UNIVERSITÀ DEGLI STUDI DI TORINO

DIPARTIMENTO DI PSICOLOGIA

DOTTORATO DI RICERCA IN NEUROSCIENZE

CICLO XXXIII

Motor representations during joint actions:
A kinematic investigation of real-time dyadic interactions.

TESI PRESENTATA DA: Matilde Rocca

TUTOR: Prof. Andrea Cavallo

COORDINATORE DEL DOTTORATO: Prof. Marco Sassoè

ANNI ACCADEMICI: 2017-2021

SETTORE SCIENTIFICO-DISCIPLINARE DI AFFERENZA: M-PSI/01

Table of contents

Acknowledgements

The work that will be presented in this thesis was made possible only through the support and guidance of my PhD supervisor: Andrea Cavallo. I would like to thank him for giving me the opportunity to work with the greatest responsibility of all: freedom. The gift of freedom has been terrifying, ghastly, and sometimes disheartening. In the end, nothing could have made my PhD journey more beautiful.

I would like to thank Prof. Cristina Becchio for welcoming me in an environment where my interests and my research were valued, even if they diverged from the main research lines of the lab. These interests grew only thanks to the passionate lessons that she offered me during my university years.

I would like to thank with the greatest devotion my misadventure companions: Eugenio and Novella. Our cyclic check-ins have been a fundamental and crucial reassurance tool for me. And without my deskmate, Eugenio, these years would have definitely lacked color.

Finally, I would like to give the warmest of thanks to all my dearest friends and to my family. Thank you for the way you stood by me during these years, picking me up when I needed to, and warming my heart up all along the way. Your love was the most important gift of all.

Summary

A vast literature suggests that, when we are engaged in a joint action with someone else, we automatically represent the actions that our partner has to perform (Sebanz et al., 2006). However, it remains unclear what the specific content of these motor representations is, and how being engaged in a joint action changes the way we represent the actions of others, compared to a non-interactive scenario.

The research presented in this thesis aimed to investigate these questions. The first study proposed a novel methodology to investigate the content of these motor representations, based on the analysis of movement kinematics during dyadic sequential motor tasks. This methodology was implemented in the experiment performed in the second study. The third study aimed at assessing whether and how being engaged in a joint action changes the way we perceive the actions performed by others, compared to a non-interactive scenario.

The results of these studies show that, when we are engaged in a joint action, we form detailed motor representations, which pertain not only what actions our partner will perform, but also how our partner will perform these actions. Furthermore, being engaged in a joint action, compared to a non-interactive situation, reduces the detrimental effect elicited by action observation, suggesting that, during joint actions, we shift from the automatic simulation to the active prediction of the actions that we observe.

These results advance our knowledge about how we represent others in our daily lives, by showing how interactivity shapes the way we process and perceive other people's actions.

1. General introduction

How do we represent other people's actions when we are actively interacting with them? A vast literature suggests that humans are not passive observers of other's movements. Our motor system is tuned to constantly anticipate, monitor, and respond to other people's actions (e.g. Rizzolatti & Sinigaglia, 2016; Sommerville & Decety, 2006; Wilson & Knoblich, 2005). To do this, we form *motor representations* about other people's actions (Jackson & Decety, 2004; Jeannerod, 2001). These representations are of fundamental importance when we are engaged in social interactions with others. Indeed, when we cooperate with someone else to achieve a common goal (i.e., perform a *joint action*), we have to represent not only our own action, but also the action that our partner has to do (Sebanz et al., 2006). Furthermore, we have to represent the overarching goal of our joint action, and the way this is achieved through our own and our partner's action (Pesquita et al., 2018; Vesper et al., 2010).

Research on joint actions has focused on exploring the existence of such representations. However, it is still not clear what their specific *content* is: do we just represent the goal of the action that our partner has to perform, or do we also represent the specific kinematics by which this goal is achieved? Furthermore, it is still not clear how the presence of a common goal, shared with the other, changes the way we perceive other people's actions: do we represent the action of others differently, when we are engaged in a joint action?

To answer these questions, the research presented in this dissertation investigated the motor representations that we form about other people's actions during joint actions, by assessing detailed aspects of upper-limb movement kinematics during real-time dyadic settings.

In this introductory chapter, I will first present an overview of the literature that has theorized and explored how we perceive the world motorically, by forming motor representations that subtend all perceived events. I will then move to the literature that has explored the motor representations that we form about other people's actions, with a focus on the studies that have assessed the presence of such representations by investigating the effect of action observation on motor execution. Then, I will present the more recent literature that has suggested how these representations might be better understood during real social interactions, and I will show how they have indeed been explored during the scenario of joint actions. Finally, after having introduced the current issues and unanswered questions in this research topic, I will provide a brief overview of the studies that will constitute the main body of the dissertation (Chapters 2-4).

1.1. Representing the world motorically

The final decades of the last century have yielded to a fundamental paradigm shift in the study of human cognition. While traditional theories considered cognition and thought to be the central core of the mind, separate from the perceptual and the motor systems, viewed simply as peripheral modules (Hurley, 2001), the new theories of *embodied cognition* offered a radically different perspective (Barsalou, 2008; Clark, 1999; Wilson, 2002). As pointed out by Clark (1998), "Biological brains are first and foremost the control systems for biological bodies. Biological bodies move and act in rich real-world surroundings". This new standpoint did not consider perception and action to be peripheral modules of the mind, but a fundamental and constitutive part of human cognition. Human minds could thus only be understood as deeply rooted in physical bodies, constantly interacting with the environment surrounding them.

An important consequence of this paradigm shift was the realization of the importance of the motor system in the study of human cognition (Jackson & Decety, 2004; see also Rosenbaum, 2005; Wilson, 2002). This view in fact suggests that our motor system is highly involved is several high-level cognitive processes, even when we are not directly involved in the execution of overt motor acts. Indeed, an extensive literature now provides empirical support to the claim that the motor system is also involved in *representing* the world that surrounds us (Jeannerod, 1994, 2001).

This idea is not new in the field of Psychology. Sperry (1952) suggested that all the perceptual and mental activity of the brain could only be understood as a means for action. Gibson (1969) used the term 'affordance' to explain how specific objects elicit specific motor acts in the observer. Shepard (1984) extended this view, by suggesting that mental activity is not simply involved in perceiving the objects that are around us, but also in forming *internal representations* of these objects, which can be elicited even in the complete absence of external information.

It is now well established that the way we *perceive* the world is strictly linked to the way we *act* and *move* in it. Perception and action can be seen as the *flip sides of the same coin* (Sommerville & Decety, 2006). Indeed, as suggested by the common-coding account, perception and action may actually share a common representational domain (see also Hommel et al., 2001; Prinz, 1990, 1997). This view is endorsed by an extensive empirical evidence, which strongly supports the idea that perceived events are represented motorically, in terms of the actions they imply. And among all the possible percepts that we can encounter, the most intriguing and important ones consist in *other human beings*.

1.2. Representing *others* motorically

The study of human cognition cannot ignore the fact that humans are, first and foremost, *social creatures*. The majority of our brain structures serve social functions and abilities (Brothers, 1990), and the structure of the human brain itself might be the result of the complex social environment that we developed during our evolution in order to survive as a species (Dunbar, 1998; Whiten & Byrne, 1997). Recently, the study of human cognition has thus often coincided with the study of the *social* aspects of cognition, in order to unveil the fundamental mechanisms that enable us to engage and participate in an inherently social world (Adolphs, 1999; Frith & Frith, 2010).

A fundamental question is at the heart of this thrilling investigation: how do we represent others? How are we able to understand, communicate with, and respond to others? These questions are starting to be answered, and once again, our motor system seems to be at the core of it all.

A growing number of researchers now suggests that our motor system is highly involved in the perception of others, so much that our *social* cognition might be more accurately described as a *motor* cognition (Casartelli & Chiamulera, 2016; Jackson & Decety, 2004). Indeed, extensive evidence has shown that we represent the actions of others in a motoric way: when we observe someone else move, our premotor cortex activates in the same way as if we were performing the observed action (Rizzolatti & Sinigaglia, 2016). The discovery of this *mirror* activation led researchers to conclude that other people's actions are indeed represented motorically, in the same way as our own actions are. This suggests that we can understand others without the need of high-level cognitive processes, but through a 'direct' perception, which involves low-level motor processes instead (Gallese, 2007).

This new perspective suggests that actions performed by others are represented and coded similarly to our own actions. This idea, which can actually be traced down to the XIX century, when authors such as Lotze (1852) and James (1890) implicitly suggested it, is deeply consistent with the common-coding account. Indeed, in the common-coding framework, perceived actions should elicit the corresponding motor representation in the observer, and this, in turn, should prime the execution of the corresponding action.

Several studies have supported the predictions outlined by the common-coding account, by investigating how observing other people's actions can affect the production of our own movements. Indeed, they showed that observing specific motor acts can *facilitate* the subsequent execution of similar actions (Brass et al., 2000, 2001; Edwards et al., 2003), and, at the same time, that observing actions that are incompatible (i.e., incongruent) with the ones to be performed can *perturb* motor execution, a phenomenon that is now often referred to as visuo-motor interference (Blakemore & Frith, 2005; Kilner et al., 2003). These studies underline an important aspect of the

representations that we form about other people's actions: they can be unveiled in the way we perform our own actions. Studies that analyzed detailed aspects of movement unfolding have in fact shown that our movements can show the kinematic trace of an observed action, by displaying parameters that are specific to the action performed by the other (Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011). These studies suggest that the *interference* that can be observed in motor execution is more similar to a *contagion* effect, as if the performed movement actually incorporates the kinematics of the action that is observed (Blakemore & Frith, 2005).

These studies have thus shown that, when we observe other people's actions, we form motor representations of their movements, and these representations can influence our own motor execution. At this point, however, an important doubt comes to mind: do we represent other people's actions only when we *observe* them? Importantly, in our daily lives we are not simply involved in observing other people's actions, but we actively engage with them, by anticipating, coordinating, responding. In other words, by *interacting*. A new question thus arises: how do we represent other people's actions when we are actively interacting with them?

1.3. Representing others during *joint actions*

When trying to unravel the fundamental mechanisms of human social cognition, an important issue emerges: how can we study the way we represent others if we study humans in isolation? Indeed, if our aim is to investigate our *social* functioning, we have no choice but to turn to the study of humans in *interactive contexts* (De Jaegher et al., 2010; Schilbach et al., 2013).

The majority of the early investigations on how we represent other people's actions have often focused on spectator-views of the mind (Becchio et al., 2010; Hutto, 2004; Schilbach, 2010; Semin & Cacioppo, 2008). Indeed, the use of 'isolation paradigms' has often lead researchers to focus only on how we view and perceive others when we *passively observe* them. Recently however, the research community has been prone to overcome this issue, by suggesting that social cognition could be better assessed during real social interactions (e.g. Astolfi et al., 2020; De Jaegher, 2009; Schilbach et al., 2013).

