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Sharing motor plans while acting jointly: A TMS study

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ABSTRACT

When acting together, we may represent not only our own individual goals but also a collective goal. Although behavioural evidence suggests that agents' motor plans might be related to collective goals, direct neurophysiological evidence of whether collective goals are motorically represented is still scarce. The aim of the present transcranial magnetic stimulation (TMS) study is to begin to fill this gap. A participant and a confederate were asked to sequentially perform a two-choice reaction time task by acting on pressure sensors. In their own turn, they saw a cue indicating whether to lift their fingers from (or to press them on) a pressure sensor to shoot a ball across the screen as fast as possible. The confederate responded with the right hand, the participant with the left hand. While the confederate acted on the sensor, the participant's motor evoked potentials (MEPs) were collected from the right Extensor Carpi Ulnaris. If participants represent their own and the confederate's actions as being directed to a collective goal, MEPs amplitude should be modulated according to the action the confederate should perform. To test this conjecture, we contrasted three conditions: a *Joint* condition, in which both players worked together with their collective goal being to shoot the ball to get it to a common target, a *Parallel* condition, in which the players performed exactly the same task but received independent outcomes for their performance, and a *Competitive* condition, in which the outcome of the game still depended on the other player performance, but without the collective goal feature. Results showed no MEPs modulation according to the confederate's action in the *Joint* condition. Post-hoc exploratory analyses both provide some hints about this negative finding and also suggest possible improvements (i.e., adopting a different dependent variable, avoiding task-switching between conditions) for testing our hypothesis that collective goal can be represented motorically.

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1. Introduction

Many of the things people do are done with others. People walk together, dance together and play video games together. A simple reflection on these examples points to a difference, which has been claimed to be critical for better understanding what is at stake with acting *together* (Bratman, 2013; Gilbert, 1990; Searle, 1990). Contrast, for instance, two friends walking together to their school with two strangers who merely happen to be walking to the same school side-by-side. While the former are usually held to be acting *together*, the latter are usually held to be acting in *parallel*, but merely *individually*. Similarly, consider two schoolmates playing a video game together, after agreeing to do it as soon as being back home from school. They are usually held to be acting together. On the contrary, two adolescents who merely happen to play a video game alongside each other are usually held to be acting in parallel but merely individually.

Appealing to the presence of two or more agents, with their actions being individually directed to an *individual* goal (e.g., going to school, playing a video game) seems, therefore, to be not sufficient for distinguishing acting together from acting in parallel but merely individually. A further condition has to be met. When two (or more) agents act together, there is a goal (at least one) to which their actions are directed and this is not, or not only, a matter of each action being individually directed to it (Butterfill, 2015; Butterfill & Sinigaglia, 2021; Sinigaglia & Butterfill, 2020). For the sake of brevity, it can be said that in such cases the actions are *collectively* directed to the goal, with this being their *collective goal*.

A natural question to ask is how collective goals are represented and how such representations impact on action preparation and execution when two (or more) agents are acting together. An attempt to directly address this question comes from a behavioural study by della Gatta et al. (2017). In their work, the authors explore how collective goal representations impact on actions by taking advantage of a two-agents' version of a circle-line paradigm typically used for investigating bimanual actions (Franz et al., 1991). Their work was structured by contrasting two agents acting together versus two agents acting in parallel but merely individually. In the first condition, participants were asked to draw with their right hand either a circle or a line together with a confederate, as if their two drawing right hands gave shape to a single design. In a second condition, participants had to draw either a circle or a line while observing the confederate drawing. Results showed that, when drawing together, participants exhibited an interpersonal coupling effect, resulting in a greater ovalization of the lines drawn together than in the parallel condition. This suggested that, when acting together, it would be almost *as if* each agent were representing the whole action bimanually. Previous studies on bimanual actions demonstrated that the circle-line coupling effect is specifically related to the goal representations, which are functionally involved in motor preparation, rather than action execution (Garbarini et al., 2012, 2013, 2014). These representations are usually labelled as *motor* representations (Jeannerod, 1988, pp. xii, 283; Rizzolatti & Sinigaglia, 2008; Santello et al., 2002; Wolpert et al., 1995). For these reasons, the authors concluded that collective goals could be represented *motorically*.

Although a number of behavioural findings have further supported, either directly or indirectly, the notion that agents' motor plans might be related to collective goals (Clarke et al., 2019; Dötsch & Schubö, 2015; Meyer et al., 2013; Ramenzoni et al., 2014; Sacheli et al., 2018; Török et al., 2019), to date little research has provided direct neurophysiological evidence of whether collective goals are motorically represented.

Some studies have explored the neural underpinnings of acting together by investigating whether agents plan and monitor their actions by taking into account the relation intervening between their own and the others' movements (Kourtis et al., 2013, 2014, 2019; Loehr et al., 2013; Novembre et al., 2014). For instance, Loehr et al. (2013) recorded EEG by couples of pianists playing a duet together. Pitches produced by each pianist were occasionally modified in a way that could affect the harmony of a chord produced by two pianists together. The results showed that altered pitches elicited a feedback-related negativity whether they concerned the pianist's own part or the confederate's part, and whether these affected individual or joint action outcomes. Similarly, Kourtis et al. (2014) recorded EEG in participants performing a toast action alone with one hand, alone bimanually and together with a confederate. The main finding was that when planning to toast together participants represented their confederate's action in addition to their own action almost as if they had to toast with both their own hands. Indeed, when participants planned to toast together with their confederate, a crucial EEG component of action planning such as the contingent negative variation, which is likely related to the activation of premotor areas, was significantly larger compared with planning the same unimanual action individually, whereas it was not significantly smaller compared with planning the same action bimanually.

Taken together, these studies indicate that agents may plan and monitor their own and their confederate's actions when acting together. However, planning and monitoring one's own and another's actions does not involve *per se* representing a collective goal. Indeed, there is consistent evidence that people may represent their confederate's actions in addition to representing their own actions even when they are acting alongside each other, with their actions being *not* collectively directed to any outcome; that is, without having any collective goal (Atmaca et al., 2011; Baus et al., 2014; Böckler et al., 2012; Sebanz et al., 2005). This means that a new approach is needed to investigate how collective goals are represented in the brain. Earlier studies all measured brain activity while comparing one individual's performance with two individuals' performances. But to individuate neuronal indicators of how a collective goal is represented, it is necessary to compare two (or more) acting in parallel with two or more individuals acting together.

The aim of the present study is to pursue such a new approach, by assessing agents' motor corticospinal excitability by means of transcranial magnetic stimulation (TMS) in situations which differ in that one involves a collective goal whereas the others do not.

Unlike previous work (della Gatta et al., 2017), we decided to contrast three distinct conditions. Indeed, contrasting two agents acting together with two agents acting in parallel, although necessary, may be not enough to isolate the neural underpinnings of collective goal representation. We believe that acting together should also be contrasted with acting competitively, as competition involves a way of relating to another's action that makes it closer to acting together than acting in parallel. In fact, competitors must take into account what the other (or the others) is (are) doing, and must act accordingly. This is not the case with acting in parallel. However, like acting in parallel, actions of competitors are directed to an individual, rather than a collective, goal. After all, there will be only one winner.

To implement these contrasts, we created a simple video game. The game requires the participants to operate on a "ball shooter" (pinball-like) to shoot a ball toward a target, by pressing their left fingers on a pressure sensor, while holding the right hand relaxed on another pressure sensor. Participants played the game with a confederate, who was sitting beside them, on their right. They had to perform their task as soon as the confederate ended to perform his/her own. In the *Joint* condition, both players (i.e., the participant and the confederate) were instructed to work together with their collective goal being to shoot the ball so as to get it to a common target. Although the execution of their actions is relatively independent from one another, this is not the case for the goal to which the actions are collectively directed. Indeed, both players win if the ball reaches the common target within a fixed time. Otherwise, they both lose. In the *Parallel* condition, each player had to shoot the ball individually, trying to reach the respective target positions within the fixed time limit. Both players could either win or lose, independently. Finally, in the *Competitive* condition, each player had to shoot the ball toward the target faster than the other player. In this case, only one player won.

Our conjecture is that if collective goals can be represented motorically, we should expect the participant to share motor plans with the confederate in the *Joint* condition differently from both the *Parallel* and *Competitive* conditions. In this case, the participant will motorically plan both his/her own and the confederate's moves as being directed to the same outcome. In other words, the participant will motorically plan the action to be performed almost as if it consists of acting on both his/her own and the confederate's ball shooter. This should not be expected in the *Parallel* as well as in the *Competitive* condition.

