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RESEARCH ARTICLE

Kinematics fingerprints of leader and follower role-taking during cooperative joint actions

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Abstract Performing online complementary motor adjustments is quintessential to joint actions since it allows interacting people to coordinate efficiently and achieve a common goal. We sought to determine whether, during dyadic interactions, signaling strategies and simulative processes are differentially implemented on the basis of the interactional role played by each partner. To this aim, we recorded the kinematics of the right hand of pairs of individuals who were asked to grasp as synchronously as possible a bottle-shaped object according to an imitative or complementary action schedule. Task requirements implied an asymmetric role assignment so that participants performed the task acting either as (1) Leader (i.e., receiving auditory information regarding the goal of the task with indications about where to grasp the object) or (2) Follower (i.e., receiving instructions to coordinate their movements with their partner's by performing imitative or complementary actions). Results showed that, when acting as Leader, participants used signaling strategies to enhance the predictability of their movements. In particular, they selectively emphasized kinematic parameters and reduced movement variability to provide the partner with implicit cues regarding the action to be jointly performed. Thus, Leaders make their movements more "communicative" even when not explicitly instructed to do so. Moreover, only when acting in the role of Follower did participants tend to imitate the Leader, even in complementary actions where imitation is detrimental to joint performance. Our results show that mimicking and signaling are implemented in joint actions according to the interactional role of the agent, which in turn is reflected in the kinematics of each partner.

Keywords Joint action · Predictive simulation · Motor signaling · Visuo-motor interference · Grasping kinematics

Introduction

Pair dancing implies two individuals dancing together but with different roles. Typically, the Leader is responsible for initiating appropriate steps to suit the music and guiding the partner via hand pressure and other body signals. In contrast, the Follower complements with the movements he/she has been prompted to make and thus ensures that smoothly synchronized and coordinated choreographies are created. Role-taking in complementary motor behaviors may be considered to be a general mechanism at the base of human coordination in joint actions, that is, any situation in which two agents must coordinate to achieve a common goal (Sebanz et al. 2006). Such complementary interactions generalize to what happens in linguistic communication, where production and comprehension never occur in isolation. Rather, the speaker's production unfolds while the listener tries to comprehend the message most probably via interactive alignment (Garrod and Pickering 2009; Menenti et al. 2012; Pickering and Garrod in press; Brennan and Hanna 2009). However, individuals' roles in everyday life interactions might not be as well

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defined as during verbal communication. In particular, coordinating in a complementary fashion requires partners to agree on a common strategy. The fact that humans are able to solve coordination problems without resorting to speech suggests that motor interaction also implies a form of communication. In line with this, Pezzulo and Dindo (2011) proposed a computational model for joint actions in which partners use strategic "signaling" aimed at sharing representations and guiding the other partner toward the achievement of joint goals. These signals constitute "coordination smoothers" (Vesper et al. 2010) that help to disambiguate the action of each partner, enhance movement predictability, and optimize motor (and verbal) effective coordination (van der Wel et al. 2011; Vesper et al. 2011; Clark 1996, 2002).

It is worth noting, however, that in pair dancing, the Leader's signaling prompts optimal coordination only if the Follower is able to use these signals to predict what the Leader is about to do. Indeed, far from passively reacting to the other's behavior, partners involved in joint actions try to make reliable predictions about the outcome of the other's movement and thus efficiently and prospectively adapt their behavior (Sebanz and Knoblich 2009; Keller et al. 2007; Sebanz et al. 2006; Knoblich and Jordan 2003). When visual information on a partner's movements is available, the visual action–perception coupling mechanism activated by passive observation (di Pellegrino et al. 1992; Fogassi et al. 2005) might be called into play in interpersonal coordination. However, *predicting* the deployment in time of partner's movements is fundamental for transforming a "passive" action–perception coupling mechanism to an "active" mechanism. Accordingly, it has been proposed that the observation of others' actions may activate the same feed-forward mechanisms used for controlling individual actions (Wolpert et al. 2003) and thus enable a person to predict another person's upcoming actions (Kilner et al. 2004; Urgesi et al. 2006) or monitor their movements (Aglioti et al. 2008; Candidi et al. 2012). This would be in line with the "emulation theory of representation" according to which internal models (developed during the interaction between the body and the environment) may be run off-line in order to permit the estimation of the outcome of planned, imagined, or observed actions (Grush 2004). In the same way, it has been shown that in the absence of online sensorimotor feedback on a partner's movements, interacting individuals achieve good temporal coordination on the basis of internal predictions (Vesper et al. 2013).

The literature on the mechanisms of motor interactions reports two apparently contradictory core findings. Indeed, on the one hand, it has been shown that action–perception mechanisms lead to "visuo-motor interference" due to covert imitation (i.e., "mirroring") of observed actions incongruent with those executed but irrelevant to the individual task (Brass et al. 2000; Kilner et al. 2003; see also Blakemore and Frith 2005 for a review) and on the other hand, van Schie et al. (2008) reported that performing complementary actions in a joint context (i.e., performing an action incongruent with a partner) does not imply any modulation of accuracy or reaction times (RTs), suggesting the absence of automatic imitation of a partner's movements in joint actions (van Schie et al. 2008, see also Ocampo and Kritikos 2010; Poljac et al. 2009). A possible reconciliation of these apparently contradictory findings might be based on the notion that being involved in a joint action requires building a shared representation of the task. Indeed, this representation may flexibly imply the use of prediction and simulative mechanisms (including mimicking) according to the nature of the interaction and of the interactional role. Investigations on whether different neurocognitive processes (e.g., signaling, predicting, and action–perception coupling) are variously recruited according to task demands are lacking. Similarly, it is unknown which interactive conditions imply the dominance of one process over the others and in which cases they sustain or hamper efficient interpersonal coordination.

