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Cognition 195 (2020) 104117

Contents lists available at ScienceDirect

Cognition

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

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ARTICLE INFO

Keywords:
Joint action
Sense of agency
Motor fluency
Pivotality
Rewards
Skin conductance

ABSTRACT

The sense of agency (SoA) experienced in joint action is an essential subjective dimension of human cooperativeness, but we still know little about the specific factors that contribute to its emergence or alteration. In the present study, dyads of participants were instructed to coordinate their key presses to move a cursor up to a specific target (i.e., to achieve a common goal). We applied random deviations on the cursor's trajectory to manipulate the motor fluency of the joint action, while the agents' motor roles were either balanced (i.e., equivalent) or unbalanced (i.e., one agent contributed more than the other), making the agents more or less pivotal to the joint action. Then, the final outcomes were shared equally, fairly (i.e., reflecting individual motor contributions) or arbitrarily in an all-or-none fashion, between the co-agents. Self and joint SoA were measured through self-reports about feeling of control, that is, using judgment of (felt) control (JoC), and electrodermal activity was recorded during the whole motor task. We observed that self and joint JoC were reduced in the case of low motor fluency, pointing out the importance of sensorimotor cues for both I- and we-modes. Moreover, while self JoC was reduced in the low pivotality condition (i.e., low motor role), joint JoC was significantly enhanced when agents' roles and rewards were symmetrical (i.e. equal). Skin conductance responses to rewards were impacted by the way outcomes were shared between partners (i.e., fairly, equally or arbitrarily) but not by the *individual* gains, which demonstrates the sensitivity of low-level physiological reactions to external signs of fairness. Skin conductance level was also reduced in the fair context, where rewards were shared according to individual motor contributions, relative to the all-or-none context, which could mirror the feeling of effective responsibility and control over actions' outcomes.

1. Introduction

The human species is characterized by its ultra-sociality and many of the most significant human accomplishments result from our ability to engage in cooperative joint actions to achieve a shared goal (Sebanz, Bekkering, & Knoblich, 2006). Any voluntary action is typically associated to a certain sense of agency (SoA), that is, a feeling of control over actions and their consequences (Chambon & Haggard, 2012; Haggard & Tsakiris, 2009; Moore, 2016). Thus, SoA is a crucial part of normal mental life and is what allows societies to hold individuals legally and morally responsible for what they do. The sense of agency in joint action is therefore a central subjective dimension of human sociality and an essential aspect of human cooperativeness. In this context, a legitimate question concerns the possible transformation of agentive awareness and identity, from a sense of individual agency to a sense of joint agency (e.g., Pacherie, 2012; Bolt, Poncelet, Schultz, & Loehr, 2016). Recent experimental work has shown that people do experience a sense of joint agency in motor coordination tasks involving two partners (e.g., Obhi & Hall, 2011; Dewey, Pacherie, & Knoblich, 2014; Bolt et al., 2016). However, relative to individual action, the SoA in joint action has received much less attention and very little is known about the concrete factors that contribute to its emergence or alteration (see Pacherie, 2012, 2014; Bolt & Loehr, 2017). As such, it is still undetermined whether low-level sensorimotor discrepancies in a joint task can alter joint agency in the same way as they alter self-agency (e.g., Metcalfe & Greene, 2007; Metcalfe, Eich, & Miele, 2013; Sidarus, Vuorre, Metcalfe, & Haggard, 2017). It also remains an open question whether signs of symmetry in agents' roles and final outcomes are more likely to give rise to a sense of joint agency, relative to asymmetry in joint action parameters (e.g., Pacherie, 2012, p. 375). For instance, let's

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https://doi.org/10.1016/j.cognition.2019.104117
Received 10 April 2019; Received in revised form 23 October 2019; Accepted 24 October 2019

imagine a piano duet whose shared intention is to produce a particular melody. Even if both pianists' actions are required to generate the musical harmony, is the experience of control over the joint task and outcome comparable in both agents if the individual parts are clearly unbalanced? In a more general context, when two or more agents have to accomplish a collaborative task, one might wonder whether the way the outcome (e.g., the chief's acknowledgement or a monetary bonus) is distributed between the partners can ultimately modulate the sense of joint agency. For example, do co-agents experience a higher SoA in a joint task where rewards are equally shared or are they mostly sensitive to the size of individual benefits? We believe that answering these questions could lead to a better understanding of the concrete factors that either promote or impede engagement in cooperative actions. In the present experimental study, we aimed at clarifying these issues by exploring the impact of the three following components: (1) the motor fluency of the joint action (i.e., by inducing sensorimotor discrepancies in the task), (2) the asymmetry of the partners' roles in the action (i.e., pivotality), and (3) the distribution of monetary outcomes between partners, on both individual and joint agency self-reports. In addition, we explored the potential influence induced by different social contexts and different levels of agency on a more implicit measure than SoA self-reports. More precisely, we focused on how the distribution of monetary rewards – which were either equally split, or proportional to the agent's contribution (i.e., fair and controllable outcomes), or randomly allocated to one of the two co-agents (i.e., unfair and uncontrollable outcomes) – could impact physiological responses such as skin conductance.

In individual action, SoA has been proposed to reflect two complementary processes: motor prediction and cognitive reconstruction (Moore & Haggard, 2008). The motor prediction view is inspired by computational theories of motor control. According to these theories, when the motor system generates a motor command, an efference copy of this command is sent to forward models whose role is to generate predictions about its sensory consequences in advance of actual execution. Error signals arising from the comparison of desired, predicted, and actual states (as estimated from sensory reafferences) are used to make corrections and adjustments. The motor prediction view holds that the signals used for motor control also provide cues to agency. In particular, it holds that the SoA is a function of the degree of congruence between predicted consequences and sensory reafferences (i.e., information about the actual state of the motor system) (Frith, Blakemore, & Wolpert, 2000). On the other hand, the cognitive reconstruction view postulates that SoA is inferred retrospectively rather than predictively, from the existence of a match between a prior thought or intention and an observed action outcome (e.g., Wegner & Wheatley, 1999; Wegner, Sparrow, & Winerman, 2004; Aarts, Custers, & Wegner, 2005; Chambon & Haggard et al., 2013). Thus, in the motor prediction view, endogenous sensorimotor processes are supposed to be the key to generate SoA, while in the cognitive reconstruction view, the emphasis is placed on general-purpose causal inference processes and on information external to the motor system, such as situational and social stimuli (see Moore, 2016; Wegner & Sparrow, 2004). More recently, SoA has been proposed to result from the weighted integration of both internal motoric and external situational cues, according to a Bayesian perspective where prior beliefs contribute to and shape the emergent SoA (see Moore & Fletcher, 2012; Haggard & Chambon, 2012; Chambon, Sidarus, & Haggard, 2014; Pacherie, 2012). Due to intrinsic differences between individual and joint actions, one might propose that internal and external cues would not necessarily be involved in the same way in self SoA and joint SoA. Indeed, even if previous findings have shown that internal cues to agency have a higher weighting than external cues in individual action (see Moore, Wegner, & Haggard, 2009), perceptual aspects of joint action are necessarily crucial due to the external dimension of partner's actions, whose sensorimotor states are not directly available (Pacherie, 2012). Therefore, in addition to self motor prediction, external situational cues are thought to be critical to SoA judgments in joint action.

In the present study, we used a novel and naturalistic computer task where dyads of participants were instructed to coordinate their actions online to move a cursor up to a specific target. While one partner was in charge of the horizontal direction, the other was able to direct the cursor in the vertical direction (see Dewey et al., 2014; van der Wel, Sebanz, & Knoblich, 2015), making the dyad's coordination absolutely necessary to perform the task and ultimately earn monetary rewards. The effects of their key presses were continuous, immediate and added to each other. Importantly, some random deviations were introduced in the cursor's trajectory to make the joint action more or less *fluent*. In some trials, the horizontal and vertical distances between the cursor and the target were unbalanced, in order to make one partner more or less *pivotal* than the other to the joint action: pivotality was thus defined *relatively* to the co-agent's role and contribution. After the cooperative actions, the distribution of individual monetary rewards was visible by both agents and was either fair (i.e., reflecting the individual motor contributions of each agent), equal (i.e., same gain for both agents), or all-or-none (i.e., one of the agents earned the entire gain while the other earned nothing). One advantage of the present task was that it reflected more naturalistic actions than previous experiments, since joint actions systematically required planning in order to sequence the entire action in several sub-actions (i.e., multiple key presses) that triggered immediate proximal effects (i.e., the cursor's moves after each key press) and delayed distal effects (i.e., the reached target and the monetary outcomes; see Metcalfe & Greene, 2007; Pacherie, 2008). After each action, participants had to evaluate how much they felt "individually" and how much they felt "together" (i.e., as a team) in control of the cursor's movements, without communicating with each other. In such a cooperative and complementary motor task (see Dewey et al., 2014), we expected co-agents to experience *shared agency* (see Pacherie, 2012; Bolt et al., 2016), meaning that they should experience a sense of *joint agency,* along with an intact sense of *self-agency*. We used self-reports about feeling of control as explicit metacognitive assessments for both individual and joint SoA. Please note that any judgment of agency (JoA) refers to the conceptual, interpretative judgment of being an agent, while feeling of agency (FoA) is the non-conceptual and low-level feeling of being an agent (see Synofzik, Vosgerau, & Newen, 2008). Thus, our measures of agency actually relied on explicit judgments of control (JoC). Note, though, that we asked our participants to report how much control they had felt rather than how much control they *thought* they had had. Then, we explored how some essential components of joint action, namely motor fluency, pivotality and rewards' distribution, could influence both the egocentric "I-mode" – where individual actions are represented independently from the other's actions – and the "we-mode" – where individual actions are represented as contributions to the team's overall action – within a joint action (see Tuomela, 2006; Tsai, Sebanz, & Knoblich, 2011; Gallotti & Frith, 2013; Dewey et al., 2014; van der Wel et al., 2015).