To test our conjecture, we delivered a single pulse TMS on the participant' left primary motor cortex and we measured motor evoked potentials (MEPs) on his/her resting right hand muscles, while he/she was observing the ball shooter acted by the confederate, before performing his/her moves. TMS on primary motor cortex is a primer for a direct assessment of the engagement of the motor processes in action planning and execution (Cattaneo et al., 2009; Duque et al., 2017), probing the state of the corticospinal tract in such a way that the fine-grained content of what is motorically represented can be distinguished.

Our prediction is that, if the collective goals are represented motorically, the participant will covertly implement the action the confederate would perform. This should result in a differential modulation of MEPs recorded from participant's right arm muscles congruent to the confederate's action in the *Joint* condition compared to both the *Parallel* and the *Competitive* conditions. Our prediction does not involve that in the *Parallel* and (even more) in the *Competitive* condition participants should never take into account what the confederate is doing. Quite the contrary. This makes the contrast between the *Joint*, the *Parallel* and especially the *Competitive* condition so critical for our study. If there will be no difference in the MEPs modulation across all the conditions, this does not rule out the possibility that participants have somehow represented the confederate's actions. However, this representation, if any, cannot be specifically related to a collective goal. Conversely, if there will be a difference in the MEPs modulation in the *Joint* condition compared to the *Parallel* as well as to the *Competitive* conditions, this means that this difference does not depend on merely taking into account the confederate's action, but it is likely related to the presence of a collective goal.

2. Method

2.1. *Power analysis and participants*

44 Healthy right-handed volunteers (half females, 18–45 years) participated in the study after written informed consent. We estimated the sample size before starting data collection on the bases of a previous study (Sartori et al., 2011) in which the dependent variable of interest, i.e., MEPs, and the experimental modulation, i.e., different types of interaction between agents, are comparable to those of the present study. To our knowledge, no other works that match both the scientific question and methods with our study have been published so far. The comparison reported in Sartori et al. that is of greatest interest for this study is the modulation of MEPs amplitude between type of interaction (Object condition at T2 *vs* No-object condition at T2), which was expected to be significant in three cases: for first dorsal interosseous muscle in whole hand grip, first dorsal interosseous muscle in precision grip, and abductor digiti minimi muscle in precision grip. Cohen's d for the three comparisons was .6, .44 and 1.37, respectively. We considered the smallest effect size and computed sample size estimation with G * Power (3.1.9.7, Faul et al., 2007) for a repeated-measure ANOVA (rm-ANOVA), with the following parameters: expected effect size $d = .44$ (i.e., $f = .22$), power of 90%, level of statistical significance of 2%, and epsilon equal to .8 (to account for possible violation of sphericity). Given that previous studies reported good to very high intra-session reliability of MEPs, as indicated by intra-class correlation coefficients between .79 and .99 (Bastani & Jaberzadeh, 2012; Biabani et al., 2018; Dissanayaka et al., 2018; Vaseghi et al., 2015) correlation among repeated measures was set at .7. The resulting sample size amounts to 40 participants.

Recruitment and testing continued until data have been collected from 40 participants who completed the study and who have not been excluded based on predefined criteria (see *Procedure and exclusion criteria*). The study has been approved by the Ethical Committee of the IRCCS Istituto Centro San Giovanni di Dio Fatebenefratelli (Brescia – 25/2020) and was carried out in accordance with the ethical standards of the Declaration of Helsinki. Given the recent COVID-19 outbreak, we carefully followed the hospital safety measures to protect participants' and experimenters' health during experimental sessions.

2.2. *Procedure and exclusion criteria*

The experiment included multiple phases (see Fig. 1). Participants (PTPs) first read and signed the informed consent form and screened for TMS contraindications (Rossi et al., 2009, Rossi et al., 2020). Participants were excluded if any contraindications to TMS were present; otherwise, they received a single-pulse TMS to locate the motor hot-spot and to identify the resting motor threshold (see *TMS*). If no MEPs could be reliably elicited, or if the resting motor threshold was higher than 84% of the maximal stimulator output, PTPs were excluded from the study. Recruited participants performed a *Warming-up* Block and a *Training* Block. The *Warming-up* Block allowed PTPs to familiarise with the task, while the *Training* Block strengthened the stimulus–response associations for the *Main Experiment* (see below). Aim of these blocks was to allow PTPs to experience both the movements that the confederate (hence CF) performed during his/her turn, as well as the related sensorimotor associations. If PTPs were not able to perform the requested action in more than 70% of the last three games of the *Warming-up* Block (see *Experiment structure* for details), they were excluded from the study. Moreover, PTPs were excluded if, during the *Training* Block, more than 50% of catch trials and more than 30% of response timing were laid outside the boundaries of 150 msec–1000 msec. If none of the previous exclusion criteria applied, participants performed the *Main Experiment* (always with a CF) and eventually the *Motor Imagery* Block (see below).

The same exclusion criteria was applied to each block of both the *Main Experiment* and the *Motor Imagery* Block. Finally, in order to reduce the variability of MEPs amplitude, we excluded from further analyses PTPs with electromyographic activity exceeding ±100 μV in the 50 msec before the TMS pulse in more than 30% of trials.

2.3. *Main experiment*

PTP and CF sat at a table side by side, on the left and on the right side, respectively; this arrangement was the most natural one because it matched the stimuli display associated with the sequence of turns (see *Trial* and Fig. 2). PTP was a volunteer from the experimental sample for which data were collected, while CF was a member of our lab who behaved as a naive participant, although his/her responses to visual stimuli were pre-programmed as described below (see *CF's behaviour and distribution of positive and negative outcomes*). Such pre-programming allows controlling CF's behaviour across participants and allows the delivering of realistic and balanced positive and negative feedback within the experiment, even if these were independent of PTP's performance.

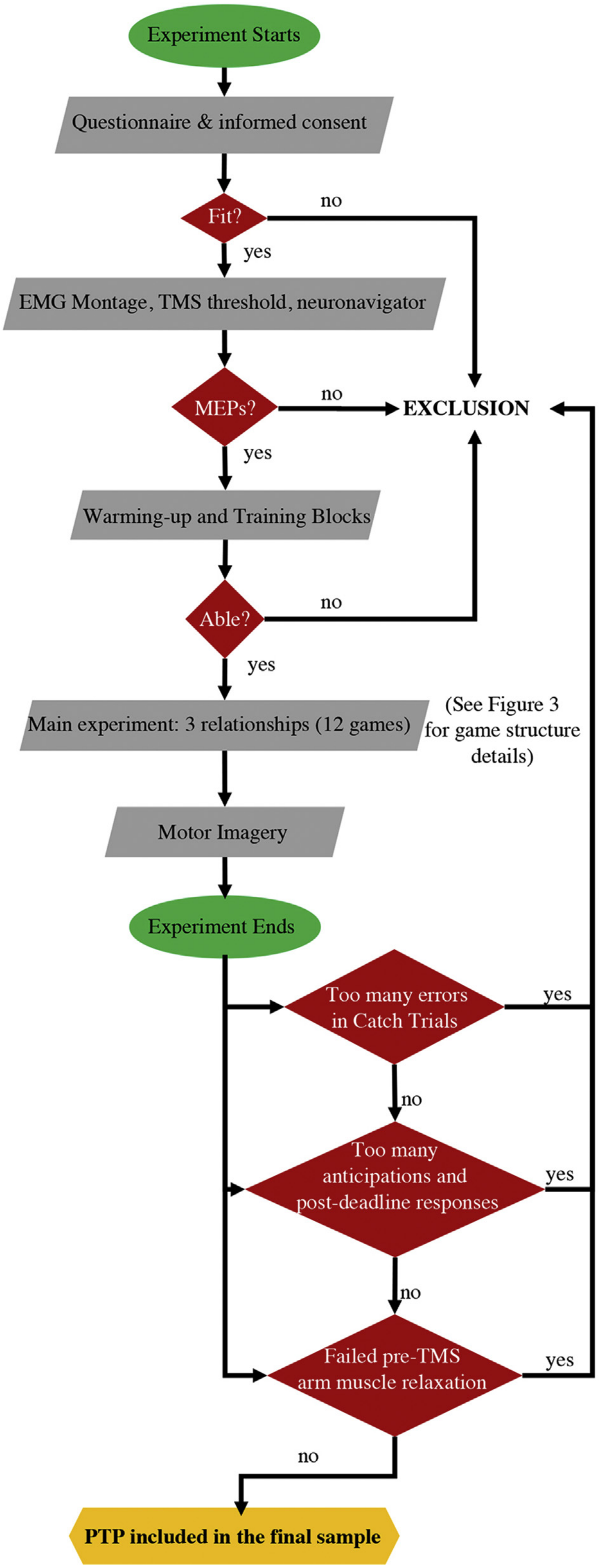

Fig. 1 – Flow chart of the experiment steps and the corresponding decisions. Decision steps followed in order to consider a PTP for the registered analyses.

