# Visuo-motor interference with a virtual partner is equally present in cooperative and competitive interactions

Vanessa Era[1,2*], Salvatore Maria Aglioti[1,2], Carolina Mancusi[1,2], Matteo Candidi[1,2*]

1 SCNLab, Department of Psychology, "Sapienza" University of Rome, Italy
2 IRCCS, Fondazione Santa Lucia, Rome, Italy
*Corresponding Authors: Vanessa Era, via dei Marsi 78, 00185, Rome, Italy, e-mail vanessa.era@uniroma1.it, phone 0039 – 06 44427724, Matteo Candidi, via dei Marsi 78, 00185, Rome, Italy, e-mail matteo.candidi.@uniroma1.it

## Abstract

Automatic imitation of observed actions is thought to be a powerful mechanism, one that may mediate the reward value of interpersonal interactions, but that could also generate visuo-motor interference when interactions involve complementary movements. Since interpersonal coordination seems to be crucial both when cooperating and competing with others, the questions arises as to whether imitation - and thus visuo-motor interference - occurs in both scenarios. To address this issue, we asked human participants to engage in high- or low-interactive (Interactive or Cued condition respectively), cooperative or competitive, joint reach-to-grasps with a virtual partner. More specifically, interactions occurred in: i) a Cued condition, where participants simply adapted their movement timing to synchronize with (during cooperation) or anticipate (during competition) the virtual partner's grasp; ii) an Interactive condition requiring the same adaptation, as well as a real-time selection of their action according to the virtual character's movement. In order to simulate a realistic human-human interaction, the virtual character would change its movement speed in consecutive trials according to participants' behaviour. Results demonstrate that visuo-motor interference – as indexed by movement kinematics (higher maximum wrist height during complementary compared to imitative power grips) - emerges in both cooperative and competitive motor interactions only when predictions about the partner's movements are needed in order to perform one's own action (Interactive condition). These results support the idea that simulative imitation is heavily present when individuals need to match their behaviours closely.

## Keywords

Cooperation, competition, motor interactions, mutual adjustment, visuo-motor interference, kinematics, reward.

## Introduction

Competition and cooperation are two basic forms of interpersonal interactions that profoundly differ in their execution being the former mainly based on the anticipation of, and the latter mainly on synchronization with, the actions of the partner. However, both forms require the ability to predict the partner's movements and to link one's own action goal to that of the partner.

Behavioral and kinematic studies indicate that individual action execution can be affected by the observation of others' actions, especially when we intentionally interact with them. Importantly, visuo-motor interference (that is the automatic tendency to simulate other's movement when performing an action) between self-executed actions and those observed in a partner might arise when visual information on the partner's movement is present (Kilner et al., 2003). This could indicate that the partner's action is co-represented in one's own motor plan, meaning that we not only represent the action that we need to perform but also our partner's action (Sebanz et al., 2006; Sacheli et al., 2015c) as also suggested by a recent study showing that participants tend to imitate the kinematics of other's actions even when this compromises the efficiency of their own movements (Forbes and Hamilton 2017). In support of this idea, studies have shown that pair performance improves when participants can directly experience their partner's action during cooperative motor interactions (Moreau et al., 2016). It is also worth noting that the process of automatically imitating the behaviour of others seems to play a crucial role in the promotion of fundamental social phenomena such as group affiliation (Hove and Risen, 2009), perhaps due to the intrinsic reward value of imitation (Walter et al., 2005). Yet the tendency to imitate others' behavior seems to be present even when imitation is detrimental to the success of competitive interactions (Cook et al., 2012; Belot et al., 2013; Naber et al., 2013). Naber et al., (2013), for example, reported that in a competitive game, humans tended to imitate an opponent's behaviour when that behaviour was visible. This is consistent with the idea that both cooperative and competitive motor interactions necessitate self-other monitoring, which is the ability to guide actions in accordance with both one's own and others' goals (Decety and Sommerville, 2004). Automatic imitation of observed actions is thus a powerful simulative mechanism that, on the one hand, helps predict other's actions and establish social bonds, but, on the other, can also be detrimental to one's own performance (Panasiti et al., 2017). The aim of this study is to investigate whether automatic imitation in cooperative and competitive social contexts is driven by the need to predict other's actions.