In the present study, we address these issues by investigating whether the kinematics of a joint grasping task is modulated by the interactional role of each individual partner. We asked pairs of same-gender participants who did not previously know each other to grasp as synchronously as possible a bottle-shaped object placed in front of them using either a power or precision grip and performing either imitative or complementary actions. Participants received asymmetric auditory instructions so that in each trial, they performed the task acting either as (1) Leader, that is, aiming to achieve their own sub-goal while being directly instructed on where to grasp the object without taking their partner's sub-goal into account (e.g., without considering whether the partner executes a precision or a power grip), or (2) Follower, that is, performing imitative or complementary actions with respect to their partner with the necessity of adapting to his/her movements (using either a precision or a power grip). In each trial, only one participant (Leader) knew in advance where to actually grasp the object. The other participant had to adapt his/her movements in order to perform an imitative/complementary action. Thus, in each trial, asymmetric information was provided to each individual. It is important to note that whatever the instruction and role, each participant had to take their partner's movements into account in order to achieve temporal coordination. We hypothesized that participants would modulate their kinematics according to their interactional role even if no role had been explicitly assigned. Specifically, when acting as Leaders, participants might easily realize that only they were aware of the message to be conveyed. Thus, leading would require the recruitment of signaling strategies to make movements as informative as possible since participants would realize that they were the only person aware of the "message" to be conveyed (e.g., bringing forward the instant in which maximal wrist velocity, maximum grip aperture, and maximum wrist height are reached in order to provide the partner with more time to disambiguate the intended movement; enhancing the difference between the grip aperture and wrist trajectory of precision and power grips; reducing the variability of the movement). In contrast, it was expected that following would require participants to rely on predictive strategies in order to "comprehend" the Leader's message; interestingly, acting as Follower may also have the detrimental effect of triggering imitation of a partner's movements even when a complementary action is required (e.g., inducing greater interference between incongruent observed and executed movements). In sum, we expected (1) the recruitment of signaling and predictive simulation to be modulated by task demands and (2) the inhibition of mimicking (when acting as Follower) to be linked to the joint performance.

Methods

Participants

Fourteen participants (8 males, average age 24.8 ± 3.9) took part in the experiment and were assigned to 7 same-gender pairs. All participants were right-handed, as confirmed by the standard handedness inventory (Briggs and Nebes 1975), reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

The experimental protocol was approved by the ethics committee of the Fondazione Santa Lucia and was carried out in accordance with the ethical standards of the 1964 Declaration of Helsinki. Participants gave their written informed consent to take part in the study, received reimbursement for their participation and were debriefed on the purpose of the experiment at the end of the experimental procedure.

Experimental stimuli and setup

Individual auditory instructions regarding the movements to be performed were administered simultaneously to both participants via headphones. Instructions consisted of two different sounds (*Leader instructions*: duration = 500 ms, intensity 4.5 db, frequency 1,378 and 215 Hz) according to the type of grip (precision or power, respectively) and two words (*Follower instructions*: "Opposite" or "Same", duration 700 ms) according to the type of action to be executed.

Each participant had to reach and grasp one bottle-shaped object (30 cm total height) which consisted of two superimposed cylinders with different diameters (small = 2.5 cm; large = 7.0 cm). The bottle-shaped object was placed in front of each participant on the center of the working surface, 45 cm away from the participant and 5 cm to the right of the midline with respect to each participant. In order to record their touch time on the bottle, two pairs of touch-sensitive copper plates (one per cylinder) were placed on the object at heights of 15 and 23 cm.

Paired participants were seated opposite each other in front of the working surface, a rectangular table of 120 × 100 cm (Fig. 1). Before each trial, each participant positioned his right hand on a starting button placed at a distance of 40 cm from the bottle-shaped object, 10 cm to the right of the midline, with the index finger, and the thumb gently opposed. The GO-signal, in addition to the feedback signal, was provided by means of a green/red LED placed near each participant next to the starting position of their hands.

Three infrared reflective markers (5 mm diameter) were attached to the participants' right upper limb at the following points: (1) wrist, dorso-distal aspect of the radial styloid process, (2) thumb, ulnar side of the nail, (3) index finger, radial side of the nail. The hand kinematics of each individual was recorded using a SMART-D motion capture system (Bioengineering Technology & Systems [B|T|S]) and stored for off-line processing. Four infrared cameras with wide-angle lenses (sampling rate 100 Hz) placed about 100 cm away from each of the four corners of the table captured the movement of the markers in 3D space. The standard deviation of the reconstruction error was always inferior to .5 mm for the three axes. Kinematics was computed for both participants at the same time.

Procedure

Participants received written instructions concerning the overall experimental procedure. They were told that their task was to grasp the bottle-shaped object in front of them *synchronously* with their partner, executing different individual movements according to auditory instructions. The instructions could either be: (1) a sound (*Leader instructions*), specifying which part of the object they would have to grasp (low-pitched sound meaning "grasp the lower part," high-pitched sound meaning "grasp the upper part"); or (2) a word (*Follower instruction*), specifying whether they had to do an imitative ("Same") or complementary ("Opposite") movement with respect to their partner. Participants were not explicitly informed about their partner's instructions nor were they told about the different roles depending on the auditory cues—they only knew that there were two different kinds of cue and that, whatever

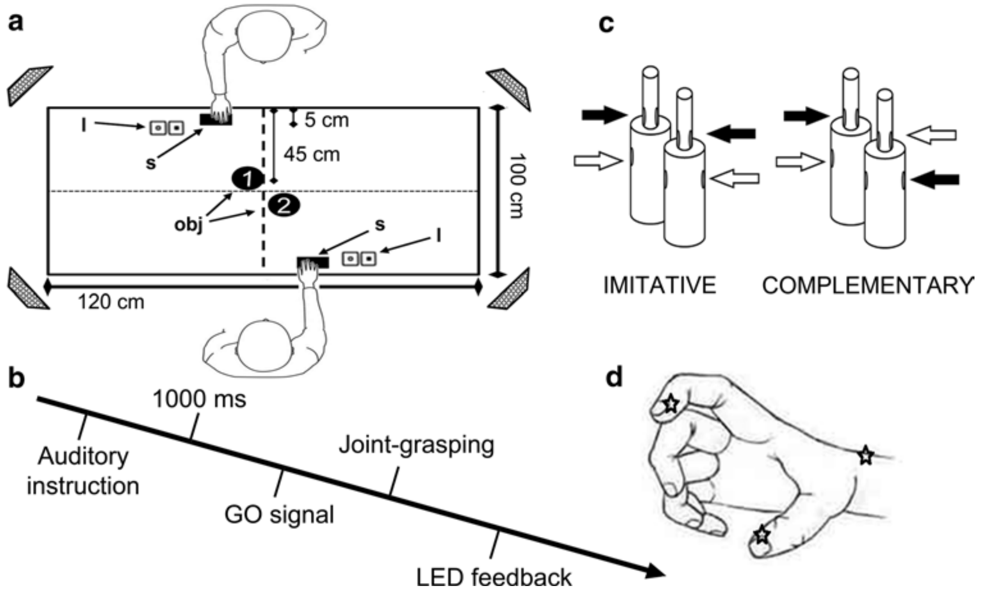

Fig. 1 The *figure* shows the experimental setup and procedure. **a** *Top-view* of the experimental setup. Participants sat in *front* of each other with their *right* hand placed on the Start button (s). They were instructed to reach and grasp their bottle-shaped object (obj) trying to be as synchronous as possible with their partner. A green/red LED (l) was placed in front of each participant to provide GO and feedback signals. **b** Trial timeline: at the beginning of each trial, participants received an auditory cue consisting of either a high-/low-pitched sound (*Leader instruction*) or a word ("Opposite"/"Same," *Follower instruction*); 1,000 ms after the onset of the instruction, the LED placed in front of each participant was turned off indicating that participants could now perform the joint grasping task; at the end of the trial, participants received feedback concerning their performance in terms of grasping synchronicity. **c** Schematic representation of the action-types (complementary/imitative) that participants were required to perform. **d** Position of the infrared reflective markers on the participants' *right* hand. Kinematics were recorded from the wrist (dorso-distal aspect of the radial styloid process), thumb (ulnar side of the nail), and index finger (radial side of the nail)

the condition, they always had to try to grasp the object as synchronously as possible. Moreover, auditory instructions regarding the movement to be performed by each individual were simultaneously administered to both participants. No explicit leader/follower role was thus assigned to the participants.

