Final Report

Aims

The overall aim of the project was to explore the possibility and provide psychophysiological evidence that, when people act together, the collective goals of their actions are represented motorically.

Acting together is a pervasive feature of human sociality. that is still little understood. It is generally explained appealing to a ‘shared’ or ‘collective’ intention. However, it is possible that when people act together, the collective goals of their actions are sometimes represented motorically. Here, our conjecture is that motor representations may enable joint action and provide interpersonal coordination around goals, even without engaging highly psychological structures such as intentions and mutual beliefs.

Behavioural findings have supported the notion that agents’ motor plans might be related to collective goals (della Gatta et al. 2017; Clarke et al., 2019; Dötsch & Schubö, 2015; Meyer et al., 2013; Ramenzoni et al., 2014; Sacheli et al., 2018; Török et al., 2019). Moreover, a few studies have provided neurophysiological evidence of whether collective goals are motorically represented (Kourtis et al., 2013; Kourtis et al., 2014, 2019; Loehr et al., 2013; Novembre et al., 2014). 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 (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.

Our project involves a series of experiments, to sequentially test specific features of the motor roots of joint action. The first experiment (Barchiesi et al. 2022) involved transcranial magnetic stimulation (TMS) to test if a motor representation of the confederate’s action is active in the motor system when two people are acting together. In this study we did not find evidence that acting jointly involved the instantiation of both players’ motor plan. However, we detected crucial differences between our paradigm and other experimental set-ups in the literature: three key factors were particularly striking: 1) Our task did not involve any form of non-trivial coordination, 2) It was possible that the signal-to-noise ratio related to the dependent variable used was low, and 3) We highlighted much more the jointness aspect of the game. In order to explore these 3 factors, we decided to run a dual-EEG (Experiment 2) and a TMS-EEG experiment (Experiment 3). In experiment 2 (Paper submitted), we tested the motor roots of acting jointly in a paradigm where motor coordination was required, and we exploited the high temporal resolution of the EEG to disentangle between the motor preparation phase and the motor execution phase. In experiment 3, we improved the original paradigm to implement a concrete collective goal and improve feedback of subjects' performance. In this case we employed TMS and TMS-EEG to test for changes in activity in the motor system.

Method (participants, instrument/measures, and procedure)

Experiment 1: TMS-MEP

<u>Experiment 1</u> is now published in Cortex as a registered report (Barchiesi et al. 2022).

The paradigm involved a simple video game (Figure 1) in which participants operated on a "ball shooter", by moving their left fingers on a pressure sensor, while holding the right hand relaxed. Two actions had to be performed, either lifting the fingers from the sensor or pressing them on it, depending on a cue, i.e., a colour change of the grey ball. Participants (PTPs) played the game sequentially with a confederate (CF), who started first. In the Joint condition, players worked together with the collective goal of shooting the ball to a common target. Players won or loosed together. In the Parallel condition, each player shot the ball individually. Players could either win or lose, independently. 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.