More specifically, we investigated whether visuo-motor interference effects emerge in cooperative and competitive contexts according to whether predictions about the partner's movements are needed to perform one's own action. Participants had to synchronize their actions with the virtual character in the cooperative context and anticipate the action of the virtual partner in the competitive one (Context factor). The task included two interactive conditions (Interactivity factor) orthogonal to the main Cooperation vs Competition manipulation: i) a Cued condition in which participants only had to adapt the timing of their movements in order to synchronize with (during cooperation) or anticipate (during competition) the virtual partner's grasp, and, ii) an Interactive condition requiring the same adaptation as in the Cued condition, plus a real-time selection of their action goal according to the virtual character's movement (thus making their goal a shared one, dependent on the movement of their partner/competitor). A bottle-shaped object was used for the grasping task. Participants in the Interactive condition did not know in advance whether they would have to perform a precision grip on the upper part of the bottle or a power grip on the lower part of it, but they were asked to either imitate (the same grip type, imitative condition, Interaction type factor) or complement (the opposite grip type, complementary condition) the virtual character's actions.

In order to make the cooperative and competitive scenarios similarly difficult, we created a virtual partner who reacted to the movements of its human partner (i.e. changing the speed of its movements in consecutive trials; see Material and

Methods). This manipulation created the need for mutual adaptation, a fundamental feature of human-human motor interactions (Konvalinka and Roepstorff, 2012; Era et al. 2018), making our task ecologically valid for the study of social motor interactions (Reader and Holmes, 2016).

We implemented the Cooperation/Competition and Interactive/Cued conditions in order to investigate whether: 1) the observation of others' actions evokes automatic imitation to the same extent in cooperative and competitive contexts; 2) visuo-motor interference is linked to the necessity of predicting someone else's actions. Recording action kinematics allowed us to measure visuo-motor interference effects in complementary compared to imitative movements. More specifically, we expected visuo-motor interference to be detected in both the reaching component (wrist height) and in the pre-shaping component (grip aperture) of the joint grasping, when performing complementary actions (as shown in Sacheli et al., 2012; 2015; 2018; Candidi et al., 2017). In more details, we expected that during the interactive condition, when performing power grips, maximum wrist height would be higher during complementary compared to imitative movements. Moreover, we expected that during the interactive condition maximum grip aperture would be bigger when performing precision grips in complementary actions compared to imitative ones.

## Materials and Methods

### Participants

Sixteen participants (age 25.21 ± 3.28, 8 males) were involved in the study. 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 and later amendments. Participants gave their written informed consent to take part in the study and were debriefed as to the purpose of the study at the end of the experimental procedures. Participants were reimbursed 7 euros/h plus up to 10 extra euros depending on their performance during the interactive task (Win trials, mentioned later).

### Stimuli

The virtual partner was created in Maya 2011 (Autodesk, Inc.) by a customized Python script (Prof. Orvalho V., Instituto de Telecomunicacoes, Porto University) and the virtual scenario was designed in 3DS Max 2011(Autodesk, Inc.). The virtual character moved according to the kinematics of a real actor's upper body [SMART-D motion capture system (Bioengineering Technology & Systems (B|T|S))] (Tieri et al., 2015) that was recorded while performing 12 reach-to-grasp movements with the dominant right hand, 6 toward the upper part of the bottle (precision grip) and 6 toward the lower part (power grip). We thus implemented 12 different movements (six precision and six power grips), that were included in the experimental task as experimental stimuli. The 3D position of 19 passive reflecting markers, attached to the participant's upper body, including right hand, forearm shoulder and chest (see Tieri et al. 2015 for further details) were recorded by means of a SMART-D motion capture system. Raw data were processed offline using SMART-D modules to reconstruct and label the markers and to interpolate short missing parts of the trajectories. The final processed human-kinematics were realized by using the commercial software MotionBuilder 2015 and 3DS Max 2015 (Autodesk Inc.) thanks to which the kinematics were implemented in a high-polygons 3D model of a caucasian male upper body. To avoid virtual character facial expressions having any unwanted influence, participants could only see it from the neck down. The duration of each clip (~2000 ms) was the same for up (precision grip) and down movements (power grip). We created five different clips for each condition, each with a different avatar movement duration. We did so by modifying the number of frames per second: 1600 ms; 1800 ms; 2000 ms; 2200 ms; 2400 ms. In order to make the virtual character reactive to participants' behaviour on a trial-by-trial basis, participants were shown stimuli with different durations according to their performance (see below). Each stimulus started with an unmoving virtual character, its hands on the table. The virtual character started its movement a variable amount of time after the auditory go signal (i.e. between 200 and 500 ms). The timing of its hand-object contact was calculated by a photodiode on the screen displaying the videos that detected the appearance of a black dot pasted on the frame where the virtual character touched the bottle.