At the beginning of each trial, participants heard their auditory cue, then, 1,000 ms after the onset of the instruction, the LED placed in front of each participant was turned off (GO-signal); in this way, the GO-signal was not affected by the difference in duration of Leader's and Follower's auditory instructions. Trials in which one of the participants released the Start button before receiving the GO-signal were considered "false-starts" and discarded from the analysis. At the end of each trial, participants received feedback (by means of the green/red LED) about their performance as a couple (win/lose trial). They won when they both respected their own instructions and achieved good synchronicity in grasping the object. The tolerance time window to evaluate synchronicity became wider/narrower trial by trial according to a staircase procedure in order to adapt to participants' performance, starting from a fixed time window of 450 ms. Participants knew their monetary reward would depend on the number of successful trials; the aim of this was to encourage the participants' commitment. Throughout the experiment, participants were instructed not to talk to each other and the experimenter checked to make sure they did not convey any verbal or facial information.

Participants performed four 24-trial sessions comprising 2 blocks each. In each session, the Leader/Follower order was counterbalanced, so that in block 1, one participant (*Leader*) received 6 high- plus 6 low-pitched sounds (in randomized order) while the partner (*Follower*) received 6 "opposite" plus 6 "same" instructions (in randomized order), and the role would then be reversed in block 2. Stimulus presentation and randomization were controlled by E-Prime1 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA).

Before recording the motor task, participants listened to the auditory instructions as long as they needed in order to achieve an errorless association of high-pitched/low-pitched sounds (Leader's instructions) and opposite/same instructions (Follower) with the correct movement; moreover, a preliminary block consisting of 8 trials was provided; in this block, each participant performed 2 trials per condition, that is, 2 trials × 2 Roles (Leader/Follower) × 2 Action-type (imitative/complementary) × 2 Movement-type (power/precision grip).

Data processing

Only correct trials (i.e., trials in which both participants respected their instructions and did not make a false start, mean accuracy = 94.46 %) were analyzed.

We considered as *behavioral measures*: (1) grasping synchronicity, that is, absolute value of the time delay between subjects' index–thumb contact-times on their bottle [abs (sbjA's contact-time on the bottle − sbjB's contact-time on the bottle)]. Please note that "contact-time" is defined as the time from the GO-signal to the instant of the participant's index–thumb contact on the bottle; and (2) RTs, that is, time from the GO-signal to the instant of the hand release of the Start button.

The SMART-D software package (B|T|S|) was used to provide a 3D reconstruction of markers positions as a function of time and to analyze the data. Trial-by-trial RTs and closure time on the bottle recorded by E-Prime were used to subdivide the kinematics recording with the aim of analyzing only the reaching-to-grasp phase, that is, from the instant the hand of the quickest participant released the Start button to the instant the hand of the slowest participant touched the bottle.

We analyzed *kinematic measures* associated with both the reaching and the pre-shaping component of the reach-to-grasp movement (Jeannerod 1981, 1984). Namely, for the reaching component, we analyzed maximum peak wrist velocity on the median plane (*V*) and wrist trajectory (indexed by the maximum peak of wrist height on the vertical plane, *H*), while for the grasping component, we analyzed maximum grip aperture (Ap, that is, the maximum peak of index–thumb 3D Euclidean distance). For each of these kinematic parameters, we extracted two variables, namely the maximum peak amplitude (max*V*, max*H,* and maxAp) and the instant at which this peak was reached (*T*-max*V*, *T*-max*H,* and *T*-maxAp). Trial-by-trial instants of maximum peaks (*T*-max*V*, *T*-max*H,* and *T*-maxAp) were normalized on movement time (final measures expressed in percentage). Moreover, with regard to the spatial variables (*H* and Ap), we also measured maximum peak wrist height and maximum grip aperture mean standard deviations (SD_max*H* and SD_maxAp) as indices of movement noise in each condition, that is, these were considered indices of how variable participants' movements were in space. As a result, we extracted three dependent variables from Ap, three from *H* and two from *V*. While the dependent variables extracted from *V* were selected to examine the temporal features of the movement, variables referring to *H* and Ap were necessary to describe spatial features, respectively, of the reaching (*H*) and grasping (Ap) components of the reach-to-grasp movement.

Behavioral or kinematic values that fell 2.5 SDs above or below each individual mean for each experimental condition were excluded as outlier values (on average, .54 % of total, namely .52 ± .89 trials). At the group level, participants with an individual mean 2.5 SDs above or below the group mean would be excluded from the analyses; however, no outlier participant was found according to this criterion.

Data analyses

With regard to mean *grasping synchronicity*, we first tested the presence of a learning curve throughout the session with a one-way ANOVA. Then, we compared participants' synchronicity in different conditions. However, since grasping synchronicity is a variable pertaining to couples (i.e., having one value per trial per each pair of participants), action-type (complementary/imitative) was the only within-couple factor to be analyzed; indeed, since in each trial one participant was playing as Leader and the other as Follower and (in complementary actions) one participant was performing a movement-type (precision/power grip) while the other was performing the opposite, it was not possible to associate trials with Leader/Follower and power/precision grip labels for couples; as a consequence, these factors were left out from the analysis and we directly compared pair performance in imitative versus complementary actions by means of a paired *t* test. All the other variables (single-subject variables) were analyzed with a repeated-measure ANOVA with Role (Leader/Follower) × Action-type (complementary/imitative) × Movement-type (power/precision grip) as within-subject factors. Since we extracted more than one variable from the same kinematic parameter (i.e., maximum peak amplitude, instant of maximum peak and—for H and Ap − SD of maximum peak), a MANOVA was first performed by pooling together all variables (mean maximum peak amplitude, mean time of maximum peak, and mean standard deviation of maximum peak) linked to the same kinematic parameter (*V*, *H*, Ap) in order to protect the analyses from family-wise error inflation. Then, post hoc ANOVAs were performed on significant effects. All tests of significance were based upon an α level of .05. Where appropriate, post hoc tests were performed using the Newman–Keuls method.