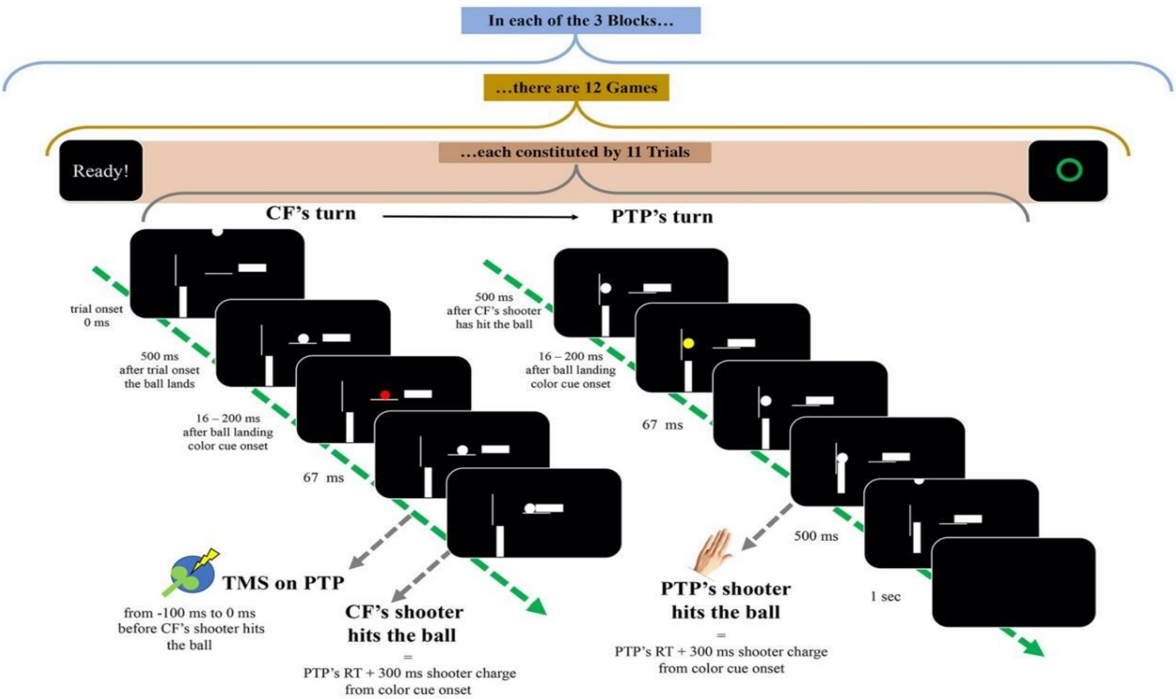


Figure 1. Typical game and trial timeline representation. The game starts with a screen, lasting 1 sec, prompting players to be ready. Central: A series of consecutive 11 trials follows. Each trial is composed by a CF turn, in which the CF performs the task, i.e. CF's shooter hits the ball after the presentation of the colour cue and a TMS pulse is delivered on PTP's left motor cortex 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.

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. To test our conjecture, we tested 40 participants. We delivered single pulse TMS on the left primary motor cortex and we measured motor evoked potentials (MEPs) from Extensor Carpi Ulnaris (ECU) and from the Flexor Digitorum Superficialis (FDS) while he/she was observing the ball shooter acted by the confederate. TMS on primary motor cortex is a primer of the engagement of the motor processes (Cattaneo et al., 2009; Duque et al., 2017). The critical variable is the difference in amplitude of ECU-MEPs between lift trials and press trials. 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 of a "press" action.

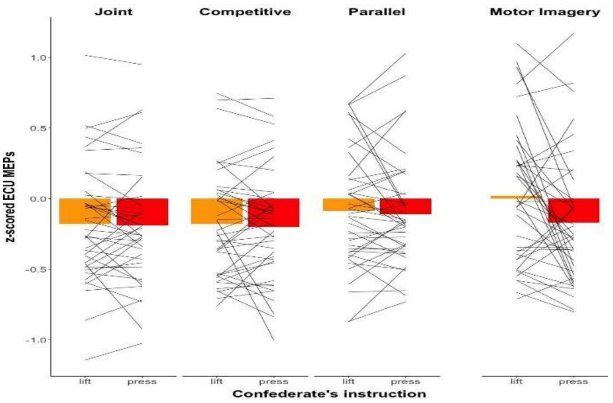
Results and Discussion

Positive control: This condition validated the methodology. As shown in Figure 2, right panel, according to our hypothesis, ECU-MEPs was greater in the CF's lift trials compared to the CF's press trials during motor imagery ($t = 2.79$, $df = 39$, p-value = 0.004).

Registered analyses: As shown in Figure 2, left panel, ECU-MEPs showed no difference between CF's lift trials and CF's press trials in joint actions ($t = 0.38$, $df = 39$, p-value = 0.35). Therefore no evidence of motor representation modulation in the Joint condition was found.

Exploratory analyses: The negative result could admit an alternative explanation that our dependent variable could have been not sensitive enough. Therefore, we 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).