By studying behavior during real social interactions, we can investigate the real nature of the motor representations that we form about other people's actions. Indeed, these representations might be not simply what allows us to *understand* others, but also what allows us to successfully *coordinate* and *cooperate* with others (Csibra, 2007; Knoblich & Jordan, 2002; Wilson & Knoblich, 2005). Furthermore, these representations might actually take form and shape *during* the course of an interaction, and this form might be dependent on the nature of the interaction itself.

In recent years, the study of human behavior during social interactions has gained enormous momentum. In particular, researchers have focused on unveiling the fundamental mechanisms that underlie simple forms of cooperative social interactions. The most simple and effective model of cooperative behavior that has been used during these years is the one of the so-called *joint actions*. Joint actions can be defined as the simplest type of collaborative social interaction where two or more individuals coordinate their actions in space and time to bring about a change in the environment (Knoblich et al., 2011; Sebanz et al., 2006). These type of interactions closely resemble the ones that often occur during our daily lives, when we engage with others to achieve a common, shared goal. Importantly, during joint actions, agents have to represent not only the

17

action that they have to perform, but also the action that their partner has to perform (Sebanz et al., 2003, 2005; Sebanz & Knoblich, 2009). This is different from the representation that might arise from the observation of other people's action. Indeed, studies have shown that during a joint action we represent the actions that are *at the disposal* of the other agent: these actions are the ones that *should* be performed, and not simply the ones that we observe (Sebanz et al., 2006; Sebanz & Knoblich, 2021). Furthermore, during joint actions, agents also have to represent the goal of the joint action itself, and how this will be achieved by the two actions involved (Pesquita et al., 2018; Vesper et al., 2010). The presence of this *common goal* might produce a substantial change in the way we *perceive* the actions of others when we observe them in the context of a joint action, compared to when we observe them in a non-interactive scenario (Sacheli et al., 2019).

Several studies have investigated the presence of these shared representations by assessing the activity in motor-related brain areas while participants observed or were engaged in joint actions: these studies allowed researchers to observe dissociable motor activity that underlie the representation of one's own, the partner's, and the joint action (for a review see Bolt & Loehr, 2021). However, few studies have investigated *what* exactly we represent about the other when we are engaged in a joint action. The existing literature suggests that we represent the *task* that our partner has to do (Atmaca et al., 2008; Schmitz et al., 2017a; Sebanz et al., 2003, 2005). However, in order to successfully engage in a joint action, we should not only represent the task that our partner has to do, but also the specific way in which this task can (or will) be achieved by our partner (Pesquita et al., 2018). An accurate prediction of the way our partner will move is indeed of fundamental importance to achieve a common goal successfully: we have to be able to anticipate the other accurately, and to monitor and adapt to his movements in a careful way (Bekkering et al., 2009; Keller et al., 2014; Sebanz & Knoblich, 2009).

These considerations also raise the possibility that, when we are engaged in a joint action, we process the actions performed by the other differently than in a non-interactive context. Indeed, observing an action performed by a 'stranger' and observing an action performed by the person whom we are interacting with might be very different processes, which may produce different effects on movement execution. This possibility has only recently been addressed and explored, although there still is a debate on whether and how the presence of a common goal might change the way we perceive other people's actions. While some studies suggest that the presence of a common goal enhances the saliency of other's actions, thus producing stronger interference effects on motor execution (e.g. della Gatta et al., 2017; Era et al., 2018), other studies suggest that, during a joint action, compared to a non-interactive situation, the action of the other is less interfering, because it is processed in the predictive terms of what it will produce in the environment (Clarke et al., 2019; Sacheli et al., 2018, 2019).

1.4. The present research

The current literature provides extensive evidence in support of the fact that we indeed form motor representations about the other's action when we are engaged in an interactive context. Yet, it is still unclear what exactly the content of such representations is. Furthermore, there is still debate about how we perceive other people's actions when we are engaged in a joint action with them, compared to a non-interactive situation.

The studies included in the present thesis aimed to address these issues, by investigating detailed aspects of upper-limb movement kinematics of pairs of agents engaged in real-time dyadic settings.

The aim of the first study (Chapter 2) was to propose an alternative approach to the study of the motor representations that we form about other people's actions during joint actions (i.e., co-representations). This was done by presenting a novel paradigm, aimed at assessing the *content* of these representations through the analysis of movement kinematics in a dyadic sequential task performed by two agents.

This task was used in the experiment presented in the second study (Chapter 3). The experimental focus was on the movement kinematics of the first agents of each pair: it was assessed whether and how their movements were affected by the action that the second agents would have performed after them. A second experimental focus was on the specificity of such modulation. By looking at the kinematic similarity between the two agents, the study aimed at investigating whether the representation of the second agents' action regarded only the *goal* of their action, or also the *kinematics* by which this goal was achieved.

The third study (Chapter 4) aimed at assessing whether and how being engaged in a joint action changes the way other people's actions affect us. This was done by assessing the presence of visuo-motor interference in different interactive contexts, where the action performed by the other could be either irrelevant or relevant to achieve a common goal. The study also aimed at investigating *how* the observed action affected movement kinematics. This was done by assessing the similarity between the kinematic profiles displayed by the two agents, and by assessing whether this similarity increased during the course of the experiment.

2. What's shared in movement kinematics: Investigating co-representation of actions through movement[1]

2.1. Introduction

In recent years, psychological research has shown a growing interest in the study of human social interaction. This has led researchers to develop new paradigms and to formulate new theories about how people adjust minds and bodies when interacting with each other (Gallotti et al., 2017; Schilbach et al., 2013). One intriguing question that arises when dealing with social interactions concerns what information actors share about each other when involved in a joint action. One of the most influential theories in this field states that, given the fundamental social nature of joint actions, people have the tendency to represent and map both one's own and others' task demands (Sebanz et al., 2003, 2005). However, this view has recently been challenged by proponents of the "referential coding account" who have criticized the apparent nonsocial nature of the tasks and methodologies used to formulate and support the co-representation theory (Dolk et al., 2011, 2014).

In the present opinion article, we briefly describe the experimental paradigms often employed to study the co-representation theory (section Co-representation theory: proponents and opponents). Then, we illustrate potential methodological issues related to these paradigms (section

A methodological problem), and finally we propose a new strategy, based on the characterization of movement kinematics, to address the open question about what is shared in shared actions (section A motor solution).

2.2. Co-representation theory: proponents and opponents

Investigating joint performance requires researchers to focus on interactive experimental settings, trying to overcome the long-lasting trend of studying humans in lonely environments (De Jaegher et al., 2010; Schilbach et al., 2013). To this end, Sebanz et al. (Sebanz et al., 2003) proposed a social version of a well-known individual Stimulus-Response Compatibility (SRC) paradigm: the Simon Task.

In the *joint* version of the task, two stimulus-response mappings of a two-choice task are distributed between two agents (e.g., Agent 1 presses for green squares; Agent 2 presses for red squares). Even with no need of taking the other's mapping into account, the results highlight an interference effect between a task-irrelevant aspect of the stimulus (e.g., its position on the screen) and a task-relevant aspect of the response (e.g., the position of the button to press). The similarity with the original Simon effect led researchers to formulate the *co-representation theory*, which states that, given the social nature of joint actions, people tend to co-represent automatically each other's portion of the task in a functionally equivalent way (Sebanz et al., 2003, 2005). This theory has received support from many other studies that have used social versions of other SRC tasks (hereinafter social-SRC tasks) to test its assumptions (e.g. Atmaca et al., 2008, 2011; Elekes et al., 2016).

The co-representation theory has nevertheless received criticism. Some authors have argued that the behavior people display during the joint Simon task derives from a universal information-processing rule, having little to do with social skills (Dolk et al., 2011, 2014). Different studies have demonstrated that a nonsocial attention-attracting event, such as a Japanese waving cat, elicits the very same behavior observed in the joint Simon task (Dolk et al., 2013; Puffe et al., 2017). The main idea, expressed by opponents of the co-representation theory in what they call the *referential coding account*, is that the other person's action simply provides a spatial reference for one's own action, in the same way as any sufficiently salient event would do. These two perspectives seem to be hardly reconcilable, lying on contrasting interpretations. The debate thus appears to have reached a stalemate, and the co-representation theory is facing an unexpected impasse.

2.3.   A methodological problem

It is worth noticing that the referential coding account does not intend to deny the social nature of joint performances: what the authors claim as nonsocial is the behavior that arises from the social-SRC tasks used to investigate the co-representation theory (e.g. Dolk et al., 2011, 2014; Yamaguchi et al., 2018). The referential coding account is in fact a nonsocial way to explain the observed effects, which thus sometimes fall in an interpretational ambiguity.

This consideration raises a methodological problem. Two possible issues may in fact concern the use of social-SRC tasks in investigating co-representations: one is interpretational, one is practical. Both issues stem from the task that the two participants perform, which is for both a key

press. This type of response is described as *discrete*, and is often contrasted with *continuous* responses (e.g. Song & Nakayama, 2009).

The interpretational issue relates to the poorness of the actions performed. Investigating joint performance with a task that involves discrete responses seems to reduce the social nature of the interaction. Using such a simple task is surely helpful in controlling the experimental setting, yet it pays the cost of dealing with an unnatural social setting. In daily environments, our social partners engage in actions that are much more complex, which we understand and predict (Hasson & Frith, 2016; Springer et al., 2012). Therefore, social-SRC tasks restrict the focus to a partner's action that may be too minimal to highlight a social effect.

The practical issue concerns the dependent measure obtained from social-SRC tasks: response time (RT). Although RT measures have helped to infer several aspects of human cognitive processes, it is well established that they restrict the investigation to a unidimensional assessment of behavior, without the opportunity of accessing the "continuity of the mind" (Song & Nakayama, 2009; e.g. Spivey & Dale, 2004). In social-SRC tasks, RTs show an interference effect, which suggest that we represent the other person's task and that this representation weakens our performance. However, RTs do not allow to access the content of this representation, limiting in a way the investigation of the phenomenon. For example, to coordinate with others, we must consider not only *what* movements others are doing, but also *how* they are moving (Gallotti et al., 2017; Keller et al., 2014). RTs can thus provide insightful information about the *what* component of co-representations, but they cannot be informative about the *how* – i.e., whether we also represent the specific movement styles of others' actions (but see Schmitz et al., 2017a).

2.4. A motor solution

To overcome the methodological issues that seem to affect social-SRC paradigms, here we propose a different experimental strategy that might shed light on the co-representation phenomenon.

We propose to turn to experimental paradigms that elicit a more complex and enriched overt motor activity. These joint *motor* tasks could help to address both the interpretational and the practical issues linked to social-SRC tasks.

On the interpretational level, dealing with a partner that makes complex movements can enhance the ecological validity of the experiments, bringing the setting closer to a real-life social interaction. Human movements present unique features that distinguish them from artificial-generated motions (Steel et al., 2014; Thompson & Parasuraman, 2012); furthermore, besides fundamental regularities (Viviani & Flash, 1995), individuals show specific movement styles (Koul et al., 2016; Ting et al., 2015). The exclusively human capability to understand, predict, anticipate, and adjust to how other people move establishes the profound social aspect of joint performances. We thus believe that, assuming the validity of the co-representation theory, the use of motor tasks could help to reject alternative nonsocial interpretations of social-SRC results.