We expected partners in the role of Leader to increase their signaling by increasing the difference between movement maximum spatial peaks (*H* and Ap) in power versus precision grips and bringing forward the time of their wrist maximum velocity peaks (*T*-max*V*) and reducing movement variability (i.e., reduction of *H* and Ap standard deviations). Conversely, we expected the movements of Followers to show an increase in mimicking in complementary trials, that is, that kinematics (maximum *H* and/or Ap) would differ between imitative and complementary trials only when participants were acting as Followers, due to the tendency to involuntarily mimic a partner even in complementary movements.

Results

Behavioral performance (grasping synchronicity) and reaction times

Grasping synchronicity showed a significant main effect of session [$F(3,18) = 3.70$, $p = .03$], suggesting the presence of a learning effect throughout the experiment. More importantly, the analysis on grasping synchronicity showed that the performance of each pair did not differ in complementary as compared to imitative trials [complementary = 112.22 ± 37.24 ms, imitative 103.32 ± 34.38 ms; $t(8) = 1.42$, $p = .19$]. This result was further supported by the analysis on single-subject behavioral performance in terms of RTs. Indeed, RTs showed neither a main effect of Action-type ($p = .95$) nor a significant Role × Action-type interaction ($p = .3$), indicating that overall imitative and complementary trials were equivalent in terms of computational cost during movement preparation. These results indicate that complementary movements were equivalent to imitative ones with regard to movement preparation and the behavioral performance of the pairs of participants (see Table 1).

However, RTs showed a significant main effect of role [$F(1,13) = 29.51$, $p < .001$], a Role × Movement-type significant interaction [$F(1,13) = 7.89$, $p = .015$] and a Role × Action-type × Movement-type significant interaction [$F(1,13) = 6.36$, $p = .025$], indicating that while participants always showed longer RTs when following as compared to when leading, the longest movement preparations were shown before performing Precision grips ($p = .02$) and particularly before complementary Precision grips ($p = .03$).

Table 1 Absence of Action-type (complementary/imitative) main effect in grasping synchronicity and reaction times

	Complementary	Imitative	p
Grasping synchronicity	112.22 ± 37.24	103.32 ± 34.38	.19
Reaction times	472.11 ± 82.79	471.79 ± 81.31	.95

The table shows that complementary actions did not imply a reduction in the ability of pairs to coordinate (in terms of grasping synchronicity) and did not involve any additional computational cost during movement preparation (as shown by reaction times). Mean grasping synchronicity and reaction times are both expressed in ms

Kinematic data

All significant effects are summarized in Table 2.

Wrist velocity peak (V)

The MANOVA on mean maximum peak and mean time of maximum wrist velocity peak on the x axis (max$V$ and T-max$V$) showed a significant main effect of Role [$F(2,12) = 19.47$, $p < .001$] and a significant Action-type × Movement-type interaction [$F(2,12) = 7.83$, $p = .007$]. With regard to the latter interaction, post hoc ANOVAs showed that—regardless of the role – imitative actions differed from complementary ones only in Power grips [max$V$, Action-type × Movement-type $F(1,13) = 8.82$, $p = .011$; T-max$V$, $F(1,13) = 14.34$, $p = .002$, respectively]. Indeed, during Imitative Power grips, participants were faster ($p = .04$) and showed a shorter deceleration time ($p = .03$). More importantly, with regard to the comparison between Leader and Follower roles, T-max$V$ showed a significant main effect of Role [$F(1,13) = 37.46$, $p < .001$] indicating that, when leading, participants brought forward the instant in which they reached wrist peak velocity; this was possibly done in order to prolong the deceleration phase and provide the partner with more time to disambiguate their movements.

Wrist height peak (H)

The MANOVA on mean maximum peak (max$H$), mean time of wrist height maximum peak on the y axis (T-max$H$), and mean maximum peak SDs (SD_max$H$) showed significant main effects of Action-type [$F(3,11) = 28.7$, $p < .001$] and Movement-type [$F(3,11) = 352.8$, $p < .001$] and a significant Action-type × Movement-type interaction [$F(3,11) = 32.0$, $p < .001$]. Moreover, the MANOVA showed Role × Action-type [$F(3,11) = 30.4$, $p < .001$], Role × Movement-type [$F(3,11) = 7.2$, $p = .006$), and Role × Action-type × Movement-type [$F(3,11) = 19.2$, $p < .001$] to be significant interactions.

A post hoc ANOVA on max$H$ revealed all the significant effects described above (see Table 2). These effects were all explained by the triple Role × Action-type × Movement-type significant interaction [$F(1,13) = 30.36$, $p < .001$], which indicated that: (i) subjects emphasized their movements overall when leading as compared to when following [Role × Movement-type, $F(1,13) = 17.69$, $p = .001$], since they reached a higher wrist max$H$ when grasping the upper cylinder with a Precision grip ($p < .001$) and (ii) followed a lower trajectory when grasping the lower cylinder with a Power grip ($p < .001$) regardless of the Action-type (complementary/imitative) they were performing (see Fig. 2 left panel).

On the contrary, when following, they behaved differently in complementary as compared to imitative actions, that is, they were influenced by their partner's movement during complementary actions. Indeed, when grasping the lower cylinder with a Power grip, participants followed a higher trajectory in complementary than in imitative trials, namely in those trials in which the partner was grasping the upper cylinder (all ps < .001) (see Fig. 3, left panel). In this condition, participants displayed imitative behavior even if they were not required to do this (i.e., when the task

Table 2 All significant effects on kinematics. *F* statistics in MANOVA are calculated according to Wilky's Lambda

Parameter	Effect	*F*	*df*
	MANOVA on *V*		
	Main effect of role	19.47***	2, 12
	Action-type × Movement-type	7.83**	2, 12
	ANOVAs on *V*		
Max*V*	Action-type × Movement-type	8.82**	1, 13
T-max*V*	Main effect of Role	37.46***	1, 13
	Action-type × Movement-type	14.34**	1, 13
	MANOVA on *H*		
	Main effect of Action-type	28.7***	3, 11
	Main effect of Movement-type	352.8***	3, 11
	Action-type × Movement-type	32.0***	3, 11
	Role × Action-type	30.4***	3, 11
	Role × Movement-type	7.2**	3, 11
	Role × Action-type × Movement-type	19.2***	3, 11
	ANOVAs on *H*		
Max*H*	Main effect of Action-type	53.97***	1, 13
	Main effect of Movement-type	408.71***	1, 13
	Action-type × Movement-type	24.28***	1, 13
	Role × Action-type	95.24***	1, 13
	Role × Movement-type	17.69***	1, 13
	Role × Action-type × Movement-type	30.36***	1, 13
SD_max*H*	Main effect of Action-type	28.64***	1, 13
	Main effect of Movement-type	5.3*	1, 13
	Action-type × Movement-type	88.71***	1, 13
	Role × Action-type	9.35**	1, 13
	Role × Movement-type	10.03**	1, 13
	Role × Action-type × Movement-type	18.47***	1, 13
T-max*H*	Main effect of Action-type	6.66*	1, 13
	Main effect of Movement-type	63.57***	1, 13
	Role × Action-type	7.64*	1, 13
	Role × Movement-type	16.49***	1, 13
	MANOVA on Ap		
	Main effect of Role	23.2***	3, 11
	Main effect of Movement-type	109.4***	3, 11
	Role × Movement-type	22.6***	3, 11
	ANOVAs on Ap		
MaxAp	Main effect of Role	31.1***	1, 13
	Main effect of Movement-type	229.66***	1, 13
	Role × Movement-type	45.18***	1, 13
SD_maxAp	Main effect of role	21.19***	1, 13
	Main effect of Movement-type	167.11***	1, 13
	Role × Movement-type	39.11***	1, 13
T-maxAp	Main effect of Movement-type	21.5***	1, 13
	Role × Movement-type	23.36***	1, 13