ECU minus FDS as exploratory dependent variable: Our rationale was that the difference between ECU-MEPs and FDS-MEPs (ECU-FDS) may better reflect movement-specific motor representations. First, we tested the sensitivity of ECU-FDS to modulations of motor representations in the Motor Imagery block and found a significant difference between CF's lift and CF's press trials ($t = 3.13$, $df = 35$, p-value = 0.002; Cohen's $d = 0.52$), with a greater effect size compared to the same comparison on the registered dependent variable (Figure 3, right panel). Since the ECU-FDS showed a greater effect-size than the registered dependent variable, we compared CF's lift and CF's press conditions also in the Joint blocks (Figure 3, left panel). This comparison resulted in a tendency towards the hypothesised direction ($t = 1.51$, $df = 35$, p-value = 0.07; Cohen's $d = 0.25$). Interestingly, results showed greater ECU-FDS in CF's lift compared to CF's press at p threshold values in the Joint condition ($t = 2.30$, $df = 12$, p-value = 0.02007; Cohen's $d = 0.64$ (medium)). However, ANOVA performed with relationship (Joint, parallel and competitive) as factor showed no significant difference between relationships ($F(2,33) = 1.09$, $p = 0.349$).



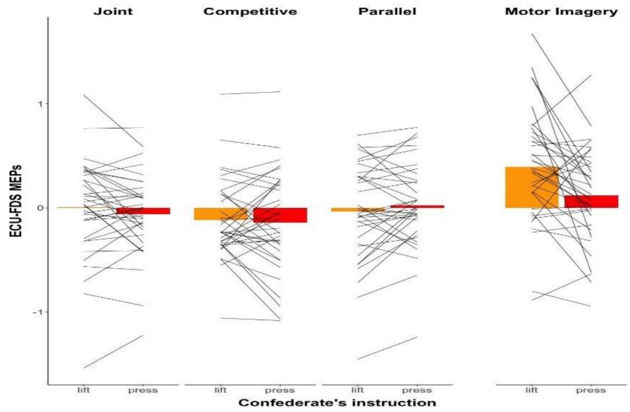


Figure 2. Left. Registered Analyses. For each block of the Main Experiment, yellow (red) bars represent the average z-scored (ECU-MEP) amplitude when CF's had to perfom a lift (press) movement. Gray lines represent the median z-scored (ECU-MEP) of each participant, for each condition.

Figure 3. Exploratory Analyses using ECU-FDS. For each block of the Main Experiment, yellow (red) bars represent the average ECU-FDS amplitude when CF's had to perfom a lift (press) movement. Gray lines represent the median ECU-FDS of each participant, for each condition.

Experiment 2: Dual-EEG

In experiment 2, we decided to introduce the coordination factor, which we believed was a key factor differentiating Experiment 1 from the majority of joint-action experiments.

We tested 20 dyads, corresponding to 40 participants. The experiment involved collection of behavioral and electroencephalography (EEG) from the dyad while they played a video game, either together (Joint condition) or each for himself, simply remaining next to each other (Parallel condition). The experimental paradigm is an adaptation of the paradigm by Satta et al. 2017 based on Barchiesi et al., 2022.

Participants sat next to each other in front of their own monitor. Each participant used a joystick with the dominant (right) hand. Each participant wore a 64-channel EEG headset. Furthermore, with two electrodes attached to the forearm of each participant, we recorded electromyographic activity of the muscles.

The Joint Action condition consisted of a coordination game in which participants manoeuvre a little man each to transport together an object inside an igloo following a traced path. The aim of the game was to be able to carry the object by coordinating with their partner without leaving the marked path. In case of victory, the igloo turned red and green; otherwise it remained white. In the Parallel Action condition, both participants each carried a separate object inside an igloo following a traced path. The task involves coordination in order not to collide, but does not involve a common goal.

The aim of the experiment was to identify neurophysiological markers of the joint action as opposed to a condition in which the participants are required to pursue their own goal individually. The target were The Contingent negative variation (CNV), which represent movement preparation phase, and the Movement Potential (MP), which represent movement execution.

Behavioural data were recorded to control for possible differences between conditions. These behavioural measures include Success rate (%), i.e., the percentage of trials in which participants reached the goal, and Reaction times (rt), i.e., the time interval (in ms) between the go signal and movement onset.

