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Wired actions: anticipatory kinematic interference during a dyadic sequential motor interaction task

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Abstract

The anticipation of other people's movements activates our motor system. Does this motor activation affect our own movement unfolding? We investigated whether performing a movement before the other might elicit a motor interference effect, similar to the one that occurs during action observation. Pairs of participants performed a sequential motor task together. While the first agent's task was kept constant throughout the entire experiment, the actions of the second agent varied depending on the size and the position of his/her target. Results showed that the movement kinematics of the first agent were influenced by the anticipation of the subsequent action of the second agent. Furthermore, we found a high kinematic similarity between agents that were part of the same pair, compared to that of artificial pairs created after data collection. These findings suggest that, during dyadic interactions, our motor behavior is influenced not only by *what* action our partner will perform, but also by *how* our partner will perform that action. The specificity of this kinematic interference may arise from a detailed, *predictive* representation of the other's action, which could be refined, through time and practice, during the course of the interaction. These novel findings further the investigation about the processes that underlie our everyday motor interactions, as they suggest that the motor system is highly permeable to others' movements. Such permeability may not only be due to a passive reaction to the others' movements, but also to an active prediction of the others' specific way of moving.

Keywords: kinematics, motor interference, anticipatory kinematic interference, sequential motor task, joint action

Introduction

Every day we act and move in a dynamic environment, where people act and move with us. Other people's actions can occur before, during, or after ours: in each case, they affect us deeply. When we observe someone performing a movement, our premotor cortex activates as if we were performing that action (Rizzolatti & Sinigaglia, 2016). This 'covert' motor activation is very specific, even involving the exact muscles used to perform the observed movement (Alaerts et al., 2010; Fadiga et al., 2005; Naish et al., 2014). However, observing other people's actions can also affect our 'overt' motor activity. When our actions occur after or while observing someone else performing different actions, our movements can display measurable effects of visuo-motor interference (Brass et al., 2001; J.M. Kilner et al., 2003). Furthermore, at the kinematic level, our movements share similarities with previously or simultaneously observed movements (Castiello, 2003; Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011), indicating that aspects of the observed movement are automatically integrated in the performed movement. This phenomenon is often referred to as *motor contagion* (Blakemore & Frith, 2005) or *motor interference* (Casartelli et al., 2016).

Interestingly, other people's actions affect us even when they have not yet taken place. Some evidence shows that, when the nature and the onset time of another's upcoming action is known, our motor system activates prior to the other's movement onset, in the same brain areas that would be activated if we were asked to prepare that movement (Kilner et al., 2004; Ramnani & Miall, 2004). This motor representation does not seem to reflect a general arousal for movement, but rather a more detailed motor preparation activity, related to the specific action that will be observed (Bozzacchi et al., 2014).

Anticipating others' movements thus affects our 'covert' motor activity. But could it also affect our 'overt' motor activity? Previous studies have shown that representing the task that our partner should perform can affect our own performance (Kourtis et al., 2013; Sebanz et al., 2003). However, it remains unclear how representing a partner's action may specifically affect our movement kinematics. If the motor representations that we form about our partner's actions are as detailed as the literature would suggest, then we should be able to see a trace of such representations in the unfolding of our own movements. We thus hypothesized that, if our motor system is activated by the anticipation of a subsequent action, then performing a movement *before* the other might elicit an *anticipatory motor interference effect*, similar to the interference that occurs during action observation, even if the other's action has not yet been observed. The presence of this interference effect would suggest that our movements incorporate information that pertain not only to our own action goals, but also to the action goals of the other, even if the other's action has yet to be performed.

To investigate this hypothesis, in the present study we recorded movement kinematics of pairs of participants performing a sequential motor task together, in which they had to move a pawn towards specific targets, one after the other, as fast and as accurately as possible. The first agent performed the same action towards the same target throughout the entire experiment, while the second agent performed different actions depending on the size and on the position of her/his target, which varied continuously during the experiment. The speed-accuracy trade-off literature (Fitts & Peterson, 1964) suggests that, when someone rapidly moves an object towards a target, the velocity and the deceleration of the movement vary depending on the distance and on the size of the target. Moving an object towards a small target, compared to a large one, requires greater precision, which is achieved by anticipating the velocity peak and by increasing the duration of the deceleration phase. This modulation is furtherly affected by the distance between the starting point and the target, so that, compared to near targets, targets that are more distant induce movements with greater velocity peaks and longer deceleration phases (Bootsma et al., 1994; Marteniuk et al., 1987).

We therefore expected the second agent's movements to show a kinematic modulation in relation to the manipulation of her/his targets. However, our experimental focus was on the first agent's movement kinematics. Indeed, if the second agent's movements trigger an *anticipatory motor interference* effect on the first agent, then his/her movements should show an unnecessary kinematic modulation, similar to the one of the second agent. The kinematic similarity between the two agents would suggest that the first agent has incorporated some features that are related to the goal of the subsequent action of the second agent.

An additional information would regard the specificity of such kinematic modulation. Indeed, the 'incorporated' features may not only relate to the *goal* of the second agent's action, but also to the specific *kinematics* displayed by that particular agent. Different studies suggest

that people show individual variations in movement kinematics that are both consistent within a given individual and different between individuals (Koul et al., 2016; Ting et al., 2015). These idiosyncrasies lead individuals to display different motor solutions to achieve the same goal. Therefore, we predicted that, if the first agent shows only a generic effect of *goal interference*, the kinematic similarity between the two agents should be unrelated to the specific motor solution expressed by the second agent. Instead, if the first agent shows also a more detailed effect of *kinematic interference*, the kinematic similarity between the two agents should increase during their interaction and should be strictly related to the specific motor solution expressed by the second agent, and thus it should be weaker if the first agent is randomly paired with a different second agent after data collection.

Methods

Participants

Twenty-one pairs of right-handed participants took part in the experiment (24 females; aged 18-35; mean age = 25.40 years; SD = 4.5). The sample size was determined in advance by power analysis using effect sizes observed in a pilot study for the two-way "session" by "target size" interaction (described below) on the % of movement to peak velocity of the first agent (partial η^2 = .40; alpha set at 0.05, and power set at 0.95). All participants were right-handed, had normal or corrected-to-normal vision, and no history of neurological disorders. The members of each pair were matched for sex and did not know each other prior to participation. The study was approved by the local ethics committee (ASL3 Genovese) and performed in accordance with the principles of the revised Helsinki Declaration (World Medical Association General Assembly, 2008). All participants provided written informed consent and received monetary compensation.