As illustrated by Fig. 2, PTP and CF faced two identical screens at approximately 1-m distance (screen model ASUS VG248QE, refresh rate = 60 Hz, resolution = 1920 × 1080, dimensions = 61 cm × 34.4 cm). Both persons placed their forearms on the table in a comfortable position to minimise EMG bursts and laid their fingers onto two flat pressure sensors (4 cm × 5.5 cm, model RP-S40-ST) fixed on the table, one for each hand. PTP and CF were asked to shoot a ball displayed on the screen to a target position, by operating a

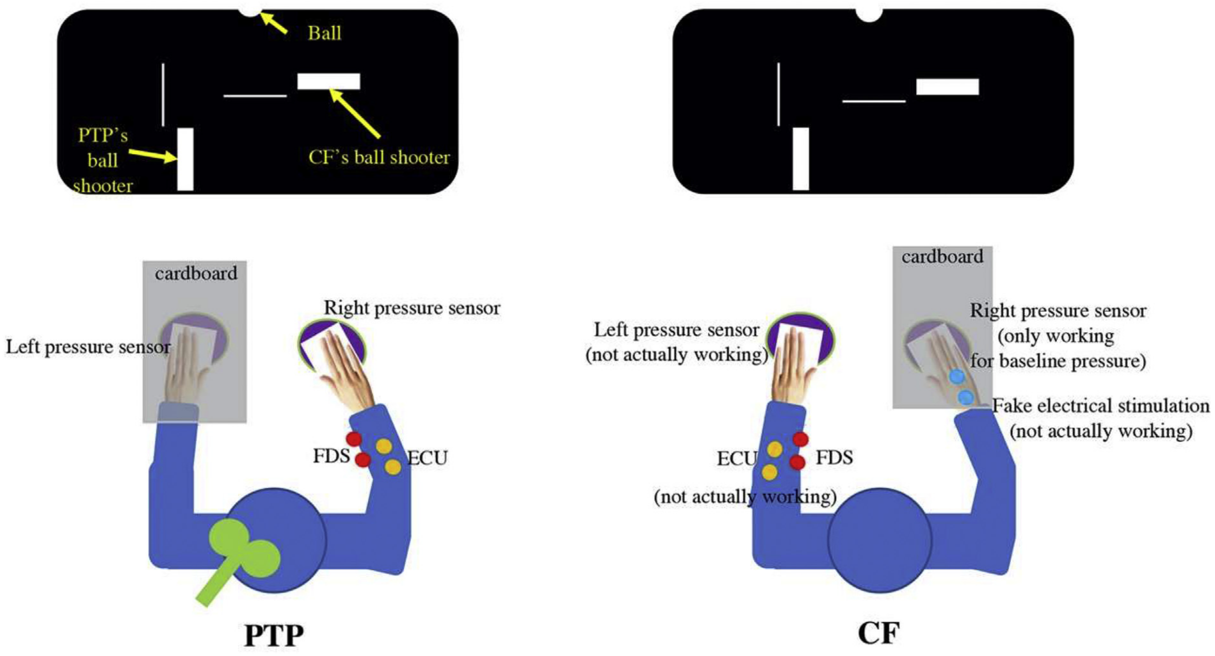

Fig. 2 – Experimental setting. PTP and CF sit alongside, watching the same scene on two separate screens. Left PTP's hand and right CF's hand is covered by a cardboard box. During the first part of the trials, the CF's turn, a single TMS pulse is delivered onto PTP's left motor cortex in order to evoke MEPs in his/her right Extensor Carpi Ulnaris muscle (ECU).

pinball-like ball shooter that can be loaded by acting on the pressure sensors. The CF pretended to perform the task with the right hand (see *CF's behaviour* section) and the PTP performed the task with the left hand. Both PTP's and CF's active hands were covered by a cardboard box to prevent players from seeing their own and the other person's hand movements. In this way, the effects that we were measuring should not have been caused by the observation of the CF's actions. Moreover, this avoids that PTPs realise that the CF's shooter is pre-programmed. A custom-made script based on MATLAB® and Psychophysics toolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) was used to show stimuli and control events on the screens.

2.4. *Trial*

In each trial, the task was performed by the CF and by the PTP sequentially. Therefore, each trial implied two turns: the CF's turn, followed by the PTP's turn (Fig. 3).

Before the onset of each trial, the script checked that there was enough pressure to detect a potential fingers lifting on both CF's right hand sensor and PTP's pressure sensors. If not enough pressure was detected on one sensor, a warning ("Please, place your fingers on sensors") was displayed on the screen until the fingers were correctly placed. When enough pressure was detected on all active sensors, the trial started.

2.4.1. *CF's turn*

At the onset of each trial, two ball shooters and two lines on a black background appeared on the screen, as shown in Fig. 3. The ball shooter on the right side was controlled by the CF, the one on the left side by the PTP. Players saw a grey ball falling from the top-central area of the screen, landing on a horizontal line after 500 msec, changing colour (either red, yellow, or orange) after a random delay between 16 and 200 msec, and then returning grey after 67 msec. The colour change was the go cue, signalling the action to be performed: red indicated press, yellow indicated lift, and orange indicated a catch trial (in this case, both the CF and the PTP had to withhold any movements for the whole duration of the trial). The CF pretended to press (or lift) his/her right hand on the sensor according to the action required by the cue and the CF's ball shooter moved towards the ball after a pre-programmed variable delay (see *CF's behaviour and distribution of positive and negative outcome*). Then, CF's ball shooter hit the ball and pushed it towards the left side of the screen. In a random interval (from −100 to 0 msec) before the CF's ball shooter hit the ball, a single TMS pulse was delivered over the PTP's left motor area to record MEPs for the right hand (see *TMS section*, Figs. 2 and 3).

2.4.2. *PTP's turn*

The grey ball hit a vertical line on the left side of the screen 500 msec after being hit by the CF's shooter (see Fig. 2), and it changed colour after a random interval between 16 and 200 msec (as in CF's turn), signalling to the PTP the action to perform, and it returned grey after 67 msec; the brief presentation of the colour cue in both turns has been chosen in order to force PTP to focus his/her attention on the ball. The colour cue could be either red (press) or yellow (lift). PTP must then press the sensor under his/her left-hand fingers (or lift his/her fingers from it) for at least 300 msec to activate the shooter and push the ball towards the top of the screen. If the action performed was incorrect (pressing instead of lifting, and vice-versa), the PTP must prolong the execution of the correct response in order to activate the shooter and hit the ball. We chose to employ this strategy in order to reduce