On the practical level, movement kinematics might constitute a much more informative dependent measure than RTs, although caution must be taken when dealing with multivariate measures that provide huge amounts of data (e.g. high levels of false positives; Simmons et al., 2011). When investigating internal processes, some authors suggest to replace RT measures with dependent variables that are more fluid, continuous, and that can change over time (Freeman et al., 2011); movement kinematics could be a good candidate because of their capacity of reflecting the

unfolding of internal dynamic processes over time (Freeman et al., 2011; Song & Nakayama, 2009). Indeed, despite the role played by inhibitory processes (for a review see Schall et al., 2017), human movements reveal a lot about both our external and our internal world. For example, movement kinematics have proven to be different depending on objects' size, shape, mass, and even texture and fragility (Ansuini et al., 2015; Castiello, 2005; Castiello et al., 1992; Jeannerod et al., 1995; Savelsbergh et al., 1996; Weir et al., 1991). Even more interestingly, kinematic features encode information about more abstract internal states, including intentions (Becchio et al., 2018; Cavallo et al., 2016), decisions (McKinstry et al., 2008), numerical representations (Song & Nakayama, 2008), and other cognitive processes (Freeman et al., 2011; Song & Nakayama, 2009). Therefore, movement kinematics could be an adequate measure to investigate complex internal representations, like those of other persons' tasks and actions.

The characterization of human movement has already been extensively investigated in social interaction studies (Krishnan-Barman et al., 2017); however, these studies often focus on distinguishing between individual and social behavior, without fully addressing the question of whether and how we use information about the others to succeed in a joint action. A vast literature suggests that our movements are different in a social setting (Becchio et al., 2010; Krishnan-Barman et al., 2017), and that they are highly influenced by other people's movements (Blakemore & Frith, 2005; Heyes, 2011). This seems to indicate that other people's actions are actually represented in our brains when we act together; yet it remains unclear how specific these representations are, and how they come into play during joint performances: How and to what extent is the representation of others' task demands integrated within one's own motor system during joint actions? Does this representation include information about the others' motor behavior? Is this information specific to the confederate one is interacting with?

To address these questions, we propose to use joint *motor* tasks involving participants in *sequential actions*, with the aim of reaching a common goal. A possible method could be to maintain the movement requirements of the first agent (A1) constant throughout the interaction, while manipulating those of the second agent (A2) – i.e., modifying the difficulty of A2's task, while keeping that of A1 constant. The kinematic profile of the first agent's movements could then be a good predictor of the movement that the second agent is *about* to make (Fig. 2.1).
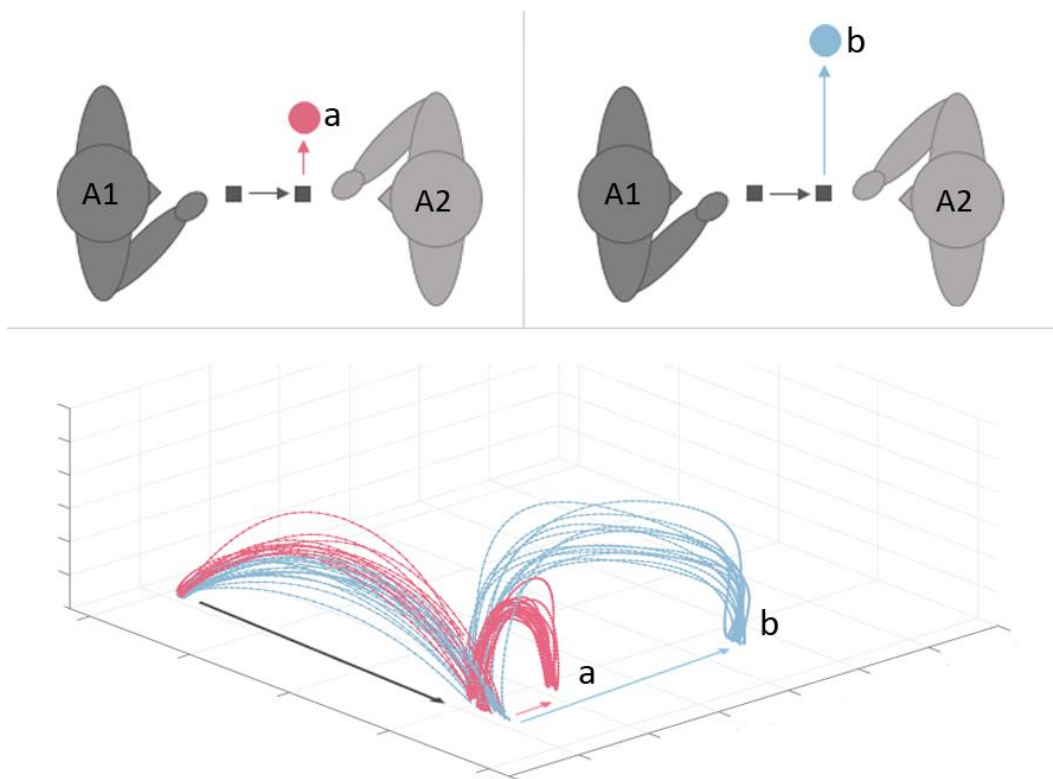
Figure 2.1.

In the joint motor task pairs of participants are asked to perform sequential actions to reach a common goal. Agent 1 (A1) is asked to move an object from the starting position to an intermediate target area. Then, A2 grasps the object in the intermediate target area and places it in a final target area that varies across trials (e.g., different distance and size; upper panels). We expect that A2's task demands will be processed by A1. If so, kinematic profiles of A1 movements should encode information about the movement that A2 is about to make (lower panel).

Compared to simultaneous actions, sequential motor tasks might increase the internal validity of the studies that aim to investigate co-representations, as they prevent from potential confounds caused by automatic imitation and motor contagion effects (Heyes, 2011; Kilner et al., 2003). These effects show how observing other people's movements affects one's own movements. However, they do not assure us about the existence of co-representations as described by Sebanz and colleagues (Sebanz et al., 2003, 2006). Indeed, the co-representation theory states that, when two agents are involved in a joint action, they form internal representations of their co-agent's task, even when they do not see the other person moving, but simply know what the other person's task is (Sebanz et al., 2003, experiment 2). This form of representation is supposed to be formed and shared in the joint action space in order to predict the others' behavior, independently from visual feedback, and, therefore, from motor resonance (Sebanz, Bekkering & Knoblich, 2006). Therefore, when a participant performs an action 'after' a co-agent, investigating the participant's movement would inform us about how the just-seen action influences his performance. Instead, when a participant performs an action 'before' a co-agent, investigating the participant's movements would inform us about how he is influenced by – and thus how he represents – an action that has yet to be performed.

Examining the similarity between the movement profiles of the two agents involved in the sequential task might then help on understanding how specific the representation of the other person's actions is, letting us begin accessing the content of co-representations.

Consider the kinematic modulation that occurs when an action is directed toward a small target: compared to large targets, movements toward small targets require greater precision, which is achieved through an earlier reach of the peak velocity and a longer deceleration phase (e.g. Marteniuk et al., 1987). We would in fact expect A2 to present an earlier time to peak velocity and

a longer deceleration phase when his movement is directed toward a small, compared to a large target. If A1's velocity profile shows a modulation similar to that of A2, we would be facing two possible explanations. The first would suggest that A1 has formed a generic representation of A2's task. A1 may in fact be simply influenced by the *target* of A2's action, and this would consequently result in A1 displaying a kinematic modulation similar to the one displayed by A2. The second explanation would instead suggest that A1 has formed a detailed representation of A2's action, including kinematic information about the specific way in which A2 is going to move. A1 would in this case present a kinematic modulation similar to that of A2 because he would be incorporating the kinematic features presented by A2. In both of these cases, we would thus observe a positive correlation between the velocity profiles of the two agents. However, the difference between these two explanations would be that only in the second case, the correlation between two agents of the same pair would be higher than any other correlation obtained by artificially permuting agents between pairs after data collection (e.g., correlation between A1 movements of pair *n* and A2 movements of pair *m*). Indeed, if A1 incorporates the kinematic specificities presented by A2, the similarity between the two agents would be *unique*.

Another interesting aspect to explore would concern how the first agent's actions change over the course of the interaction. Building a representation of a person's actions may be a process that needs time and practice. The quantification of this kinematic adaptation could help to investigate how we learn to adjust to others in a joint task, and this would lead to explore the applicability of other theoretical models, such as associative learning (Catmur et al., 2009) and predictive coding (Kilner et al., 2007), to the joint action domain.

Furthermore, sequential motor tasks could provide a good tool to investigate whether co-representations arise exclusively in the joint action domain, where a common goal has to be

achieved. Recent literature suggests that common goals might not be fundamental for creating social interactions (Gallotti et al., 2017). At the same time, other evidence points to consider common goals at the heart of reciprocal motor influence (della Gatta et al., 2017). In order to disentangle these different perspectives, it could be useful to investigate, through the manipulation of the instructions, whether and how others' motor representations change as a function of the presence/absence of a common goal.

2.5. Conclusion

With the present opinion paper, we aimed at describing and facing the methodological issues connected to the paradigms currently used to support the co-representation theory. We presented an alternative approach to investigate the co- representation of actions, focused on the use of joint motor tasks.

We believe that shifting the attention to movement kinematics, and specifically to those emerging during sequential joint actions, could further the current understanding of how people successfully engage in joint performances. On the one hand, it is reasonable to think that the co-representation theory may gain from a motor approach the possibility of discarding the current criticism. On the other hand, a motor approach might provide the opportunity of bringing the investigation forward. Movement kinematics could in fact be a good tool to investigate not only how we *form* representations about others, but also how we *use* co-representations to coordinate and adjust to others.

3. Wired actions: Anticipatory kinematic interference during a dyadic sequential motor interaction task.[2]

Abstract

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

---

everyday motor interactions, as they suggest that the motor system is highly permeable to others' movements. Such permeability may not only be due to a passive reaction to the others' movements, but also to an active prediction of the others' specific way of moving.

3.1. Introduction

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

Interestingly, other people's actions affect us even when they have not yet taken place. Some evidence shows that, when the nature and the onset time of another's upcoming action is known,

our motor system activates prior to the other's movement onset, in the same brain areas that would be activated if we were asked to prepare that movement (Kilner et al., 2004; Ramnani & Miall, 2004). This motor representation does not seem to reflect a general arousal for movement, but rather a more detailed motor preparation activity, related to the specific action that will be observed (Bozzacchi et al., 2014).