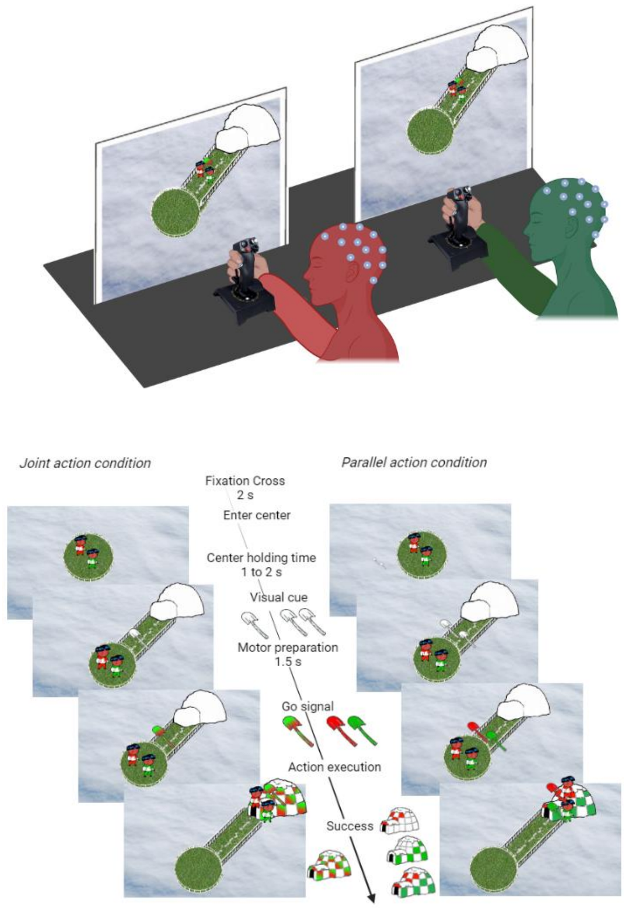


Figure 4. Paradigm of experiment 2. The upper part depicts the experimental setup. The lower part shows the strucure of a trial.

Results and Discussion

Success rate. We found no statistically significant differences between Joint and Parallel conditions (p = .512; JA Condition: Mean = 0.897, SD = 0.081; PA Condition: Mean = 0.889, SD = 0.007). This indicated that the JA and PA conditions did not differ in terms of task complexity.

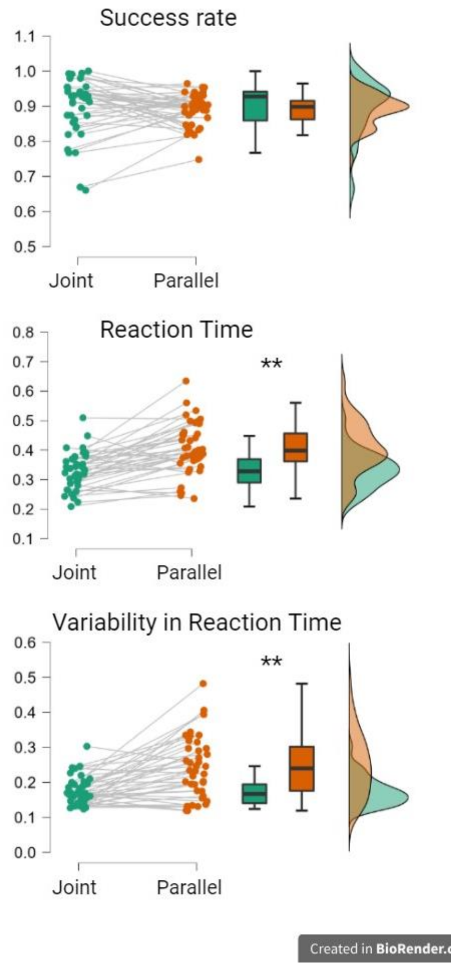
Reaction Time. RTs were significantly higher in the PA compared to the JA Condition (main effect of Condition: F (1, 38) = 37,867, p <.001, pη2 = .499; mean RT for JA Condition: 0.329, SD = 0.062, mean RT for PA Condition: 0.406, SD = 0.089). In addition, variability in RTs, quantified by standard deviation, was higher in the PA compared to JA condition (F (1,38) = 29.801, p <.001, pη2 = .440; mean variability for JA: 0.173, SD = 0.040; mean variability for PA: 0.246, SD = 0.089). The main effect of Player (p = .752) and Condition*Player interaction (p = 0,295) were not significant. Behavioral results are depicted in Figure 5.