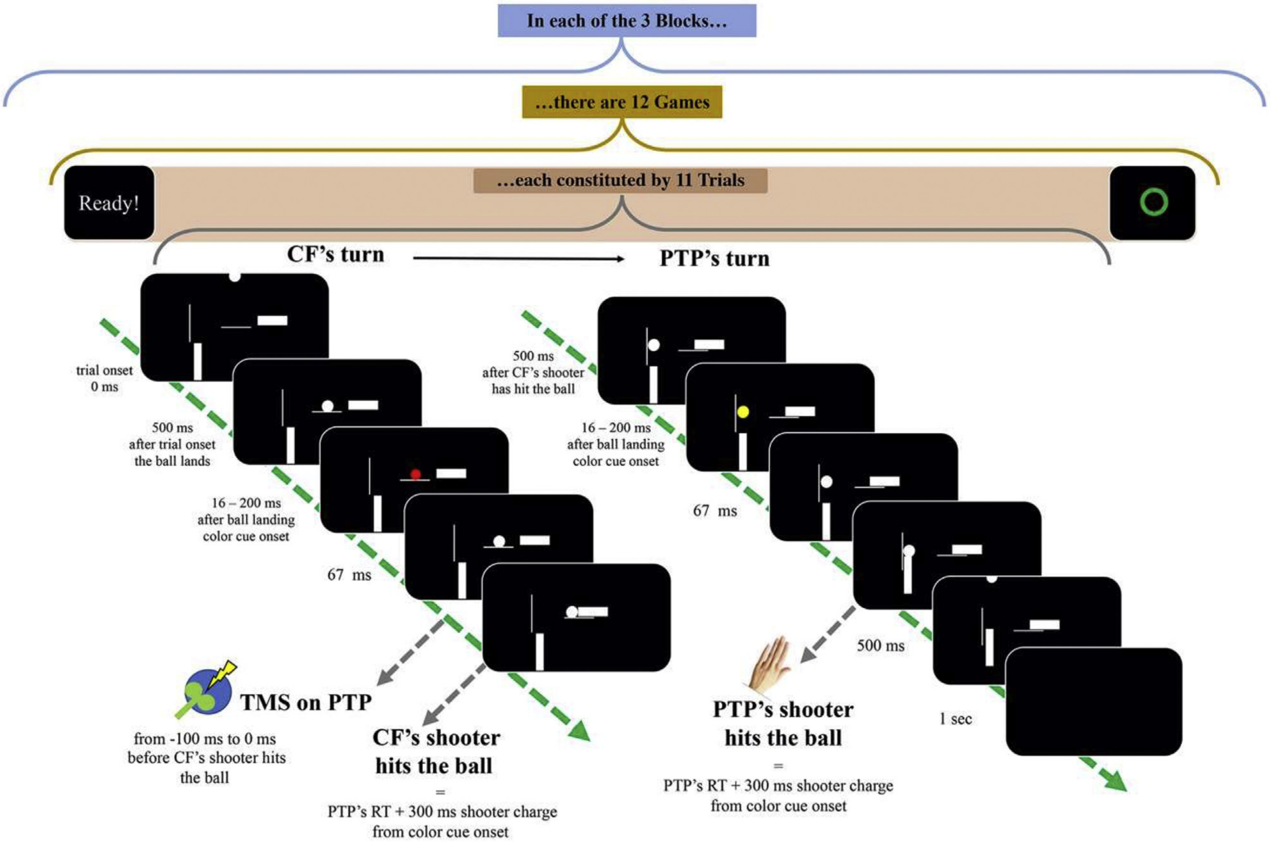

Fig. 3 – Typical game and trial timeline representation. *Up, Left*: the game starts with a screen, lasting 1 sec, prompting players to be ready. *Central*: A series of consecutive 11 trials follows. Each trial is composed by a CF turn, in which the CF performs the task, i.e., CF's shooter hits the ball after a pre-programmed delay from the presentation of the colour cue and a TMS pulse is delivered on PTP's left motor cortex randomly between −100 and 0 msec before CF's shooter hits the ball; then, the PTP's turn starts and PTP performs the task by lifting/pressing his/her hand on the pressure sensor as response to the cue. Catch trials are not represented in this plot. *Up, Right*: after the conclusion of all the trials of a game, a feedback screen is presented, showing the compound outcome. Milliseconds reported next to each display represent the delay from the previous display. Note that TMS will be always within 100 and 400 msec from actual PTP's median RT (see *CF's behaviour and distribution of positive and negative outcome*).

anticipation of responses, since incorrect responses were associated with a high cost. If either PTP's RTs or CF's RTs were slower than 1000 msec and 1100 msec respectively, the shooter would anyway shoot the ball. The trial ended when the ball reached the upper part of the screen (500 msec after being hit by the PTP shooter).

At the end of a trial, both players received feedback on their performance, appearing on their side of the screen, in the following conditions only: If their RT was too fast, a warning "Wait for the cue before moving" was displayed for 2 sec on the corresponding side of the screen. If their RTs were too slow, the warning "Try to be faster"" was displayed for 2 sec on the corresponding side of the screen (see *CF's behaviour and distribution of positive and negative outcomes*). At the end of the catch trial, a positive feedback ("Well done") or a negative feedback ("Pay attention") was presented on the screen, depending on whether they remained still or not.

After 1 sec of blank screen, a new trial started.

2.5. *Experiment structure*

Trials were grouped into "games" including 9 trials and 2 catch trials randomly presented (11 trials per game in total). At the beginning of each game, "Ready" was displayed at the centre of the screen for 1 sec. At the end of each game, the outcome was presented as a visual feedback on the screen for 5 sec, representing the performance for all trials together (Figs. 3 and 4).

Overall, 3 blocks were performed, each one including 12 games (plus another game at the start, that was run as a wash-out without any feedback and was excluded from analyses). Each block involved a different relationship between the two players: Joint, Parallel or Competitive. Order of the blocks was counterbalanced across participants with latin square. The relationship between players for each block was defined at the beginning of the block with instructions to the players, as well as by the type of outcome presented at the end of each game.

2.6. *Instructions and outcome feedback*

In the *Joint* condition, players were instructed to play *together*. The result of each game depended on their joint performance. Players were informed on the outcome of their joint performance with a single circle in the middle of the screen. This circle could be either green, signalling that the sum of their joint RTs was below a given threshold in the majority of the trials, or red in case the threshold was exceeded in the majority of trials. Players' collective goal is to win as many games as possible.

In the *Parallel* condition, players were instructed to play alongside and to expect two distinct and independent outcomes. Each participant was informed on his/her own individual performance in a separate sensory modality. The PTP saw a circle either green or red on his/her side of the screen if his/her RTs were below or over a given deadline in the majority of the trials. Players were told that CF received his/her outcome feedback by a tactile stimulus delivered through electrodes on her right hand. By hiding CF's performance outcome feedback, we aim to further differentiate the *Parallel* from the *Competitive* condition.

In the *Competitive* condition, players were instructed to play one *against* the other, with their goal being to win more games than the other participant. Both players were informed on who was the fastest in the majority of trials. Two circles were presented as outcome feedback, one for each side of the screen. The fastest/slowest between the PTP and CF observed a green/red circle on his/her side of the screen.

Complete instructions can be found in Appendix A.1. Outcome feedback is shown in Fig. 4. Note that feedback screens for CF did not represent the actual players' outcomes, but they were pre-programmed (see *CF's behaviour and distribution of positive and negative outcomes*).

2.7. *CF's behaviour and distribution of positive and negative outcomes*

To obtain the same ratio between positive and negative outcomes across blocks and across PTPs, CF's responses were pre-programmed by the script based on PTP's behaviour, while CF only pretended to perform the task.

For each trial, CF's RTs were calculated as the median of PTP's RTs in the previous five trials plus a variable number between −100 msec and +100 msec. As such, RTs were either slower (Slow trials) or faster (Fast trials) than PTP's median RT. For the first trial, CF's RT was 400 msec; for trials 2 to 5, the median of the available previous trials was used. Therefore, the valid time-range of CF's responses was 50–1100 msec. By adding a 300 msec of shooter loading, the resulting interval range between the colour cue presentation and the movement of CF's shooter was 350–1400 msec. Despite the valid time-range for CF being wider than the valid time-range for the PTP, it is very unlikely that extreme values are programmed. For example, to obtain a RT equal to 50 msec, at least three PTP's RTs in the previous five trials should be 150 msec or shorter and the program should randomly select −100 from ±100 range.

In order to simulate a non-perfect performance, in 4 trials per block CF was too slow, while in other 4 trials his/her performance was too fast. Within one block, the feedback screen for one catch trial signalled that CF has moved, leading to negative feedback.

The outcome feedback was provided at the end of each game so that the win/loss ratio out of 12 games was 50%, i.e., 6 wins and 6 losses, for each relationship. Despite the outcome feedback being independent of participant's behaviour, they were programmed to be realistic, considering the relationship between PTP's RTs and CF's RTs in the 9 non-catch trials within a game.

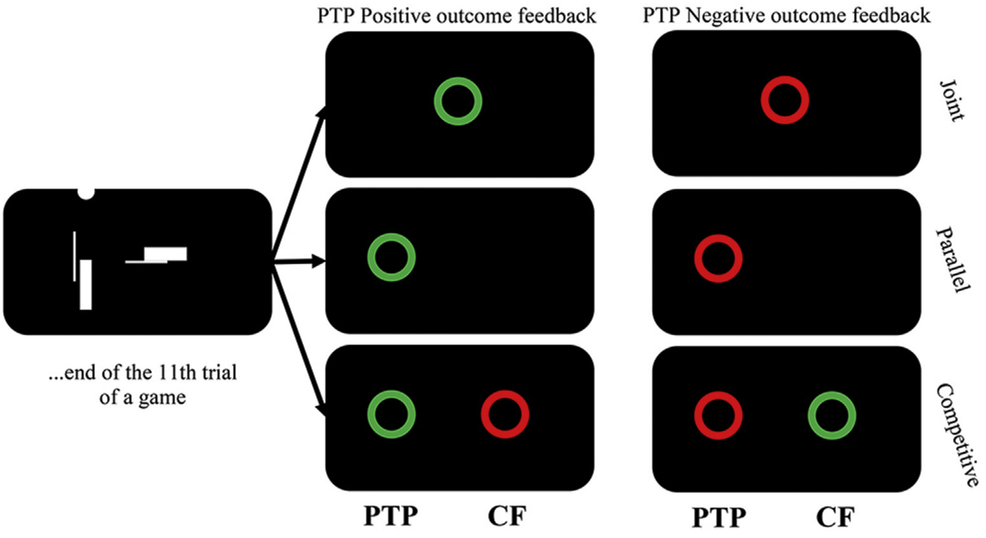

Fig. 4 – Outcome feedback. Types of outcome feedback provided on the screen, labelled according to PTP's perspective. The green circle, shown on the PTP's side of the screen for *Parallel* and for *Competitive* condition, and on the center of the screen for the *Joint* condition, represents a success in the game. Conversely, the red circle represents a loss in the game. In the *Parallel* condition, only the outcome feedback for the PTP is displayed, while the CF pretends to receive outcome feedback through fake skin stimulation.