Firstly, we expected motor fluency to impact both individual and joint SoA, in the sense that high random deviations in the cursor's trajectory should reduce the sense of control (JoC) over the action (Metcalfe & Greene, 2007; Metcalfe et al., 2013; Sidarus et al., 2017). Indeed, random turbulences dynamically disrupt the action at the sensorimotor level (i.e., predictive component) which is fundamental to the basic feeling of motor control. This impact of motor fluency should be particularly substantial in individual JoC since it is supposed to rely heavily on internal motoric cues (Chambon, Moore, & Haggard, 2015; Chambon, Wenke, Fleming, Prinz, & Haggard, 2013; Moore et al., 2009). However, if joint SoA relies more on perceptual cues, this effect should be reduced in collective JoC.

Secondly, we expected the roles' asymmetry between co-agents (i.e., pivotality factor) to differently influence individual and joint JoC. On the one hand, if individual JoC is egocentric and depends on the degree of match between the predicted consequences of one's motor commands and the perceived action effects (Dewey et al., 2014), low pivotality to the joint action should reduce the individual JoC compared to high pivotality, due to the parallel diminution of individual motor contribution. Indeed, it has been proposed and shown that an increased physical effort could enhance the sense of self-agency since it is an essential phenomenological aspect of action control (Demanet, Muhle-Karbe, Lynn, Blotenberg, & Brass, 2013; Minohara et al., 2016; Pacherie, 2008). On the other hand, counter to what was observed for self-agency, it has been shown that agents' roles asymmetry within a cooperative action did not impact joint agency if it based on a "we-mode" whereby people's sense of control reflects the combined contributions of both partners rather than their own individual contributions (see Pacherie, 2013; van der Wel et al., 2015; Bolt et al., 2016). Thus, similarly to what was observed in leader-follower situations (van der Wel et al., 2015), joint JoC should not differ significantly between low pivotality and high pivotality. However, the aforementioned studies only focused on dichotomous dominant-dominated roles (e.g., leader-follower) without any comparison to more balanced roles. As suggested by Pacherie (2012), we further hypothesized that more balanced and egalitarian roles (i.e., equivalent pivotality) would enhance joint JoC relative to asymmetric roles (i.e., low and high pivotality).

Thirdly, in line with the results of the few studies that have investigated the postdictive effects of rewards or outcomes on individual sense of agency (Di Costa, Théro, Chambon, & Haggard, 2018; Yoshie & Haggard, 2013; Takahata et al., 2012) we expected that individual gains would retrospectively bias both individual and joint JoC even if no data are currently available concerning the effect of rewards on joint JoC. Following the I- and we- mode logics, we reasoned that individual SoA should be linked to the agent's individual interests, being enhanced when the gains are maximal and being reduced when the gains are minimal. This would reflect the fact that individual actions' outcomes are also represented independently from the co-agent's outcomes. Conversely, we expected that joint SoA would be particularly biased by the way monetary rewards were *distributed* between partners, with an enhanced joint SoA in cases of equal gains, relative to situations of unequal gains (i.e., in fair and arbitrary gains' distribution). Indeed, while contexts of unequal gains should promote an individualistic processing of joint action-related cues, situations of equal gains should reduce such biases in favor of a more holistic representation, combining both egocentric and allocentric cues. This hypothesis is also in line with the idea that egalitarian joint actions are more likely to give rise to a sense of joint agency in comparison to hierarchically or asymmetrically structured actions (see Pacherie, 2012, pp 375–376).

Beside exploring the influence of some important internal (sensorimotor) and extrinsic (rewards) factors on both self and joint JoC, we also investigated physiological reactions (i.e., skin conductance) to outcomes' distribution between partners. Skin conductance can basically be subdivided into two components: a phasic component referring to short-lasting changes in electrodermal activity, which can be either spontaneous or related to a particular event, such as event-related skin conductance responses (SCRs), and a tonic component which could refer to the skin conductance level (SCL) during a longer period and in the absence of phasic SCRs (see Boucsein et al., 2012). Some studies have suggested that both components rely on different neural processes thus providing complementary information about sympathetic nervous system arousal (Dawson, Schell, & Filion, 1990; Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004). SCR has been proposed to reflect electrodermal concomitants that appear during stimulation and information processing and is particularly sensitive to habituation, while SCL is used as an indicator of changes in more general psychophysiological states (e.g., states of stress or emotion), due to sympathetic nervous system arousal (Boucsein, 2012). Monetary gains and losses have been shown to globally modulate both SCRs (e.g., Delgado, Gillis, & Phelps, 2008) and SCL (Crone, Somsen, Beek, & Van Der Molen, 2004; Gomez & McLaren, 1997) in normal individuals. In social situations of games (e.g., ultimatum game), some authors (see Civai, Corradi-Dell'Acqua, Gamer, & Rumiati, 2010; Civai, 2013; Srivastava, Espinoza, & Fedorikhin, 2009) demonstrated that SCRs were enhanced whenever one's own interest was at stake. However, no previous study has explored the implicit reactions to rewards' distribution after a motor task requiring a real motor cooperation between two partners. In such a collaborative context, are the agents more sensitive to their individual interests or to the way outcomes were shared between the co-agents? To answer this question, we measured both SCRs to rewards and SCL within the contextualized blocks, where individual gains could be either linked to individual motor contributions (fair context), or equally (equality context) or arbitrarily (all-or-none context) distributed across partners. If participants are reactive to this particular collaborative situation, then we should find a main effect of the way outcomes were shared between co-agents while the correlation between the individual monetary gains and the SCR amplitudes should be low or absent. We also expected SCRs to be particularly reduced in the equality context since the gains were constant and could lead to habituation (i.e., half of the total reward) compared to fair and all-or-none rewards. Because SCR amplitude has been shown to be invariant with respect to motor effort measured in terms of number of key presses (e.g., Carriero, 1975; Kohlisch & Schaefer, 1996), we did not expect any particular effect of fluency and pivotality factors. Regarding the tonic component of skin conductance, we hypothesized that SCL would be higher in blocks of arbitrary all-or-none gains relative to blocks of fair and equal gains because of stress enhancement caused by a context perceived as unfair (Salvia, Guillot, & Collet, 2012; Shapiro, Rylant, de Lima, Vidaurri, & van de Werfhorst, 2017; Van't Wout, Kahn, Sanfey, & Aleman, 2006). More specifically, we expected this difference to be particularly salient between all-or-none (unfair) and fair rewards contexts. Indeed, we believe that the context of fair rewards provides an adequate way to generate an implicit feeling of responsibility and control over the joint action's outcomes since individual gains were the exact transcription of the individual motor contributions of the co-agents, in contrast to contexts of equal and all-or-none rewards where final gains were out of control. Thus, it is possible that the feeling of control induced by fair rewards would lead to a reduction of SCL, as it has been observed in experiments where participants believed they could exert control on the duration of aversive stimuli (e.g., Geer & Maisel, 1972; Glass, Singer, Krantz, Cohen, & Cummings, 1973; Staub, Tursky, & Schwartz, 1971).

2. Method

2.1. Participants

Based on the standardized effect size of the fluency factor (η_p^2 = 0.19) that was obtained during pilot studies, we determined N > 30 in order to ensure a satisfying statistical power ([1 – β] > 95%) and a good replicability rate. Then, we recruited 44 adults (24 females; mean age = 23.75, SD = 3.38) to constitute 22 same-gender dyads (12 pairs of females, 10 pairs of males) where age difference between teammates was controlled to be as low as possible (mean age difference in dyads = 3.05, SD = 3.19). We ensured that teammates did not know each other before the experimental session and they were not allowed to speak and communicate until the end of the experiment. They were all right-handed, neurologically healthy individuals, with normal or corrected-to-normal vision. Participants provided written informed consent and were compensated with money according to their overall performances (i.e., from 15 euros to 20 euros).

The 44 participants were included in the behavioral analysis. Nevertheless, we had to remove 9 datasets from the physiological analysis given that 3 participants did not demonstrate any visible skin conductance response to stimuli, 2 participants unintentionally disconnected their finger electrodes in the middle of the recording, 2 participants demonstrated a flat signal at several time points due to an apparent bad connection between the electrodes and the amplifier, and one team (i.e., 2 participants) had no EDA recording during the first block due to an experimental blunder. Thus, 35 participants remained in the final physiological analysis (20 females; mean age = 23.64, SD = 3.25). This study was performed in accordance with the declaration of Helsinki and the Comité de Protection des Personnes (CPP) Ile de France II granted ethical approval.

2.2. Material

Both partners sat next to each other at a table, with an approximate distance of 50 cm between them. They both wore headphones playing white noise and were separated by a divider fixed in the middle of the table, thus preventing them from speaking together and from seeing what the other was doing during the task. The participant who was located on the left of the divider was referred to as the "player1" while the participant located on the right was labeled as "player2" during the entire task. Two identical LCD 19'' monitors (1280 × 1024 at 60 Hz), one on either side of the divider, displayed the exact same duplicated image at a viewing distance of approximately 60 cm from each partner. Partners also had their own keyboard to complete the task and to respond to the questions with the right hand, without being seen by the other player. We positioned stickers representing arrows (i.e., up, down, left or right) on the relevant keys to facilitate their identification. We used Matlab R2016b and the Psychophysics Toolbox Version 3 (PTB-3) (Brainard & Vision, 1997; Pelli, 1997; Kleiner et al., 2007) to write and run the joint task.

While they were performing the main task, electrodermal activity was recorded from the left hand of both partners. More precisely, GSR finger electrodes (ADInstruments, New Zealand) were positioned on their left index and middle fingers. Data were digitized at 1000 Hz and collected using PowerLab amplifiers and the LabChart7 software (ADInstruments, New Zealand).