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

To investigate this hypothesis, in the present study we recorded movement kinematics of pairs of participants performing a sequential motor task together, in which they had to move a pawn toward specific targets, one after the other, as fast and as accurately as possible. The first agent performed the same action toward the same target throughout the entire experiment, while the second agent performed different actions depending on the size and on the position of her/his

target, which varied continuously during the experiment. The speed–accuracy trade-off literature (Fitts & Peterson, 1964) suggests that, when someone rapidly moves an object toward a target, the velocity and the deceleration of the movement vary depending on the distance and on the size of the target. Moving an object toward a small target, compared to a large one, requires greater precision, which is achieved by anticipating the velocity peak and by increasing the duration of the deceleration phase. This modulation is furtherly affected by the distance be- tween the starting point and the target, so that, compared to near targets, targets that are more distant induce movements with greater velocity peaks and longer deceleration phases (Bootsma et al., 1994; Marteniuk et al., 1987).

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

An additional information would regard the specificity of such kinematic modulation. Indeed, the "incorporated" features may not only relate to the goal of the second agent's action, but also to the specific kinematics displayed by that particular agent. Different studies suggest that people show individual variations in movement kinematics that are both consistent within a given individual and different between individuals (Koul et al., 2016; Ting et al., 2015). These idiosyncrasies lead individuals to display different motor solutions to achieve the same goal. Therefore, we predicted that, if the first agent shows only a generic effect of goal interference, the

kinematic similarity between the two agents should be unrelated to the specific motor solution expressed by the second agent. Instead, if the first agent shows also a more detailed effect of kinematic interference, the kinematic similarity between the two agents should increase during their interaction and should be strictly related to the specific motor solution expressed by the second agent, and thus it should be weaker if the first agent is randomly paired with a different second agent after data collection.

3.2. Method

3.2.1. Participants

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

3.2.2. Apparatus

Participants of each pair (hereinafter *first agent* and *second agent*) sat at opposite sides of a table (60 cm X 140 cm), facing each other (see Fig. 3.1). One of six possible sheets of paper (45 cm X 32 cm X 0.5 mm) was placed along the table's midline, equidistant from both agents. Two squares were drawn on one of the short sides of each paper, exactly along both agents' midline. The first square, called "starting point" (2 cm X 2 cm), was drawn to be 15 cm distant from the first agent's side of the table; here, a little pawn (height = 2 cm; base $\emptyset$ = 1.5 cm) was placed. The second square, called "Target 1" (4 cm X 4 cm), was drawn 15 cm far from the starting point, equidistant from the two agents. On the left-hand side of the first agent, along the table's midline, a circle, "Target 2V," was drawn on the paper. Depending on the condition, Target 2V could differ in size (small: $\emptyset$ = 1.5 cm; large: $\emptyset$ = 2.5 cm) and in distance (short: 10 cm; medium: 20 cm; long: 35 cm) from Target 1. On the right-hand side of the first agent, along the table midline, at a distance of 15 cm from Target 1, a paper-made square, called "Target 2C" (4 cm X 4 cm), was fixed to the table. Target 2V and Target 2C were always present on the table during the entire experiment.
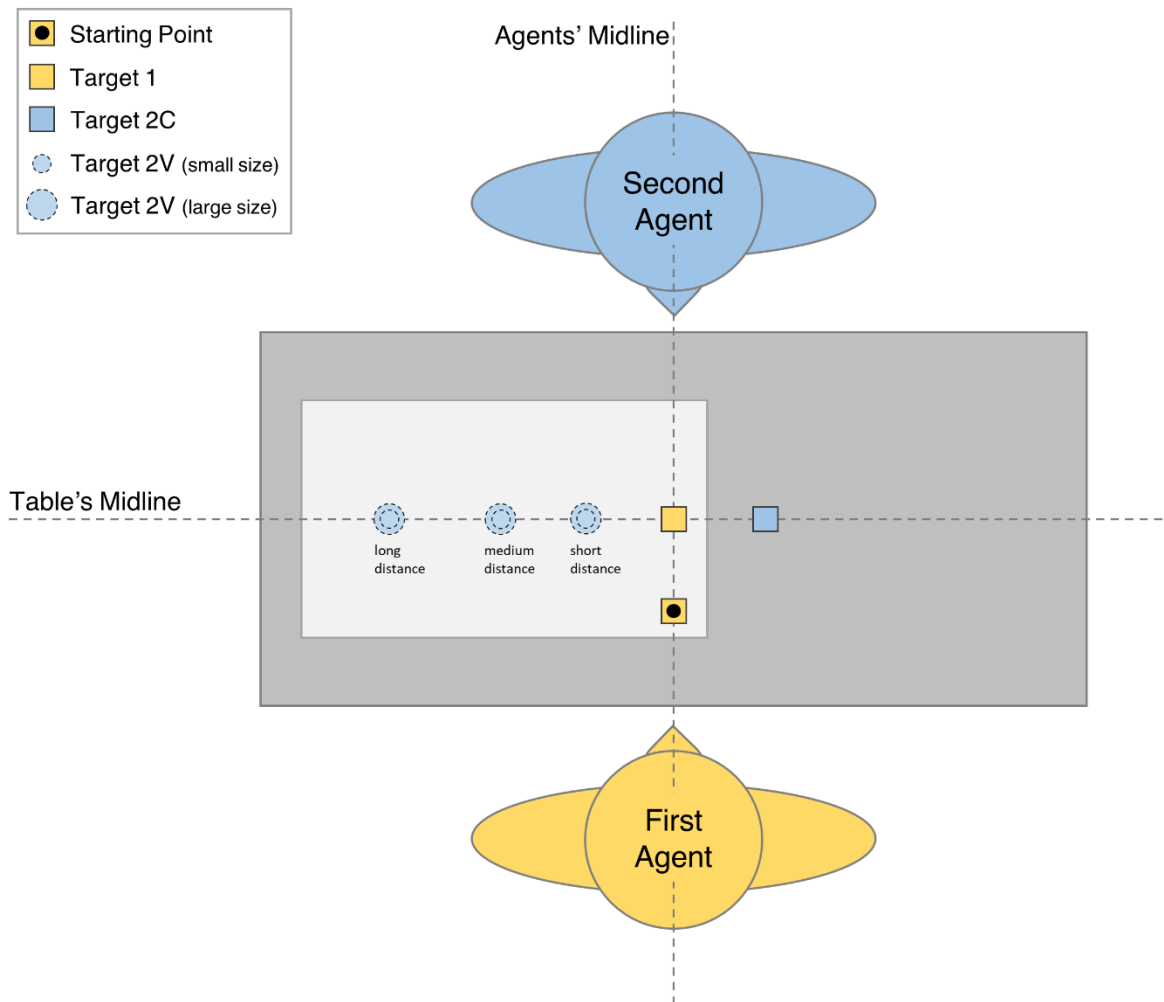
Figure 3.1. Schematic Representation of the Experimental Set-Up

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

3.2.3. Procedure

Participants of each pair were asked to perform a sequential task together with the instruction of being as quick and as accurate as possible. At the beginning of each trial, the first agent had the

left hand resting on the left knee, the right wrist resting on the table, the forearm pronated, the right arm oriented in the parasagittal plane passing through the shoulder, and the right hand in a semipronated position, holding the pawn positioned on the "starting point". The second agent was asked to keep the left hand on the left knee, the right arm oriented in the parasagittal plane passing through the shoulder, the forearm pronated, the wrist resting on the table, and the hand in a semipronated position, with the tips of the thumb and the index finger on a tape-marked point.

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

After the first agent's movement, the second agent had in turn to reach and grasp the pawn from Target 1 and, depending on the experimental session, move the pawn toward either Target 2V (*variable target* session) positioned on his or her right, or Target 2C (*constant target* session) positioned on his or her left. During both sessions (*variable target* and *constant target*), Target 2V varied in size (small, large) and in distance from Target 1 (short, medium, long) during each block, while Target 2C did not vary in size or in distance from Target 1. The variations of Target 2V thus always occurred between blocks, regardless of whether the second agent had to move the pawn towards that specific target or towards Target 2C.

The second agent was instructed to start her/his part of the action only when the first agent had positioned the pawn on Target 1. The experimenter visually monitored the performance of each trial to ensure the second agent's compliance to this requirement.

When the sequence of actions was concluded, the first agent grasped the pawn with the left hand, and set it back on the starting point. After that, both agents were instructed to return to their

starting positions. When both agents' right hands were in the respective starting positions, a new trial was prompted with the beep sound.

Participants performed a total of 240 trials divided in four sessions (2 *constant target* sessions and 2 *variable target* sessions) of 60 trials. Each 60-trial session was divided in 3 blocks of 20 trials: 5 trials of practice and 15 experimental trials. There were thus 45 experimental trials per session (i.e. 3 blocks * 15 trials), leading to a total of 90 experimental trials per condition (*constant target* and *variable target*). Within each block, the configuration of targets in the table did not change (e.g., during a variable target session, the second agent had to move the pawn toward the small and far Target 2V 20 times in a row). The sequence of the sessions was alternated following an ABAB design, and the order was counterbalanced across participants. Within each session, blocks were presented in a pseudorandomized order. The entire experiment lasted approximately 40 min.

3.2.4. Kinematic recording

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

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

3.2.5. Kinematic data processing

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

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

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

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

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

3.2.6. Data Analysis

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

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

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

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

To further evaluate the level of similarity between movements of the two agents in the variable target session, we correlated the %PV of first agents with that of second agents across all 90 experimental trials. The correlation coefficients of the 20 pairs were then converted into z-scores by means of the Fisher z transformation, in order to obtain normally distributed values. We then performed a one-sample t test to verify whether the transformed correlation coefficients were significantly greater than 0. The same approach was applied on the agent's %PD. To test the robustness of the correlations and to verify whether the correlation coefficients were pair-specific,

we then performed a nonparametric permutation test on both variables (10,000 permutations). Permutations were performed as to create artificial combinations of 20 pairs of participants. The 90 trials of first agent's movements of pair n were correlated with the 90 trials of second agent's movements of pair m, keeping fixed the experimental conditions (e.g., first agent's trial t in the condition short target distance/small target size, correlated with second agent's trial t in the same condition). For each of the 10,000 combinations we obtained 20 correlation coefficients that were then converted into z-scores and submitted to a one-sample t test. This allowed us to compare the t-value obtained from the one-sample t test performed on the real pairs with an empirical null distribution of t-values, which led to an empirical p value [empirical $p = (r + 1)/(n + 1)$, where n is the total number of permutations and r is the number of permutations that produced a t-value greater than or equal to the t-value obtained from the real pairs; (Davison & Hinkley, 1997)].

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

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

For the second analysis, which aimed to rule out the possibility that first agents were influenced by the movement performed by second agents in the preceding trial, we performed a one-tailed paired-sample t test, which compared the difference between the %PV of the two agents

calculated between actions occurring within the same trial (i.e., %PV of first agent in trial t − %PV of second agent in trial t; lag 0 delta) with the difference of the %PV calculated between the actions of first agents in one trial (t) and the actions of second agents in the preceding trial (t − 1; i.e., lag 1 delta). We expected lag 0 deltas to be lower than lag 1 deltas. The same analysis was performed for the %PD.