Across the 12 games of each block, CF's slow responses were distributed unevenly, ranging from 2 trials out of nine (in one game) to 7 trials out of nine (in one game). In the remaining games, CF responses were slow in 3 and 6 trials (in two games, respectively), as well as in 4 and 5 trials (in three games, respectively). As for PTP's outcome feedback, these were given at the end of each game. In the Joint condition, the feedback was negative when the CF's RT were too slow (this happens in games with 5, 6, and 7 slow trials out of nine – 6 games) and positive when CF's RT were too fast (in games with 2, 3, and 4 trials out of nine – 6 games). The opposite outcome feedback was delivered to the PTP on the correspondent games during the *Competitive* condition. Instead, during the *Parallel* condition, the outcome evaluation was randomly distributed across games, i.e., no connection was made between CF's performance and PTP outcome. Indeed, since this relationship is meant to create a setting for two individuals to play the same game in the same room, but not jointly, the outcome feedback for the PTP was independent of CF's responses.

2.8. *Warming-up and Training Blocks*

Before the *Main Experiment*, PTP underwent two blocks in which he/she performed both turns of the trial by himself/herself, i.e., both CF's turn and PTP's turn. In this case, the PTP used the right hand to shoot the ball to the left side, and the left hand to shoot the ball up to the top of the screen.

In the *Warming-up* Block, PTP played a full set of 13 games to get familiar with the paradigm. During these trials, the speed of the ball was very slow at the beginning and increased in each game, to reach the speed of the *Main Experiment* in the last 6 games.

During the *Training* Block, PTP were required to play a full set of 13 games, performing both CF turn and PTP turn, as in the *Warming-up* Block. The *Training* Block aimed to let PTP have a first-person experience of what CF did in his/her turn during the *Main Experiment*. Before PTP started the *Warming-up* and *Training* Blocks, it was told that CF had already performed his/her *Warming-up* and *Training* Blocks. No TMS was delivered during these two blocks.

Since *Warming-up* and *Training* Blocks were run to familiarise with the task and to build a sensori–motor association between colour cues and responses, we differentiated the feedback in these blocks compared to the blocks of the *Main Experiment*. First, if PTP provided the wrong response to the cue, the ball was immediately hit by the shooter and, at the end of the trial, “wrong response” appeared on the screen on the side of the error. Second, the feedback at the end of each game was split to show separately the percentage of correct responses and the percentage of correct non-response in catch trials. If percentages were below the thresholds for exclusion criteria, the percentages were shown in red.

2.9. *Motor Imagery Block*

The *Motor Imagery Block* was run at the end of the *Main Experiment* and it was derived from a pilot experiment that we have run as a positive control to show evidence that MEPs can be manipulated in our experimental setting (See Appendix A.3). In this block, PTP played 13 games alone; Each trial included two turns: In the first turn (CF's turn in the Main Experiment), PTP had to imagine performing the correct response with their right hand; in the second turn (PTP's turn in the Main Experiment), PTP's task was to move their left hand to activate the ball shooter, exactly as in the *Main Experiment*. The rationale for this choice originates from the conjecture that motor imagery should produce muscle-specific effects on MEPs similar to those we predict in the joint condition. In line with previous studies on motor imagery (Lebon et al., 2019; Rossi et al., 1998), we expected that motor imagery selectively increases MEPs amplitude in the muscles involved in the imagined actions.

2.10. *MEPs acquisition and preprocessing*

We stimulated PTP's left primary motor cortex using a Super Rapid transcranial magnetic stimulator connected to a 70-mm figure-of-eight coil (Magstim Company, Whitland, UK). We recorded electromyographic signals (EMG) from PTP's Extensor Carpi Ulnaris (ECU) and from the Flexor Digitorum Superficialis (FDS) on the resting right forearm using two couples of disposable surface electrodes. The former were used to obtain MEPs (ECU-MEPs) employed in our primary analyses, the latter to control muscle contraction in the arm before TMS delivery. Two pairs of electrodes were attached to CF's left forearm, but they were not connected to the amplifier.

The EMG was acquired using a g.HIamp multichannel amplifier (g.tec medical engineering GmbH), sampled at 9600 Hz. A band-pass filter between 10 and 2500 Hz and a notch-filter was applied for visualisation only, as needed.

To identify the region to stimulate and the stimulation intensity, we proceeded as follows:

1. To locate the cortical hotspot of ECU, i.e., the spot that produces higher MEPs on average, we moved the centre of the coil roughly 3–4 cm to the left from the vertex;
2. In that position, single pulses were delivered starting from 30% of the intensity of the stimulator up to 70%, in 5% steps. This step-wise procedure helped naive participants to relax and get acquainted with the setting and the stimulation sensations.
3. We then grid-searched the left hemisphere by moving the centre of the coil of ~1 cm in different directions, in an area roughly circumscribed by a 4 × 4 cm square, in order to find the hotspot.

Once identified the hotspot, we found the resting motor threshold (rMT) of ECU with the PEST algorithm (Awiszus, 2003, 2011; Rossi et al., 2009, Rossi et al., 2020) throughout the experiment, TMS stimulation intensity was set at 120% of the rMT of ECU.

We employed a neuronavigation system (SofTaxic 3.4.3, E.M.S., Bologna, Italy) to keep the coil stable on the hotspot throughout the experiment. PTP's head fiducials were co-registered to a standard head 3D reconstruction.

We delivered one TMS pulse in each trial during CF turn, −100 to 0 msec before the CF's shooter moves; in this way, TMS was always delivered between 100 and 400 msec from median PTP's RT (see *Trial* and Fig. 3).

In order to avoid potential biases, MEPs were analysed as blinded data according to the following steps: firstly, we applied off-line a band-pass filter between 10 and 2500 Hz and a 50 Hz notch filter to reduce artefacts. We calculated for each MEP the peak-to-peak amplitude by subtracting the lowest peak from the highest one in an individualised window between 10 and 50 msec after the TMS pulse. Finally, we visually checked and corrected if the peaks have been measured on artifactual activity.

In order to reduce the variability of the MEPs, we checked if both ECU and FDS were relaxed before TMS pulses; we classified a muscle as relaxed if the EMG did not exceed ±100 μV peak-to-peak amplitude in the 50 msec before the TMS pulse. Trials in which this threshold was exceeded were excluded from analyses. MEPs having peak-to-peak amplitude smaller than 50 μV were also discarded from the analyses. Finally, median MEP were calculated for each condition, to reduce the impact of possible outlier values (Wilcox, 2009).

In order to "wash out" the effects of the previous relationship block, the first game of each block was excluded from analyses. The MEPs of TMS trials in which the CF provided responses too fast and too slow (8 times per block) were not analysed.

To sum up, for each condition (*Joint*, *Parallel*, and *Competitive*), 9 TMS pulses were delivered for each of 12 games, resulting in 108 pulses. Considering that CF's performance was too fast or too late in 8 trials per block, this leaves a maximum of 100 analysable trials per block.

Therefore, MEPs were calculated based on a maximum of 50 trials for each cue colour and for each condition, which is greater than the majority of TMS experiments involving MEPs and greater than the necessary number of trials to obtain very high reliability of MEPs (Bastani & Jaberzadeh, 2012; Biabani et al., 2018). The high number of MEPs increases the reliability of MEPs and statistical power.

2.11. *Registered statistical analyses*

If PTPs represent the collective goal motorically, they should represent the hand actions (right hand fingers extension or pression) that the CF is expected to perform according to the presented cue.

To test our conjecture of shared motor plans, the critical variable is the *difference* in amplitude of ECU-MEPs between lift trials and press trials in CF's turn. The analysis of this difference makes it more likely that our results are explained by the instantiation of a motor representation, and excludes more general factors such as increased/decreased arousal, or salience of the stimuli; indeed, while these factors are known to have nonspecific effects on MEPs amplitude, in our case the MEPs difference for lift and for press trials indicates a selective modulation of the muscle involved in one of the two actions.

Given that ECU is an extensor muscle, if the PTP covertly implements the CF's action, then ECU-MEPs should be higher in trials in which CF is supposed to perform a "lift" action than in trials in which he/she should perform a "press" action. This will be tested by comparing the median ECU-MEPs recorded in "lift" trials with the median ECU-MEPs recorded in "press" trials in the *Joint* condition using a one-tail repeated-measures *t*-test. If results indicate that the "lift-press" difference is significantly greater than zero, we will proceed to compare it across conditions.