Results from the MANOVAs on wrist velocity on the median plane (*V*), wrist height on the vertical plane (*H*), and absolute grip aperture (Ap) are separately reported as well as all the post hoc ANOVAs on velocity, wrist height, and grip aperture maximum peaks (max*V*, max*H,* and maxAp) and instants (time, *T*) of maximum peaks (*T*-max*V*, *T*-max*H,* and *T*-maxAp) and—for the spatial parameters—mean standard deviations (SD_max*H* and SD_maxAp). See main text for a detailed description

* $p < .05$; ** $p < .01$; *** $p < .001$

required a complementary action). This effect emerged only when participants were acting as Followers and may have been the consequence of visuo-motor interference between self-executed actions and those observed in their partner. We expected this mimicking to emerge also in the complementary condition when participants grasped the upper part of the object (i.e., while their partner was grasping the lower part); however, the small variation of peak max*H* when

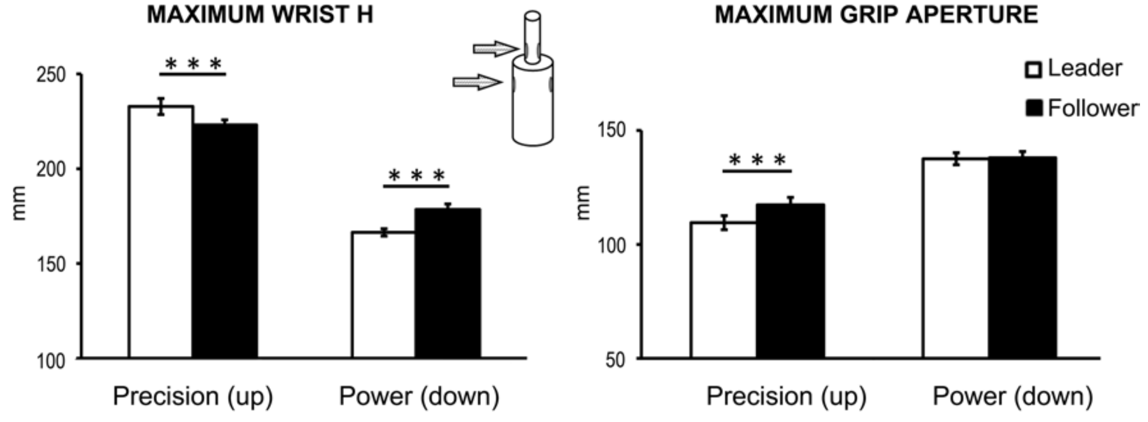

Fig. 2 "Signaling" strategies applied by Leaders; data on maximum wrist height and maximum grip aperture. The *graphs* show the significant Role × Movement-type interaction for both max$H$ [$F(1,13) = 17.69$, $p = .001$; $p < .001$] and maxAp [$F(1,13) = 45.18$, $p < .001$; $p < .001$]. These effects indicate that when participants acted as Leaders, they significantly emphasized the features of their movements in order to make their behavior easier to disambiguate. With regard to max$H$, their wrist exhibited a higher trajectory when grasping the *upper* part of the bottle and a lower trajectory when grasping the bottom part when they were leading as compared to when they were following. With regard to maxAp, they showed a smaller grip aperture when grasping the smaller part of the object. It is worth noting the absence of a significant difference between complementary and imitative actions shown by Leaders indicating that they were not influenced by their partner's behavior. Thus, Leaders do not need to use mimicking when observing the Follower's actions The fact that a significant effect of maxAp was found only in Precision grips may be due to both the fact that the features of the recorded parameter (peak Ap) imply a ceiling effect in power grips and to the more accurate nature of the planning for precision grips. *Error bars* indicate SEM. ***$p < .001$