Apparatus

Participants of each pair (hereinafter 'first agent' and 'second agent') sat at opposite sides of a table (60 cm x 140 cm), facing each other (see Fig. 1). One of six possible sheets of paper (45 cm x 32 cm x 0.5 mm) was placed along the table's midline, equidistant from both agents. Two squares were drawn on one of the short sides of each paper, exactly along both agents' midline. The first square, called 'starting point' (2 cm x 2 cm), was drawn to be 15 cm distant from the first agent's side of the table; here, a little pawn (height = 2 cm; base ∅ = 1.5 cm) was placed. The second square, called 'target 1' (4 cm x 4 cm), was drawn 15 cm far from the 'starting point', equidistant from the two agents. On the left-hand side of the first agent, along the table's midline, a circle, 'target 2V', was drawn on the paper. Depending on the condition, 'target 2V' could differ in size ('small': ∅ = 1.5 cm; 'large': ∅: = 2.5 cm) and in distance ('short': 10 cm; 'medium': 20 cm; 'long': 35 cm) from 'target 1'. On the right-hand side of the first agent, along the table midline, at a distance of 15 cm from 'target 1', a paper-made square, called 'target 2C' (4 cm x 4 cm), was fixed to the table. 'Target 2V' and 'target 2C' were always present on the table during the entire experiment.
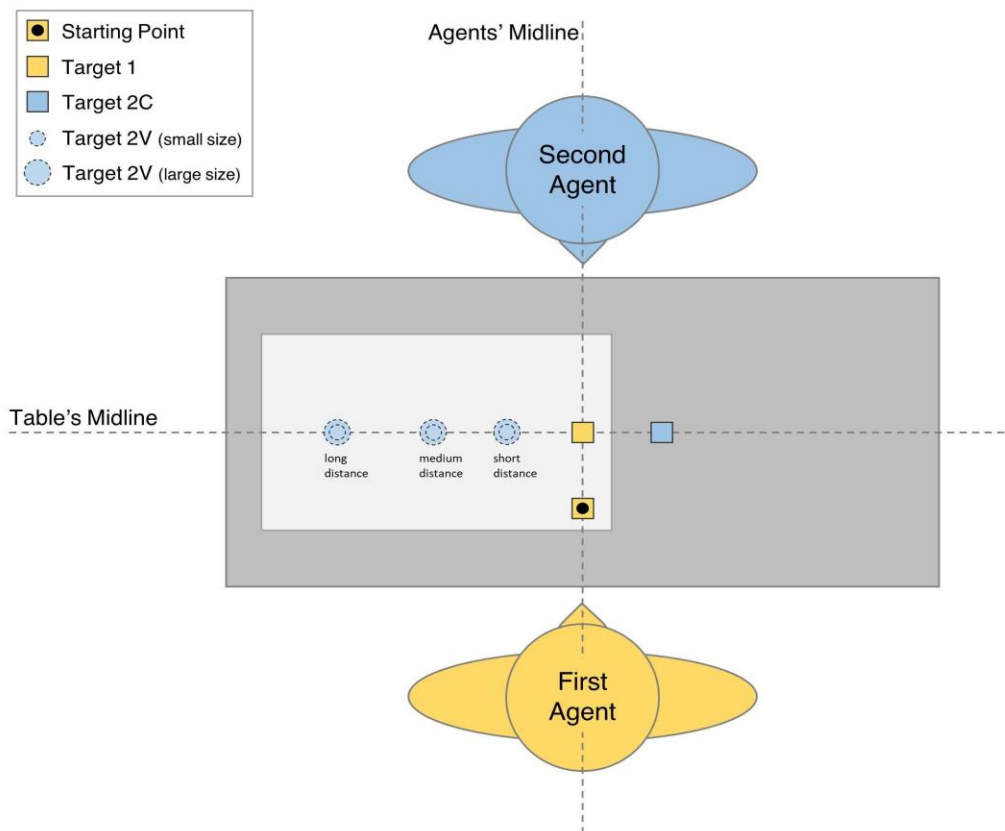

Fig. 1.

Schematic representation of the experimental set-up. The image represents the experimental set-up schematically (not to scale), where the first and the second agent sat in front of each other, at opposite sides of a table.

Procedure

Participants of each pair were asked to perform a sequential task together with the instruction of being as quick and as accurate as possible. At the beginning of each trial, the first agent had the left hand resting on the left knee, the right wrist resting on the table, the forearm pronated, the right arm oriented in the parasagittal plane passing through the shoulder, and the right hand in a semi-pronated position, holding the pawn positioned on the 'starting point'. The second agent was asked to keep the left hand on the left knee, the right arm oriented in the parasagittal plane passing through the shoulder, the forearm pronated, the wrist resting on the table, and the hand in a semi-pronated position, with the tips of the thumb and the index finger on a tape-marked point.

For the entire experiment, the first agent's task was to move the pawn from the 'starting point' to 'target 1'. A beep sound (frequency: 750 Hz; duration: 150 ms) prompted the start of each trial.

After the first agent's movement, the second agent had in turn to reach and grasp the pawn from 'target 1' and, depending on the experimental session, move the pawn towards either 'target 2V' (*variable target* session) positioned on his/her right, or 'target 2C' (*constant target* session) positioned on his/her left. During both sessions, 'target 2V' varied in size (*small*, *large*) and in distance from 'target 1' (*short*, *medium*, *long*), while 'target 2C' did not vary in size or in distance from 'target 1'. The second agent was instructed to start her/his part of the action only when the first agent had positioned the pawn on 'target 1'. The experimenter visually monitored the performance of each trial to ensure the second agent's compliance to this requirement.

When the sequence of actions was concluded, the first agent grasped the pawn with the left hand, and set it back on the 'starting point'. After that, both agents were instructed to return to their starting positions. When both agents' right hands were in the respective starting positions, a new trial was prompted with the beep sound.

Participants performed a total of 240 trials divided in four sessions (2 *constant target* sessions and 2 *variable target* sessions) of 60 trials. Each session was divided in three blocks of 20 trials: 5 trials of practice and 15 experimental trials. Within each block, the configuration of targets in the table did not change (e.g. during a *variable target* session, the second agent had to move the pawn towards the small and far 'target 2V' 20 times in a row). The sequence of the sessions was alternated following an ABAB design, and the order was counterbalanced across participants. Within each session, blocks were presented in a pseudo-randomized order. The entire experiment lasted approximately 40 minutes.

Kinematic recording

Movement kinematics were recorded using a near-infrared camera motion capture system (frame rate: 200 Hz; Vicon Nexus v.2.5). Eight cameras were placed in a semicircle at a distance of 1.5–2m from the table where the participants were performing the task.

Participants' right hands were outfitted with six lightweight retro-reflective hemispheric markers (6 mm in diameter). Being interested on the transport phase of the action, all data analyses were performed on the kinematic profile of the marker placed, for both agents, on the radial aspect of the wrist (Castiello et al., 1993; Crippa et al., 2015). An additional marker was placed on the pawn that participants moved during the experiment.