Specifically, our conjecture would be supported if the "lift-press" difference in ECU-MEPs would be higher in the *Joint* condition compared to both the *Parallel* and to the *Competitive* conditions. Therefore, we will separately calculate for each relationship a compound measure "ECU-MEP_diff" by subtracting the median of the ECU-MEPs in press trials, from the same measure recorded during lift trials. Then, a one-way rm-ANOVA with factor Relationship (3 levels: Joint, Parallel, Competitive) will be performed on ECU-MEP_diff, with cut-off *p*-value at .02. In case non-sphericity corrections will be needed, Greenhouse-Geisser correction will be applied. If significant, two planned comparisons, *Joint* versus *Parallel* and *Joint* versus *Competitive*, will be conducted using one-tail paired *t*-tests. We will apply Bonferroni correction, considering a total of two one-tail comparisons, resulting in a cut-off *p*-value of .02.

Eventually, as a positive control, we will test the difference in median ECU-MEPs amplitude between motor imagery of lift and press movements using a one-tail repeated-measures *t*-test.

In case the dependent variable is not normally distributed, values will be z-score transformed.

3. Results

3.1. *Registered analyses*

We enrolled 44 participants. Each session lasted approximately 2.5 h, including about 30 min for session set up, 30 min to train participants, and 1.5 h for testing. No adverse effects due to TMS application were reported.

3.2. *Exclusion criteria*

No participants reported contraindications to TMS. One participant had a resting motor threshold above 84% of the maximal stimulator output, one dropped out the experimental session before the motor threshold hunting procedure. After removal of trials with excessive pre-TMS contraction, two participants were left with only 69% and 67.6% of valid trials in one of the *Main Experiment* conditions, and were hence excluded from the registered analyses. No participant was excluded due to poor performance. After the application of exclusion criteria, the analysed sample included data from 40 participants.

3.3. *Final sample*

The final sample included 22 females, mean age: 28.4 ± 5.9 SD years, mean Oldfield: 74.5% ± .2% SD. The mean TMS intensity was 65% ± 9.6% SD of the maximal stimulator output.

In the last three games of the *Warming-Up* block, on average participants responded correctly in 91.4% ± 6% SD of the trials.

In the *Training* block, participants responded on average to 6.1% ± 5.2% SD of the catch trials, and outside the

150–1000 msec time-window on average in 3.5% ± 2.1% SD of the trials.

In the *Main Experiment* blocks, no participant was excluded due to a high number of responses to catch trials (mean = 8.9% ± 8.7% SD), or for responses produced outside the 150–1000 msec time-window on normal trials (mean = 4.8% ± 4% SD).

Considering only the cohort of participants included for further analysis, on average 2.3% ± 5% SD of trials were excluded due to excessive pre-TMS muscular contraction or due to MEPs smaller than 50 μV.

After the above mentioned data pre-processing, on average 49.4 ± 2.6 SD trials were left in each cell of the experimental design (minimum trial number per condition = 32).

3.4. *Motor imagery block*

To test whether MEPs amplitude could be modulated in association to motor representations in our experimental setting, we conducted a "Motor Imagery positive control" block at the end of the *Main Experiment* blocks, and compared the median value of the ECU-MEPs for CF's lift trials with those obtained for the CF's press trials.

First, data distribution was checked through a Shapiro–Wilk Normality Test ($W = .89$, p-value = .001). Since the data were not normally distributed, we applied a z-score transformation to the whole dataset (including all the conditions involving TMS), separately for each participant. After z-scoring, the adopted normality-test showed no evidence of deviation from normal distribution ($W = .96$, p-value = .156). We carried out a "one-tail" t-test comparison between z-scored ECU-MEPs evoked during the presentation of CF's lift cues and z-scored ECU-MEPs evoked during presentation of CF's press cues (Fig. 5, right panel). According to our hypothesis and in line with results of the pilot study, we expected a greater z-scored ECU-MEPs amplitude in the CF's lift trials compared to the CF's press trials. The one-tail paired sample t-test comparison indicates greater z-scored ECU-MEPs amplitude in CF's lift trials compared to CF's press trials [t = 2.79, df = 39, p-value = .004; Cohen's d = .44 (small)].

3.5. *Joint condition*

As stated in the registered analysis, firstly we aimed at testing whether participants in the Joint condition activated motor representations corresponding to the actions the CF should have performed. As in the case of Motor Imagery positive control, we expected that the amplitude of ECU-MEPs was greater in CF's lift trials compared to CF's press trials.

We initially checked the distribution of the difference between ECU-MEPs in CF's lift versus CF's press, by applying the Shapiro–Wilk Normality Test to the data. Given that data were not normally distributed ($W = .90$, p-value = .003), we applied a z-score transformation to the whole dataset (including all the conditions involving TMS) separately for each participant. After z-scoring, the adopted normality-test showed no evidence of deviation from normal distribution (Shapiro-test: $W = .98$, p-value = .872). The one-tail paired sample t-test comparison on z-scored ECU-MEPs showed no indication of greater amplitude in CF's lift trials compared to CF's press trials [t = .38, df = 39, p-value = .35; Cohen's d = .06 (negligible)]. Given that our main hypothesis was not corroborated, no further registered analyses were performed (Fig. 5, left panel).

3.6. *Exploratory analyses*

Registered analyses showed no evidence of motor representation modulation in the Joint condition. This would seem to be in contrast with our hypothesis that when acting together people can represent the collective goal of their actions motorically. However, the negative result could admit an alternative (partially, at least) explanation appealing to the effect size. Indeed, the motor representation modulation was previously found to be smaller in the Joint condition compared to a bimanual control condition (della Gatta et al., 2017). This could indicate that our dependent variable could have been not sensitive enough. We then decided to set a new dependent variable that included contributions not only from the Extensor Carpi Ulnaris (ECU), but also from the Flexor Digitorum Superficialis (FDS).

3.7. *Z-scored (ECU) minus z-scored (FDS) as exploratory dependent variable*

Registered analyses included only ECU as the muscle recorded to extract MEPs even though we recorded FDS activity as well to control for potential pre-TMS contraction. In order to select an intensity for cortical stimulation, procedures for threshold hunting are usually based on one recorded muscle only (Rossini et al., 2015). Even though criteria and procedures for intensity settings might be created to include more than one muscle (Ubaldi, Barchiesi, & Cattaneo, 2015), this is a less conservative approach. The potential problem we foreseen with the inclusion of FDS-MEPs as part of the registered dependent variable was that they might have been extremely small, so that little or no modulation by our manipulation could be observed due to potential floor effects; our line of reasoning was that, while it was useful to record FDS activity as a pre-TMS contraction control, including FDS-MEPs into the dependent variable measure could in principle have generated noisier data compared to using ECU alone. However, given that FDS-MEPs were not too small, this additional information might contribute to producing a sharper measure of activated motor representations.

We thus exploited, as a dependent variable, the difference between ECU-MEPs and FDS-MEPs (ECU-FDS). Our rationale was that ECU-FDS may better reflect movement-specific motor representations; indeed ECU is more active while extending fingers and wrist, while FDS is more active while flexing fingers: if we consider the negative value of FDS-MEPs we expect that they behave similarly to ECU-MEPs, i.e., being higher in CF's lift trials compared to CF's press trials; thus ECU minus FDS should maintain or increase the direction of the ECU-MEP modulation if a specific motor representations was instantiated. At the same time, subtracting FDS-MEPs from ECU-MEPs should reduce noise due to nonspecific common factors such as arousal, attention, and electrodes cross-talk.

Therefore, we tested the sensitivity of ECU-FDS to modulations of motor representations as in the *Motor Imagery* block, and we then applied this measure to test our main hypothesis. These steps are explained in detail below.

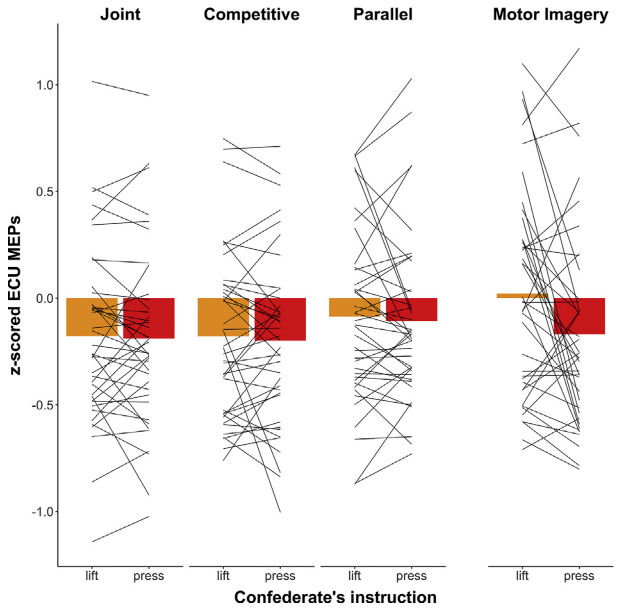

Fig. 5 – Results of Registered Analyses. For each block of the *Main Experiment*, yellow (red) bars represent the average z-scored (ECU-MEP) amplitude when participants were presented with a yellow (red) CF's cue, i.e., a lift (press) instruction. Grey lines represent the median z-scored (ECU-MEP) of each participant, for each condition.