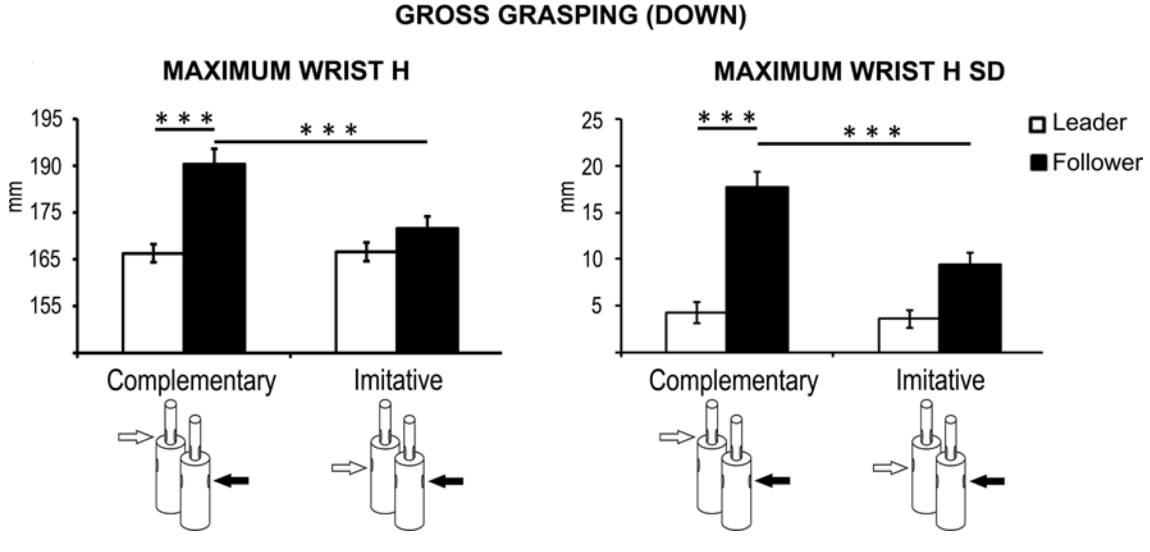

Fig. 3 Visuo-motor "interference effects" between self-executed actions and those observed in partners when participants were acting as Followers. Data on mean maximum wrist height (max$H$) and mean standard deviation of maximum wrist height (SD_max$H$) in Power grips only. The *graphs* show the significant interaction between Role × Action-type × Movement-type as shown by both max$H$ [$F(1,13) = 30.36$, $p < .001$; all ps $< .001$] and SD_max$H$ [$F(1,13) = 18.47$, $p < .001$; all ps $< .001$]. These effects suggest that the comparable level of grasping synchronicity in complementary as compared to imitative actions executed by pairs was achieved at the expense of the Follower's individual effort to inhibit an automatic tendency to imitate the partner's movements in complementary trials. The fact that a significant effect was more evident when participants were grasping the lower part of the bottle-shaped object is due to the features of the recorded parameter (peak *maximum H*), which imply a ceiling effect when participants correctly grasp the upper cylinder with a precision grip. *Error bars* indicate SEM. ***$p < .001$

participants were grasping the upper part of the object may have concealed the effect in the complementary–Precision grip condition. In these trials, participants may have followed a lower trajectory (as they might have been mimicking the movement of the Leader) but the need to reach the upper part of the bottle could have induced a correction that made the wrist height peak identical during complementary and imitative conditions.

A post hoc ANOVA on SD_max*H* again showed all the above-listed significant effects. Indeed, although overall complementary actions were more variable than imitative ones [main effect of Action-type $F(1,13) = 28.64$, $p \leq .001$], this was true only when subjects were acting as Follower [Role × Action-type, $F(1,13) = 9.35$, $p = .009$; $p < .001$] and performing a Power grip on the lower cylinder (Role × Action-type × Movement-type, $F(1,13) = 18.47$, $p < .001$; all *p*s < .001] (see Fig. 3, right panel).

Finally, the ANOVA on *T*-max*H* showed a significant main effect of Action-type [$F(1,13) = 6.66$, $p = .02$] which was further explained by the Role × Action-type [$F(1,13) = 7.64$, $p = .016$] significant interaction. Indeed, the latter indicated that while participants did not change their behavior in complementary as compared to imitative movements when acting as Leader ($p = .9$), they reached their height maximum peaks later in imitative movements as Follower ($p = .001$). Moreover, results showed that height peaks were always reached later when participants performed Precision grips on the upper cylinder [main effect of Movement-type $F(1,13) = 63.57$, $p < .001$], as might be expected given the longer trajectory implied by this condition); however, the Role × Movement-type [$F(1,13) = 16.49$, $p = .001$] significant interaction indicated that when acting as Leader (as compared to when acting as Follower, $p = .003$), participants brought forward the instant at which they reached the maximum peak in wrist height, in order to provide the partner with more time to disambiguate their movements.

Grip aperture (Ap)

The MANOVA on mean maximum grip aperture (maxAp), mean time of maximum grip aperture (*T*-maxAp), and on mean maximum grip aperture SDs (SD_maxAp) showed significant main effects of Role [$F(3,11) = 23.2$, $p < .001$] and Movement-type [$F(3,11) = 109.4$, $p < .001$], and a significant interaction between Role × Movement-type [$F(3,11) = 22.6$, $p < .001$]. Post hoc ANOVAs on maxAp and SD_maxAp both showed the significant main effect of Role [$F(1,13) = 31.1$, $p < .001$ and $F(1,13) = 21.19$, $p < .001$, respectively], indicating that, when leading, individuals had a smaller grip aperture which was much less variable. Moreover, the Role × Movement-type significant interaction [$F(1,13) = 45.18$, $p < .001$ and $F(1,13) = 39.11$, $p < .001$, respectively] demonstrated that, although overall Precision grips implied a smaller grip aperture which was more variable as indicated by the main effect of Movement-type on maxAp [$F(1,13) = 229.66$, $p < .001$] and on SD_maxAp [$F(1,13) = 167.11$, $p < .001$], Leaders emphasized their movements performing smaller Precision grips ($p < .001$, see Fig. 2, right panel) which were significantly less variable ($p < .001$).

Finally, the post hoc ANOVA on *T*-maxAp showed a significant main effect of Movement-type [$F(1,13) = 21.50$, $p < .001$] and a significant interaction between Role × Movement-type [$F(1,13) = 23.36$. $p < .001$], indicating that although it took more time for subjects to reach the maximum grip aperture in Power grips, when leading (as compared to when following, $p < .001$), participants brought forward the instant in which they reached maximum grip aperture in order to provide the partner with more time to disambiguate their movements.

The dark side of interactions

Given the results described above, we further analyzed our data in order to verify whether the enhancement of wrist max*H* of participants in complementary as compared to imitative actions when they were acting as Follower [i.e., max*H* Role × Action-type × Movement-type significant interaction [$F(1,13) = 30.36$, $p < .001$, all *p*s < .001] was actually due to detrimental interference effects (Kilner et al. 2003) between the self-executed actions and those observed in their partner. Tellingly, behavioral studies (Ocampo and Kritikos 2010; Poljac et al. 2009; van Schie et al. 2008) have reported the absence of visuo-motor interference in joint-like contexts, which some authors associate with the presence of an integrated representation of both participants' actions in a shared motor plan (Sebanz et al. 2006). Thus, the presence of covert imitation (involuntary mimicry) is probably the result of an un-integrated representation of the task during planning which in turn has a negative impact on joint performance.

To this aim, we analyzed the trials with reference to pair performance (i.e., grasping synchronicity) and collated the data from the 25 % best and 25 % worst trials for each couple; thus, we were able to compare the kinematics of "effective" interactions (i.e., the trials showing the highest degree of synchronicity) directly with "ineffective" interactions (i.e., the trials with the lowest degree of synchronicity) by means of between-group *t* tests per each condition corrected for multiple comparisons (final threshold $p_{\text{corr}} = .05/8 = .006$). Results showed that the only condition in which the max*H* data significantly differed between effective and ineffective interactions was in complementary–Power grips when subjects were following [$t(81) = -3.01$; $p_{\text{corr}} < .02$); see Fig. 4, left panel].

In other words, only the least coordinated interactions (i.e., the ones in which participants did not achieve good synchronicity) were characterized by detrimental imitative behavior in Followers, while the best synchronized interactions were characterized by the absence of the interferential effect of mimicry.