Kinematic Data Processing

After data collection, each trial was individually inspected for correct marker identification and then run through a low-pass Butterworth filter with a 15 Hz cutoff. For data processing and analysis, a MatLab custom script (MATLAB; MathWorks, Natick, MA) was used to compute the variables of interest. Each variable was computed within the time window from movement onset to movement end. For the first agent, movement onset was defined as the first time point, after the beep sound, at which the velocity of the wrist crossed a 20 mm/s threshold; movement end was defined as the time point at which the velocity of the wrist dropped below a 20 mm/s threshold. For the second agent, movement onset was defined as the first time point, after the grasping of the pawn, at which the velocity of the wrist was higher than in the previous time point; movement end was defined as the time point at which the wrist velocity dropped below a 20 mm/s threshold.

Within these time windows, we computed for both agents the following variables:

- *% of movement to peak velocity* (%PV), defined as the normalized movement time at which the wrist showed the highest velocity;
- *% of movement to peak deceleration* (*%PD*), defined as the normalized movement time at which the wrist showed the highest deceleration.

- *Wrist velocity* (mm/sec), defined as the module of wrist's velocity. In order to compare the shape of the velocity profile between conditions and between participants, the variable was then expressed with respect to normalized (%) movement durations. For each movement, *wrist velocity* thus consisted of 10 values, representing the velocity from 0% to 100% of the movement time, at increments of 10%.

Data analysis

Data of one pair of participants were excluded from the analyses due to outlier values (-3 SD from the group average) of the participant acting as second agent, for the dependent measure *%PD*.

For *%PV* and *%PV*, we conducted, separately for each agent, repeated measures ANOVA with 'session' (2 levels: *variable target*, *constant target*), 'target size' (2 levels: *small*, *large*) and 'target distance' (3 levels: *short*, *medium*, *long*) as within-subject factors.

For *wrist velocity*, we conducted separately for each agent of the pair a repeated measures ANOVA with 'session' (2 levels: *variable target*, *constant target*), 'target size' (2 levels: *small*, *large*), 'target distance' (3 levels: *short*, *medium*, *long*) and '% of movement' (10 levels: from 10% to 100% in 10 steps) as within-subject factors. For all ANOVAs, a Greenhouse-Geisser correction was applied to the degrees of freedom when needed.

Significant interactions yielded by ANOVAs on second agents were followed up by Bonferroni-adjusted post hoc tests ($\alpha = .05$). ANOVAs on first agents were instead followed up by planned comparisons, in order to inspect only the differences that were found significant on second agents.

To further evaluate the level of similarity between movements of the two agents in the *variable target* session, we correlated the *%PV* of first agents with that of second agents across all 90 trials. The correlation coefficients of the 20 pairs were then converted into z-scores by means of the Fisher z-transformation, in order to obtain normally distributed values. We then performed a one-sample t-test to verify whether the transformed correlation coefficients were significantly greater than 0. The same approach was applied on the agent's *%PD*. To test the robustness of the correlations and to verify whether the correlation coefficients were pair-specific, we then performed a non-parametric permutation test on both variables (10000 permutations). Permutations were performed as to create artificial combinations of 20 pairs of participants. The 90 trials of first agent's movements of pair *n* were correlated with the 90 trials of second agent's movements of pair *m*, keeping fixed the experimental conditions (e.g. first agent's trial t in the condition short target distance/small target size, correlated with second agent's trial t in the same condition). For each of the 10000 combinations we obtained 20 correlation coefficients that were then converted into z-scores and submitted to a one-sample t-test. This allowed us to compare the t-value obtained from the one-sample t-test performed on the real pairs with an empirical null distribution of t-values, which led to an empirical p-value [empirical p = (r+1)/(n+1), where *n* is the total number of permutations and *r* is the number of permutations that produced a t-value greater than or equal to the t-value obtained from the real pairs; Davison & Hinkley, 1997],

Additional analyses were performed to investigate the possible presence of a learning process during the experiment, and to rule out the possibility that first agents were simply influenced by the movement performed by second agents in the preceding trial.

For the first analysis, we compared the difference between the *%PV* of the two agents *(i.e. %PV of first agent - %PV of second agent)* in the first five trials of each block with that observed in the last five trials of each block, by means of a one-tailed paired-sample t-test. We expected the differences to be lower in the last five trials, compared to the first five trials. The same analysis was performed for the *%PD*.

For the second analysis, we performed a one-tailed paired-sample t-test to compare the difference between the *%PV* of the two agents calculated between actions occurring within the same trial (i.e. *%PV* of first agent in trial t - *%PV* of second agent in trial t; lag 0 delta) with the difference of the *%PV* calculated between the actions of first agents in one trial (t) and the

actions of second agents in the preceding trial (t-1; i.e. lag 1 delta). We expected lag 0 deltas to be lower than lag 1 deltas. The same analysis was performed for the *%PD*.

An additional control analysis was performed to investigate the possibility that second agents were influenced by the movements performed by first agents before them. Using the method of Granger causality (Granger, 1969), for each pair of participants we first computed a univariate autoregression of the second agent's *%PD* (i.e. second agent's *%PD* in trial t-1 used to predict second agent's *%PD* in trial t). We then included in the model the first agent's *%PD* as an additional predictor (i.e. first agent's *%PD* in trial t), and checked whether this predictor added explanatory power to the regression by means of a F-based Wald test.

Results

For the repeated measures ANOVA on the *%PV*, the analysis on second agents revealed significant main effects of 'session' ($F_{(1,19)} = 34.36$; $p < .001$; partial $\eta^2 = .644$), 'target distance' ($F_{(1.46,27.66)} = 7.64$; $p = .005$; partial $\eta^2 = .287$) and 'target size' ($F_{(1,19)} = 41.06$; $p < .001$; partial $\eta^2 = .684$). The analysis also revealed a significant 'session' by 'target distance' interaction ($F_{(1.52,28.92)} = 4.28$; $p = .033$; partial $\eta^2 = .184$), and a significant 'session' by 'target size' interaction ($F_{(1,19)} = 18.65$; $p < .001$; partial $\eta^2 = .495$). No other interactions reached statistical significance (p_s ranging from .256 to .927; see supplementary Table 1 for detailed results). Post hoc comparisons revealed that, only in the *variable target* session, participants reached the velocity peak earlier when target 2V was at the short distance ($M = 34.6\%$, 95% CI = [32.3, 37.0]), compared to when it was both at medium distance ($M = 37.4\%$, 95% CI = [35.3, 39.5]; $p < .001$) and at long distance ($M = 37.2\%$, 95% CI = [35.1, 39.3]; $p = .004$) from target 1. Furthermore, only in the *variable target* session, participants reached the velocity peak earlier when target 2V was small ($M = 34.4\%$, 95% CI = [32.0, 36.8]), compared to when it was large ($M = 38.4\%$, 95% CI = [36.5, 40.3]; $p < .001$; see Fig. 2a).