2.3. The joint task

In this joint motor task, communication between partners was not allowed. Participants were instructed to coordinate their actions in order to move a cursor from the center of the screen up to a specific square (i.e., the target), before the end of the timer countdown (Fig. 1). One of the two partners could only move the cursor in the vertical direction while the other partner could only move it in the horizontal direction. They were told that the computer could generate some random deviations in the trajectory of the cursor, making the trials more or less difficult to achieve. Participants knew that each successful trial would bring one point to the team but that this point could be differently allocated between both partners. They were also aware that the points they got would be converted into money at the end of the experiment. Nevertheless, they did not know that the experiment was designed to make sure that both partners would ultimately earn the same amount of points. At the end of each trial, partners were invited to independently rate their "individual feeling of control" and their "joint feeling of control" concerning the cursor's movement.

2.4. Procedure & stimuli

2.4.1. Training phase

The experiment began with a short training session aimed at familiarizing the participants with the task. It consisted in one block of 20 trials where the general instruction was to reach the square containing the highest number (e.g., "3") – similarly to the main task – by moving the cursor with key presses. This training session was very similar to the joint task except that participants performed this training session alone, each in turn. Thus, in contrast to the main task, participants were able to move the cursor on both vertical and horizontal axes, that is, left and right (with K and L keys) and up and down (with Q and W keys). Moreover, there was no random deviation applied on the cursor trajectory, and the four peripheral squares – including the potential target – were always located at the same place, respecting an equal distance between the screen center and the target on both X and Y axes (OT_x = 12.5 cm ; OT_y = 12.5 cm).

2.4.2. Experimental phase

The individual training phase was immediately followed by the joint task that was made up of 192 trials divided into 6 blocks. Before each block, participants were instructed to stay calm and to relax during a 2-minute period in order to record electrodermal baselines. Then, the instructions' screen was displayed during 5 s and informed players about which buttons to press – which axis to control – during the forthcoming block. The axis to be controlled was reversed after each block (e.g., if player1 was responsible for X-axis in the 1st block, she became responsible for Y-axis in the 2nd block etc.) so that partners equally controlled both directions overall (i.e., vertical control during 3 blocks and horizontal control during 3 blocks). While the levels of fluency and pivotality factors were mixed within the blocks, levels of rewards' distribution were blocked in order to generate contexts of fairness, equality and unfairness. Thus, the 6 experimental blocks were composed of 2 blocks of equal rewards, 2 blocks of fair rewards and 2 blocks of arbitrary all-or-none rewards. The order of the blocks was randomly generated. Each block consisted of 30 regular trials and 2 catch trials: 1 catch trial without any deviation in the cursor's trajectory (as in the training phase) and 1 catch trial with very high deviations in the cursor's trajectory, making the achievement of those catch trials respectively very easy or impossible. The main purpose of catch trials was to break the monotony of the task. By largely changing the magnitude of random deviations in catch trials, relative to regular trials, we intended to induce a feeling of more distributed random noise in participants.

At the beginning of each trial, a square colored with a random mixture of grey shades appeared at the center of the screen while 4 peripheral uniform grey squares (sides = 90px*0.294 mm = 2.65 cm) were arranged symmetrically along both X and Y axes originating from the screen center (see Fig. 1). After a 2-second delay, the white cursor (diameter = 15px*0.294 mm = 4.41 mm) appeared in the center of the screen, within the central square. The 7-second countdown appeared on the top of the screen and began simultaneously to the cursor's onset. The square to reach (i.e., the target) was the peripheral square containing the larger number (i.e., from 2 to 5) in comparison with the 3 remaining peripheral squares (i.e., the distractors) that all contained the number "1". In each team, one participant was able to move the cursor vertically (i.e., along the X-axis) using K (left) and L (right) keys of an AZERTY keyboard, while the other teammate was able to move the cursor horizontally (i.e., along the Y-axis) using Q (up) and W (down) keys. Thus, motor coordination between both agents was absolutely crucial to successfully move the cursor from the center of the screen to the target. Each key press triggered a 6px (i.e., 0.18 cm) move of the cursor on the axis that was controlled by the player (e.g., "K" press moves the cursor 6px to the left) and also moved the cursor by 1 to 4.5 px on the other axis (i.e., controlled by the other player) according to the "fluency condition", in order to generate some noise in the expected trajectory of the cursor. The same amount of deviation was applied for both players' key presses. The effects of the key presses were continuous, immediate and added to each other. Thus, the actual cursor's moves resulted from the vector combination of both – more or less – deviated trajectories produced by the players' key presses.

If the correct square (i.e., the target) was reached before the end of

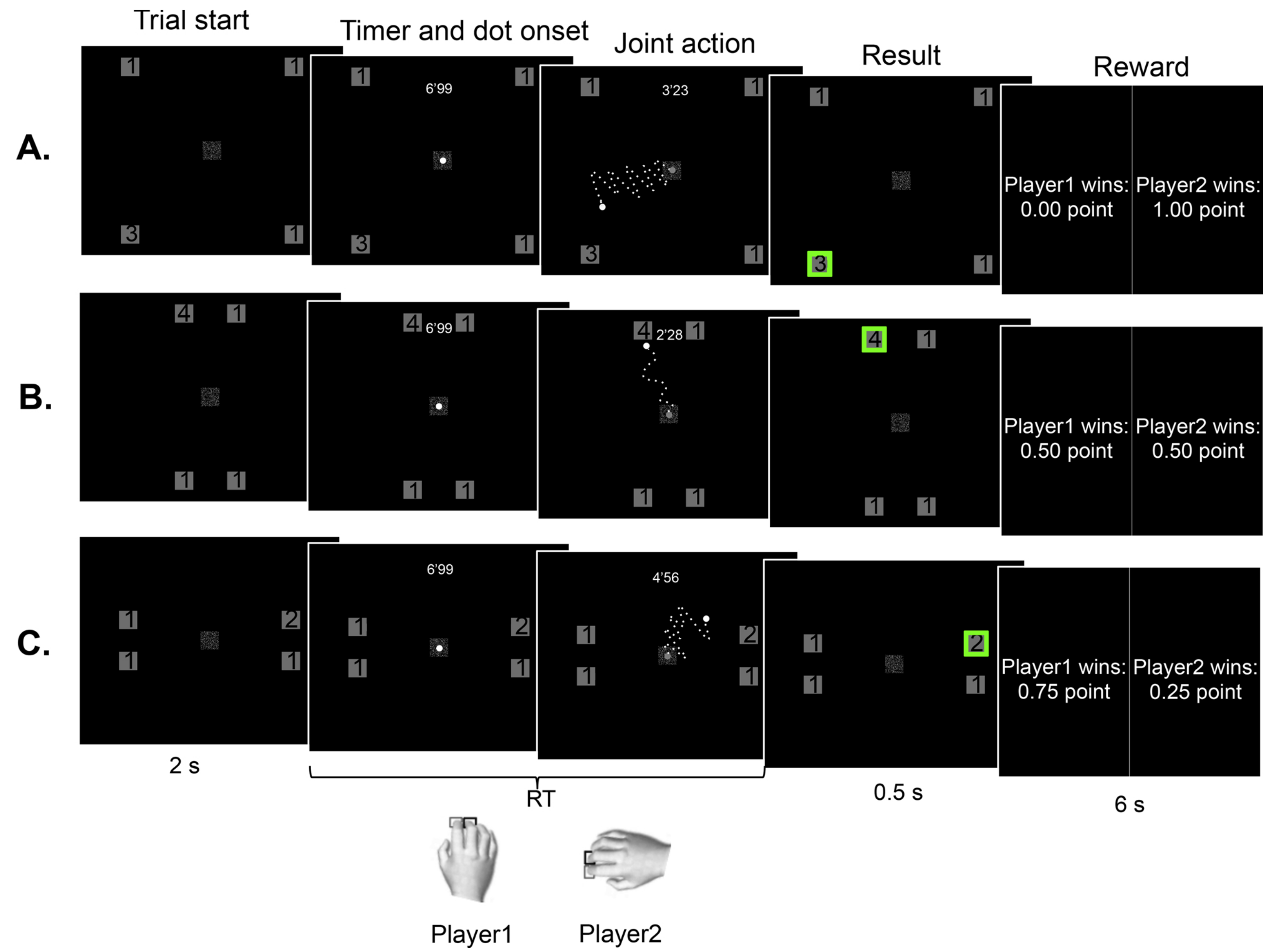

Fig. 1. Schematic representation of the joint task procedure and stimuli. Three example trials combining the fluency, pivotality and reward factors where player1 is controlling the horizontal axis and player2 is controlling the vertical axis. In example (A), pivotality is equivalent for both players, motor fluency is low (important cursor deviations) and monetary reward is randomly distributed in an all-or-none fashion. In example (B), pivotality is reduced for the player1 and is relatively enhanced for the player2, motor fluency is high (low cursor deviations) and monetary reward is equally shared between players. In example (C), pivotality is reduced for player2 and is relatively enhanced for player1, motor fluency is low (high cursor deviations) and monetary reward is fairly distributed between players (according to individual motor contributions to the joint action). Please note that pivotality, fluency, rewards' distribution and axis control factors were fully crossed.

the countdown, the cursor disappeared and the target was framed in green during 500 ms, meaning that the trial was successful. On the contrary, if a wrong square (i.e., a distractor) was reached, the cursor disappeared and the distractor was framed in red during 500 ms. If the countdown ended before the target was reached, the cursor disappeared but the squares remained on the screen during 500 ms. In those two last situations, the trial was counted as failed.

Fluency factor. To manipulate the basic *feeling of control* (i.e., JoC) of participants, random deviations were applied to the trajectory of the cursor in order to decrease the JoC when the deviations were important (i.e., from 3.5 px to 4.5 px in 50% of trials) compared to when they were low (i.e., from 1 px to 2 px in 50% of trials). These deviations could be positive (50% of trials) or negative (50% of trials), meaning that they could be congruent (e.g., target on the right, deviation on the right) or incongruent with the actual direction to the target.