### Interactive task

We used an ecological and well-controlled human-avatar interactive task (Sacheli et al., 2015a; 2015b; Candidi et al., 2017; Sacheli et al., 2018) that has been shown to recruit the same processes as human-human interaction, namely mutual adjustment and automatic imitation (Sacheli et al., 2012; 2013; Candidi et al., 2015; Curioni et al., 2017). An important feature of the task was that neither the interaction goal nor the participants' own action goal could be achieved without considering the virtual partner's movements and adapting online to them. Participants sat at a table with a bottle-shaped object placed 45 cm in front of them. A monitor positioned behind the bottle-shaped object showed a virtual partner facing the participant. In front of this virtual partner was a virtual object identical to that of the participants (Fig.1). Participants were asked to reach and grasp the bottle-shaped object placed in front of them. With their index finger and thumb touching each other, they positioned their right hand over a start-button placed 40 cm from the bottle-shaped object and 10 cm to the right of the table's midline. In order to record participants' touch-time on the bottle, two pairs of touch-sensitive copper plates were placed at 15 cm and 23 cm of the object's height. Given the shape of the object, the virtual character would either grasp the lower part with a whole-hand grasp (power grip), or the upper part with a thumb-index finger precision grip. Participants were asked to perform opposite (complementary) or same (imitative) movements with respect to those of the virtual partner. In the Imitative condition, participants had to grasp the same part of the object with the same grasp type as the virtual partner. In the Complementary condition, conversely, participants had to perform the opposite movement as the virtual partner (one grasping the upper part via precision grip, the other grasping the lower part via power grip, or vice-versa) (Fig.1). In one of the two experimental sessions, participants were instructed to grasp the object as synchronously as possible with their virtual partner (Cooperative session). In the other (Competitive session), human participants were instructed to grasp the object before the virtual partner (notably, the virtual character's movement speed changed according to the behaviour of its partner, thus helping participants feel that their partner was actually competing). Moreover, participants were required in separated blocks to: 1) on-line adapt to the partner's movement by performing either the same action or a different one (Interactive coordination condition) without knowing in advance whether this would mean performing a precision grip on the upper part or a power grip on the lower part; or 2) grasp the upper or lower part of the bottle-shaped object regardless of what movement their partner performed (Cued coordination condition). In 20% of the trials, in order to catch participant's attention, the virtual partner performed a movement correction (switching from a precision to a power grip, or vice versa) during the reaching phase . These trials were excluded from the analyses.

The trial timeline (Fig.2) went as follows: participants would hear the Imitative/Complementary or Up/Down auditory instruction, release the start button and reach-to-grasp the bottle-shaped object. Auditory instructions concerning the movement to be executed were delivered to participants prior to each trial via headphones. For the cued condition, the instructions consisted of two sounds having the same duration (200 ms) and different frequency: i) "high-pitched" , 1479 Hz, indicating that participants had to grasp the upper part of the bottle, ii) "low-pitched",115.5, Hz indicating that participants had to grasp the lower part of the bottle. For the interactive condition, participants heard a voice pronouncing the first two syllables of the Italian word opposite and same, lasting 200 ms each. When participants started their movement before hearing the instruction, the trial was classified as a false start and discarded from the analyses. At the end of each trial, participants would receive feedback about their performance (win/loss trial) by way of green or red LED lights. A win trial meant that participants had followed their auditory instructions (i.e., correctly performed complementary/imitative or up/down movements) and met the requirements of the respective sessions (grasping synchrony in the cooperative, grasping before the virtual partner in the competitive in both the Cued and Interactive conditions). The action was considered synchronous in the Cooperative session if the time-delay between participant and virtual character index-thumb bottle contact-times fell within a given time-window. This time-window was narrowed or widened on a trial-by-trial basis according to a stair-case procedure. Alternatively, the action was considered fast enough to win a Competition trial when the participant touched the object a certain time-window before the virtual partner. A stair-case procedure was used here as well to narrow or widen the time-window on a trial-by-trial basis. This procedure allowed us to change the time-window so as to tailor the task difficulty to the specific performance of each participant. In order to motivate the individual and create commitment to the task, participants knew that their final monetary reward depended on the number of wins accumulated during the experimental sessions. The intertrial interval was not fixed, but depended on the time participants took to go back from the bottle to the starting position. Indeed, the experimenter manually moved to the next trial as soon as participants went back to the starting position and pressed the start button.