The ANOVA conducted on first agents' *%PV* revealed a significant main effect of 'session' ($F_{(1,19)} = 4.95$; $p = .038$; partial $\eta^2 = .207$. The analysis also revealed a significant 'session' by 'target size' interaction ($F_{(1,19)} = 9.89$; $p = .005$; partial $\eta^2 = .342$) and a significant 'session' by 'target distance' by 'target size' interaction ($F_{(1.59,30.23)} = 4.67$; $p = .024$; partial $\eta^2 = .197$). No other effects reached statistical significance (p_s ranging from .058 to .930; see supplementary Table 1 for detailed results). Planned comparisons on the contrasts that were found significant on second agents revealed that, as for second agents, during the *variable target* session, first agents also reached the velocity peak earlier when target 2V was small ($M = 51.5\%$, 95% CI = [49.4, 53.6]), compared to when it was large ($M = 52.4\%$, 95% CI = [50.1, 54.8]; $p = .020$; see Fig. 2a).

The ANOVA on second agents' *%PD* revealed significant main effects of 'session' ($F_{(1,19)} = 249.53$; $p < .001$; partial $\eta^2 = .929$) and 'target size' ($F_{(1,19)} = 28.08$; $p < .001$; partial $\eta^2 = .596$). Main effects were further qualified by a significant 'session' by 'target size' interaction ($F_{(1,19)} = 28.99$; $p < .001$; partial $\eta^2 = .604$). No other effects reached statistical significance (p_s ranging from .106 to .521; see supplementary Table 2 for detailed results). Post hoc comparisons revealed that, only in the *variable target* session, participants reached the deceleration peak

earlier when target 2A was small ($M = 56.8\%$, 95% CI = [52.6, 60.9]), compared to when it was large ($M = 64.8\%$, 95% CI = [59.9, 69.7]; p < .001; see Fig. 2b).

The ANOVA conducted on first agents' *%PD* revealed a significant main effect of 'session' ($F_{(1,19)} = 7.85$; $p = .011$; partial $\eta^2 = .292$), and a significant 'session' by 'target size' interaction ($F_{(1,19)} = 9.79$; $p = .006$; partial $\eta^2 = .340$). No other effects reached statistical significance (p_s ranging from .065 to .627; see supplementary Table 2 for detailed results). Planned comparisons on the contrasts that were found significant on second agents revealed that, in the *variable target* session, first agents also reached the deceleration peak earlier when target

2V was small (M = 80.7%, 95% CI = [77.6, 83.8]) compared to when it was large (M = 83.1%, 95% CI = [79.8, 86.3]; p = .027, see Fig. 2b).
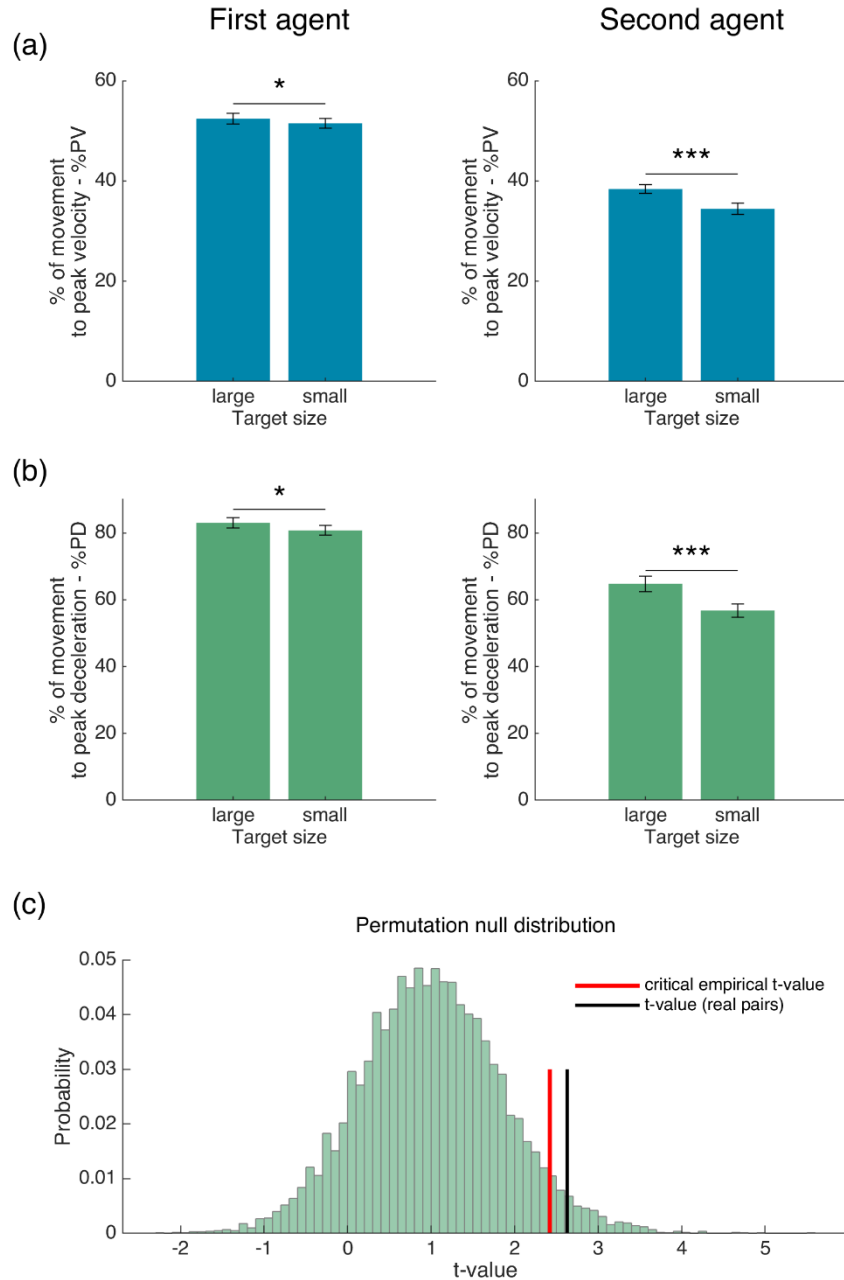

Fig. 2.

Results of *% of movement to peak velocity (%PV)*, *% of movement to peak deceleration (%PD)* and permutation test. The graphs in panel (a) and (b) show the values of the *%PV* (a) and the *%PD* (b), separately for the first (left graphs) and the second agent (right graphs), during the *variable target* session, as a function of the size of the target of the second agent (i.e. target 2V). Bars indicate *SE*. Asterisks denote significant pairwise comparisons (*p < .05; ***p < .001). Panel (c) shows the empirical distribution of the t-values obtained on 10000 combinations of 20 artificial pairs of participants. The red line represents the critical t-value. The black line represents the t-value obtained from the real pairs of participants.

