intention in action, whether action is self-generated or generated by a partner. Hence, IB appears to be more of a marker of intentionality, as its name suggests, rather than of the sense of agency per se. Following this line of thought, we suggest that a “we-intentionality” hypothesis might be more relevant than the “we-agency” hypothesis.

One could argue that the lack of IB in the robot condition may be due to the lower percentage of initiator trials compared to follower trials. Such an argument is based on the premise that participants would not be agents to the same extent when they were following action than when they were initiating it. However, the initiator/follower roles were attributed a posteriori based on whether participants were the first to reach a force criterion. It did not mean that followers were passive or did not take part in the decision to act. Participants were actually asked to follow their partner when she/he initiated the action, which meant that followers had to actively turn their handle jointly with their partner. As a matter of fact, followers did show the IB effect when they were paired with a human partner. Fig. 6 illustrates this point. It shows a zoom of an example of the trajectories of two co-actors when they started the action. One can see that the initiator began to turn the handle and waited for the follower to catch up. Then, the follower overtook the initiator who had to catch up and so forth until the two co-actors ended up changing direction. This example highlights how the follower could take an active part in the decision process. In addition, we performed a verification procedure to account for the imbalance between initiator and follower roles in the robot partner condition and the outcome of the analyses remained unchanged.

Movement data collected via the handles might shed light on why IB was suppressed when participants interacted with the robot. Interaction forces were higher and participants changed direction more often with the human partner than with the robot. Hence, there seems to have been some kind of standoff or negotiation taking place at the kinesthetic level between human co-actors that disappeared when the partner was a robot. This kinesthetic negotiation between co-actors might be crucial for IB to occur in the context of joint action. It could conceivably be instrumental in forming a joint intention that will enable IB. We tentatively suggest that it could facilitate communication of intention between partners. Incidentally, it could ease turn taking, which would explain why participants were better at balancing the initiator role when paired with a human being than with the robot. More research in robotics is needed to model human–human kinesthetic joint action and the paradigm that we used here offers an adequate way to evaluate those models.

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Declaration of Competing Interest

None.

Appendix

See Table 1.

Table 1
Answers of participants to the questions of the debriefing interview. These answers were transcribed and translated from French into English.

Participant index number	Question 1: Do you have any comment about the experiment?	Question 2: Did you notice a difference between the two blocks where you interacted with your partner?	Question 3: In fact, you were interacting with a human partner in one block and with an automated artificial system in the other. Did you realize that?
1	Sometimes, we often disagreed. One of us started, the other one did not follow and finally we sometimes would run out of time. Well, only two or three times, otherwise it was ok. The white noise was tiring after a while.	No, I did not notice any differences	Not at all, but then, it’s more straightforward because actually in block B [ed: human partner] we disagreed more often than in block A [ed: robot partner], so it’s logical but, no, I did not realized it at all.
2	I do not know. I thought it was always the same time between the small click and the beep. Well, except in some cases when it changed. Otherwise, I believe it was fun.	Yes, maybe a bit, well, I had the impression that I felt more where she wanted to go in block B [ed: human partner]. I had the impression to be able to play more – between quotation marks – with her and know where she wanted to go when it was starting again each time. She was less shy at the beginning and she was going straight to the place.	No, well, no, no, well, I did not wonder, I did not ask myself this question actually.
3	I thought the noise was disturbing.	She was doing more in the second block [ed: human partner].	No

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Table 1 (*continued*)