Cooperation and competition mean participants must perform two completely different behaviours: synchronize to the partner's movements while cooperating, and anticipate the partner's movements while competing. In order to make the two tasks equally difficult, the virtual partner adapted the duration of its movements according to the participant's performance. It did so in two different ways: in the Cooperative session, the virtual character modified its velocity (by increasing or reducing it) after two consecutive trials in which participant's asynchrony was smaller than the assigned value. It did so for a third trial. If no such trend occurred, the virtual character's movement velocity remained unchanged. This was done in order to make the virtual character's movements more predictable to poorly performing participants (the virtual character was "committing" more to smooth the interaction) and less predictable to well performing participants, as it has been shown that making one's own behaviour more predictable helps to simplify coordination during joint-actions (Vesper et al., 2010 for a review). In the Competitive session, instead, the virtual partner got faster on the third trial following two consecutive trials in which participants had grasped the object before the virtual character by more milliseconds than the assigned value; conversely, when participants grasped the object after the virtual character by more milliseconds than the assigned value for two consecutive trials, the virtual partner became slower on the following trial. The virtual partner's velocity remained the same in the rest of the trials. Thus the virtual character was more "competitive" with participants who had performed better in previous trials. In general, these modifications allowed us to tailor the task difficulty according to the performance of each participant in both the Cooperative and Competitive sessions. Movements were always performed with the right, dominant hand. It is worth noting that in both the interactive and the cued conditions the virtual partner's movements could not be ignored because participants needed to start their movements after the virtual partner started moving. Even more importantly, they needed to anticipate (competition) or synchronize with (cooperation) the movements of the virtual partner. Thus, participants always acted as followers, meaning that they always started moving after the virtual partner, as in situations in which the Guslinger effect is investigated. This effect consists in an advantage in action execution when participants react to the movement of another person in comparison to when they start moving. Interestingly, such an effect is present in both cooperative and competitive situations (Weller et al, 2018). Participants performed one 112-trial Cooperative and one 112-trial Competitive session (in a counterbalanced order between participants). In each session, participants performed 14 x 2 (Complementary/Imitative) x 2 (Precision/Power grip) x 2 (Interactive/Cued) trials. Stimuli presentation and randomization were controlled by E-Prime2 software (Psychology Software Tools Inc., Pittsburgh, PA).

### Kinematics Recording

Reflective infrared markers (5 mm diameter) were attached to participants' right upper limbs at the following points: i) thumb, ulnar side of the nail, ii) index finger, radial side of the nail and iii) wrist, dorso-distal aspect of the radial styloid process. Movement kinematics were recorded with a SMART-D motion capture system [Bioengineering Technology & Systems (B|T|S)]. Four infrared cameras with wide-angle lenses (sampling rate 100 Hz) placed about 100 cm away from each of the table's four corners captured the movement of the markers in 3D space. When calibrating the motion capture system, in order to ensure an accurate reconstruction of the 3D space where the interaction took place, the standard deviation of the reconstruction error was always lower than 0.5 mm for the three axes.

### Experimental Design and Statistical Analysis

Excluded from the analyses were those trials in which participants i) missed the touch-sensitive copper-plates, preventing a response from being recorded, ii) released the start button before the "go" instruction, or iii) did not respect their complementary/imitative or up/down instructions (on average, excluded trials = 8.31 ± 5.4% of total).

*Behavioral measures*

1. Accuracy, i.e. number of movements executed correctly (according to the instructions, data were coded as "0" and "1", meaning inaccurate and accurate respectively);
2. Reaction Times (RTs), i.e. time from the go-signal to the release of the start button (Participants were told that they could start their movements as soon as the avatar started moving. The "go signal" was thus the moment in which the avatar started moving);
3. Grasping Asynchrony (GAsynchr), i.e. absolute value of time delay between the participant's and virtual character's index-thumb contact-times on the bottle-shaped object (for the Cooperative session), and time delay (with algebraic sign) between the participant's and virtual character's index-thumb contact-times on the bottle-shaped object (for the Competitive session). We corrected GAsynchr values trial-by-trial in order to take the changes in virtual character's movement velocity into account for the computation of GAsynchr. More specifically, since interacting with a faster (Competition) or less predictable (Cooperation) virtual partner would make the interaction more difficult in comparison to interacting with a slower (Competition) or more predictable (Cooperation) one, we corrected GAsynchr values, in order to avoid this bias in the analysis of participant's performance. More specifically, in the Cooperative session, we applied a 20 ms bonus (i.e. we subtracted 20 ms from GAsynchr) every time the virtual character changed its velocity, thus becoming more difficult to predict. In the Competitive session, instead, we subtracted from or added to GAsynchr, depending on whether the participant had anticipated or lagged behind the virtual competitor, a number of ms equal to the difference between the duration of the standard clip (2000 ms) and the one actually presented to the participant. In other words, when participants were presented with a clip lasting 1800 ms, we subtracted 200 ms from GAsynchr (i.e. bonus for performance on faster clips), while we added 400 ms to GAsynchr when participants were presented with a clip lasting 2400 ms (i.e. malus on performance for slower clips).

We calculated the individual mean value in each condition for each of these behavioral measures. The resultant values were entered in different within-subject ANOVAs (see below).