The ANOVA on second agents' *wrist velocity* revealed significant main effects of 'target distance' ($F_{(1.69,32.11)}$ = 458.03; $p <$ .001; partial η^2 = .960), 'target size' ($F_{(1,19)}$ = 19.73; $p <$ .001; partial η^2 = .509) and '% of movement' ($F_{(2.16,41.13)}$ = 302.44; $p <$ .001; partial η^2 = .941). Notably, the analysis revealed a significant 'session' by 'target size' by 'target distance' by '% of movement' four-way interaction ($F_{(3.87,73.47)}$ = 3.68; $p =$ .009; partial η^2 = .162; see supplementary Table 3 for detailed results). Post hoc comparisons revealed that, in the *variable target* session, for all of the three distances between target 2V and target 1, at 20% of the movement time, participants moved significantly faster when target 2V was small, compared to when it was large (p_s ranging from .008 to .0497). This difference was also present at 30% of the movement time, when target 2V was at the short ($p =$ .038) and at the medium distance ($p =$ .013) from target 1. Instead, from 50% up to 100% of the movement time, for all of the three distances between target 2V and target 1, participants moved significantly faster towards large targets, compared to small targets (p_s ranging from .000 to .025; see Fig. 3). Only one significant comparison was found during the *constant target* session: when target 2V was at the short distance, at 90% of the movement time, participants were faster when target 2V was large, compared to when it was small ($p =$ .048).

For what concerns first agents' *wrist velocity*, the ANOVA revealed a significant main effect of 'session' ($F_{(1,19)}$ = 11.68; $p =$ .003; partial η^2 = .381) and a significant main effect of '% of movement' ($F_{(1.61,30.53)}$ = 200.01; $p <$ .001; partial η^2 = .913). Importantly, as for second agents, the ANOVA yielded a significant 'session' by 'target size' by 'target distance' by '% of movement' four-way interaction ($F_{(2.72,51.59)}$ = 3.58; $p =$ .023; partial η^2 = .158; see supplementary Table 3 for detailed results). Planned comparisons on the differences that were found significant on second agents revealed that, in the *variable target* session, when target 2V was at the short distance from target 1, at 50% of the movement time participants were faster when target 2V was small, compared to when it was large ($p =$ .047). When target 2V was located at the medium distance from target 1, from 70% up to 100% of the movement time participants were faster when target 2V was large, compared to when it was small (p_s ranging from .005 to .022; see Fig. 3). The other planned comparisons on the differences that were found significant for second agents in the *variable target* session were not found to be significant for first agents (p_s ranging from .056 to .824). The comparison found significant for second agents in the *constant target* session was not found to be significant for first agents ($p =$ .935).
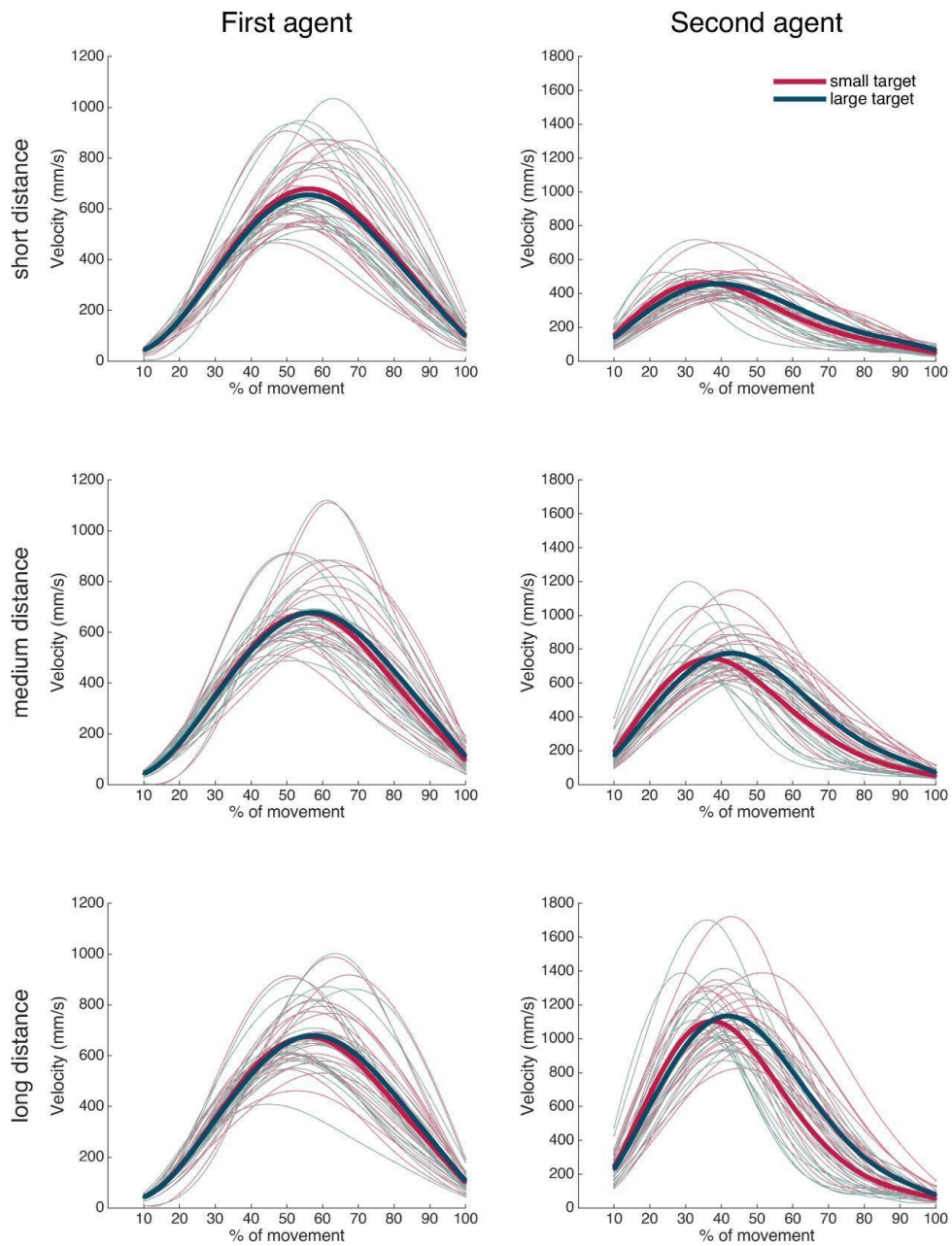
Fig. 3

Results of the analyses on *wrist velocity*. The graphs represent the modulation of *wrist velocity,* during the *variable target* session, over different percentages of movement both for first agents (left graphs) and second agents (right graphs), when target 2V was small or large. Graphs in different rows represent the modulations observed when target 2V was at the short (first row), medium (second row), and long distance (third row). Thin lines represent a single participant's mean; thick lines represent the observed group mean.