Pivotality factor. The perceived motor contribution was also manipulated by creating some conditions where the vertical and horizontal distances between the initial position of the cursor (i.e., O) and the target (i.e., T) were clearly unbalanced (see Fig. 1.B & Fig. 1.C). This was done in order to make one player perceptibly more *pivotal* to the joint action than the other. Thus, in 1/3 of trials, the perceived motor contribution was equivalent for both partners (i.e., OT_x = 12.5 cm; OT_y = 12.5 cm; see fig1.A); in 1/3 of trials, the distance between the center and the target was reduced on X-axis (OT_x = 3.5 cm; OT_y = 12.5 cm; see fig1.B) so that the player who was responsible for the Y-axis was more pivotal than the other player; and in the last 1/3 of trials, the distance was reduced on Y-axis (OT_x = 12.5 cm; OT_y = 3.5 cm; ; see fig1.C) so that the player who was responsible for the X-axis was more pivotal than the other.

Reward factor. Each succeeded trial was rewarded by 1 point that was distributed in different ways between both partners. Indeed, in 1/3 of trials, the reward was *equally* shared between both agents so that they both earned 0.5 point (see Fig. 1.B). In 1/3 of trials the reward was *fairly* shared between both partners (see Fig. 1.C), meaning that the ratio of point they earned corresponded to their individual motor contribution to the joint action (e.g., if player1 and player2 respectively contributed 60% and 40% to the joint action – as measured by their respective number of key presses –, then player1 earned 0.6 point and player2 earned 0.4 point). In the remaining 1/3 of trials, the reward was *randomly* and *entirely* distributed to only one of the partners (see Fig. 1.A), meaning that the other partner earned nothing (e.g., player1 earned 0 points and player2 earned 1 point). The gains – including 0 when the trials were failed – were displayed on the screens during 6 s at the end of each trial. Participants could see how much they themselves and their partners individually earned after each trial so that they could subjectively appreciate how the gains were distributed between both players (i.e., equally or not), without knowing the experimental parameters underpinning this distribution (e.g., whether it was random or linked to motor contribution, etc.). To emphasize these contexts of fairness, equality or unfairness, each block was linked to one kind of reward.

Self-reports of Feeling of Control. At the end of each trial, participants were asked two questions concerning their JoC. One question evaluated their individual JoC and was formulated in the following way: “How much did you feel *individually* in control of the cursor’s movement?”. The other question evaluated their joint JoC and could be translated as: “How much did you feel *together* in control of the cursor’s movement?”. These questions were asked in French and the difference between the individual and the collective JoC was emphasized by using the different personal pronouns “tu” (second-person singular) and “vous” (second-person plural). The order of these two questions was randomized so that each question was presented an equal number of times as the first or the second question. Participants were instructed to answer both questions, one after the other, by using a 9-point scale where “1” meant that they did not feel in control at all, and “9” meant that they felt totally in control. Time to answer was not limited. The next trial started once both players had answered both questions.

2.5. Data analysis

2.5.1. Behavioral data

Behavioral data were analyzed from regular (i.e., catch trials were excluded from the analysis) and successful trials only. We analyzed the main effects and interactions of the three factors *fluency*, *pivotality* and *rewards* on individual JoC on the one hand and on joint JoC on the other hand. We used R (R Core Team, 2018) and lme4 (Bates, Maechler, & Bolker, 2012) to perform linear mixed effects analyses. As fixed effects, we entered fluency, pivotality and rewards’ distribution into the model (without the triple interaction term that was not of prime interest). As random effects, we entered random intercepts as well as random slopes for all fixed effects that vary within the levels of the players nested in teams. Degrees of freedom and p-values were approximated from the calculated likelihood ratio tests by using the Satterthwaite’s method (see Kuznetsova, Brockhoff, & Christensen, 2017; Luke, 2017). P-values from post-hoc t-tests were Bonferroni corrected regarding the number of performed comparisons.

2.5.2. Physiological data

Physiological data were also analyzed from regular and successful trials. Preprocessing was performed with Ledalab software v.3.4.9 and custom-built scripts running on Matlab. Data were first down-sampled to 100 Hz and artifacts were removed in a semi-automatic manner involving visual inspection. Then, we performed a Continuous Decomposition Analysis (CDA) based on standard deconvolution to split skin conductance (SC) data into its tonic and phasic components (see Benedek & Kaernbach, 2010). Concerning the phasic component of skin conductance, we focused on event-related responses (SCRs) by calculating the amplitudes’ sum of significant SCRs (reconvolved from corresponding phasic driver –peaks) from 1 to 5 s after the rewards’ distribution onset (see recommendations from Boucsein, 2012; Boucsein et al., 2012). Concerning the tonic component of skin conductance, we focused on mean magnitude within each block (SCL), after the identification and suppression of specific and non-specific SCRs (based on the CDA). Each block was characterized by a specific kind of rewards’ distribution (i.e., equally, fairly, randomly distributed). Moreover, individual SCRs amplitudes and individual SCL were transformed into within-subjects Z-scores, at each point of time (i.e., every 10 ms) of the skin conductance recording (e.g., Mori & Iwanaga; 2017), in order to reduce between-subjects variability and normalize the data. P-values from post-hoc t-tests were Bonferroni corrected regarding the number of performed comparisons.

3. Results

The dataset underlying the current results can be found at Le Bars et al. (2019).

3.1. Behavioral data

3.1.1. Preliminary analysis

Performances in the joint task were close to ceiling (Mean = 95.36, SD = 7.73) but were significantly lower [$F(1, 40) = 6.24$, $p = 0.0167$, $\eta_p^2 = 0.14$] when there were high deviations (Mean = 91.54, SD = 9.29, 95% CI [96.2, 100]), relative to low deviations (Mean = 99.36, SD = 2.37, 95% CI [85.5, 94.5]), in the cursor’s trajectory.

As expected, the correlation between individual and joint JoC ratings was positive and high [$R = 0.51$, 95% CI [0.49, 0.53], $t(6040) = 46.5$, $p < 0.0001$, $R^2 = 0.26$], meaning that subjective judgments of control assessed by both questions partly relied on the same information conveyed by the task. Moreover, after having computed the individual motor contributions by dividing the number and timing of each player’s key presses by the total amount and timing of key presses performed by both players, we confirmed that the pivotality factor triggered significant differences in players’ real motor contribution (or effort) to the joint action [$F(2, 126) = 9.81$, $p = 0.00011$, $\eta_p^2 = 0.14$]. Indeed, when one of the partners was more pivotal than the other, her motor effort ratio was logically significantly higher [Mean effort ratio = 0.59, SD = 0.029, 95% CI [0.53, 0.59]; $t(126) = 4.43$, $p < 0.001$, $d = 3.12$] than mean motor effort ratio in low pivotality condition [Mean effort ratio = 0.41, SD = 0.076, 95% CI [0.40, 0.47]] and mean motor effort ratio in equivalent pivotality condition [Mean effort ratio = 0.50, SD = 0.041, 95% CI [0.47, 0.53]; $t(126) = 2.32$, $p = 0.027$, $d = 2.53$].

Correlations between individual JoC ratings and individual values of rewards [$R = 0.13$, 95% CI [0.10, 0.16], $t(6040) = 10.27$, $p < 0.0001$, $R^2 = 0.017$] on the one hand, and between joint JoC ratings and individual values of rewards [$R = 0.096$, 95% CI [0.06, 0.12], $t(6040) = 7.48$, $p < 0.0001$, $R^2 = 0.009$] on the other hand, were positive and significant, but low. Thus, participants’ responses to both questions were weakly linked to rewards’ values.