*Motion kinematics analysis*

Motion tracking was continuously recorded during the experimental blocks. Participants' start button hand release-times and index-thumb bottle contact-times were then used to subdivide the kinematics recordings into segment corresponding to the reach-to-grasp phase (from start button hand-release to index-thumb contact-times). We then analyzed:

1. Wrist trajectory as indexed by the maximum peak of wrist height on the vertical plane (*Maximum Wrist Height*) for specific information on the movement's reaching component;
2. Maximum grip aperture (*Maximum Grip Aperture*, i.e., the maximum peak of index-thumb 3D Euclidean distance) for specific information on the movement's grasping component. One participant was excluded from the Maximum Grip Aperture analysis because of recording problems.

At the trial level, behavioral or kinematic values that fell 2.5 SDs above or below each individual mean for each experimental condition were excluded as outliers. GAsynchr was computed as an absolute value in the Cooperative session, while in the Competetive session it retained the algebraic sign. Thus two different ANOVAs on GAsynchr were performed, one for each session. These ANOVAs had INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) factors (see below). All the other behavioural and kinematic indexes were analysed through repeated measures ANOVAs with CONTEXT (Cooperative/Competitive) x INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) factors (i.e., 2x2x2x2 within-subject design) (see below). We used non-parametric tests with regard to Accuracy. All tests of significance were based on an $\alpha$ level of 0.05. Post-hoc tests were performed using the Newman-Keuls method when appropriate. Statistical analyses were performed using Statistica 8 software (StatSoft).

We also measured for Win trials, or the number of correct trials in which Grasping Asynchrony was below the threshold time-window (and which corresponded to the amount of money earned at the end of the experiment).

In order to appropriately test the evidence for null results (Jarosz & Wiley, 2014; Masson, 2011; Rouder, 2014; Wagenmakers, 2007) we ran Bayesian Paired Sample T Tests on participants' Maximun Wrist Height, as well as on the Win trials in Cooperative and Competitive Contexts (JASP version 0.8.12, Love et al., 2015).

## Results

### *Behavioral measures*

GAsynchr was computed as an absolute value in the Cooperative session, while in the Competitive session it retained the algebraic sign. We thus performed two different ANOVAs on GAsynchr, one for each session. The ANOVAs had INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) factors. Data were normalized on the individual grand mean and s.d. (Z-transformation) because of Normality violations in the GAsynchr data's distribution.

*Grasping Asynchrony*

*Cooperative session*

The ANOVA on GAsynchr did not show any significant main effects or interactions (all *P*s> 0.13).

*Competitive session*

The ANOVA on GAsynchr showed a significant main effect of INTERACTIVITY (F(1,15) = 34776, *P* < 0.001, ηp2 = 0.99), indicating that participants performed worse (i.e. higher GAsynchr) in the Interactive condition than the Cued one. The ANOVA on GAsynchr also showed a significant INTERACTION TYPE x MOVEMENT interaction (F(1,15) = 124.71, *P* < 0.001, ηp2 = 0.89). Post-hoc tests indicated that when grasping the lower part of the bottle and performing complementary actions, participants performed worse than when grasping the upper part of the bottle (*P* < 0.001) and performing imitative movements (*P* < 0.001). On the other hand, when grasping the upper part of the bottle and performing imitative actions, participants performed worse than when grasping the lower part of the bottle (*P* < 0.001) and performing complementary movements (*P* < 0.001).

*Accuracy*

Accuracy did not differ across conditions (Chi sqr = 13.97, *P* = 0.53).

*Reaction Times*

The CONTEXT (Cooperative/Competitive) x INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) ANOVA on Reaction Times showed a significant main effect of CONTEXT (F(1,15) = 13.16,*P*= 0.002,$\eta p^2$ = 0.47), indicating that participants started moving later in the Cooperative session than in the Competitive one. The ANOVA also showed a significant main effect of INTERACTIVITY (F(1,15) = 34.16, *P* < 0.001, $\eta p^2$ = 0.69) explained by longer Reaction Times in the Interactive condition than in the Cued one. Moreover, the ANOVA on Reaction Times showed a significant INTERACTION TYPE x MOVEMENT interaction (F(1,15) = 9.07, *P* = 0.008, ηp2 = 0.38). Post-hoc tests showed reaction times were slower when performing precision grips as opposed to power ones during the imitative condition (*P* = 0.023) but not the complementary one (*P* = 0.46).

Win trials

We computed the means of the win trials in both Cooperative and Competitive contexts. We ran a Bayesian Paired Sample T Test on the difference between win trials in the Cooperative and Competitive contexts that showed moderate evidence in favour of the null hypothesis ($BF_{10}$ = 0.29). Win trials were thus similar in cooperative and competitive contexts.