The z-transformed correlation coefficients of the *%PV* and of the *%PD* of the two agents during the *variable target* session resulted both to be significantly greater than 0 (*%PV*, t_{19} = 2.127, $p < 0.05$; *%PD*, t_{19} = 2.630, $p < 0.01$). However, the permutation test revealed that the observed t-value was significantly above the critical t-value (i.e. the 95% percentile of t-values obtained with 10000 permutations) only in the *%PD* (*empirical p* = .033, see Fig. 2c; *%PV empirical p* = .325).

Additional analyses on *%PV* showed that the difference between the *%PV* of the two agents was not significantly lower in the last five trials of each block, compared to the first five trials (t_{19} = 0.131; p = .449). Moreover, the difference between the *%PV* of the actions of the two agents occurring within the same trial (i.e. lag 0 delta) was not significantly lower than the difference between the *%PV* of the actions of the first agent in one trial and the actions of the second agent in the preceding trial (i.e. lag 1 delta; t_{19} = 1.506; p = .074).

Additional analyses on *%PD* showed that the difference between the *%PD* of the two agents was significantly lower in the last five trials of each block, compared to the first five trials (t_{19} = 1.853; p = .040; see Fig. 4a). Furthermore, the difference between the *%PD* of the actions of the two agents occurring within the same trial (i.e. lag 0 delta) was lower than the difference between the *%PD* of the actions of the first agent in one trial and the actions of the second agent in the preceding trial (i.e. lag 1 delta; t_{19} = 4.334; $p < .001$; see Fig. 4b).

The control analysis performed on *%PD* to investigate whether second agents were influenced by the movements performed by first agents before them revealed that, in none of the
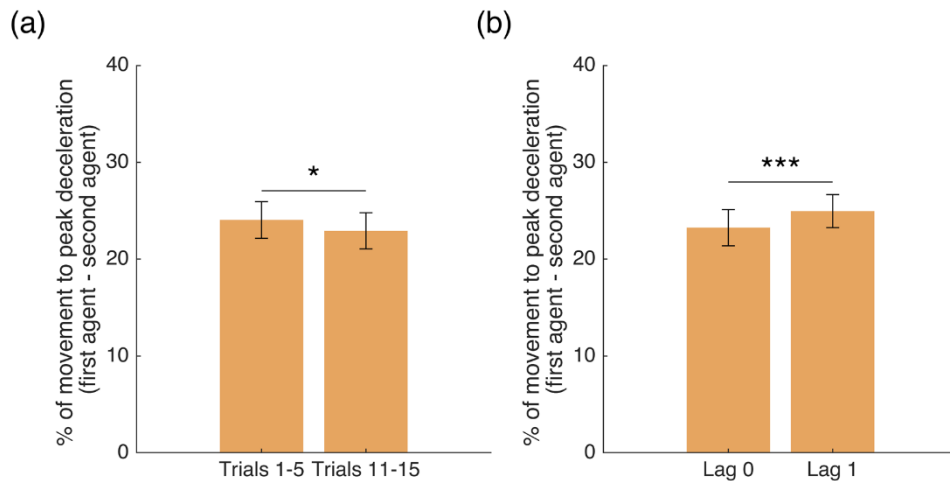
Fig. 4

Results of additional analyses on the difference between the *%PD* of the two agents. The graph in panel (a) shows the difference between the *%PD* of the two agents in the first and in the last five trials of each block. The graph in panel (b) shows the difference between the *%PD* of the actions of the two agents occurring within the same trial (i.e. lag 0), and of the actions of the first agent in one trial and the actions of the second agent in the preceding trial (i.e. lag 1). Bars indicate *SE*. Asterisks denote significant difference (**p* < .05; ****p* < .001).

participants' pairs, first agent's values in trial *n* added explanatory power to the second agent's autoregression model (p_s ranging from .46 to .99).

Discussion

Performing a movement *while* someone else is moving, or *after* someone else has moved, elicits a motor interference effect (Kilner et al., 2003; Press et al., 2011). In the present study, we investigated whether performing a movement *before* the other could also result in a motor interference effect similar to the one that occurs during action observation.

An *anticipatory* motor interference effect

We found that participants asked to perform the first part of the action (i.e. first agents) showed a kinematic modulation relative to the size and distance of the targets of the participants asked to complete the action sequence (i.e. second agents), even if this was unnecessary for the purpose of their task.

Consistent with the *motor interference* effect that typically arises during or after the observation of an action that is incongruent with the one that should be performed, our findings indicate that a motor interference effect arises also when the action of the other person has not yet been performed, but can be *precisely anticipated.* Indeed, the anticipation of the subsequent action of the second agents affected the first agents' movements, in what we may call an *anticipatory* motor interference effect.

The observed effect could also be considered as resulting from a 'distractor effect' elicited by the presence of target 2V (the target of second agents that changed in size and distance), which would have interfered with first agents' movements by evoking a different motor program (Castiello, 1996; Tipper et al., 1997). However, first agents showed the kinematic modulation relative to target 2V only during the *variable target* session, and not during the *constant target* session, exactly as second agents did. Since target 2V varied continuously during the experiment, a 'distractor effect' should have been present during both sessions. Instead, the fact that first agents showed the kinematic modulation only during the *variable target* session indicates that the effect was driven not simply by the presence of target 2V, but specifically by the fact that the agent in front of them would have *moved* towards that specific target. These effects could then be explained by the greater saliency that target 2V had during the *variable target* session, compared to the *constant target* session. Indeed, during the *variable target* session, the size and the distance of target 2V indicated to first agents what action second agents would have performed after them. The knowledge of the second agent's goal could thus have been, per se, the driver of the interference effect we found.

However, our results suggest that the kinematic modulation shown by first agents was *not only* affected by the goal of second agents, but *also* by how this goal was achieved (i.e. the kinematics of second agents' movements). Evidence for this specific kinematic interference is provided by the high kinematic similarity that was found between the two agents of each pair, by comparing the kinematic similarity of the real set of 'first agent - second agent' pairs with that of

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artificial sets of pairs. We found that, in the case of *%PD*, the kinematic similarity between the real pairs was stronger than any other similarity obtained between the artificial pairs. The kinematic modulation showed by first agents was thus pair-specific, suggesting that first agents were not simply incorporating the *goal* of the subsequent action, but that they were also incorporating more detailed aspects related to the specific movement *kinematics* that the agent in front of them would have displayed.