Contingent Negative Variation. The CNV amplitude was higher when participants were performing the task in parallel compared to when they were performing the task in the joint condition (t (39) = -2.83, p =0.007, Cohen's d = -0.45; mean CNV for JA: -3.98, SD = 1.77; mean CNV for PA: -4.65, SD = 2.25). A following cluster-based permutation t-test considering the signal on all channels in the same averaged time interval showed that this effect, i.e., a higher CNV for the parallel condition compared to the joint condition, was widespread on the scalp, involving 40 channels. In central-parietal channels, where the CNV showed negative values, there was a significant negative cluster indicating more negative value for the parallel condition than for the joint condition (p=0.002).

Movement Related Potential. Results on MP followed the same pattern as on CNV. The comparison of the MP amplitude preceding the movement onset on the two channels in which the MP was maximum, i.e., Cz and C1, showed that the signal was higher in the parallel condition than in the joint condition (t (39) = -3.27, p =0.002, Cohen's d = -0.52; mean MP for JA: -5.03, SD = 2.25; mean MP for PA: -5.88, SD = 2.87). This effect was widely distributed, as shown by two significant clusters, one negative over central-parietal electrodes and one positive over frontal electrodes.

Overall our results suggest that neurophysiological processes associated with movement preparation and movement execution, i.e. CNV and MP, are modulated by acting jointly. Importantly, at odd with previous literature, in which the joint condition was compared with a solo condition, where CNV and MP were increased in joint conditions (Kourtis et al 2019). This effect has been explained by a possible activation of a motor representation that includes both the actions of the subject and the actions of the confederate. However, in our study CNV and MP were higher when participants act in parallel compared with when acting jointly. A possible explanation is that the variability of movements was higher in the parallel condition and therefore could be less predictable. This feature increased the load of motor processes associated with action preparation and execution, given the need to coordinate with the CF even in the parallel condition.

Figure 5. Success rate, reaction time and variability in reaction times of movement execution in experiment 2.