Kinematics measures

*Maximum Wrist Height*

The CONTEXT (Cooperative/Competitive) x INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) ANOVA on Maximum Wrist Height showed a significant INTERACTIVITY x INTERACTION TYPE x MOVEMENT interaction (F(1,15) = 10.52, *P* = 0.005, ηp2 = 0.41). Post-hoc tests indicated that when performing power grips during the interactive conditions, maximum wrist height was higher during complementary than imitative movements (P < 0.001). In the cued condition, maximum wrist height did not differ for complementary and imitative movements (P = 0.53) (Fig.3). In line with previous studies (Sacheli et al., 2012; 2013; 2015 a; 2015b; Candidi et al., 2015; Curioni et al., 2017), this result highlights the presence of visuo-motor interference between self-executed actions and those observed in the partner as an index of automatic imitation. All lower-level interactions and main effects (reported in Table 1) were accounted for by this higher order interaction.

In sum, results from the Maximum Wrist Height analyses showed that visuo-motor interference effects were present in both cooperative and competitive contexts. In order to test the null effect of CONTEXT over the wrist interference effect, we calculated visuo-motor interference effect indexes separately for Cooperative and Competitive contexts by subtracting the means of Maximum Wrist Height in imitative trials when performing power grips from those in complementary trials. We ran a Bayesian Paired Sample T Test between visuo-motor Interference indexes for Cooperative and Competitive contexts. They showed moderate support of the null hypothesis ($BF_{10} = 0.29$). Visuo-motor interference effects were thus similar in cooperative and competitive contexts.

### *Maximum Grip Aperture*

The CONTEXT (Cooperative/Competitive) x INTERACTIVITY (Interactive/Cued) x INTERACTION TYPE (Complementary/Imitative) x MOVEMENT (Power/Precision grip) ANOVA on Maximum Grip Aperture (index-thumb) showed a significant main effect of INTERACTIVITY ($F(1,14) = 46.36$, $P < 0.001$, $\eta p2 = 0.77$), indicating a larger maximum grip aperture in interactive than cued actions. As expected, this analysis also showed a significant main effect of MOVEMENT ($F(1,14) = 351.41$, $P < 0.001$, $\eta p2 = 0.77$), indicating that performing precision grips resulted in smaller maximum grip aperture than power grips. The ANOVA on Maximum Grip Aperture also showed a significant CONTEXT x INTERACTIVITY interaction ($F(1,14) = 11.7$, $P = 0.004$, $\eta p2 = 0.46$). Post-hoc tests indicated that during competitive interactions, maximum grip aperture was larger in the Interactive condition than the Cued one ($P < 0.001$). Moreover, during the Interactive condition, maximum grip aperture was larger in the Competitive than the Cooperative context ($P = 0.002$), while while there was no such difference between the two contexts in the Cued condition ($P = 0.29$). No other main effect or interaction reached statistical significance (all *P*s > 0.1).

## Discussion

In the present study we investigated whether visuo-motor interference effects during cooperative and competitive motor interaction are linked to the necessity of predicting someone else's actions. Results showed that the automatic imitation of the partner's action during complementary motor interactions emerges in both cooperative and competitive social contexts, as indexed by comparable visuo-motor interference effects. However, this effect is specific for conditions that require making predictions about the partner's goals (Interactive condition).

### *Visuo-motor interference during cooperative and competitive interactions.*

Individuals must predict their partner's actions during real life motor interactions that involve a shared goal. They must then use that prediction to plan and adjust their own actions so as to achieve that shared goal (Sebanz et al., 2006). When dancing tango, for example, which is a cooperative context, the dancers need to predict and adapt to each other in order to perform the choreography fluidly. When playing football, a competitive context, the goalkeeper and offensive player must predict one another's action in order to anticipate that action and "beat them to" the shared goal. Importantly, motor interactions are characterized by the emergence of dynamic, real-time, mutual adaptations supported by the continuous integration of predictions about one's own and other's actions. This type of integration process allows inter-actors to adjust their movements mutually on a moment-to-moment basis (Hasson and Frith, 2016) and thus achieve shared goals that depend on the goal of the other individual regardless of whether they are cooperative or competitive. Indeed, no type of goal would be achieved if individuals were to ignore the others' movements (Sacheli et al., 2015c).