First, we processed FDS data with the same preprocessing pipeline employed for ECU pre-processing (see the registered analyses) and checked that each participant and each condition included at least 30 trials in which ECU-MEPs had been evoked, i.e., amplitude over 50 uV. Based on this criteria, four participants were excluded from further analyses, leaving 36 participants for the following exploratory analyses. Since the median amplitude of FDS (381 μV ± 294.4 SD) and ECU (1058.90 μV ± 606.7 SD) were not comparable across participants (Wilcoxon-test: *W* = 1121, *p*-value = .00000001), we decided to z-score the whole dataset separately for each muscle, within each participant. In this way, the range of amplitudes of the two muscles would be comparable. We hence set our exploratory dependent variable as ECU-FDS, i.e., "median of z-scored ECU-MEPs minus median of z-scored FDS-MEPs", computed for each cell of the experimental design.

We then tested the sensitivity of ECU-FDS to detect changes in motor representation by comparing CF's lift versus CF's press trials in the Motor Imagery positive control, as we did in the registered analyses. Since data distribution indicated no deviation from normal distribution (Shapiro Test: *W* = .95, *p*-value = .144), we proceeded with a one-tail paired sample *t*-test comparing ECU-FDS in CF's lift and CF's trials. The comparison showed a statistically significant difference between CF's lift and CF's press trials along with the hypothesised direction [t = 3.13, df = 35, *p*-value = .002; Cohen's *d* = .52 (medium)], with a greater effect size compared to the same comparison on the registered dependent variable (Fig. 6, right panel).

Finally, since the ECU-FDS showed a qualitatively greater effect-size than the registered dependent variable, we compared CF's lift and CF's press conditions also in the Joint blocks (Fig. 6, left panel). This comparison produced a slight tendency towards the hypothesised direction [t = 1.51, df = 35, *p*-value = .07; Cohen's *d* = .25 (small)].

3.8. *Task switching costs and fatigue*

Considering that the experiment was lengthy, that participants performed all conditions one after another, and that conditions were motorically identical, we further ran analyses to control the effect of task-switching and fatigue. We reduced the dataset to include only the first block, transforming the experimental design into a mixed design with the colour cue (associated with CF's lift and press) as a within-subject factor and the conditions (Joint, Parallel, Competitive) as between-subject factor. In this way, we considerably reduced both the length and the switching costs of the experimental session, at the cost of power reduction. In the following analysis we took advantage of the exploratory ECU-FDS dependent variable, because it turned out to be slightly more sensitive to the construct we aimed to measure. The ECU-FDS dependent variable was constructed in the same way as described in the previous analysis, but calculating ECU and FDS z-scores after considering only the first block.

First, we looked into the Joint condition, as in the previous registered and exploratory analyses. Data did not deviate from normality (*W* = .96, *p*-value = .819), so we proceeded by comparing the ECU-FDS on CF's lift trials against CF's press trials by performing a one-tail paired sample *t*-test (Fig. 7). Results showed greater ECU-FDS in CF's lift trials compared to CF's press trials at *p* threshold values [t = 2.30, df = 12, *p*-value = .02007; Cohen's *d* = .64 (medium)]. Following the logic of the registered analysis plan, we reduced the lift/press factor to one measure consisting of the ECU-FDS index recorded on CF's lift trials minus the same index recorded on CF's press trials; we then performed a between-subjects ANOVA with relationship as the only factor. Before performing the ANOVA, we checked deviation from normality of the new dataset (Shapiro-Test: *W* = .968, *p*-value = .383). ANOVA produced no significant difference between relationships [*F*(2,33) = 1.09, *p* = .349].

Eventually, we explored whether the effect found on the joint condition in the previous analysis deteriorated with the progression of the experimental session. We performed a one-way ANOVA with the order of the Joint block as between-subjects variable; the dependent variable ECU-FDS was constructed in the same way as described in the previous analysis, but calculating ECU and FDS z-scores once only the Joint blocks were considered (Fig. 8). Similarly to the previous analysis, we condensed the differential effect of CF's lift and press as ECU-FDS on CF's lift minus ECU-FDS on CF's press. ANOVA on Joint blocks tended to significance: *F*(2,33) = 3.82, *p* = .032.

4. Discussion

Our study aimed at investigating the neural underpinning of acting together. Our main conjecture was that when acting together people can represent collective goals motorically. If this were the case, from the point of view of each participant's motor system it would be almost as if they were representing the whole action. This would mean that in each participant there are motor processes concerning not only actions they will perform but also actions the confederate will perform.

In order to test this conjecture, we carried out a TMS experiment exploring, for the first time, whether and how collective goals can be represented motorically. In doing this, we exploited the amplitude of MEPs as an indirect measure of the excitability of the motor cortex. Specifically, we assessed the variations in MEPs amplitude of participants when acting together with a confederate. We expected that, if participants represented the collective goal motorically, their MEPs amplitude would vary according to the actions the confederate had to perform.

In our pre-registered experimental plan, we included criteria that allowed us to control for some basic aspects of task execution: exclusion based on reaction times ensured that participants had learnt the association between stimuli and action to perform and that they were engaged in the task during their turn to move; exclusion based on catch trials ensured that participants were also engaged during the confederate's turn and attended to the instructions they received. Given the low number of errors in task performance, we could infer that participants were following instructions and that the task was easy to perform.

The choice of MEPs as a dependent variable was based on previous literature supporting that the representation of actions in motor areas is associated with muscle-specific increase in MEP amplitude. Indeed, modulation of MEP amplitude has been found for motor processes as action planning and execution (van Elswijk et al., 2008), as well as action observation (Bardi et al., 2015; Cattaneo et al., 2013) and motor imagery (Lebon et al., 2019). In line with this literature, we included two motor imagery blocks in the pilot experiment, and one in the *Main Experiment*, to show evidence that MEPs could be modulated in our experimental setting. As expected, we found that MEP amplitude in ECU muscle increased when participants imagined to lift their fingers, a movement that would require contracting the ECU, compared with when they imagined to press their finger, a movement that requires to relax the ECU.

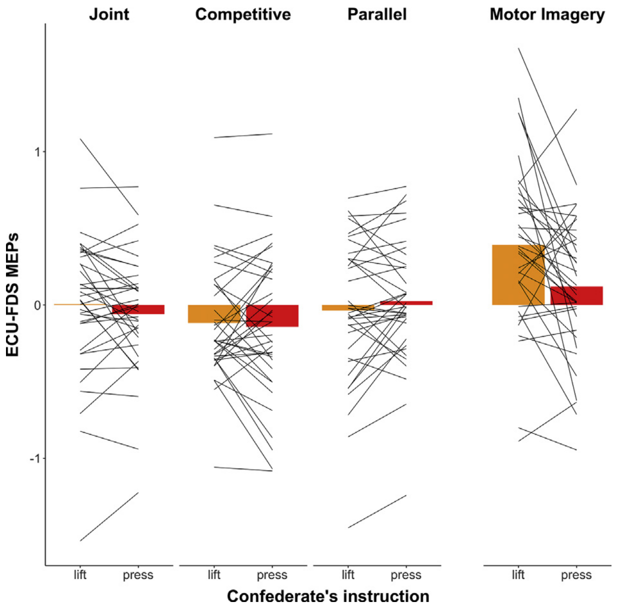

Fig. 6 – Results of Exploratory Analyses using ECU-FDS. For each block of the *Main Experiment*, yellow (red) bars represent the average ECU-FDS amplitude when participants were presented with a yellow (red) CF's cue, i.e., a lift (press) instruction. Grey lines represent the median ECU-FDS of each participant, for each condition.

We therefore exploited MEP amplitude to test the conjecture of a motor representation of collective goal in acting together. Unfortunately, we did not find evidence under the pre-registered analyses of a modulation of the motor representation of the confederate's action in the Joint condition. Given the lack of participants' MEPs modulation by the action performed by the confederate, no comparisons were run between the Joint condition and the two other conditions of the task, i.e., the Parallel and the Competitive conditions.

Even though we have to consider that, differently from previous studies, the present work involves TMS on the primary motor cortex, this negative result would seem to be in contrast with a large amount of behavioural (Clarke et al., 2019; della Gatta et al., 2017; Meyer et al., 2013; Sacheli et al., 2018; Török et al., 2019) and electrophysiological (Kourtis et al., 2013, 2014, 2019; Loehr et al., 2013; Novembre et al., 2014) studies suggesting that when acting together agents represent their confederate's action in addition to their own action almost as if they had to perform the whole action.