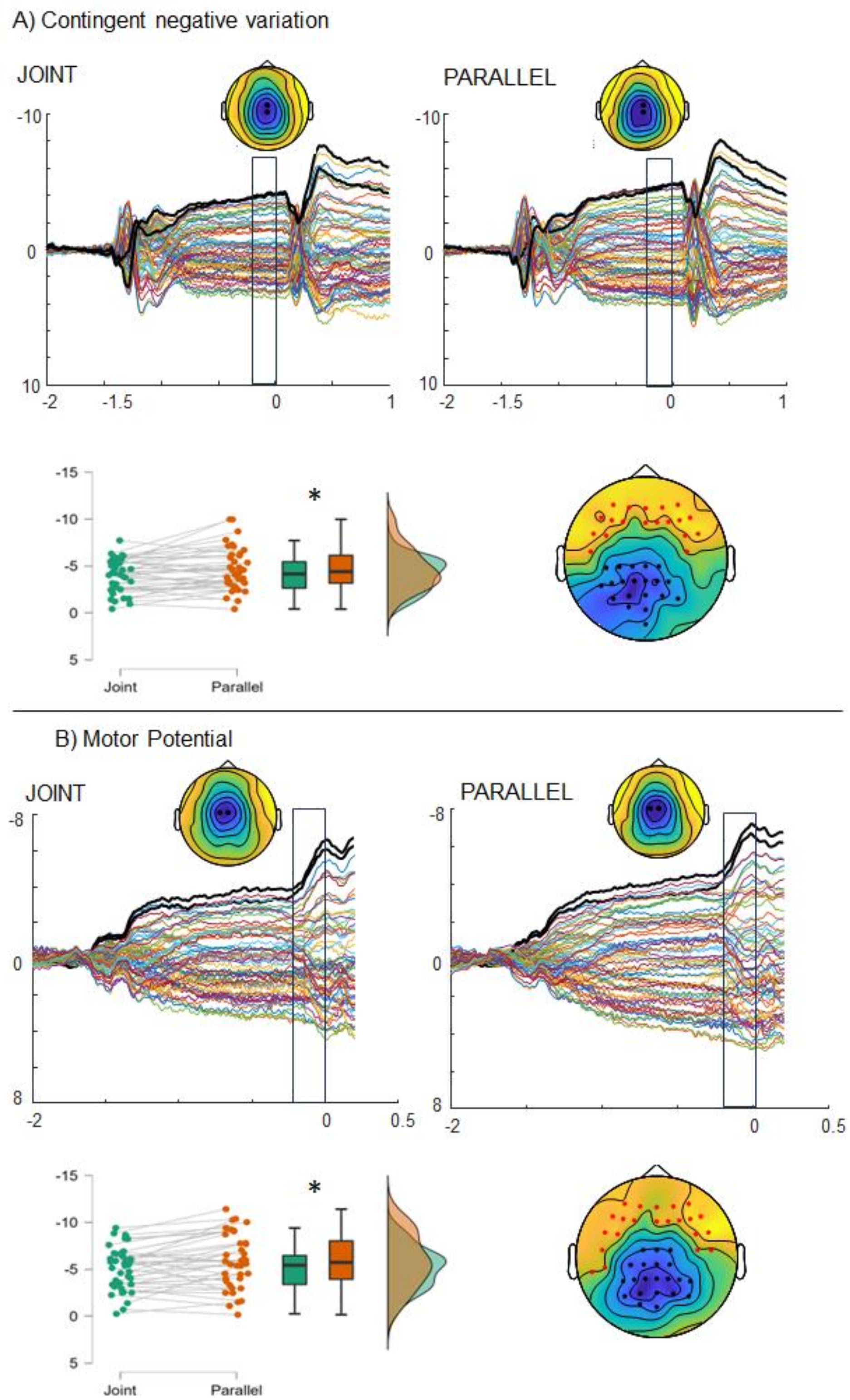


Figure 6.
A. Contingent Negative Variation (CNV). B. Movement-Related Potential (MRP). The upper part of the panels show the average of the EEG signal for the joint (left) and for the parallel (right) conditions. Black lines in the butterfly graph represent the two electrodes in which the signal is maximum, corresponding to the black circles in the topographical plots. The bottom left of each panel displays the results of the t-test comparisons. The bottom right of each panel displays the topographical distribution of the significant positive (red asterisks) and negative (black asterisks) clusters resulting from the cluster-based permutation t-test

Experiment 3: TMS-MEP-EEG (M1-SMA)

In this experiment, we aimed at implementing the paradigm used in Barchiesi et al 2022 to increase the concreteness of the goal sharing, studying the role of areas coding more abstract motor commands compared to M1, such as supplementary motor area (SMA), and a finer measure of representational corticospinal excitability. For this, were recorded TMS-evoked potentials (TEPs) as they allow to explore the motor system beyond cortico-spinal tract.

We compard a Joint condition, where participants have a collective goal, with a Solo condition, where participants act alone; The solo condition represents a typical control condition employed in literature. If significant differences were found between the Joint and Solo condition, we planned to compare the joint condition with a competitive condition.

Figure 8. Paradigm of experiment 3. Typical game and trial timeline representation. Each trial is composed by a CF turn, in which the CF performs the task, i.e. CF's shooter hits the wheel after the presentation of the colour cue and a TMS pulse is delivered on PTP's left motor cortex 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. CF and PTP receive feedback on their performance at the end of the trial.