Finally, in light of this evidence, we applied a correlational approach to further explore the relationship between

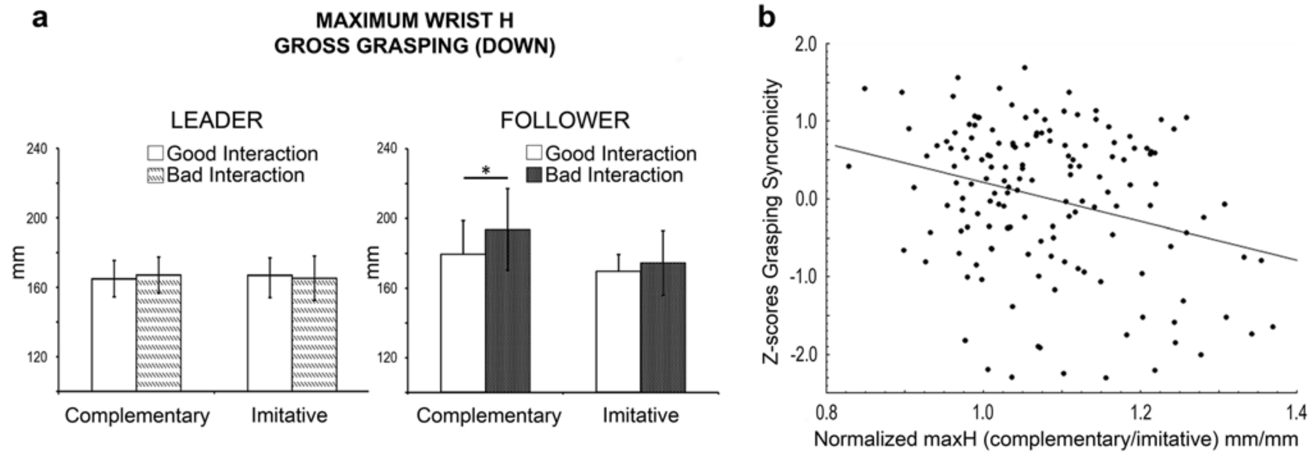

Fig. 4 The *graphs* illustrate the results of an analysis of the link between involuntary mimicry and joint performance. On the *left*, **a** the *histograms* illustrate the results of the between-group *t* tests comparing max*H* data of trials showing the 25 % best/worst performances in terms of grasping synchronicity for each couple. Results showed that the only condition in which the max*H* significantly differed between "Good" interactions (i.e., trials showing the highest degree of synchronicity) and "Bad" ones (i.e., trials showing the lowest degree of synchronicity) was in complementary—power grip condition when participants were acting as Follower. This effect was further explored with a correlational approach. On the *right*, **b** the *graph* shows a significant correlation ($r = -.29$, $p < .001$) between the "interference effect" shown by the max*H* of Followers in complementary movements and joint performance. Note that on the *y* axis, *Z* scores have been reported with the opposite sign (see the formula in the main text), so that higher *Z* scores correspond to better performance. The correlation suggests involuntary mimicry exhibited by Followers was a marker of poorer joint coordination. *Error bars* indicate SDs. $^*p < .05$

the "interference effect" and the joint performance emerged from the analyses reported above along the continuum of participants' joint behavior. In order to be able to collate the data pertaining to all the participants and to correlate a "pure" measure of the interference effect in pair performance, we performed a *Z* transformation of grasping synchronicity in the condition of interest (i.e., Follower–complementary–Power grip) and reversed the sign (i.e., reported the opposite value) so that higher values indicated higher synchronicity:

$$-\frac{(\text{single trial } - \text{individual average value of the condition})}{\text{individual SD of the condition}}$$

Then, we correlated these values trial by trial with the index of involuntary mimicry in max*H* in this condition (namely, the ratio between max*H* in each Follower–complementary–Power grip trial and the mean participant's max*H* in the Follower–imitative–Power grip condition).

$$\frac{\text{single trial max}H\text{ in Follow Complementary Gross grasping}}{\text{individual mean max}H\text{ in Follow Imitative Gross grasping}}$$

Results showed a highly significant negative correlation between these indices ($r = -.29$, $p < .001$; see Fig. 4, right panel), indicating that the higher the interference effect in the Follower, the poorer the joint performance.

Thus, although several factors may play a role in determining trial-by-trial joint performance, "interference" between self-executed actions and those observed in their partner when participants acted as Followers worsened the coordination between pairs.

Taken as a whole, these results suggest that in our joint task, involuntary mimicry constitutes a marker of the least coordinated interactions. This effect may be a consequence of the failure to integrate the sub-tasks of each individual partner in the same motor representation during the planning process.

Discussion

In the present study, we sought to determine whether and how the kinematics of a joint grasping task is modulated by the participants' interactional roles (Leader/Follower) when no explicit instruction on how to coordinate their movements is provided. The results show that the employment of mimicking, prediction, and signaling (three neurocognitive processes which are crucially involved in joint actions) is profoundly influenced by the interactional role of each partner. Significantly, the specific signatures of each process are reflected in the kinematics of each partner. This is one of first attempts (see also Sacheli et al. 2012) to explore dyadic coordination during face-to-face interactive tasks requiring participants to coordinate their goal-directed actions in a realistic environment. Indeed, although they are worthy of note, most of the joint action studies performed thus far (e.g., Sartori et al. 2011, 2012; van Schie et al. 2008; Ocampo and Kritikos 2010; Poljac et al. 2009) mainly use *joint-like interactions* where, in line with previous classical mirror-neuron inspired approaches (e.g., Stanley and Miall 2009; Rizzolatti and Craighero 2004), observers automatically react to the actions of a partner rather than being involved in realistic interactions. Moreover, studies of online face-to-face motor interactions have not directly addressed the specific role of signaling, prediction, and action–perception coupling (see for instance Becchio et al. 2008a, b; Georgiou et al. 2007) or have focused on the timing component of bi-personal coordination (Noy et al. 2011; Vesper et al. 2011; Konvalinka et al. 2010). Our results showed, on the contrary, that (1) when acting as Leader, participants tried to make their kinematics more "communicative" by using signaling to increase the predictability of their movements, and that (2) only when acting in the role of Follower did participants tend to imitate the Leader in the complementary action condition, where mimicking had a negative outcome on joint performance.

Leading and signaling strategies

When acting as Leaders, participants adopted "signaling strategies" (Pezzulo and Dindo 2011; Vesper et al. 2010). Specific kinematic cues provided by leaders (e.g., bringing forward the instant in which kinematic peaks were reached, boosting of movement features and reduction of movement variability) allowed partners to have more time and to more easily interpret the intentions of their action.

The tendency to increase signaling and to reduce variability in movements when interacting as a Leader in a pure motor task parallels previous findings in both verbal (Clark 1996, 2002) and motor communication (Sartori et al. 2009) domains. Moreover, these results somehow hark back to the findings of "experimental semiotics" (Galantucci 2009) regarding the emergence of communication during interactions mediated by nonverbal exchanges of information. However, it is worth noting that our participants were not explicitly instructed to "communicate" anything to their partner. Rather, they were simply asked to grasp their respective objects as synchronously as possible.