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

3.3. Results

For the repeated measures ANOVA on the %PV, the analysis on second agents revealed significant main effects of 'session' ($F_{(1,19)} = 34.36$; $p < .001$; partial $\eta^2 = .644$), 'target distance' ($F_{(1.46,27.66)} = 7.64$; $p = .005$; partial $\eta^2 = .287$) and 'target size' ($F_{(1,19)} = 41.06$; $p < .001$; partial $\eta^2 = .684$). The analysis also revealed a significant 'session' by 'target distance' interaction ($F_{(1.52,28.92)} = 4.28$; $p = .033$; partial $\eta^2 = .184$), and a significant 'session' by 'target size' interaction ($F_{(1,19)} = 18.65$; $p < .001$; partial $\eta^2 = .495$). No other interactions reached statistical significance (p_s ranging from .256 to .927; see Appendix A, Table 1 for detailed results). Post hoc comparisons

revealed that, only in the variable target session, participants reached the velocity peak earlier when target 2V was at the short distance ($M = 34.6\%$, 95% CI = [32.3, 37.0]), compared to when it was both at medium distance ($M = 37.4\%$, 95% CI = [35.3, 39.5]; $p < .001$) and at long distance ($M = 37.2\%$, 95% CI = [35.1, 39.3]; $p = .004$) from target 1. Furthermore, only in the variable target session, participants reached the velocity peak earlier when target 2V was small ($M = 34.4\%$, 95% CI = [32.0, 36.8]), compared to when it was large ($M = 38.4\%$, 95% CI = [36.5, 40.3]; $p < .001$; see Fig. 3.2a).

The ANOVA conducted on first agents' %PV revealed a significant main effect of 'session' ($F_{(1,19)} = 4.95$; $p = .038$; partial $\eta^2 = .207$. The analysis also revealed a significant 'session' by 'target size' interaction ($F_{(1,19)} = 9.89$; $p = .005$; partial $\eta^2 = .342$) and a significant 'session' by 'target distance' by 'target size' interaction ($F_{(1.59,30.23)} = 4.67$; $p = .024$; partial $\eta^2 = .197$). No other effects reached statistical significance (p_s ranging from .058 to .930; see Appendix A, Table 1 detailed results). Planned comparisons on the contrasts that were found significant on second agents revealed that, as for second agents, during the variable target session, first agents also reached the velocity peak earlier when target 2V was small ($M = 51.5\%$, 95% CI = [49.4, 53.6]), compared to when it was large ($M = 52.4\%$, 95% CI = [50.1, 54.8]; $p = .020$; see Fig. 3.2a).
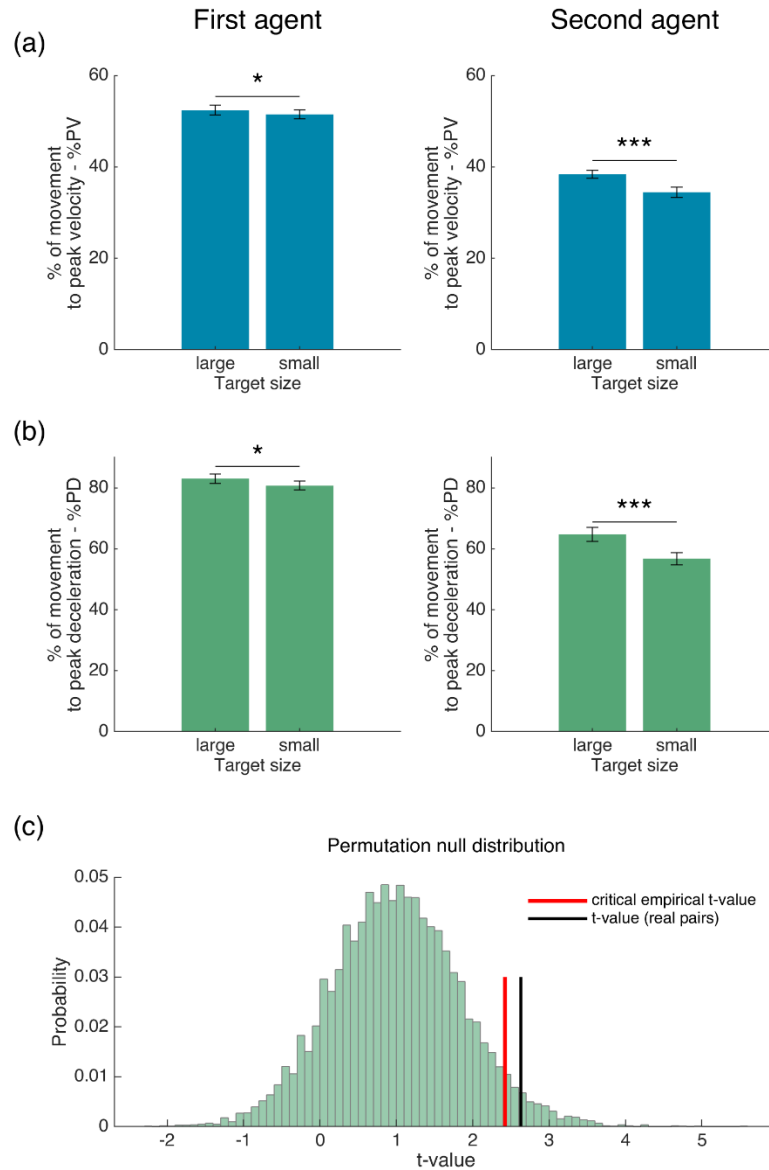
Figure 3.2. Results of Percentage of Movement to Peak Velocity (%PV), Percentage of Movement to Peak Deceleration (%PD), and Permutation Test

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

The ANOVA on second agents' %PD revealed significant main effects of 'session' ($F_{(1,19)}$ = 249.53; $p < .001$; partial $\eta^2 = .929$) and 'target size' ($F_{(1,19)} = 28.08$; $p < .001$; partial $\eta^2 = .596$). Main effects were further qualified by a significant 'session' by 'target size' interaction ($F_{(1,19)}$ = 28.99; $p < .001$; partial $\eta^2 = .604$). No other effects reached statistical significance (p_s ranging from .106 to .521; see Appendix A, Table 2 for detailed results). Post hoc comparisons revealed that, only in the variable target session, participants reached the deceleration peak earlier when target 2A was small ($M = 56.8\%$, 95% CI = [52.6, 60.9]), compared to when it was large ($M = 64.8\%$, 95% CI = [59.9, 69.7]; $p < .001$; see Fig. 3.2b).

The ANOVA conducted on first agents' %PD revealed a significant main effect of 'session' ($F_{(1,19)} = 7.85$; $p = .011$; partial $\eta^2 = .292$), and a significant 'session' by 'target size' interaction ($F_{(1,19)} = 9.79$; $p = .006$; partial $\eta^2 = .340$). No other effects reached statistical significance (p_s ranging from .065 to .627; see Appendix A, Table 2 for detailed results). Planned comparisons on the contrasts that were found significant on second agents revealed that, in the *variable target* session, first agents also reached the deceleration peak earlier when target 2V was small ($M = 80.7\%$, 95% CI = [77.6, 83.8]) compared to when it was large ($M = 83.1\%$, 95% CI = [79.8, 86.3]; $p = .027$, see Fig. 3.2b).

The ANOVA on second agents' wrist velocity revealed significant main effects of 'target distance' ($F_{(1.69,32.11)} = 458.03$; $p < .001$; partial $\eta^2 = .960$), 'target size' ($F_{(1,19)} = 19.73$; $p < .001$; partial $\eta^2 = .509$) and '% of movement' ($F_{(2.16,41.13)} = 302.44$; $p < .001$; partial $\eta^2 = .941$). Notably, the analysis revealed a significant 'session' by 'target size' by 'target distance' by '% of movement' four-way interaction ($F_{(3.87,73.47)} = 3.68$; $p = .009$; partial $\eta^2 = .162$; see Appendix A, Table 3 for detailed results). Post hoc comparisons revealed that, in the *variable target* session, for all of the three distances between target 2V and target 1, at 20% of the movement time, participants

moved significantly faster when target 2V was small, compared to when it was large (p_s ranging from .008 to .0497). This difference was also present at 30% of the movement time, when target 2V was at the short ($p = .038$) and at the medium distance ($p = .013$) from target 1. Instead, from 50% up to 100% of the movement time, for all of the three distances between target 2V and target 1, participants moved significantly faster towards large targets, compared to small targets (p_s ranging from .000 to .025; see Fig. 3.3). Only one significant comparison was found during the constant target session: when target 2V was at the short distance, at 90% of the movement time, participants were faster when target 2V was large, compared to when it was small ($p = .048$).

For what concerns first agents' wrist velocity, the ANOVA revealed a significant main effect of 'session' ($F_{(1,19)} = 11.68$; $p = .003$; partial $\eta^2 = .381$) and a significant main effect of '% of movement' ($F_{(1.61,30.53)} = 200.01$; $p < .001$; partial $\eta^2 = .913$). Importantly, as for second agents, the ANOVA yielded a significant 'session' by 'target size' by 'target distance' by '% of movement' four-way interaction ($F_{(2.72,51.59)} = 3.58$; $p = .023$; partial $\eta^2 = .158$; see Appendix A, Table 3 for detailed results). Planned comparisons on the differences that were found significant on second agents revealed that, in the variable target session, when target 2V was at the short distance from target 1, at 50% of the movement time participants were faster when target 2V was small, compared to when it was large ($p = .047$). When target 2V was located at the medium distance from target 1, from 70% up to 100% of the movement time participants were faster when target 2V was large, compared to when it was small (p_s ranging from .005 to .022; see Fig. 3.3). The other planned comparisons on the differences that were found significant for second agents in the variable target session were not found to be significant for first agents (p_s ranging from .056 to .824). The comparison found significant for second agents in the constant target session was not found to be significant for first agents ($p = .935$).