Task (Figure 8): 20 participants were required to operate on a "shooter" with their right hand on a pressure sensor to shoot a wheel in the upper part of the screen and create a cycle, i.e., either a bicycle or a monocycle depending on condition. Two actions were performed, either lifting the fingers or pressing them , depending on a cue, i.e., a colour change of the grey wheel. In the Joint condition, participants (PTPs) and a confederate (CF) worked together to create a tandem bicycle. In this case players win or lose together. In the Competitive condition, each player shoots the wheel to the upper part of the screen and his/her monocycle is built if he/she is faster than the other player. In this case, only one player wins. In the solo condition, there is no confederate and the PTP plays alone.

The target neurophysiological markers of our analysis were: a) the difference in MEPs between ECU-FDS; b) TEPs after stimulation of M1; c) TEPs after stimulation of SMA.

Results and discussion

MEPs: As it can be seen in figure 9, ECU-FDS MEPs were modulated by the instantiation of a collective goal, but only in participants that started the experiment in the Joint condition (p=0.01). Specifically, in the joint condition, ECU-FDI MEPs are modulated according to what the CF is cued to perform, suggesting that the representation of the CF's action leaks into muscle activity. In the solo condition, no significant modulations were found.

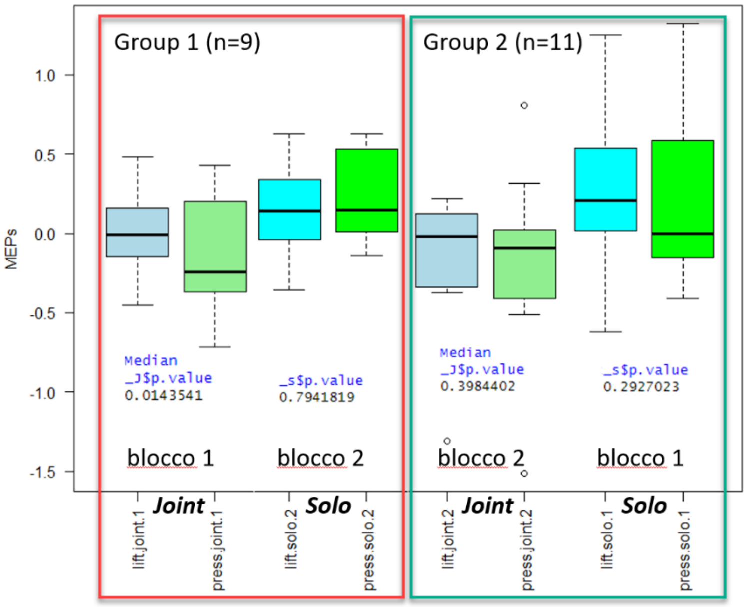


Figure 9. Results on ECU-FDS. For each block of the Experiment 3, bars represent the average ECU-FDS amplitude when participants were presented with a CF's cue, i.e., a lift or press instruction. Yellow bars correspond to lift and red bars correspond to press.

TEP in M1 and in SMA (figure 10): M1-TEPs and SMA-TEPs presented the typical pattern of alternation of positive and negative peaks in both joint and solo conditions. SHAM-TEPs were small in amplitude and accounted for artifactual auditory components. Cluster-based permutation t-tests to compare Joint and Solo conditions separately for M1, SMA and SHAM stimulations did not reaveal any cluster of significant differences.

Conclusions and Recommendations

Our study did not find conclusive evidence of an instantiation of a collective motor plan when acting together in several conditions of Joint actions.

When the joint action did not involve motor coordination and the collective goal was abstract (Experiment 1), the motor system was minimally affected by the representation of a shared goal. When motor coordination between participants and confederates was required (Experiment 2), a higher activation in the motor system was found for acting in parallel compared with acting jointly. Finally, having a more concrete goal and a finer measure of motor representation (Experiment 3), corroborated the findings of experiment 1, suggesting an instantiation of a collective motor plan measured in the cortico-spinal tract, but did not show modulations of the cortical activity in the motor network.