A potential explanation of this contrast could be that, differently from most previous studies, the task we used to investigate collective goal representation did not require an ongoing motor coordination between the participants and their confederate other than merely taking their own turn in playing the game. Indeed, the Joint condition differed from both the Parallel and the Competitive conditions with respect to the action outcome only. However, although in the Joint condition the participants' and confederate's actions were directed to a collective goal (i.e., pressing the ball to a common target within a fixed time), their actual execution was relatively independent. No participants could help or do anything in order to improve the performance of their confederate. They had just to wait for their own turn, exactly as in the Parallel and Competitive conditions.

The absence of motor coordination challenges might have played a role in reducing the motor involvement in the Joint condition. Our aim was exploring the neural underpinning of collective goal representation. The negative results concerning the lack of participants' MEPs modulation by the confederate's action would not exclude that the motor system can be significantly involved in collective goal representation when the achievement of the collective goal requires motor coordination.

Following this line of reasoning, a compatible explanation of the lack of participants' MEPs modulation could invoke the effect size. Indeed, della Gatta et al. (2017) found that the modulation of motor representation in the Joint condition was smaller than when bimanual coordination was actually required. Our negative result could be therefore due, at least partially, to the reduced size of the modulation of motor representation in absence of coordination challenges.

In order to overcome this potential limitation, future studies could take advantage of a finer measurement of motor representation. MEPs amplitude is a well-established measure of corticospinal excitability. However, it is known to be modulated by multiple factors, including both motor and non-motor factors (Andersen et al., 1999; Hajcak et al., 2007; Löfberg et al., 2014; van Elswijk et al., 2007, 2008). For this reason we decided, in the explorative analyses, to exploit the combination of the MEPs amplitude from the two (antagonist) recorded muscles as a dependent variable (ECU-FDS). Subtracting FDS-MEPs from ECU-MEPs should reduce noise due to nonspecific common factors such as arousal, attention, and electrodes cross-talk. To this regard, it is worth noting that the *Motor Imagery* positive control (our "ground truth") showed a greater effect size for ECU-FDS compared to ECU alone. Interestingly, the choice of ECU-FDS as a new dependent variable in the Joint condition resulted in a trend towards a significant participants' MEPs modulation according to the action the confederate should perform.

Another (and complementary) way of overcoming the potential limitation of this study might require slight modification of the experimental setting. To this regard, participants might be asked to assemble an object together, like a jigsaw puzzle, with each of them adding the missing piece. This might emphasise the sense of doing something together, while keeping the stimuli presentation identical throughout conditions.

Coordination challenges and experimental settings beside, it is worth noting that the present study exploited only MEPs as a dependent variable, thus, we cannot exclude that the jointness of the task modulates activity in action-related regions outside the primary motor cortex. For sake of speculation, premotor cortices might be actually modulated, but suppress their output to the primary motor cortex so that the latter receives no afferent input from them; if this was the case a double-coil approach would come in handy to test this hypothesis (Bestmann & Duque, 2016; Duque et al., 2017; Maule et al., 2015).

Another potential explanation of our null effect is that TMS stimulation distracted participants from the confederate's turn events. Although we cannot completely rule out this possible explanation, we think that it is unlikely, since TMS was delivered towards the end of the confederate's cue presentation, so the potential attentional modulation should not be relevant and differ between conditions as well. However, the issue of the TMS timing might have played a role in the lack of MEP modulation; indeed it can be argued that participants suppressed the modulation derived from the confederate's cue colour change, and since the TMS pulse was provided close to the confederate's response, this putative inhibition could have suppress the signal of interest. In contrast, a TMS pulse closer to the cue colour change might have reduced the influence of a potential inhibition, increasing the likelihood of detecting MEPs modulation. Future experiments are required to explore this issue.

A final limitation of the signal-to-noise ratio to overcome concerned the fact that the whole experimental session was lengthy and tiring. The task was identical across the three conditions; the only difference pertained to the instructions as well as to the outcome feedback. It is possible that participants automatized their behaviour as the session

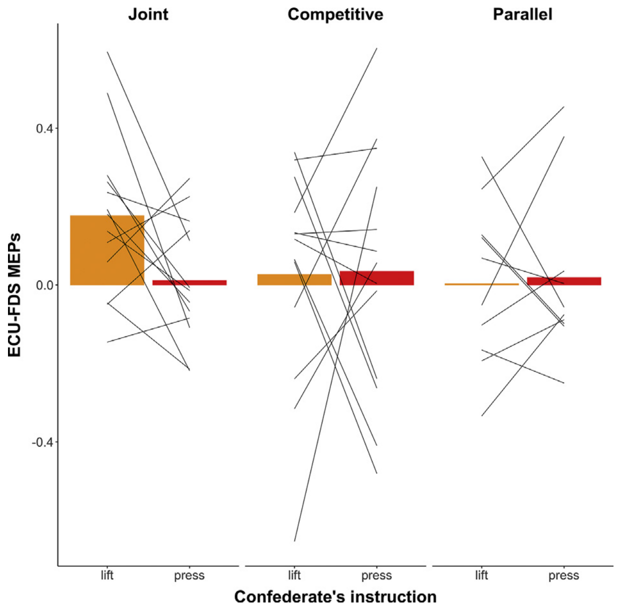

Fig. 7 – Results of Exploratory Analyses using ECU-FDS considering only the first block performed by each participant. For each block of the *Main Experiment*, yellow (red) bars represent the average ECU-FDS amplitude when participants were presented with a yellow (red) CF's cue, i.e., a lift (press) instruction. Grey lines represent the median ECU-FDS of each participant, for each condition.

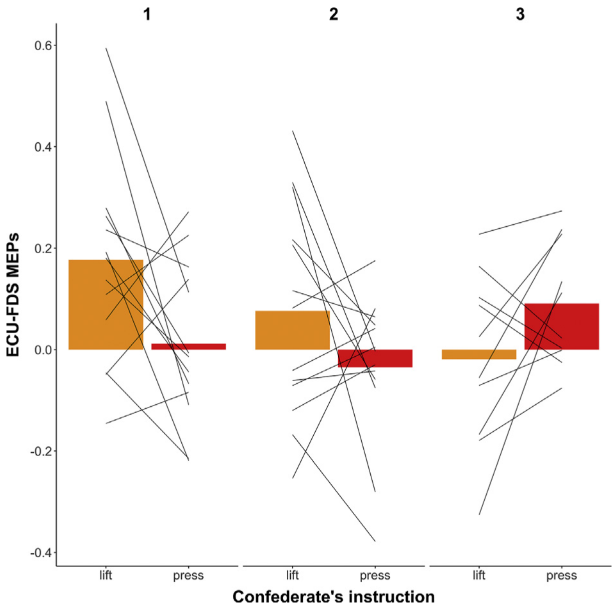

Fig. 8 – Results of Exploratory Analyses using ECU-FDS exploring considering only the Joint condition. For each block order of the Joint blocks, yellow (red) bars represent the average ECU-FDS amplitude when participants were presented with a yellow (red) CF's cue, i.e., a lift (press) instruction. Grey lines represent the median ECU-FDS of each participant, for each condition.

proceeded. In order to reduce the possible effect of task switching and fatigue, we considered in the explorative analyses only data from the first block in all the three conditions, thus simulating a virtual between-subjects experiment. Interestingly, we found that in the first block of the Joint condition participants exhibited a significant ECU-FDS modulation reflecting the action the confederate should perform – even though ANOVA between conditions provided no indication of differential modulation. Finally, we investigated whether the ECU-FDS modulation in the Joint condition shown in the previous exploratory analysis was affected according to the block position within the experimental session. We found a trend towards an ECU-FDS modulation related to the block position.

The present study was a first attempt to explore collective goal representation by taking advantage of single pulse TMS and MEPs recording in agents acting together with a confederate. Our conjecture was that when acting together participants could represent collective goals motorically and this would have modulated their MEPs according to the action the confederate should perform. Unfortunately, we did not find any significant MEPs modulation when participants acted together with the confederate. Although this negative result, we do believe that our study involves some fruitful hints to take into consideration for future testing of collective goals in healthy and psychiatric populations.

Author contributions

Guido Barchiesi: Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization.

Agnese Zazio: Methodology, Formal analysis, Investigation, Writing - Review & Editing.

Eleonora Marcantoni: Investigation, Writing - Review & Editing.

Martina Bulgari: Investigation, Writing - Review & Editing.

Chiara Barattieri di San Pietro: Investigation, Writing - Review & Editing.

Corrado Sinigaglia: Conceptualization, Writing - Original Draft, Supervision, Project administration, Funding acquisition.

Marta Bortoletto: Methodology, Resources, Data Curation, Writing - Original Draft, Supervision, Project administration, Funding acquisition.

Open practices

The study in this article earned Open Data, Open Materials and Preregistered badges for transparent practices. Materials and data for the study are available at https://gin.g-node.org/GuidoBarchiesi/JA_TMS_2022.

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Supplementary data

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