It could be argued that the high kinematic similarity found between the two agents was due to second agents being influenced by the movement performed by first agents *before* them. However, the nature of the kinematic modulations displayed by the two agents implicitly suggests that this possibility might have not occurred. Indeed, the kinematic modulation shown by second agents was in line with the speed-accuracy trade-off literature, and, compared to first agents, it was much more pronounced, which makes it unlikely that first agents' movement kinematics were the driver of second agents' modulations. This idea is also supported by the control analysis that we performed on the *%PD* of the two agents, which showed that, in none of the participants' pairs, first agents' movements Granger-caused the movements performed by second agents. This suggests that the kinematic modulation shown by second agents was more likely related to their own targets' variation, rather than being driven by first agents' kinematic modulation.

It is important to underline the novelty of the methodology used in the present study. Indeed, other studies related to the motor interference literature show that the observer incorporates, in his own movement, features that relate to the specific kinematics that are used to achieve the goal (Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011). These studies often use actions performed by the same model, who deliberately changes the movement kinematics used to achieve the goal: the observer is thus presented with actions that are more or less 'rational' for the purpose of achieving the goal (Forbes & Hamilton, 2017; McGuigan et al., 2011). However, producing an 'irrational' action itself might convey a specific meaning to the performed movement. For example, exaggerated trajectories are typically perceived as more salient and are often used to communicate something to the observer (Pezzulo et al., 2013; Vesper et al., 2016). It is thus plausible that observers consider the 'irrational' movement as an essential part of the goal of the observed action, which could lead them to imitate the 'irrational' kinematics in order to imitate the goal of the action more carefully (Gergely et al., 2002; Wild et al., 2010).

In our experiment, second agents were not given any instruction on how to perform their movements. Based on previous studies (Cavallo et al., 2018; Koul et al., 2016; Ting et al., 2012) we assumed that each second agent would present a different, idiosyncratic, motor solution to perform the task, and thus that they would display slightly different movement kinematics to achieve the same goal. These idiosyncrasies were indeed evident from the results of an unsupervised dimensionality reduction procedure – i.e. t-distributed Stochastic Neighbor Embedding (Van Der Maaten & Hinton, 2008) – that we performed on the kinematics of second agents (Fig. 5). As a consequence, the high kinematic similarity that we found between the real 'first agent - second agent' pairs provides evidence that first agents were incorporating features related to the specific motor solution expressed by the second agent they were interacting with. To the best of our knowledge, these findings represent the first empirical evidence about the existence of pair-specific processes of motor interference.

Representing the other's upcoming movements

Our findings might be well explained by the interactive nature of the task performed by the two agents. Indeed, the task was presented as a dual-game, where the two participants shared a common goal (i.e. complete the entire action sequence as quickly and as accurately as possible). This allows us to equate the task to a *joint action* (Rocca & Cavallo, 2018). The existing literature defines joint actions as a specific type of interaction, where two or more agents coordinate their actions in space and time to achieve a shared outcome in the environment (Sebanz et al., 2006). Authors have theorized that, in order to engage in a joint action successfully, people have to represent not only their own task, but also the task performed by their partner.

Recent studies have shown that this 'other-representation' can affect the unfolding of our movements. Schmitz and colleagues showed that task constraints that apply only to the action of the other can produce an effective change in our own movements (Schmitz et al., 2017). Our results could thus be reasonably explained by the fact that first agents were representing the task that second agents would have performed after them. The 'other-representation' may have interfered with the motor performance of first agents, leading them to display, in their own movement kinematics, aspects that were related to the subsequent action of second agents.

Furthermore, our results suggest that this 'other-representation' might be more detailed than previously thought. Indeed, we found that the kinematic modulation showed by first agents was not simply the result of a *goal* interference, but also the result of a more specific *kinematic*
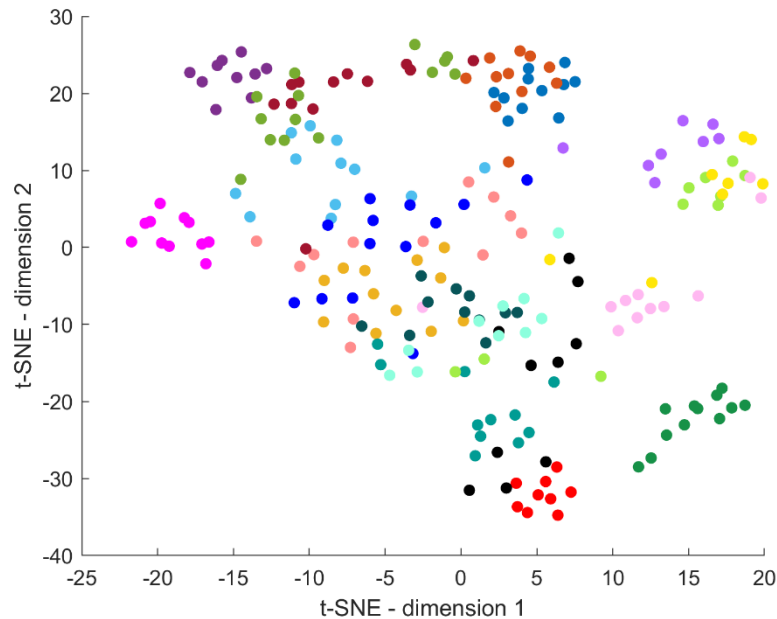

Fig. 5.

Result of t-SNE. The image shows the result of the t-distributed Stochastic Neighbor Embedding (i.e. t-SNE) performed on the movements of second agents during the *variable target* session, when target 2V was large and located at the long distance. Each color represents a different second agent; each dot represents a movement. Movements of the same second agent appear clustered and separable from the movements of other second agents.

interference. This might indicate that, during joint actions, we do not only keep an internal model of our own and our partners tasks, but we also encode the specific kinematic features displayed by our action partners, and this affects our own movements.