3.1.2. Individual JoC

The individual JoC was assessed by asking participants to rate their “personal” feeling of control about the cursor’s movements on a 9-point scale after each trial. As expected, analysis of individual JoC scores revealed a significant main effect of fluency [$\beta = 0.34$, $F(1, 22.91) = 36.31$, $p < 0.0001$] showing that individual JoC was higher when there were low deviations (Mean high fluency = 6.77, SD = 1.81, 95% CI [6.71, 6.84]), relative to high deviations (Mean low fluency = 6.42, SD = 1.85, 95% CI [6.36, 6.49]), in the cursor’s trajectory (see Fig. 2.A). We also found a significant main effect of pivotality on individual JoC scores [$F(2, 26.73) = 14.74$, $p < 0.0001$], with a reduced score for low pivotality [Mean low pivotality = 6.34, SD = 1.90, 95% CI [6.26, 6.43]] relative to equal [Mean equal pivotality = 6.75, SD = 1.83, 95% CI [6.68, 6.84], $\beta = -0.26$, $t(21.20) = 5.42$, $p = 0.0001$] and to high pivotality [Mean high pivotality = 6.71, SD = 1.75, 95% CI [6.64, 6.79], $\beta = -0.25$, $t(21.23) = 4.35$, $p = 0.0008$]. Individual JoCs did not significantly differ between equal and high pivotality [$\beta = -0.01$, $t(40.78) = 0.77$, $p = 1$]. Rewards’ context (i.e., equal, fair and random all-or-none) did not trigger significant differences on individual JoC [$F(2, 20.99) = 2.91$, $p = 0.077$]. By splitting the all-or-none rewards condition into full and null gains, we found a significant effect of rewards’ distribution [$F(5, 30.1) = 7.98$, $p = 0.0014$], revealing that the null gains [Mean null gains = 6.11, SD = 1.59, 95% CI [5.60, 6.61]] globally led to a reduced individual JoC compared to full gains [Mean full gains = 6.76, SD = 1.52, 95% CI [6.28, 7.24], $\beta = -0.65$, $t(21.5) = -4.37$, p = 0.0003], equal gains [Mean equal gains = 6.70, SD = 1.25, 95% CI [6.31, 7.09], β = -0.59, t(22.7) = -3.95, p = 0.0007] and fair gains [Mean fair gains = 6.65, SD = 1.16, 95% CI [6.29, 7.01], β = -0.54, t (21.2) = -3.00, p = 0.0058] as shown in fig.2.C. Full, equal and fair gains were not associated to significantly different individual JoCs. This result is coherent with the significant – but weak – positive correlation we found between individual JoCs and individual gains since null gains were associated to lower individual JoC scores. There was a significant interaction [F(4, 50.05) = 7.01, p = 0.00015] between rewards' context and pivotality factors (see fig.2.B and fig.2.H) and post-hoc t-tests revealed that the individual JoC for high pivotality was significantly reduced in the case of all-or-none rewards [Mean high pivotality & all-or-none rewards = 6.40, SD = 1.83, 95% CI [6.26, 6.54]] compared to both equal [Mean high pivotality & equal rewards = 6.80, SD = 1.71, 95% CI [6.67, 6.93], β = -0.18, t(27.26) = 3.165, p = 0.0342] and fair rewards [Mean high pivotality & fair rewards = 6.94, SD = 1.66, 95% CI [6.82, 7.07], β = -0.25, t(20.93) = 3.35, p = 0.0279], while no significant differences due to reward's distributions emerged in the low and equivalent pivotality conditions. This reduction of the JoC scores for all-or-none rewards contexts in the high pivotality condition was thus mainly driven by the null gains. Moreover, as shown in fig.2.H, the difference between high and low pivotality was also mainly driven by the fairness of rewards. Indeed, when rewards were fairly shared, individual JoC was significantly higher in high pivotality condition [Mean high pivotality & fair rewards = 6.94, SD = 1.66, 95% CI [6.82, 7.07]] relative to low pivotality condition [Mean low pivotality & fair rewards = 6.17, SD = 1.86, 95% CI [6.03, 6.31], β = 0.41; t(27.20) = 6.10, p < 0.0001)]. This difference between high and low pivotality was marginally significant when rewards were equally shared (β = 0.14; t(28.60) = 2.43, p = 0.064) and non significant when rewards were randomly distributed in an all-or-none manner (β = 0.037; t(26.90) = 0.65, p = 1). Fluency and pivotality factors significantly interacted [F(2, 40.47) = 3.64, p = 0.035] showing that individual JoC was significantly reduced in trials with high cursor deviations, relative to trials with low cursor deviations, in equivalent pivotality [Mean high fluency & equivalent pivotality = 6.98, SD = 1.67, 95% CI [6.88, 7.08]; Mean low fluency & equivalent pivotality = 6.51, SD = 1.97, 95% CI [6.39, 6.64]; β = -0.25, t(36.16) = 6.04, p < 0.001] and high pivotality conditions [Mean high fluency & high pivotality = 6.92, SD = 1.71, 95% CI [6.67, 6.93]; Mean low fluency & high pivotality = 6.49, SD = 1.76, 95% CI [6.67, 6.93]; β = -0.23, t (28.32) = 5.60, p < 0.001], but not in low pivotality conditions [Mean high fluency & low pivotality = 6.41, SD = 1.99, 95% CI [6.29, 6.54]; Mean low fluency & low pivotality = 6.27, SD = 1.80, 95% CI [6.15, 6.38], β = -0.08, t(22.04) = 1.37, p = 1], as shown in fig2.G. This interaction could logically be explained by the fact that, in the low pivotality condition, motor contribution is also significantly lower (see preliminary analysis) resulting in a reduced appreciation of motor noise. The interaction between fluency and rewards was only close to significance [F(2, 59.97) = 2.83, p = 0.067].

To summarize, individual JoC was globally enhanced in situations of high motor fluency (fig.2.A) and in situations of high and equal pivotality (fig.2.B). The interaction between pivotality and rewards' context shows that the difference between high and low pivotality was the greatest in the "fairness" context.

3.1.3. Collective JoC

The collective JoC was assessed by asking participants to rate their "collective" feeling of control, as a team, about the cursor's movements on a 9-point scale after each trial. Analysis of joint JoC revealed a significant main effect of fluency [β = 0.17, F(1, 34.87) = 24.11, p < 0.0001] meaning that joint JoC was higher when there were low deviations [Mean high fluency = 6.94, SD = 1.80, 95% CI [6.88, 7.00]], relative to high deviations [Mean low fluency = 6.71, SD = 1.79, 95% CI [6.65, 6.78]], in the cursor's trajectory (see Fig. 2.D). There was also a significant main effect of pivotality on joint JoC scores [F(2, 30.39) = 13.86, p < 0.0001], with an enhanced joint JoC for equal pivotality [Mean equivalent pivotality = 7.01, SD = 1.81, 95% CI [6.93, 7.09]] relative to low pivotality [Mean low pivotality = 6.69, SD = 1.84, 95% CI [6.60, 6.77], β = 0.15, t(30.13) = 4.815, p = 0.0001] and to high pivotality [Mean high pivotality = 6.79, SD = 1.73, 95% CI [6.72, 6.87], β = 0.06, t(26.52) = 4.10, p = 0.001], while low and high pivotality did not significantly differ [t(40.47) = -1.713, p = 0.28]. Effect of rewards' context (i.e., equal, fair and random all-or-none) on joint JoC was also significant [F (2, 27.27) = 11.67, p = 0.00022], showing that equal rewards [Mean equal rewards = 7.14, SD = 1.17, 95% CI [6.77, 7.50]] led to a significantly higher joint JoC relative to both fair [Mean fair rewards = 6.87, SD = 1.16, 95% CI [6.51, 7.23], β = 0.08, t(37.93) = 3.97, p = 0.0009] and all-or-none rewards contexts [Mean all-or-none rewards = 6.73, SD = 1.85, 95% CI [6.65, 6.81], β = 0.13, t (23.96) = 3.268, p = 0.0098], which did not significantly differ [β = 0.13, t(25,48) = -0,16, p = 1]. This global enhancement of joint JoC in equal rewards condition was also confirmed when we split the all-or-none rewards condition into full and null gains [F(3, 39,1) = 11.64, p < 0.0001]. Indeed, we observed that the equal gains [Mean equal gains = 7.14, SD = 1.17, 95% CI [6.77, 7.50]] globally led to an increased joint JoC compared to full gains [Mean full gains = 6.96, SD = 1.35, 95% CI [6.54, 7.38], β = 0.18, t(50.0) = 1.90, p = 0.0489], null gains [Mean null gains = 6.41, SD = 1.36, 95% CI [5.99, 6.82], β = 0.73, t(48.9) = 7.69, p < 0.0001] and fair gains [Mean fair gains = 6.87, SD = 1.16, 95% CI [6.51, 7.23], β = 0.27, t(38.6) = 3.00, p = 0.0047] as shown in fig.2.F. However, null gains were also associated to a significantly reduced joint JoC relative to full gains [β = -0.55, t(5845.1) = -9.33, p < 0.0001] and fair gains [β = -0.46, t(43.6) = -3.97, p = 0.0003]. This result is coherent with the significant – but weak – positive correlation we found between collective JoC and individual gains since null gains were globally associated to lower collective JoC scores. Moreover, there was a significant interaction [F(4, 41.44) = 2.90, p = 0.033] between rewards' context and pivotality factors (see fig.2.E) and post-hoc t-tests revealed that the joint JoC was significantly enhanced for equal rewards in low pivotality condition [Mean low pivotality & equal rewards = 6.99, SD = 1.71, 95% CI [6.86, 7.12]] counter to fair [Mean low pivotality & fair rewards = 6.42, SD = 1.93, 95% CI [6.27, 6.56], β = 0.20, t (85.65) = 5.04, p < 0.0001] and all-or-none rewards [Mean low pivotality & all-or-none rewards = 6.66, SD = 1.86, 95% CI [6.52, 6.81], β = 0.06, t(88.34) = 3.58, p = 0.0261]. Joint JoC was also significantly enhanced for equal rewards in high pivotality conditions [Mean high pivotality & equal rewards = 7.06, SD = 1.63, 95% CI [6.94, 7.18]], relative to fair [Mean high pivotality & fair rewards = 6.71, SD = 1.76, 95% CI [6.58, 6.85], β = 0.08, t(85.63) = 3.078, p = 0.0252] and all-or-none rewards [Mean high pivotality & all-or-none rewards = 6.60, SD = 1.78, 95% CI [6.46, 6.74], β = 0.13, t(88.33) = 4.19, p = 0.0009], while the joint JoC was not significantly enhanced for equal rewards in equivalent pivotality condition [Mean equivalent pivotality & equal rewards = 7.16, SD = 1.72, 95% CI [7.03, 7.29]], relative to fair [Mean equivalent pivotality & fair rewards = 6.96, SD = 1.80, 95% CI [6.82, 7.10], t(21.73) = 1.613, p = 1] and all-or-none rewards [Mean equivalent pivotality & all-or-none rewards = 6.92, SD = 1.90, 95% CI [6.77, 7.06], t(34.09) = 1.88, p = 0.61]. The significant differences between equal and all-or-none rewards contexts were mainly driven by the null gains. Finally, fluency and pivotality factors did not significantly interact [F(2, 52.24) = 1.67, p = 0.198] and the interaction between fluency and reward was not significant either [F(2, 37.87) = 0.34, p = 0.71].

In sum, collective JoC was globally enhanced in situations of high motor fluency (fig.2.C), in situations of equal pivotality (fig.2.E), and in situations where rewards were equally shared ("equal" gains, fig.2,F).