Participant index number	Question 1: Do you have any comment about the experiment?	Question 2: Did you notice a difference between the two blocks where you interacted with your partner?	Question 3: In fact, you were interacting with a human partner in one block and with an automated artificial system in the other. Did you realize that?
4	No, not really. But then, I still do not understand the purpose of the experiment. But I find it interesting. We want to know; we want to go deeper. Because, after a while, we know what we are doing but we do not know the goal of the experiment. We believe things and then we are waiting for an answer. And then, no, I have nothing to say.	I felt that as we got used, but without really being aware of it, I have the impression, that, we tried to be synchronized to the best. I mean that in block A [ed: human partner] there was really a difference and we tried to think in the same way on the handle's level.	No, not at all.
5	The noise, it's not super nice. It gets tiring to do all those repetitions. That's all.	Yes, well during block A [ed : robot partner] I did not feel her and in block B [ed : human partner] I felt her	No, no
6	Yes, actually, in this part, after we act, there are two choices, that is, estimating the duration between the stopper and the sound and then estimating responsibility. I think that the longer I evaluated the duration to be, the lesser I felt responsibility.	No	I didn't know.
7	Nothing particular	Yes, I felt that there was more emptiness in block A [ed : robot partner] whereas in block B he had a tendency to take the lead and I was following. And in block A, I was taking the lead. I felt that. Otherwise, I felt that he was doing more of the opposite of what I was doing when he was pulling to the left for instance, I tended to pull in the opposite direction.	For the second block, I knew it was my partner. For the first block, as there weren't a lot of conflicts, it's not a big surprise.
8	We lose track of time a bit, especially when time has to be evaluated. I had the impression that when the sound came faster, I would rate each of us as 50/50. I had the impression that when we were more together, the time was shorter. I noticed that I would often move the two gauges similarly. I mean… well… or the opposite, the longer it was, the more I felt he was leading.	I had the impression that on the 1st block [ed : human partner], he was always going to the right and I did not make the same comment to myself about block 2 [ed : robot partner].	No, I did not suspect that at all.
9	Not right now. It's true that it was a bit repetitive. In the beginning, I wasn't sure I understood the instructions and what was expected from me. Then it was ok. The first phase of the experiment was useful to actually understand what was expected in terms of instructions.	I do not know. It's complicated, because in block A [ed : human partner] there was a phase where I wondered if it was really my partner that I felt in terms of coordination of movements or if it was just my own influence. And in block A [ed : human partner], I was more focused and in the second phase of block B [ed : robot partner] I was maybe more confident of the fact that he was the one moving. But, I was maybe a bit more tired, so, all in all, I am not sure that my impression was really relevant.	No. The only thing is that I had the impression that my human partner was allowing me to be in charge more often in block B [ed : robot partner], but I would not have been able to guess if I hadn't been told that it was not him. I did not have a different feeling or a feeling that could have hinted me that it wasn't him.
10	Nothing	No	No
11	Not really. Well, actually, I did not really have the impression of feeling what he was doing on the handle. Sometimes, I felt it clearly and sometimes I had an impression as if his finger was not placed on it.	Yes, in block B [ed: human partner], I had a better sense of what he was doing and also I had the impression that he was taking the initiative more often. In block A [ed: robot partner] I did not feel the same. I felt he was cooperating more. I first felt a force and then it would go in the same direction as me.	No, no idea, not at all.
12	Well, I find that estimating time is difficult. Mainly, this is what I found was not easy to find.	Not really. Sometimes, I felt like she wasn't following me or that I was moving alone in block A [ed: human partner] mostly, a little less in block B [ed: robot partner].	No, no, no.

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Table 1 (*continued*)