The emergence of such a specific representation raises the question of when and how it is formed during the interaction. Compared to a simple representation of the other's task, building a representation of the other's specific way of moving might be a process that needs time and practice to develop. Although our experiment was not designed to investigate this aspect, our data suggest the presence of a learning process. In the follow-up analysis, we found that the difference between the *%PD* of the two agents decreased during the course of each experimental block, with a significant difference between the first five and the last five trials of each block (see Fig. 4a). The presence of this learning process might be interpreted in two ways. On the one hand, the kinematic modulation shown by the first agent might be simply due to a memory-driven effect, elicited by the observation of the movement performed by the second agent in the *previous trial*: this might have led the first agent to copy, in each trial, some features displayed by the second agent in the preceding trial. On the other hand, the observed effect on the first agent might be due to a refinement of the motor representation of the second agent's action: such a refinement would be at the base of the predictive process that triggers the anticipatory interference. To disentangle between these alternative interpretations, we compared the difference between the *%PD* of the two agents calculated between actions occurring within the same trial (i.e. lag 0 delta) with the difference of the *%PD* calculated between the actions of first agents in one trial and the actions of second agents in the preceding trial (i.e. lag 1 delta). We found that lag 0 deltas were significantly smaller (i.e. the *% of movement to peak deceleration* was more similar between the two agents) compared to lag 1 deltas (see Fig. 4b). These results suggest that first agents were not simply copying the previous action of second agents, but that they were actively refining their representation of second agents' movement kinematics in a predictive way. Therefore, when building a representation of the other's action, a learning process could allow one to shift from an initial generic representation of the other's task towards a specific detailed representation of the other's movements. It is important to note that the presence of this learning process was not supported by the analyses performed on the *%PV*. The significant correlation found for *%PV* was also not pair specific, even if first agents showed, within this variable, a modulation relative to the size of the targets of second agents. The contrasting behavior shown by these two kinematic variables suggests that representing another's action might in some cases remain a generic process that does not take into account the other's specific way of moving.

An important aspect that would be interesting to address in the future concerns the automaticity of the emergence of these 'other-representations'. As mentioned above, building a representation of the other's specific way of moving might be a process that needs time and practice to occur. This process may be effortful, and it is plausible that such an effort might be spent only when it is necessary – i.e. when we are engaged in a *joint action* with the other. The existing literature indeed suggests that different motor planning processes might be at stake when performing a joint action, compared to an individual action (Kourtis et al., 2010, 2013; Sacheli et al., 2018). The current literature provides conflicting evidence about how being involved in a joint action affects our movements. Recent evidence shows that the reciprocal motor influence might be enhanced when sharing a joint goal with the other (della Gatta et al., 2017). However, other studies show that, during joint actions, motor interference effects seem to be reduced

(Sacheli et al., 2018). The sequential motor task used in our experiment could constitute a useful paradigm to disentangle between these different perspectives, since the motor influence originates from *anticipating* the action of the other.

The involvement of the motor system during the anticipation of the other's actions occurs exclusively when we know how the other will move and when he/she will move (Bozzacchi et al., 2014; Kilner et al., 2004). Furthermore, this anticipatory motor activation seems to be enhanced when we are *interacting* with the other (Kourtis et al., 2010, 2013). Thus, if building a representation of the other's action is a process that occurs only during joint actions, we should find no evidence of an *anticipatory kinematic interference* effect during the sequential motor task when the two agents are not sharing the same goal – i.e. when their actions are perceived as *individual*.

Finally, these findings can also be considered from the perspective of theories postulating a putative impact of aberrant motor control and motor representation mechanisms in clinical conditions such as autism spectrum disorder (ASD) (Casartelli et al., 2016, 2017; Gallese et al., 2013). These theories emphasize the link between 'motor control' and 'perception'. The key concept is that movement differences between typical and atypical individuals are likely to contribute to the difficulties that individuals with ASD encounter during social interactions. An intriguing hypothesis is that the motor idiosyncrasies showed by ASD people (Cavallo et al., 2018) would impede them to translate the 'external' social information (i.e. other's action) into an 'internal' motor representation (Casartelli et al., 2016). Future research might build on the experimental paradigm proposed in this study to first probe which levels of motor representation mechanisms (e.g. goal level, movement kinematics level) are impaired in people with ASD, and then to test whether ASD motor representations could benefit from a reduction of the 'motor distance' (i.e. increased motor similarity) between two agents involved in an interaction.

Conclusion

When we perform a movement *before* the other, our movements incorporate aspects that are related to the other's upcoming action. Furthermore, movement kinematics are not only modulated by the goal of the other's action, but also by the way in which the other will specifically move to achieve his goal. These novel findings further the investigation about the processes that underlie our everyday motor interactions with others. They suggest that the motor system is highly permeable to the movements of others, but more importantly, they suggest that this permeability might not only result from a passive reaction to the others' movements, but also from an active prediction of the others' specific way of moving.

Context of the research

The current study is part of a body of work investigating the role of individual motor resources within the complex integration of perception and action during motor interactions. Predictive ability is commonly assumed to be at the heart of interactions, but the contribution of individual motor resources to making accurate predictions of our own and others' actions is a poorly understood area of research. Here, we provided evidence that the permeability of the motor system is based on an active prediction of the others' specific movement kinematics.

Future works will build on these findings by conducting a series of experiments to identify i) the electrophysiological markers of the motor representation of the 'own', the 'other', and the 'joint' action; ii) the intra- and inter-brain connectivity networks related to motor interactions; iii) how these networks are affected in pathological conditions like ASD.

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Figure captions

Fig. 1

Schematic representation of the experimental set-up. The image represents the experimental set-up schematically (not to scale), where the first and the second agent sat in front of each other, at opposite sides of a table.

Fig. 2

Results of *% of movement to peak velocity (%PV)*, *% of movement to peak deceleration (%PD)* and permutation test. The graphs in panel (a) and (b) show the values of the *%PV* (a) and the *%PD* (b), separately for the first (left graphs) and the second agent (right graphs), during the *variable target* session, as a function of the size of the target of the second agent (i.e. target 2V). Bars indicate *SE*. Asterisks denote significant pairwise comparisons (*$p < .05$; ***$p < .001$). Panel (c) shows the empirical distribution of the t-values obtained on 10000 combinations of 20 artificial pairs of participants. The red line represents the critical t-value. The black line represents the t-value obtained from the real pairs of participants.

Fig. 3

Results of the analyses on *wrist velocity*. The graphs represent the modulation of *wrist velocity,* during the *variable target* session, over different percentages of movement both for first agents (left graphs) and second agents (right graphs), when target 2V was small or large. Graphs in different rows represent the modulations observed when target 2V was at the short (first row), medium (second row), and long distance (third row). Thin lines represent a single participant's mean; thick lines represent the observed group mean.

Fig. 4

Results of additional analyses on the difference between the *%PD* of the two agents. The graph in panel (a) shows the difference between the *%PD* of the two agents in the first and in the last five trials of each block. The graph in panel (b) shows the difference between the *%PD* of the actions of the two agents occurring within the same trial (i.e. lag 0), and of the actions of the first agent in one trial and the actions of the second agent in the preceding trial (i.e. lag 1). Bars indicate *SE*. Asterisks denote significant difference (*$p < .05$; ***$p < .001$).

Fig. 5

Result of t-SNE. The image shows the result of the t-distributed Stochastic Neighbor Embedding (i.e. t-SNE) performed on the movements of second agents during the *variable target* session, when target 2V was large and located at the long distance. Each color represents a

different second agent; each dot represents a movement. Movements of the same second agent appear clustered and separable from the movements of other second agents.