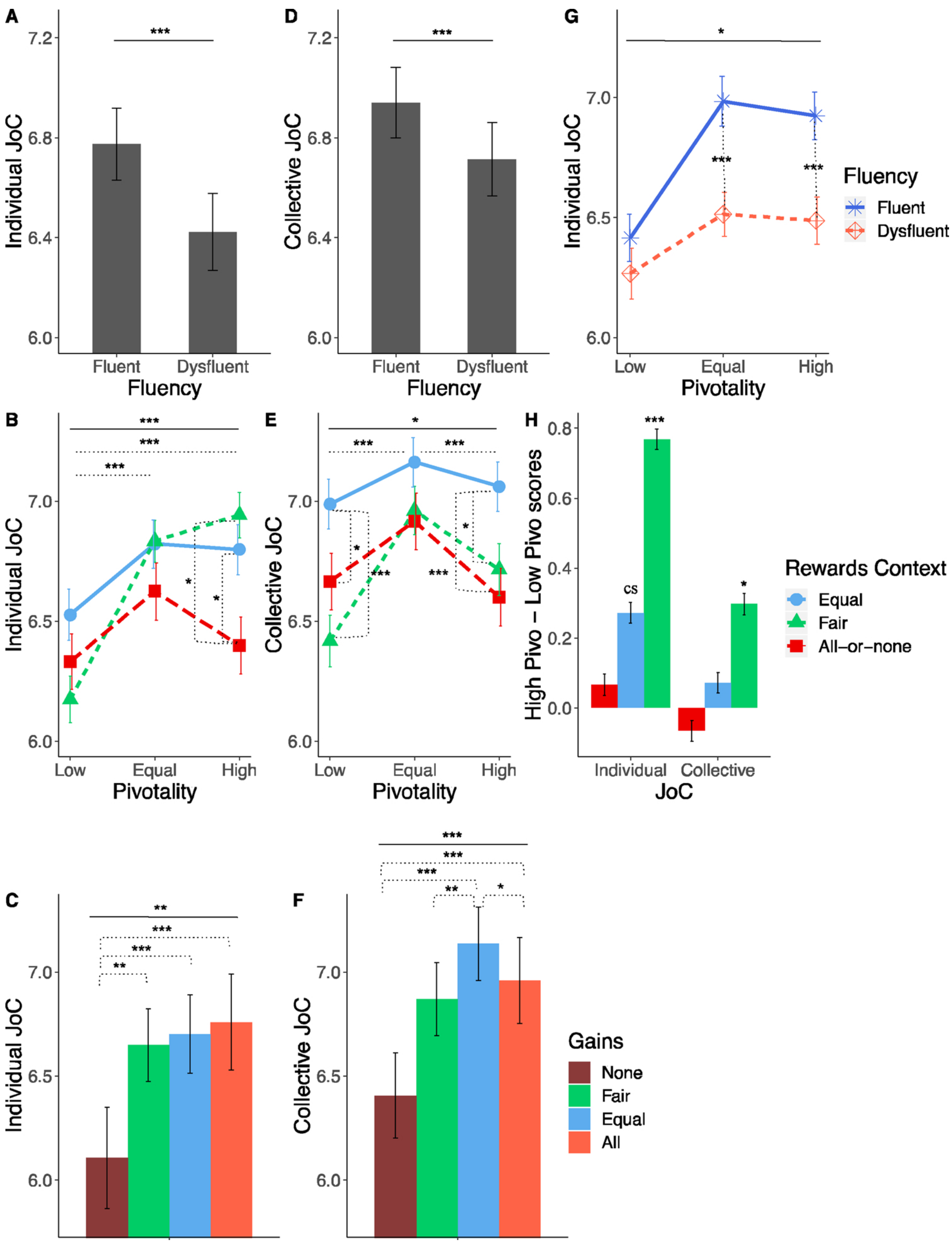

Fig. 2. Impact of motor fluency on judgment of individual control (A) and on judgment of collective control (D). Interaction between pivotality and rewards' context on judgment of individual control (B) and on judgment of collective control (E). Impact of individual gains on judgment of individual control (C) and on judgment of collective control (F). Interaction between fluency and pivotality on judgment of individual control (G). Differences between high and low pivotality according to rewards' distribution for both individual and collective JoC (H). Overall, pivotality is a critical factor when judging *one's own individual* control, especially when resources are distributed fairly, whereas judgment of collective agency is oblivious to individual pivotality but overall sensitive to whether resources are equally distributed among partners.
N.B. : *cs* = close to significance; * = $p <$ 0.05; ** = $p <$ 0.01; *** = $p < 0.001$; full lines in fig A, C, D & F report the significance level of main effects, full lines in fig. B, E & G report the significance level of interactions; dashed grey lines in fig. B, C, E, F & G report the significance level of post-hoc comparisons.

3.2. Physiological data: electrodermal activity

3.2.1. Preliminary analysis

The correlation between SCR amplitudes to rewards and individual rewards' values was not significant [R = -0.012, t(3705) = -0.73, p = 0.47, R^2 = 0.00014], even when we removed the blocks with equal rewards that were constant and potentially linked to habituation [R = -0.015, t(3455) = -0.74, p = 0.4567, R^2 = 0.00023].

The correlation between individual JoC ratings and SCR amplitudes to rewards was negative and significant, but low [R = -0.04, t(3705) = -2.45, p = 0.014, R^2 = 0.0016], meaning that participants' SCRs were weakly linked to individual JoC ratings in the sense that the higher the SCRs to rewards, the lower the self-reported individual JoC. The correlation between collective JoC ratings and SCR amplitudes to rewards was not significant [R = -0.0014, t(3705) = -2.45, p = 0. 93, R^2 = 0.000002].

3.2.2. SC phasic component

While the rewards' distribution factor (i.e., equal, fair and all-or-none) was properly balanced and crossed with the other experimental factors (i.e., motor fluency and pivotality), this was not the case for rewards' values (i.e., individual gains) that were linked to the ratio of individual motor contributions in the fair condition and had fixed values in the equal and random ones. We, therefore, ran two separate repeated-measures ANOVAs to explore the impacts of rewards' values on the one hand and rewards' distribution on the other hand on SCR amplitudes.

Firstly, we analyzed whether there was an impact of individual gains on SCR amplitudes. To do so, we ran a repeated measures ANOVA where rewards' values were classified within three different levels of individual gains (i.e., low individual gains < 0.40; middle individual gains = 0.40 – 0.60; high individual gains > 0.60). Consistently with the absence of significant correlation between SCR amplitudes and

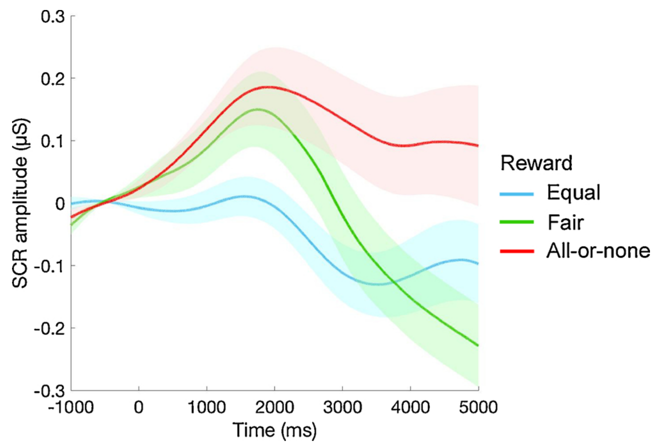

Fig. 3. SCR mean amplitude (± SE) as a function of time and rewards' distribution. Rewards' onset corresponds to 0 ms on x-axis. For presentation purposes, baseline mean activity from -1000 ms to 0 ms before the reward was subtracted from mean activity in the presented epoch. When rewards are fairly distributed (green), skin conductance activity drops rapidly compared to when rewards are randomly distributed in an all-or-none manner. In the "equal" context, the very low mean SCR is due to physiological habituation (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

rewards' values, the main effect of individual gains was not significant either [$F(2, 99) = 1.71$, $p = 0.186$, $\eta^2 = 0.03$].

Secondly, we ran a repeated measures ANOVA with the fully crossed factors fluency, pivotality and rewards' distribution, and we specifically analyzed their main effects in order to ensure a sufficient number of SCRs in all the conditions (i.e., stimuli do not systematically elicit SCRs, see Boucsein et al., 2012). We found no significant main effects of fluency [$F(1, 618) = 0.032$, $p = 0.86$, $\eta_p^2 = 0.001$] and pivotality [$F(2, 618) = 0.194$, $p = 0.82$, $\eta_p^2 = 0.01$] but a significant main effect of rewards' distribution [$F(2, 618) = 3.74$, $p = 0.0242$, $\eta_p^2 = 0.12$] (see Fig. 3 and Fig. 4.A.). Post-hoc analyses revealed that SCR amplitudes were significantly higher in the case of all-or-none rewards [Mean SCR z-scores to all-or-none rewards = 0.32, SD = 0.12; 95% CI [0.06, 0.44], $t(618) = 2.67$, $p = 0.0078$, $d = 2.45$] compared to equally distributed rewards [Mean SCR z-scores to equal rewards = 0.07, SD = 0.08]. The difference between SCR amplitudes induced by all-or-none and fair rewards [Mean SCR z-scores to fair rewards = 0.14, SD = 0.12, 95% CI [-0.12, 0.21]] was only close to significance due to the Bonferroni correction [95% CI [-0.199, 0.129], $t(618) = 1.86$, $p = 0.063$, $d = 1.50$]. However, SCR amplitudes to equal and fair rewards were not significantly different [95% CI [-0.199, 0.129], $t(618) = 0.81$, $p = 0.42$, $d = 0.69$].

In sum, in a collaborative context, phasic component of skin conductance (SCR) significantly reflects how the gains were distributed between partners but not what was individually earned.

3.2.3. SC tonic component

There were 3 different types of blocks based on rewards' distribution (i.e., equally, fairly, randomly distributed) while all levels of Pivotality and Fluency factors were counterbalanced within each block. The one-way repeated measures ANOVA revealed a significant main effect of rewards' distribution on blocks' SCL [$F(2, 99) = 4.34$, $p = 0.0157$, $\eta_p^2 = 0.08$] and post-hoc t-tests showed that SCL was significantly higher in blocks of all-or-none rewards [Mean SCL z-scores in all-or-none rewards blocks = 0.30, SD = 0.26; $t(99) = 2.93$, $p = 0.0042$, $d = 2.88$], relative to blocks of fair rewards [Mean SCL z-scores in fair rewards blocks = -0.45, SD = 0.26], as shown in Fig. 4.B. However, SCL was not significantly different in blocks of all-or-none rewards and blocks of equal rewards [Mean SCL z-scores in equal rewards blocks = -0.01, SD = 0.008; $t(99) = 1.24$, $p = 0.22$, $d = 1.69$]. There was no significant difference in SCL between blocks of equal and fair rewards either [$t(99) = -1.70$, $p = 0.093$, $d = 2.39$].