In order to successfully predict what other people will do next (Frith and Frith 2006) it is necessary to read the kinematics of their ongoing movement (Krishnan-Barman et al., 2017; Ansuini et al., 2014; Reader et al., 2018). The kinematics of our actions differ depending on whether we perform actions with a social or non-social intention (Ansuini et al., 2008). Social context also plays a major role. For example, participant pairs requested to reach and grasp an object and place it on the table together (cooperative condition) or one before the other (competitive condition) showed two different kinematics profiles in the reach to grasp phase for the two interactive contexts (Georgiou et al., 2007). Moreover, motion kinematics information is sufficient for people to determine whether someone is grasping an object with a cooperative or competitive intent (Manera et al., 2011).

In this study we investigated whether the automatic imitation of someone else's actions are modulated by cooperative and competitive social contexts that imply the real-time prediction of the other's movements. In particular, we explored: i) whether visuo-motor interference effects that have been demonstrated to emerge during cooperative motor interaction also emerge in competitive ones, and ii) whether these effects are specific to situations in which action prediction and adaptation are needed (Interactive condition) as opposed to when these predictions may be neglected (Cued condition).

One main result of the present study is that the automatic imitation of the partner's movements (possibly relying on sensorimotor simulation) during complementary motor interactions emerges in both cooperative and competitive social contexts, as indexed by comparable visuo-motor interference effects. However, this effect is specific for conditions that require making predictions about the partner's goals (Interactive condition). More specifically, the present results on maximum wrist height showed that visuo-motor interference effects (Kilner et al., 2003) between self-executed actions and those observed in the partner emerged in both cooperative and competitive contexts only during the Interactive condition. This evidence strengthens the link between motor simulation, automatic imitation and action prediction in interactive contexts (Sacheli et al., 2015b; Candidi et al., 2014; Aglioti et al., 2008; Abreu et al., 2017, Chinellato et al., 2014, Ménoret et al., 2013). Although we expected to find visuo-motor interference effects in both maximum wrist height and maximum grip aperture, the fact that they were present only in maximum wrist height might be due to the fact that visuo-motor interference effects seem to be more stable in the reaching component (as indexed by maximum wrist height) in comparison to the pre-shaping component (as indexed by maximum grip aperture). This is in keeping with another study using the same experimental task (Sacheli et al., 2013) and reporting visuo-motor interference effects in maximum wrist height but not maximum grip aperture.

At the behavioral level, the fact that participants achieved an equal level of performance during complementary and imitative interactions is in line with previous studies showing that complementary interactions are not more difficult than imitative ones (Ocampo and Kritikos, 2010; Sacheli et al., 2012; 2013). This is different from what happens in the imitation inhibition tasks (Brass et al., 2000) where participants perform actions at the same time, but do not need to predict the partner's action in order to perform one's own. In this type of task performing incongruent actions is usually more difficult than performing congruent ones. While the present results are in line with previous studies showing that imitative behavior also emerges when people compete with others (Cook et al., 2012; Belot et al., 2013; Naber et al., 2013), this is the first time that visuo-motor interference effect has been investigated during realistic competitive motor interactions in which the goal of the individual action is linked to that of the interacting partner. Moreover, in order to make the human-avatar interaction more realistic, we created a virtual partner who could react to the movements of its human partner, thus preserving the feature of mutual adaptation shown to be a fundamental feature of human-human motor interactions (Era et al., 2018, Konvalinka and Roepstorff, 2012).

*Visuo-motor interference is linked to the rewarding value of interpersonal interactions.*

In the present study, we adjusted the difficulty of the interaction so that participants could obtain a similar number of win trials in cooperative and competitive contexts. This might imply that the two contexts elicited a comparably rewarding experience in participants and may also explain why visuo-motor interference was comparable in the two interactive contexts.

It is worth noting that behaving in social contexts entails a reward value for individuals. Activations in the reward-related brain regions - and particularly in the ventral striatum - have been seen when people act in social situations characterized by mutual contingency between the co-agents. Examples include acting in synchrony (Miles, et al., 2009), engaging in direct eye contact (Pfeiffer et al., 2014; Redcay et al., 2010; Schilbach et al., 2010) or cooperating with others (Rilling et al., 2002). A recent study showed that observing social interactions characterized by shared intentions recruits reward-related areas such as the bilateral ventral striatum, while the observation of actions guided by parallel intentions does not (Eskenazi et al., 2015). Thus, not only does interacting with others generate a rewarding experience, but a comparable rewarding experience emerges when observing others interacting (Eskenazi et al., 2015). This rewarding experience might reinforce our motivation to engage in social interactions with others. Several studies have showed that positive interactions generate higher trustworthiness (Fehr and Fischbacher, 2004). Research on joint action in humans has shown that inducing trust in individuals before they engage in joint-action leads to them having higher heart-rate synchrony during interaction, which may be a physiological marker of interpersonal trust (Mitkidis et al., 2015).