Our study contributes to extend current knowledge by showing that during motor interaction, individuals not only take the partner's task into account (Sebanz et al. 2003, 2005, 2007; Tsai et al. 2008; Atmaca et al. 2008, 2011), but, as indexed by the implementation of signaling, they implicitly take on a specific role according to their own and their partner's instructions (sub-goal distribution in light of the joint goal); indeed, they would not have needed to "signal" (i.e., communicate) their intent if they did not represent both their own and their partner's task realizing that their partner would more easily adapt to their movements if their own actions were more predictable. Our study also expands previous findings on planning strategies used during pure temporal or haptic coordination (Vesper et al. 2011, 2013; van der Wel et al. 2011) by showing that the same principle of predictability plays a role during face-to-face visuo-motor interactions requiring coordination in both space and time. Significantly, our study demonstrates that predictability becomes a strategy to create a purely motor form of shared language which allows participants to achieve a joint goal.

It is worth noting that our experimental design may have facilitated the emergence of signaling. In particular, it cannot be excluded that the asymmetric assignment of information to Leaders and Followers induced the former to enhance "communication" with their partner. It is possible that joint actions characterized by perfectly symmetrical information (e.g., in cases where both participants are aware of the task) might favor the emergence of communication (and consequently of signaling) to a lesser extent. However, joint actions are situations where two agents coordinate with each other to jointly induce a specific environmental change (Sebanz et al. 2006). Since during interpersonal coordination, neither partner has direct access to the programming of the other's action, both individuals necessarily need to predict what the other is going to do (Sebanz and Knoblich 2009). Interestingly, a similar process may also occur in language production and comprehension where both speakers and listeners make predictions during conversation in order to monitor the upcoming utterances (Pickering and Garrod in press). Thus, it is possible that during any kind of interaction, each partner is aware that the other can only infer part of the information necessary for interaction. As a consequence, any interaction potentially requires/includes an exchange of information on which communicative behaviors are built. In our task, the Leader uses signaling to "help" his/her partner to perform his/her task and thus to contribute toward achieving the common reward. This would be in line with evolutionary theories suggesting that the use of ostensive signals and the ability to learn from them is typically human (Csisbra and Gergely 2011), and that "intentionality" might have been one of the key features that allowed the development of a "proto-language" deriving from the primate ability to imitate manual gestures (Arbib 2005).

Following and interference effects

In keeping with previous findings (van Schie et al. 2008), we show that performing complementary movements in joint contexts does not imply any additional cost at a behavioral level. Indeed, the results for grasping synchronicity and RTs (an index of the length of movement preparation) showed no differences between imitative and complementary trials. Nevertheless, data indicate that the kinematics of participants acting as Followers were prone to interference when they had to perform movements which were incongruent with (i.e., complementary to) those of the Leader. Indeed, Followers displayed signs of involuntary mimicry in the reaching component (wrist height on the *y* axis, max*H* and SD_max*H*). Thus, it might be that the comparable level of synchronicity reached in complementary as compared to imitative actions was achieved at the expense of the Follower's individual effort to inhibit an automatic tendency to imitate his/her partner's movements (i.e., mimicking). When this inhibition was not effective, "visuo-motor interference" emerged, with a negative impact on joint performance. The noise of Followers' movements in complementary actions indicates the presence of interference effects between action perception and execution which have been associated with the recruitment of a simulative fronto-parietal "mirror" network (Rizzolatti and Sinigaglia 2010; Blakemore and Frith 2005; Kilner et al. 2003). Evidence that involuntary mimicry only emerged when participants had to act as Follower—i.e., when they needed to predict the intentions of their partner's hand and to adapt to it—highlights the close link between "simulation" and prediction and the fact these motor processes are differently recruited according to the demands of the task (Vesper et al. 2013). It has been shown that fronto-parietal areas are recruited during joint actions (Newman-Norlund et al. 2007) and may be responsible for the execution of both imitative and complementary actions (Catmur et al. 2007, 2009; see also Sartori et al. 2011, 2012). However, our results show that the involuntary mimicry exhibited when participants acted as Followers was associated with worse pair performance. This result parallels the detrimental effect of automatic imitation (indexed by reduced payoff) in strategic contexts reported by a previous study (Cook et al. 2012). Thus, the result is in line with neuroimaging literature suggesting that the putative mirror system may not be the only neurocognitive basis of motor interactions (Kokal and Keysers 2010; Kokal et al. 2009). "Simulative" processes (e.g., "emulation," Grush 2004) are likely to be recruited to achieve better temporal and spatial predictions of a partner's actions. Such predictions are necessary to allow smooth coordination which cannot be achieved simply on the basis of reactive processes (Keller et al. 2007; Sebanz et al. 2006; Knoblich and Jordan 2003). However, these active and predictive "simulative processes" need to be distinguished from action–perception coupling and passive "mirroring." Indeed, mere resonance during face-to-face interaction would result in visuo-motor interference with consequent detrimental effects. Motor resonance and flexibility of the action–perception coupling (Catmur et al. 2007, 2009) may be a key feature in the creation of "interpersonal links" between interacting partners. In any case, these processes may not suffice to achieve good joint coordination. Our data suggest that efficient joint performance requires the ability to inhibit automatic resonance and to predict a partner's goal without the need to imitate it.

Conclusions

A variety of processes, ranging from automatic entrainment (Schmidt et al. 2011) to high-level planning processes (e.g., perspective-taking), play a role during joint actions (Knoblich et al. 2011). Within this framework, action–perception coupling mechanisms (i.e., mirroring) are only part of a wider range of strictly interdependent neurocognitive processes which support coordination in interactive contexts (Pezzulo et al. in press). Our study expands previous research on real-life hand-to-hand human interactions by proving that during a realistic joint grasping task, not only participants' prior intentions (Becchio et al. 2008a, b, 2010; Sartori et al. 2009; Georgiou et al. 2007) but also the actual "interactive roles" taken by each individual modulate the features of movements. In particular, being the Leader of an interaction implies the (intentional) recruitment of communicative behaviors (e.g., signaling) in order to convey essential information to the interacting partner. Acting as Follower implies adaptation to a partner not only on the basis of good predictive abilities but also depending on the ability to inhibit automatic resonance in order to focus on the partner's (and on the joint) goal. This supports the notion that joint actions imply a form of communication during which smooth coordination is achieved only when partners send motor signals effectively and are prompt to interpret them. As in pair dancing, only when both Leader and Follower do their job efficiently can a synchronized complementary choreography be obtained.

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Conflict of interest The authors declare that they have no conflict of interest.

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