The z-transformed correlation coefficients of the %PV and of the %PD of the two agents during the variable target session resulted both to be significantly greater than 0 (%PV, $t_{19} = 2.127$, $p < 0.05$; %PD, $t_{19} = 2.630$, $p < 0.01$). However, the permutation test revealed that the observed t-value was significantly above the critical t-value (i.e., the 95% percentile of t-values obtained with 10000 permutations) only in the %PD (empirical $p = .033$, see Fig. 3.2c; %PV empirical $p = .325$).
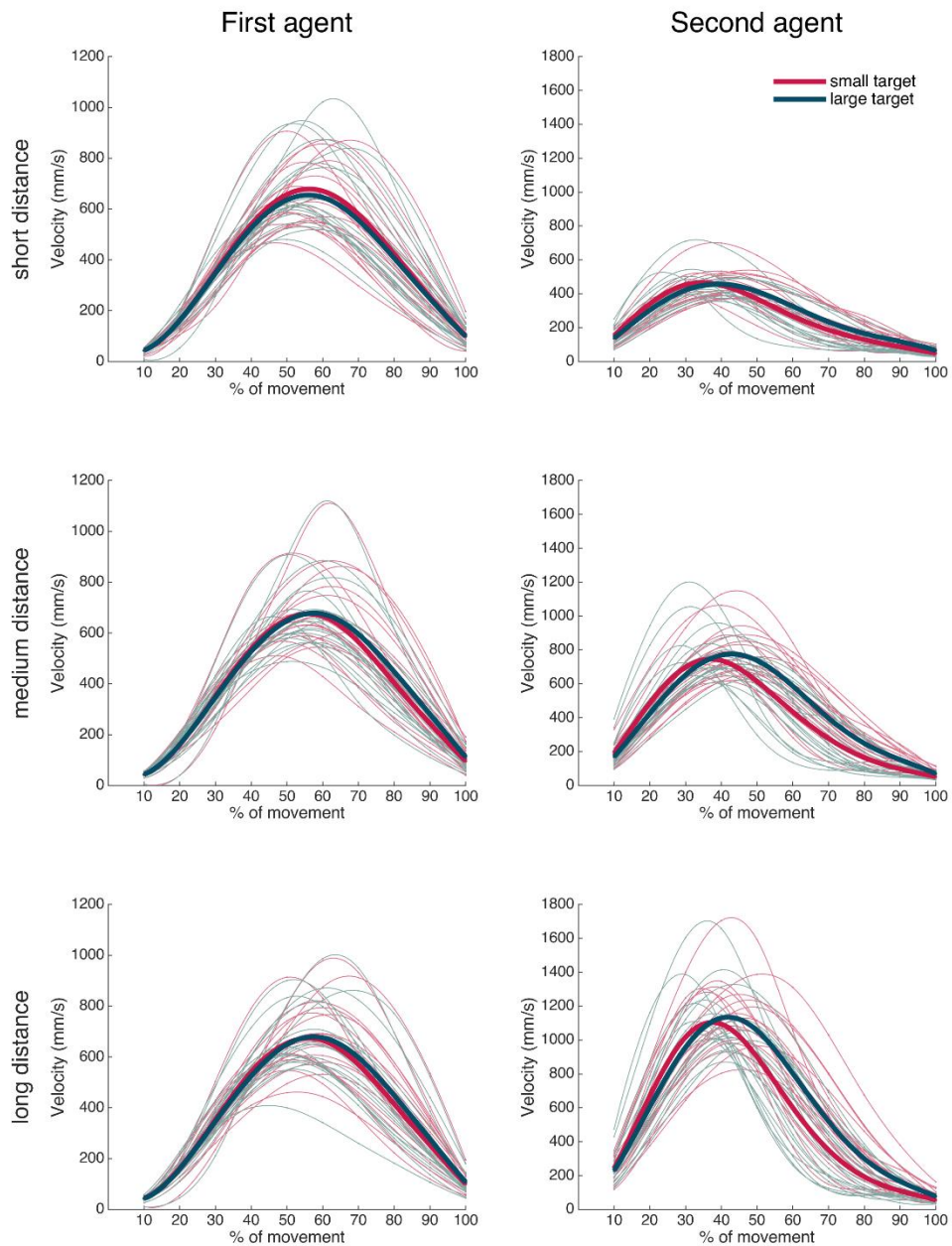
Figure 3.3. Results of the analyses on wrist velocity.

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

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

Additional analyses on %PD showed that the difference between the %PD of the two agents was significantly lower in the last five trials of each block, compared to the first five trials (t_{19} = 1.853; p = .040; see Fig. 3. 4a). Furthermore, the difference between the %PD of the actions of the two agents occurring within the same trial (i.e., lag 0 delta) was lower than the difference between the %PD of the actions of the first agent in one trial and the actions of the second agent in the preceding trial (i.e., lag 1 delta; t_{19} = 4.334; p < .001; see Fig. 3.4b).

The control analysis performed on %PD to investigate whether second agents were influenced by the movements performed by first agents before them revealed that, in none of the participants' pairs, first agent's values in trial n added explanatory power to the second agent's autoregression model (p_s ranging from .46 to .99).

(a) (b)
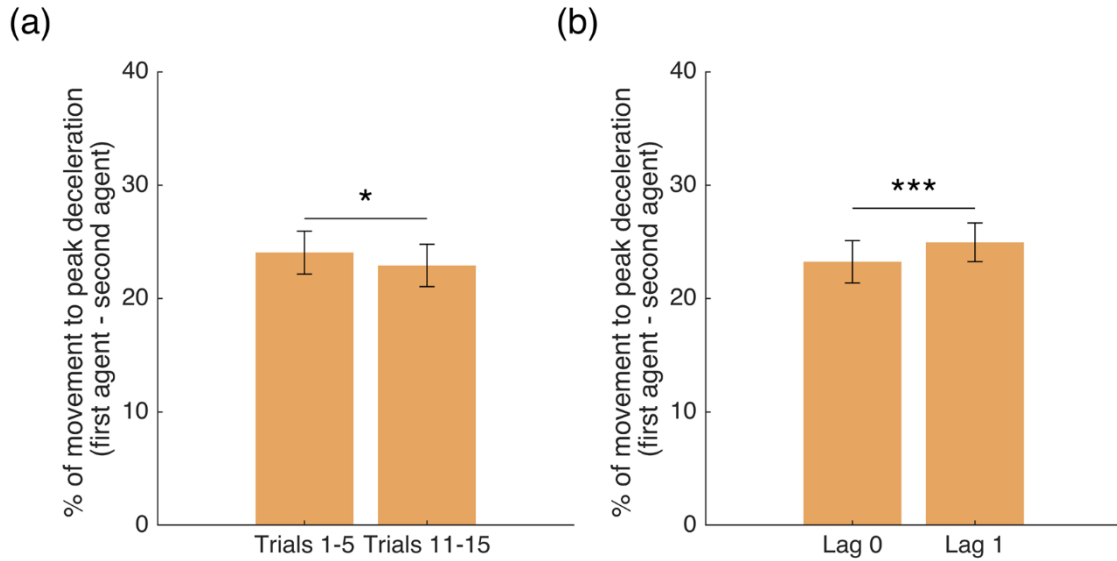
Figure 3.4. Results of additional analyses on the difference between the %PD of the two agents.

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

3.4. Discussion

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

3.4.1. An anticipatory motor interference effect

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

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

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

2V indicated to first agents what action second agents would have performed after them. The knowledge of the second agent's goal could thus have been, per se, the driver of the interference effect we found.

However, our results suggest that the kinematic modulation shown by first agents was not only affected by the goal of second agents, but also by how this goal was achieved (i.e., the kinematics of second agents' movements). Evidence for this specific kinematic interference is provided by the high kinematic similarity that was found between the two agents of each pair, by comparing the kinematic similarity of the real set of 'first agent - second agent' pairs with that of artificial sets of pairs. We found that, in the case of %PD, the kinematic similarity between the real pairs was stronger than any other similarity obtained between the artificial pairs. The kinematic modulation showed by first agents was thus pair-specific, suggesting that first agents were not simply incorporating the goal of the subsequent action, but that they were also incorporating more detailed aspects related to the specific movement kinematics that the agent in front of them would have displayed.

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

suggests that the kinematic modulation shown by second agents was more likely related to their own targets' variation, rather than being driven by first agents' kinematic modulation.

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

In our experiment, second agents were not given any instruction on how to perform their movements. Based on previous studies (Cavallo et al., 2018a; Koul et al., 2016; Ting et al., 2012) we assumed that each second agent would present a different, idiosyncratic, motor solution to perform the task, and thus that they would display slightly different movement kinematics to achieve the same goal. These idiosyncrasies were indeed evident from the results of an unsupervised dimensionality reduction procedure – i.e., t-distributed Stochastic Neighbor Embedding (Laurens van der Maaten & Geoffrey E., 2008) – that we performed on the kinematics of second agents (Fig. 3.5). As a consequence, the high kinematic similarity that we found between

the real 'first agent - second agent' pairs provides evidence that first agents were incorporating features related to the specific motor solution expressed by the second agent they were interacting with. To the best of our knowledge, these findings represent the first empirical evidence about the existence of pair-specific processes of motor interference.
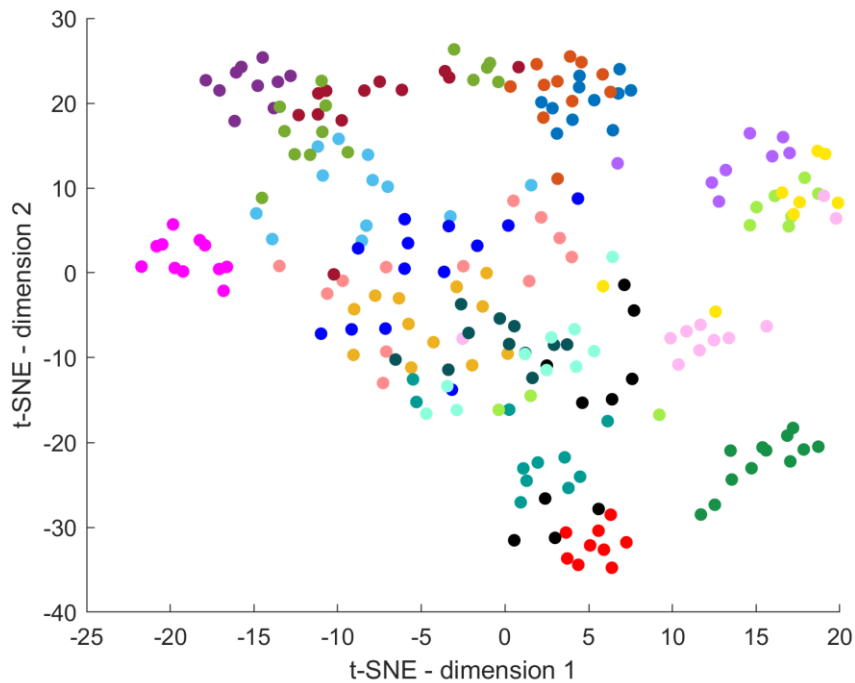
Figure 3.5. Result of t-SNE

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

3.4.2. Representing the other's upcoming movements

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

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

Furthermore, our results suggest that this 'other-representation' might be more detailed than previously thought. Indeed, we found that the kinematic modulation showed by first agents was not simply the result of a goal interference, but also the result of a more specific kinematic interference. This might indicate that, during joint actions, we do not only keep an internal model of our own and our partners tasks, but we also encode the specific kinematic features displayed by our action partners, and this affects our own movements.