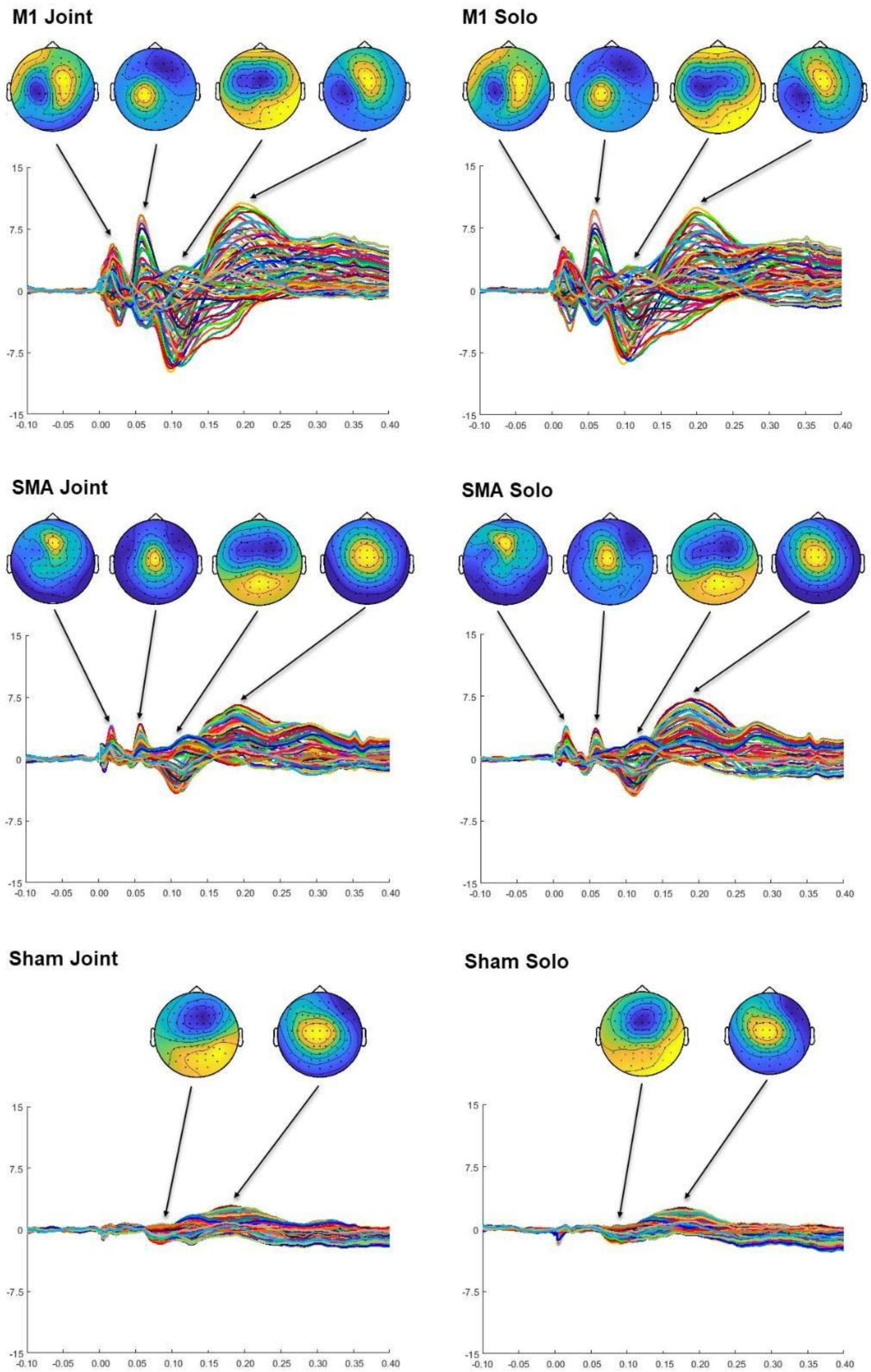


Figure 10.
Top: Results on TEPs of M1 stimulation. Time 0 corresponds to the delivery of the TMS pulse.
Middle: Results on TEPs of SMA stimulation. Time 0 corresponds to the delivery of the TMS pulse.
Botto,: Results on TEPs of SHAM stimulation. Time 0 corresponds to the delivery of the TMS pulse.