Participant index number	Question 1: Do you have any comment about the experiment?	Question 2: Did you notice a difference between the two blocks where you interacted with your partner?	Question 3: In fact, you were interacting with a human partner in one block and with an automated artificial system in the other. Did you realize that?
13	I think that the noise… Well, then, it might just be me, because I rarely listen to music with headphones.	Yes, enormous. Sometimes in block B [ed: robot partner] I felt like there was nothing anymore on the other side. In block A [ed: human partner], I felt that she was very quick. I was sometimes waiting in block B and I had the impression that the movement came after a few seconds but slowly, not at all like during the other block.	I was wondering. It wasn't quick enough for my partner. She was super quick.
14	For the two experiments that lasted more than 20 min, I would say that from the middle onwards my concentration was often less important than at the beginning. I could not concentrate on the two elements, that is, on the duration and whether it was really me who initiated the movement or not. However, when only duration had to be estimated, then I felt more comfortable, for instance.	I thought the feedback or the feeling was less important in block B [ed : human partner], whereas it was quicker in block A [ed : robot partner].	Well, I was puzzled sometimes as the movement was so fast on block A that it wasn't possible to respond so fast. But I wasn't focused on it.
15	No that's it. Difficult to concentrate on the long run. Well, after some time I felt tired. This is why I had the impression of not being as concentrated. That's all.	No, not really. He was maybe hesitating more in the second block [ed: human partner], but I'm not sure. And rarely, but sometimes, he was going against my direction, even though the instructions required to go in the same direction.	No, not at all.
16	The only thing is related to the sound system. Regarding the exercise and the experiment itself, the training is not adequate. I found it harder when we did the combined experiment together than during training. Apart from that, it's ok.	She was less passive in block B [ed: robot partner].	Seriously! I didn't realize at all.
17	I think I noticed something: When we were together and we had to concentrate on following the other or not, I found that the time between arriving at the end and the beep was shorter. It never went very far. Well I think, just that.	The effort that I was applying on the device was greater in the first case [ed: human partner] than in the second [ed: robot partner]. I thought it was freer as if she was always following me. In the second block [ed: robot partner], it was more fluent, there was less resistance.	No, I did not notice.
18	No. Tiredness is annoying. I had the impression that the effect was the opposite of what was expected. If the goal is that we would become more and more synchronous, then the exact opposite happened.	Yes, in the B [ed: robot partner], he was slower.	No, but I felt there was a change in the person in front of me.
19	I had the impression that I was always the one to choose whether the sound was high or low. Even when my partner decided to go toward the high pitch sound, if I decided to go for the low, I went back to the low.	For me, there wasn't really any difference, but I felt that in block B [ed: human partner] we bickered more, whereas in block A [ed: robot partner] it was more monotonous.	No, even if I nevertheless felt a difference between the two.
20	I was less able to focus on the sound. I preferred focusing on the distribution of reactions rather than the sound. Therefore, I was more concentrated on this. Then, I wonder how this will be useful for you.	I thought that in block B [ed : human partner], she tended to take the lead more and move in one shot. In block B [ed : human partner], I felt the sound came later.	No, I don't think I could have guessed who was who.
21	No	Yes, I felt that we were often not parallel. Sometimes in block B [ed: robot partner], we felt that one of us was going on one side while the other was going the other way.	Not at all.
22	Not really. Well, the part with the sound was more complicated. This is the thing where it was the hardest for me to really give the right one.	Yes, in block A [ed: robot partner] I was leading whereas in block B [ed: human partner] my partner was the one leading more.	No, not at all. Well, at the end, I thought it was weird that at the end of block A [ed: robot partner], it was always me leading. I thought she was sleeping or what.

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Table 1 (*continued*)

Participant index number	Question 1: Do you have any comment about the experiment?	Question 2: Did you notice a difference between the two blocks where you interacted with your partner?	Question 3: In fact, you were interacting with a human partner in one block and with an automated artificial system in the other. Did you realize that?
23	It becomes more and more difficult to perceive the time scales. I was thinking about a clock. I imagined the clock hand. Truly, when it happens like that. I think that I didn't estimate as well at the end. Then, regarding the finger, I think that following or generating the movement changes our perception of the noise.	Yes, in block B [ed: human partner], she was quicker, whereas in block A [ed: robot partner] it would take a second before she reacted.	No, I did not suspect that, but it makes sense.
24	During the first part, I was leading. In the second part, I noticed that, even if I didn't put my hand, it moved. Especially in the second part, when I was responding, as soon as I took a little bit of time to adjust, he would take over.	Yes, in block B [ed: human partner] I collaborated better with the person than in block A [ed: robot partner]. In block A [ed: robot partner], I was almost always taking the decision and I think he was just complying.	No.
25	It was mostly when we had our finger on the handle, when we had to reach the stopper, at the beginning, it was not very easy to differentiate whether the other participant or myself was going in one direction or the other. As the experiment continued, it became clearer and clearer that he was pushing in one direction or that I was pushing in one direction. I do not know if this is because he started pushing more rapidly or with more conviction.	Yes, sometimes there were hesitations on who was going to go toward one side or the other. So I had the impression to push harder. Because sometimes when he was pushing harder, I felt that I wasn't the one pushing, so I could figure out if I was going in one direction or if he was. There were even two or three times when I tried to go in one direction and he directly said "no, we're going in the other direction". So that was clear. That was in block B [ed: robot partner].	No, I was just wondering why my partner had changed the way he thought.
26*	I thought maybe the frequency of the sounds influenced me. Because, maybe you wanted to see what influence the frequency had. What I wanted to know was if it was maybe not my partner that was moving but if it was really the machine. Actually, I wanted to know if I was being manipulated. Maybe I'm talking nonsense. I figured you had something planned. I was led to believe that my partner was the one who was doing this. But, actually, no, it was the machine that was doing that. For a while, I thought it often went to the right. I figured it wasn't possible. Always going to the right is necessarily something that is quite embarrassing. I wanted to know if it was the machine that was making the movement or if it was really my partner.	Partner? That's still the question. Was it my partner or was it the machine?	Well, I asked that question to myself after a while.

* Excluded participant.

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