The emergence of such a specific representation raises the question of when and how it is formed during the interaction. Compared to a simple representation of the other's task, building a representation of the other's specific way of moving might be a process that needs time and practice to develop. Although our experiment was not designed to investigate this aspect, our data suggest the presence of a learning process. In the follow-up analysis, we found that the difference between the %PD of the two agents decreased during the course of each experimental block, with a significant difference between the first five and the last five trials of each block (see Fig. 3.4a). The presence of this learning process might be interpreted in two ways. On the one hand, the kinematic modulation shown by the first agent might be simply due to a memory-driven effect, elicited by the observation of the movement performed by the second agent in the previous trial: this might have led the first agent to copy, in each trial, some features displayed by the second agent in the preceding trial. On the other hand, the observed effect on the first agent might be due to a refinement of the motor representation of the second agent's action: such a refinement would be at the base of the predictive process that triggers the anticipatory interference. To disentangle between these alternative interpretations, we compared the difference between the %PD of the two agents calculated between actions occurring within the same trial (i.e., lag 0 delta) with the difference of the %PD calculated between the actions of first agents in one trial and the actions of second agents in the preceding trial (i.e., lag 1 delta). We found that lag 0 deltas were significantly smaller (i.e., the *% of movement to peak deceleration* was more similar between the two agents) compared to lag 1 deltas (see Fig. 3.4b). These results suggest that first agents were not simply copying the previous action of second agents, but that they were actively refining their representation of second agents' movement kinematics in a predictive way. Therefore, when building a representation of the other's action, a learning process could allow one to shift from an

initial generic representation of the other's task towards a specific detailed representation of the other's movements. It is important to note that the presence of this learning process was not supported by the analyses performed on the %PV. The significant correlation found for %PV was also not pair specific, even if first agents showed, within this variable, a modulation relative to the size of the targets of second agents. The contrasting behavior shown by these two kinematic variables suggests that representing another's action might in some cases remain a generic process that does not take into account the other's specific way of moving.

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

The involvement of the motor system during the anticipation of the other's actions occurs exclusively when we know how the other will move and when he or she will move (Bozzacchi et

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

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

3.5. Conclusion

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

4. Visuo-motor interference is modulated by task interactivity: a kinematic study[3]

Abstract

How does interactivity change the way we perceive other people's actions? Using a machine-learning approach, in the present study we investigated how action observation affects the kinematics of reach-to-grasp movements performed in interactive and non-interactive settings. Results revealed that the detrimental effect of visuo-motor interference is reduced when the action performed by the other is relevant to achieve a common goal. Inspection of kinematic profiles revealed that the interference was driven by the observation of the movement performed by the other, but also by the object the other manipulated. These findings support the idea that during joint actions we form dyadic motor plans, in which both our own and our partner's actions are represented in predictive terms, with respect to the common goal to be achieved. These predictive representations relate not only to what our partner's movement will produce, but also to the unfolding of the movement itself.

---

[3] *In preparation*: Rocca, M., Sacheli, L. M., Romeo, L., Cavallo, A. (in prep.). Visuo-motor interference is modulated by task interactivity: a kinematic study

4.1. Introduction

Observing other people's movements is an active process. When we observe someone else move, in addition to visual regions, our brain activates the very same motor regions that we would use to perform the observed movement (Rizzolatti & Sinigaglia, 2016). This process appears to be beyond our direct control, and has noticeable effects on our overt motor behavior.

Indeed, when we act during or in response to another person's movement, our motor behavior shows the effects of the observed action, a phenomenon often referred to as *visuo-motor interference* (Blakemore & Frith, 2005). Converging evidence indicates that, as a result of visuo-motor interference, reaction times are slower, and movement itself becomes less precise and more variable (Brass et al., 2001; Kilner et al., 2003). Furthermore, the executed movement shows a pattern of kinematic similarity to the observed movement (Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011).

Recently, a new question has been raised, led by a growing interest in understanding human cognition from its *social* perspective (De Jaegher et al., 2010; Schilbach et al., 2013): does visuo-motor interference differ when we are actively engaged in an interactive context with the other?

To address this question, recent studies have compared the effects of action observation on behavior in interactive and non-interactive settings, using the scenario of *joint actions* as a model for interactivity (Sebanz et al., 2006; for a recent review, see Sebanz & Knoblich, 2021). Joint actions can be defined as the simplest type of collaborative social interaction, where two or more individuals coordinate their actions to produce a change in the environment. Compared to a non-interactive context (where two agents pursue individualistic goals), during a joint action, two agents *share* the same goal, which is achieved by the two actions of the pair. Therefore, the action

of the other is of great importance in achieving the desired *shared* outcome, and thus needs to be taken into account and monitored (Vesper et al., 2010, 2017).

How does this translate into the context of visuo-motor interference? Some studies show that, compared to a non-interactive scenario, visuo-motor interference is reduced during joint actions (Clarke et al., 2019; Sacheli et al., 2018, 2019). These studies suggest that, during joint actions, we shift from the automatic simulation of an observed action to the active prediction of the consequences of a partner's action. In this framework, the other's action is not disruptive, as it becomes part of a dyadic motor plan, in which it is processed in terms of its predicted effects on the environment.

However, other studies suggest that, compared to a non-interactive setting, a joint action setting enhances the effect of visuo-motor interference (della Gatta et al., 2017; Era et al., 2018). This is explained by the fact that, during a joint action, the action performed by the other becomes part of our own action goal, and needs to be represented and monitored, leading to a higher motor activation during action observation, and thus to more visuo-motor interference.

Although these results seem to be hardly reconcilable, a fundamental difference between them might lie in the way joint actions have been operationalized. Namely, whereas in the studies that found high visuo-motor interference, a joint action was defined as a condition in which the other's *movement* was relevant to achieve the common goal (e.g., perform movement A, while the other performs movement B, to achieve AB), in the studies that found low visuo-motor interference, a joint action was operationalized as a condition in which the *outcome of the movement* of the other was relevant to achieve the common goal (e.g., perform movement A to produce X, while the other performs movement B to produce Y, to achieve XY).

With this in mind, in the present study, we aimed to shed light on the potential modulations of visuo-motor interference during joint actions, by assessing its presence during three different interactive scenarios, in which the action of the other was either i) irrelevant, ii) relevant (in terms of the performed *movement*), or iii) relevant (in terms of the performed *movement* and the produced *outcome*).

To this end, we used a motion-capture system to record the kinematics of sequential reach-to-grasp movements performed by pairs of agents (i.e., a participant and a confederate). The confederate was instructed to reach for an object, grasp it - either with a precision grip (PG) or with a whole-hand prehension (WHP) - and then move it from a start position to a target position. Once the confederate grasped the object, the participant had to grasp a second object and move it to a different target position (Fig. 4.1). The combination between the type of grasp adopted by the confederate and the type of grasp adopted by the participant could be either *congruent* (i.e., if they both adopted the same type of grasp) or *incongruent* (i.e., if the confederate adopted a PG and the participant adopted a WHP, or vice-versa).

These motor sequences were performed under three different conditions (i.e., interactive scenarios). In the *Non Interactive* condition, the goal was *individualistic*: each agent was instructed to perform his/her own part of the action as quickly and accurately as possible. In the *Joint* condition, the goal was *shared* between the agents: they were asked to complete the sequence of actions as quickly and accurately as possible. In the *Joint Outcome* condition, the goal was not only *shared*, but also required to produce a sensory outcome (i.e., a colored circle), which was a direct result of the actions performed by the two agents during the sequence (e.g., yellow circle, if they both performed a PG action; blue circle, if they both performed a WHP action; green circle, if they performed two different actions), as quickly and accurately as possible.

Our first experimental focus was on the kinematic difference between *congruent* and *incongruent* trials, during each of the three conditions. Using a machine-learning approach, we assessed the presence of visuo-motor interference by examining the extent to which movement kinematics as a whole could distinguish between movements performed during *congruent* trials and movements performed during *incongruent* trials. In line with the existing literature (Dijkerman & Smit, 2007; Kilner et al., 2003), we expected a high kinematic difference (i.e., the presence of visuo-motor interference) during the *Non Interactive* condition. Compared to the *Non Interactive* condition, we expected a lower kinematic difference (i.e., less visuo-motor interference), during the *Joint Outcome* condition, consistent with studies suggesting that during joint actions in which agents collaborate to produce a change (i.e., an outcome) in the environment, the detrimental effect of visuo-motor interference disappears (Clarke et al., 2019; Sacheli et al., 2018, 2019). Instead, we expected a higher kinematic difference (i.e., more visuo-motor interference) during the *Joint* condition, compared to the *Non Interactive* condition, in line with findings suggesting that when the *movement* of the other is relevant to achieve a common goal, the detrimental effect of visuo-motor interference increases (della Gatta et al., 2017).

Furthermore, we aimed at investigating the visuo-motor interference effect in a comprehensive manner, by looking at fine-grained aspects of movement unfolding. Thus, our second experimental focus was on the specific effects of visuo-motor interference on participants' movement kinematics. Consistent with previous studies, we expected that participants would incorporate some kinematic components of the confederate's movement into their own movement kinematics (Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011). We expected this embodiment to result in kinematic patterns that were similar to the observed action (e.g., wider grip aperture after the observation of a WHP action,

compared to the observation of a PG action). Furthermore, we expected participants to show, during the course of the experiment, a gradual and increasing convergence towards the observed kinematic profile displayed by the confederate (Rocca & Cavallo, 2020).
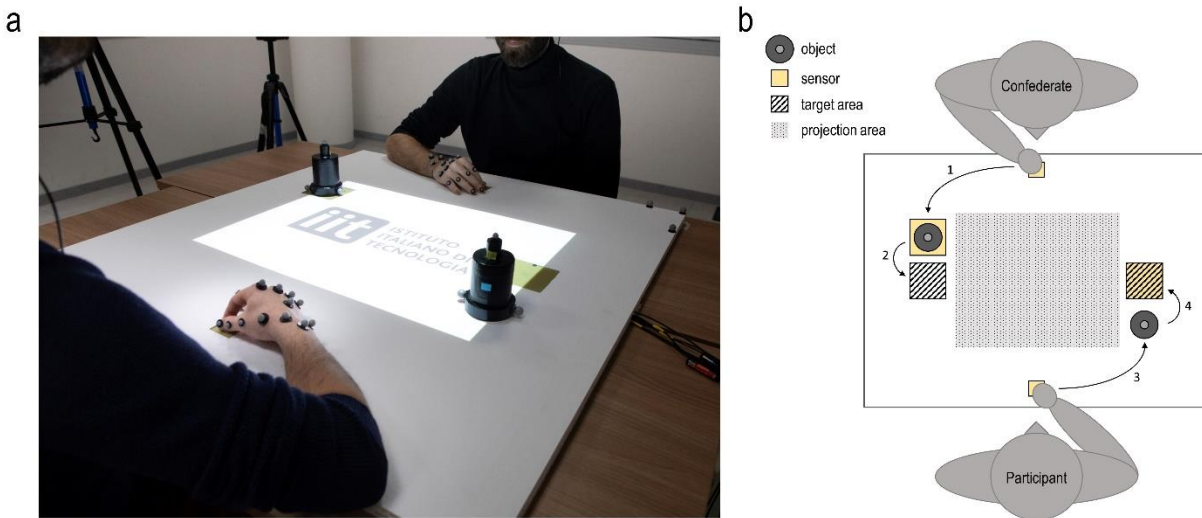
Figure 4.1

Experimental set-up. Panel (a) shows a photo of the experimental set-up, in which the participant and the confederate keep their hands on their respective starting positions. The bright area represents the projection area. During the experiment, the projection area was dark. Projections were used only during catch-trials, during error trials, and during the Joint Outcome condition. Panel (b) shows a schematic (not in scale) representation of the experimental set-up. The numbers refer to the order in which the actions were performed during each motor sequence (i.e., trial).