Behavioral and kinematic studies (Wang and Hamilton 2012, for a review) have indicated that automatic imitation is a fundamental mechanism that shapes the way we interact with others. We (unconsciously) tend to mimic others' behavior, and this tendency also influences the relationship among the inter-actors: people who mimic each other more are more likely to engage in positive social interactions (Lakin and Chartrand, 2003; Lakin et al., 2003; Kämpf et al., 2017). Studies on cooperative joint-actions have shown that automatic imitation in the form of visuo-motor interference emerges when participants are performing complementary movements (Sacheli et al., 2012; 2013; 2015a; Candidi et al., 2015; 2017; Curioni et al., 2017). Importantly, this only seems to happen when it is necessary to predict the partner's movements in order to adapt to them (Sacheli et al., 2015b). Interestingly, visuo-motor interference also seems to be influenced by the social interpersonal relationship between interacting agents: when interacting with a negative interpersonal bond, participants do less mapping of others' behavior onto ones' own sensorimotor system (Sacheli et al., 2012). Similarly, automatic imitation in participants with a negative bias towards the out-group is reduced when interacting with an out-group partner (Sacheli et al., 2015b). These studies suggest that the reward value of motor interactions shapes the way people interact with each other. Accordingly, a recent study on patients with Parkinson's disease - studied as a model of dysfunctional dopaminergic system - showed that patients not taking dopaminergic medication were unable to differentiate their motor behaviour both when acting in isolation or in social conditions, regardless of whether they were cooperative or competitive contexts (Straulino et al., 2016). This result supports the hypothesis that the dopaminergic reward system is involved in shaping the mechanisms that underlie social interactions (Pfeiffer et al., 2014).

## Conclusion

By using a mutually adaptive human-avatar interactive grasping set-up and measuring behavioral and motion kinematics indexes, we showed, for the first time during naturalistic motor interactions, that visuo-motor interference effects (possibly underpinned by sensorimotor simulation) are linked to the need to predict someone else’s motor behavior during motor interactions. Importantly, these visuo-motor interference effects are comparable when cooperating or competing with others, which hints at the pervasiveness of simulative imitation in interactions.

**Compliance with Ethical Standards:**

Conflict of Interest: The authors declare that they have no conflict of interest

Ethical approval: All procedures performed in study involving human participants were in accordance with the ethical standards of the institutional research committee (Fondazione Santa Lucia) and with the 1964 Helsinki declaration and its later amendments.

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Figure and Table Legends

**Table1**

Results of the ANOVA on Maximum Wrist Height.

**Figure 1**

Participants were asked to reach and grasp the bottle-shaped object placed in front of them. They needed to perform opposite (complementary) or same (imitative) movements with respect to the virtual partner. In the Imitative movements condition, participants had to grasp the same portion of the object as the virtual partner (both performing power or precision grips on the lower or upper part of the bottles, respectively, drawings highlighted in violet). In the Complementary movement's condition, conversely, participants had to perform movements opposite to those of the virtual partner (one grasping the upper part via precision grip, the other grasping the lower part via power grip, or vice-versa, drawings highlighted in green). Moreover, in one of the experimental sessions, participants were instructed to grasp the object as synchronously as possible with their virtual partner (Cooperative session, uppermost drawings). In another experimental session (Competitive session, lowermost drawings), participants were instructed to grasp the object before the virtual partner.

**Figure 2**

Trial timeline

Participants would hear the Imitative/Complementary or Up/Down auditory instruction, release the start button and reach-to-grasp the bottle-shaped object. At the end of each trial, participants would receive feedback about their performance (win/loss trial) by way of green or red LED lights. A win trial meant that participants had followed their auditory instructions (i.e., correctly performed complementary/imitative or up/down movements) and met the requirements of the respective sessions (grasping synchrony in the cooperative (green frame), grasping before the virtual partner in the competitive (red frame))

**Figure 3**

Graph of Maximum Wrist Height Results: The ANOVA showed a significant INTERACTIVITY x INTERACTION TYPE x MOVEMENT interaction ($F(1,15) = 10.52$, $P = 0.005$, $\eta p2 = 0.41$). Post-hoc tests indicated that when performing power grips during the interactive conditions, maximum wrist height was higher during complementary than imitative movements ($P < 0.001$). This result highlights the presence of visuo-motor interference between self-executed actions and those observed in the partner as an index of automatic imitation.

**Figure 4**

Graph of Reaction Times Results

**Figure 5**

Graph of Grasping Asynchrony Results

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## Authors contribution:

Designed research: VE, SMA, MC; Performed research: VE, CM; Analyzed data: VE, CM, MC; Wrote the paper: VE, SMA, MC.