In sum, the tonic component of skin conductance is reduced in "fair" contexts, where individual outcome is directly linked to each partner's individual motor contribution, relative to the "all-or-none" context.

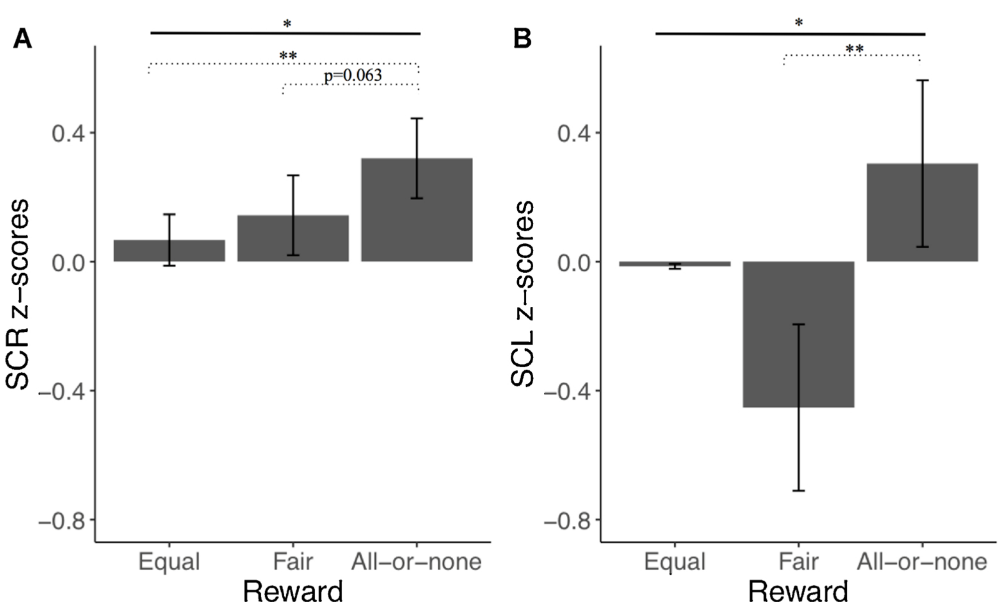

Fig. 4. Phasic (A) and tonic (B) components of skin conductance as a function of rewards' distribution between partners. SCR amplitudes z-scores (± SE) were calculated from 1 to 5 s after rewards' distribution. SCL z-scores (± SE) were calculated from activity recorded in entire blocks where rewards were only distributed in a particular way (i.e., either equally, fairly or randomly shared). The phasic component of skin conductance (A) is significantly and marginally enhanced for all-or-none rewards relative to equal and fair rewards, respectively. The tonic component of skin conductance (B) is significantly reduced in fair contexts, where individual outcome is directly linked to each partner's motor contribution, relative to arbitrary all-or-none outcomes contexts. N.B. : * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

4. Discussion

The aim of the present experiment was twofold. First, we examined whether some important variables of realistic joint action could modulate the metacognitive individual and collective feelings of control (JoC). Thus, dyads of participants were instructed to coordinate their actions online to achieve a common goal (i.e., reaching a specific target) while the three following parameters were manipulated: motor fluency, agents' roles and outcomes' sharing. As expected, participants reported a weaker feeling of individual control in the case of high random deviations (i.e., low fluency), confirming the important contribution of sensorimotor cues to self agency judgments (Metcalfe & Greene, 2007; Metcalfe et al., 2013; Sidarus et al., 2017). Moreover, we observed that a reduced motor role (i.e., low pivotality condition) in the joint action decreased the individual JoC compared to both high and equivalent motor roles. The fact that high and equivalent motor roles did not trigger significantly different individual JoC suggests that the individual SoA or I-mode (see Tuomela, 2006; van der Wel et al., 2015) was actually determined by the strict physical parameters of the individual contribution to the joint action, that is the actual distance to be covered and the individual motor effort to accomplish, regardless of the relative role of the co-agent. In fact, the low pivotality condition was the sole condition where the distance to be covered between the cursor and the target was reduced for the concerned agent. This distance was strictly similar in both equal and high pivotality conditions, only the co-agent's relative roles were different. Thus, the equivalence of individual JoC in both equal and high pivotality conditions indicates that participants were not influenced by the co-agents' roles and focused on self-related cues to judge their self agency. Furthermore, while the number of individual key presses was approximately equivalent in both high and equal pivotality conditions, it was necessarily reduced in the low pivotality condition for the concerned agent. The associated decrease of individual SoA could then reflect the concomitant reduction of individual motor effort in low pivotality conditions, as it has been previously shown (e.g., Demanet et al., 2013; Minohara et al., 2016). Further studies are needed to properly dissociate how perceptual cues and motor cues differently contributed to this pivotality effect. Due to the strong sensorimotor link which is acquired through experience between the physical distance to a goal and the required motor effort to reach it, theories of affordances have proposed that in action context, distance is actually perceived in terms of motor effort (e.g., Gibson & James, 2014; Proffitt, Stefanucci, Banton, & Epstein, 2003; Woods, Philbeck, & Danoff, 2009; Witt, Proffitt, & Epstein, 2004). Therefore, we believe that even if the level of motor effort had been implicitly kept constant across all pivotality conditions, differences in perceptual distances and perceived roles would still have produced similar effects.

The agents' motor role also influenced the effects of motor fluency in the sense that the impact of fluency on individual JoC was no longer significant in the low pivotality condition. This may be due to the concomitant reduction of motor effort that subsequently made the impression of dysfluency negligible. Again, this interaction highlights the contribution of self-related sensorimotor cues to individual SoA.

Besides the influence of sensorimotor components, we observed a weak linear link between individual JoC and individual gains, which was confirmed when we split the all-or-none rewards context condition into full gains (i.e., participants earned 1 point) and null gains (i.e., participants earned 0 point). Indeed, the null gains, corresponding to the lowest possible reward in the current task, were associated to a significantly reduced individual JoC relative to all the other rewards. Because rewards' values were unpredictable in the all-or-none condition (i.e., randomly generated), this result is rather coherent with the idea of a retrospective bias induced by negative outcomes on individual SoA (Takahata et al., 2012; Yoshie & Haggard, 2013). However, there was no main effect of rewards' context (i.e., how rewards were shared between participants) on individual JoC, which suggests that external allocentric cues did not exert an important bias on metacognitive self-agency. The significant interaction between rewards' context and pivotality shows that the arbitrary distribution of rewards significantly reduced the individual JoC in the case of high pivotality, but this effect was mainly driven by the null rewards. Moreover, we observed that the difference of individual JoC between high and low pivotality was more specifically driven by fair rewards. Thus, the individual motor contribution seems to be of particular importance for judging of one's own control in a situation where resources are fairly distributed between the partners.

Collective JoC was also reduced in the case of high random deviations in the cursor's trajectory (i.e., low fluency), revealing that the "we-mode" does depend on individual sensorimotor information, as expected. This effect is not surprising given that the question explicitly asked participants to rate their JoC about the cursor's movements. However, the effect size of motor fluency on individual JoC (i.e., $\beta = 0.34$) is twice the effect size of motor fluency on collective JoC (i.e., $\beta = 0.17$). This could mean that joint JoC derives from the individual JoC where internal sensorimotor information is supposed to be of prime importance (e.g., Moore et al., 2009). It also indicates that sensorimotor cues are given less weight during the Bayesian integration of multiple cues when it comes to forming a judgment about joint agency – relative to self agency – perhaps to place heavier emphasis on situational cues (see Pacherie, 2012). Indeed, internal sensorimotor states of the co-agent are not available so that the agent has to rely on her own sensorimotor state as well as on the external evidence of a shared control.

Interestingly, the pivotality factor did not influence joint JoC in the same way as it influenced individual JoC. Consistently with previous work proposing that unbalanced agents' roles (i.e., leader-follower configuration) should not necessarily impact the feeling of control in cooperative joint actions involving shared goals (i.e., the we-mode, see Pacherie, 2013, 2014; van der Wel et al., 2015), we found that high and low motor roles (i.e., high and low pivotality) did not trigger significant differences in collective JoC. However, we observed an enhancement of collective JoC when agents' roles were perfectly symmetric, relative to asymmetric roles (i.e., high and low pivotality). This suggests that the we-mode requires the integration of both self- and other- related signals, contrary to the I-mode that only focuses on self-related cues. The decrease of joint JoC in situations of asymmetric motor roles could also be envisioned through the perspective of the co-representation of others' actions. It has been shown that co-agents rely on task co-representation to achieve motor coordination in a task with asymmetric constraints (e.g., Sebanz, Knoblich, & Prinz, 2003). For instance, if a co-agent is encountering an obstacle, the individual action of the other co-agent is also disturbed, even if she is not intrinsically concerned by this obstacle (e.g., Schmitz, Vesper, Sebanz, & Knoblich, 2017). Thus, in the present task, such co-representations could explain why joint JoC is equivalently decreased in both high and low pivotality conditions: when the agent has the higher motor role, it means that the co-agent gets the relatively lower motor role and the co-representation of this lower pivotality to the joint action would finally decrease the collective JoC. Because there was not equivalent global effect of asymmetric pivotality on self SoA (i.e., individual JoC was only reduced for low pivotality condition but not for high pivotality condition), one might propose that the symmetrical co-representation of the other's actions is of particular importance for the emergence of a joint SoA.

In addition to the modest link between collective JoC and individual gains, we also found a main effect of outcomes' sharing, showing a higher collective JoC when rewards were equally shared between the co-agents, relative to both arbitrary and fair rewards. When splitting the all-or-none rewards context into null (i.e., individual gain equals 0) and full gains (i.e., individual gain equals 1), equal rewards were still linked to the highest score of joint JoC while the null rewards significantly decreased the collective JoC ratings relative to all the other rewards' configurations. Besides the retrospective dimension of such a bias on self-reports, this result demonstrates again the importance of symmetric and balanced parameters in complementary joint action to facilitate the emergence of a metacognitive we-mode. It also indicates that individual interests remain crucial and are not completely suppressed within joint agency. Interestingly, we observed that the enhancement of collective JoC induced by equal rewards was significant in conditions of unbalanced pivotality only. One might suggest that when asymmetric agentic situations were associated with equal rewards, this last perceptual sign of symmetry exerted a retrospective influence on collective JoC, which offset the impact of individual motor contributions. This could mean that participants processed the final outcomes as potential feedback about their performance and contributions. As such, it makes sense that symmetrical outcomes did not significantly bias joint JoC in conditions where the co-agent's role was already symmetrical but did so in conditions of asymmetrical roles. This is also in line with the proposal that perceptual cues make a particularly high contribution to joint SoA.

Altogether, these behavioral results suggest that individual and collective JoC are not based on exactly the same processes and information. Individual and collective JoC both showed an impact of internal motor prediction (i.e., motor fluency), but individual JoC particularly relies on egocentric extrinsic cues while the collective JoC additionally relies on allocentric cues related to others' contributions. The observation of different extrinsic criteria to rate individual and joint JoC, within the same joint action, suggests that both I- and we-modes coexist in parallel during a cooperative and complementary motor task, at least at a metacognitive level, which is consistent with the concept of shared agency (Bolt et al., 2016; Pacherie, 2012). From a more practical viewpoint, these data could also indicate that earning the exact same reward or taking equivalent part to a collaborative project improve the metacognitive feeling of acting together. The complementary roles of co-agents (i.e., either vertical or horizontal control) and the common goal characterizing the current joint task may certainly have enhanced the observed preference for symmetrical parameters regarding the collective JoC (see Dewey et al., 2014). These results could also be interpreted in light of the hierarchical model of action intentions (see Pacherie, 2008, 2012) that allows distinguishing between three levels of action intentions. According to this model, the highest level consists in a *distal intention* including the main goal and the conceptual plan of the action. The second level refers to a *proximal intention* that aims to anchor the previous conceptual plan in the situation of action, being constrained by current perceptual information. Finally, the lowest level is labeled as *motor intention* and is responsible for the precision and smoothness of action execution, involving motor representations that code for transitive movements where the motor sequence is determined by the goal of the action. On this hierarchical model, the sense of control depends on the degree of match between the predicted consequences of the intended action and its actual consequences at each of these three levels of intention. In the present experiment, the distal intention would refer to the global aim to win monetary rewards. Therefore, it is coherent to observe a significant reduction of both individual and collective JoC in situations where participants earned nothing (i.e., the null gains in the all-or-none rewards context) since the distal intention was completely unfulfilled. Interestingly, it seems that the distal intention inherent to the we-mode (joint JoC) differed slightly from the distal intention inherent to the I-mode (individual JoC), by favoring the symmetry of gains, i.e., the condition in which the joint JoC was the highest. The pivotality factor, for its part, could be envisioned as a manipulation of the proximal intention in view of the perceptual information which was provided in order to turn the abstract goal into a more concrete schema that meets the situational constraints (i.e., the location of the target). Again, while the I-mode was apparently linked to a proximal intention that only focuses on the individual physical parameters of the action to perform (i.e., individual JoC is significantly reduced in situations of low contribution), the we-mode was associated to a proximal intention which included both representations of co-agents' roles (i.e., collective JoC was significantly enhanced in situations of equal motor roles). Lastly, the motor noise generated via the fluency factor was supposed to influence the motor intention level by creating discrepancies in the sensorimotor signals. Regarding the individual and collective JoC ratings, motor intentions linked to both I- and we- modes appeared to be effectively disturbed by the high random deviations, especially in the I-mode where the effect was descriptively stronger.

However, it is important to note that we only used explicit measures of SoA which are more permeable to retrospective causal attribution processes and to experimental confounds like demand effects (see Gallagher, 2000; Moore, 2016). Thus, additional studies are needed to explore in more detail whether implicit measures of agency (e.g., intentional binding or sensory attenuation) better reflect individual or joint JoC in such a naturalistic joint action task, in order to draw more definite conclusions regarding the automatic aspect of the we-mode or we-identity (Obhi & Hall, 2011).

Second, we explored whether physiological reactions to monetary outcomes reflected the particular social context inherent to a cooperative motor task and could be linked to different levels of SoA. In order to create contexts of fairness (i.e., individual outcomes were linked to individual motor contributions), equality (i.e., individual outcomes were equally shared between co-agents) and arbitrariness (i.e., the entire outcomes were arbitrarily attributed to one or the other co-agent), rewards were coherently distributed in one of these three specific ways within each block. Importantly, individual gains earned by co-agents were visible by both of them. As we expected, we found a main effect of rewards' distribution on SCRs and more particularly, arbitrary all-or-none rewards triggered enhanced SCRs compared to equal rewards. We believe that this result is certainly due to the physiological habituation to equal rewards that were constant within the "equality blocks" (Boucsein, 2012; Boucsein et al., 2012). Furthermore, all-or-none outcomes also led to marginally enhanced SCRs compared to fair rewards that yet varied more (i.e., fair rewards could take any decimal value between 0 and 1), making them less prone to physiological habituation. One might argue that this marginal difference could result from the higher predictability of rewards within the fair blocks since individual gains were linked to motor contributions. Nevertheless, the exact amount of rewards could hardly be predicted on the basis of the motor effort. Moreover, SCRs are rather insensitive to the predictability of non-aversive stimuli (Geer & Maisel, 1972; Grillon, Baas, Lissek, Smith, & Milstein, 2004; Bach & Friston, 2012) and "unpredictability is not intrinsically anxiogenic" (see Staub et al., 1971, Boucsein, 2012). Thus, this SCR modulation could rather reflect the fact that arbitrary all-or-none rewards took an unfair dimension in such a collaborative context (see Salvia et al., 2012; Shapiro et al., 2017; Van't Wout et al., 2006) while fair rewards were more "controllable". In addition, counter to what was found in social games (e.g., Civai et al., 2010; Civai, 2013; Srivastava et al., 2009), there was no significant link between SCR amplitudes and the amount of individual gains, even when equal and predictable gains were removed from the analysis. This suggests that, in social interactions requiring a real motor cooperation between players and not just a decision based on competing motives of self-interest and fairness (e.g., the ultimatum game), participants' implicit reactions reflect more the social fairness of the situation than their individual interests, which fits well with the reciprocity model (see Fehr & Gächter, 2000). This also constitutes additional evidence showing the intrinsically cooperative and pro-social dimension of human behaviors (e.g., Silk & House, 2011). Interestingly, we also found a difference due to rewards' distribution in skin conductance level (SCL) that is supposed to reflect more general psychological states than SCR (see Boucsein, 2012; Braithwaite, Watson, Jones, & Rowe, 2013). Indeed, SCL was significantly higher in arbitrary all-or-none blocks relative to fair blocks while there was no statistical difference between SCL recorded in arbitrary all-or-none and equal blocks. The fact that this difference emerged between fair and all-or-none blocks and not between equal and all-or-none blocks implies that it could be the particular feeling of exerting a form of control on the forthcoming outcome that reduces the players' sympathetic arousal and their general level of stress. As a matter of fact, in fair blocks, it is the number of key presses that modulated the final gain, which was not the case in equal blocks where gains were constant and known beforehand, neither in all-or-none blocks where entire rewards were arbitrarily attributed to one or the other player. Thus, the current fair condition could also be conceived as a context where agents felt that they caused and controlled the final outcomes. This feeling matches the basic definition stating that SoA refers to the experience of being in control of one's own actions and, through them, of events in the external world (e.g., Haggard & Tsakiris, 2009). Moreover, the result of a reduced SCL in the fair/responsibility context is in line with the observation of a reduced SCL in conditions where participants thought they could exert a sort of control on aversive stimuli. This SCL reduction has been labeled as "controllability" effects in literature (e.g., Boucsein, 2012; Gatchel, McKinney & Koebernick, 1977; Geer & Maisel, 1972). Therefore, one might argue that the SCL reduction observed in conditions of controllability constitutes a way to capture the implicit feeling of control and responsibility over action outcomes which is an essential dimension of SoA.

To conclude, in the present cooperative joint task, we observed that explicit self agency did rely on sensorimotor information as well as on self-related extrinsic cues. Consequently, self agency was particularly sensitive to fairness of resources distribution, that is, to whether rewards were distributed proportionally to the players' contribution. Explicit joint agency was modulated by both motoric and allocentric cues. Indeed, judgment of joint control was enhanced when partners made similar motor contributions and when rewards were equally shared between co-agents. This is consistent with the idea that the we-mode within a joint task relies on the co-representation of partner's role and outcome. Thus, additionally to sensorimotor aspects, metacognitive self agency is reliant on pivotality and fairness while metacognitive joint agency is sensitive to equality contexts. Moreover, we observed that skin conductance responses were related to the social fairness of the context but not to individual interests. Skin conductance level was also reduced in the fair context compared to the arbitrary all-or-none context, which could implicitly reflect the feeling of effective responsibility and control over actions' outcomes.

Declaration of Competing Interest

The authors declare they had no conflicts of interest with respect to their authorship or the publication of this article.

Acknowledgments

This research was supported by the Agence Nationale de la Recherche [grant number ANR-16-CE28-001401] and by the EUR Frontiers in Cognition [grant number ANR-17-EURE-0017]. V.C. was supported by ANR-10-IDEX-0001-02 PSL (program "Investissements d'Avenir"), and ANR-16-CE37-0012-01. The authors also thank Morgan Beaurenaut and Nura Sidarus for their help with data collection and analysis.

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