4.2. Method

4.2.1. Participants

Sixteen participants took part in the experiment (9 females; aged 25-40; mean age = 29.06 years; SD = 4.34). All participants were right-handed, had normal or corrected-to-normal vision, and no history of neurological disorders. The study was approved by the local ethics committee (ASL3 Genovese) and performed in accordance with the principles of the revised Helsinki Declaration (World Medical Association, 2008). All participants provided written informed consent and were naïve with respect to the purpose of the experiment.

4.2.2. Apparatus

Participants performed the experiment together with a confederate (male, 35 years old). They sat at opposite sides of a table (140 x 120 cm), facing each other (Fig. 4.1). A two-layer reinforced honeycomb plastic panel (100 cm X 110 cm) was placed on the center of the table. Four square-shaped cavities were carved out from the first layer of the panel and replaced with four square-shaped sensors. Each sensor was constructed to be sensible to both press and release actions. There were two *small* sensors (4.3 cm X 4.3 cm) and two *large* sensors (9.8 cm X 9.8 cm). The two *small* sensors were placed along the two agents' midline, 11 cm distant from the two sides of the panel that faced each agent. These sensors were used as the starting point for both the participant's and the confederate's actions. The two *large* sensors were placed as follows. One was placed 15 cm distant from the confederate's right-hand side of the panel, and 35 cm distant from the side of the

panel that faced the confederate. The other was placed 15 cm distant from the participant's right-hand side of the panel, and 50 cm distant from the side of the panel that faced the participant.

Two identical objects (height: 13 cm) were placed on the table, 15 cm distant from each agent's right-hand side of the panel, and 35 cm distant from the side of the panel that faced each agent. The objects were designed to be grasped with either a precision grip (PG), or a whole-hand prehension (WHP). They consisted of two superimposed cylinders with different diameters (upper part: height = 3 cm, Ø = 2.5 cm; lower part: height = 10 cm, Ø = 5.5 cm). Two colored labels (blue and yellow; 1.5 cm X 1 cm) were applied on each object. One label was applied on the upper (i.e., small) part of the object, and the other on the bottom (i.e., large) part. The association between color and upper/lower part of the object was counterbalanced between participants. In front of the confederate's object, a square-shaped target (9.8 cm X 9.8 cm) was drawn on the panel and represented the confederate's action target area. The participant's target area coincided with the *large* sensor placed in front of her/him.

A projector was positioned on the ceiling above the table and was used to deliver visual stimuli on the panel.

Both the participant and the confederate were outfitted with headphones, through which they received auditory instructions and signals.

4.2.3. Procedure

The experiment was explained to participants as a simple sequential task. Participants were told that the general rule of the task was to reach and grasp - either with a PG or with a WHP - the object that was in front of them, and place it on the target area as quickly and as accurately as

possible. Participants could start their action only *after* having observed the confederate reaching and lifting his own object. The two types of grasp (i.e., PG and WHP) were associated with the two colored labels placed on the two objects.

At the beginning of each trial, both the confederate and the participants were instructed to hold the same starting position, which consisted in keeping the left hand on the left knee, the right arm oriented in the parasagittal plane passing through the shoulder, the forearm pronated, the wrist resting on the table, and the hand in a semipronated position, with the thumb and the index finger opposed and pressing the small sensor positioned in front of them (Fig. 4.1a). Only when the two agents were in their starting positions, they heard on their headphones the instructions relative to the type of grasp to perform during the sequence. These instructions were in the form of colors (e.g., "blue" = grasp the object with a precision grip). The confederate's instruction regarded only the type of grasp that he had to perform. The participants' instruction regarded instead the two types of grasp to be performed during the sequence. The confederate thus heard only one color, while participants heard two colors: the first color described the type of grasp that the confederate had to perform, and the second color described the type of grasp that the participant had to perform. After the instructions (jittered interval: 1000, 2000 or 3000 ms), the confederate heard a beeping sound (frequency: 750 Hz; duration: 150 ms). This sound was his GO signal: when he heard it, he could release the sensor and start to reach, grasp, and move his object into its target area. The participant's GO signal consisted instead in the moment when the confederate lifted his object. If the participant or the confederate started to move before their own GO signal, an error signal appeared at the center of the table, and the trial was discarded (N = 270, equal to 7% of the trials). The trial concluded when the participant finally placed his/her object on its target area (Fig. 4.1b). At this point, after 2000 ms from the end of the action sequence, both agents heard a lower beeping

sound (frequency: 440 Hz; duration: 200 ms), which signaled them to use their left hands to put the objects back to their initial starting areas, and to return to their starting position to receive new instructions.

Participants performed these motor sequences in three different conditions. I) In the *Non Interactive* condition, we told the participants that the goal of the task was *individualistic*: they had to perform *their own* action as quickly and as accurately as possible. At the end of their movement, they received a negative auditory feedback in case they performed their own part of the action sequence too slowly. The feedback consisted in a male voice saying "too slow", and was delivered only when the participants' movement time was above 2 standard deviations from a reference mean, which we acquired from a pilot experiment (PG mean $\pm$ SD = 912 ms $\pm$ 121 ms; WHP mean $\pm$ SD = 834 ms $\pm$ 113 ms). II) In the *Joint* condition, we told the participants that the goal of the task was *shared* with the confederate: as a pair, they had to perform *the sequence* of actions as quickly and as accurately as possible. During this condition, the negative auditory feedback that could be delivered depended on the sum of the movement times of both the confederate's and the participant's actions in each sequence (PG-PG mean $\pm$ SD = 1613 ms $\pm$ 159 ms; WHP-WHP mean $\pm$ SD = 1475 ms $\pm$ 149 ms; PG-WHP or WHP-PG mean $\pm$ SD = 1570 ms $\pm$ 165 ms). III) In the *Joint Outcome* condition, the goal of the task was also referred to as *shared*, but, importantly, it was made to be perceived as a tangible sensory outcome, produced physically in the environment by the two actions performed by the pair. We told participants that, during this condition, the combination of the two actions performed by the pair during the sequence produced a colored circle at the center of the table ($\emptyset$ = 15 cm). The color of the circle was a direct result of the two types of grasp performed. The circle could thus be: i) yellow, if both agents performed the same (i.e., congruent) type of grasp associated with the yellow label (e.g., PG-PG action sequence); ii)

blue, if both agents performed the same (i.e., congruent) type of action associated with the blue label (e.g., WHP-WHP action sequence); iii) green, if the two agents performed different (i.e. incongruent) types of grasp (i.e., PH-WHP action sequence, or WHP-PG action sequence). In this framework, we told participants that the goal was to produce the final, colored circle as quickly and as accurately as possible. The negative auditory feedback that could be delivered was computed in the same way as in the *Joint* condition.

The order of presentation of the conditions was counterbalanced between the participants. During each condition, the participants performed 20 experimental trials for each of the four possible action sequences (i.e., PG-PG, PG-WHP, WHP-PG, WHP-WHP), leading to a total of 80 experimental trials per condition, and 240 total experimental trials. Before each condition, participants performed 10 practice trials. The experimental trials were randomly interspersed with catch trials (20% of total number of trials, i.e., 16 trials per condition), which were designed to maintain the participants' attention focused on the action performed by the confederate across all trials, and across all conditions. A catch trial appeared identical to an experimental trial, up until the moment when the confederate grasped his object. At that moment in fact, a question mark was projected near the object of the confederate: this instructed the participant to avoid performing the movement, and to just inform the experimenter on whether the action performed by the confederate was the right one or the wrong one, relatively to the instruction that the participant heard at the beginning of the trial. In half of the catch trials, unbeknownst to the confederate, he received the instruction to perform an action that was different as compared to what was expected by the participant (i.e., wrong). The entire experiment lasted for approximately 60 minutes. Stimuli presentation and trial randomization were controlled through E-Prime software v. 2.0 (Psychology Software Tools Inc., Pittsburgh, PA).

4.2.4. Kinematic Recording

Movement kinematics were recorded using a near-infrared camera motion-capture system (frame rate: 100 Hz; Vicon Nexus v.2.5). Eight cameras were placed in a semicircle at a distance of 1.5–2 m from the table where the two agents were seated.

Both agents' right hands were outfitted with 20 retro-reflective hemispheric markers (6 mm in diameter). Data analyses were performed on the kinematic profile of the markers placed on the tip of the thumb, on the tip of the index finger, and on the radial aspect of the wrist. Four additional markers were placed on each of the two objects used.

4.2.5. Kinematic Data Processing

After data collection, each trial was individually inspected for correct marker identification and then run through a low-pass Butterworth filter with a 8 Hz cutoff. Trials in which the quality of marker reconstruction was poor (N = 79, equal to 2% of the trials) and trials in which either the confederate or the participant performed wrong or inaccurate movements (N = 142, equal to 4% of the trials) were discarded from the dataset and not considered for further analyses. For data processing and analysis, a MatLab custom script (MATLAB; MathWorks, Natick, MA) was used to compute the variables of interest. Each variable was computed within the time window from onset to offset of the reach-to-grasp phase of the movement. For both agents, movement onset was defined as the first time point at which the velocity of the wrist crossed a 20-mm/s threshold. Movement offset was defined as the time point, within 10 ms before and 10 ms after the object started to be lifted, at which the velocity of the wrist was at the lowest. Within these time windows, we computed for both agents the following kinematic features:

- Wrist Velocity (WV), defined as the module of wrist velocity (mm/s);

- Wrist Acceleration (WA), defined as the rate of change of wrist velocity (mm/s^2);

- Wrist Jerk (WJ), defined as the rate of change of the module of wrist acceleration (mm/s^3);

- Grip Aperture (GA), defined as the distance between the marker placed on the tip of the thumb and the marker placed on the tip of the index finger (mm);

- Wrist Height (WH), defined as the z-component of the marker placed on the wrist (mm).

Each of these variables was expressed with respect to normalized (%) rather than absolute (ms) duration, and was then resampled at intervals of 10% of the normalized movement time.

4.2.6. Data Analysis

The resulting dataset of 3349 reach-to-grasp movements performed by the participants was divided into two subsets depending on the type of grasp performed by the participants (i.e., PG or WHP). The PG subset consisted of 1651 reach-to-grasp movements. The WHP subset consisted of 1698 reach-to-grasp movements. All the analyses reported below have been performed on the PG subset and then replicated on the WHP subset.

4.2.7. Catch trials

The level of attention paid by participants during the three conditions was assessed by measuring participants' response accuracy during catch trials. The non-parametric Wilcoxon rank sum test was used to evaluate differences between conditions.

4.2.8. Quantification of visuo-motor interference during Non Interactive, Joint and Joint Outcome conditions

To quantify the presence of visuo-motor interference, we used a machine-learning approach. The kinematic features of participants' reach-to-grasp movements were used as predictors to classify the action performed by the confederate. The confederate's action could be *congruent* (when, compared to the participant, he performed the same type of grasp) or *incongruent* (when, compared to the participant, he performed a different type of grasp). To investigate the modulation of visuo-motor interference between the *Non Interactive*, the *Joint* and the *Joint Outcome* conditions, we trained, validated, and tested, for each experimental condition, 100 support vector machines regularized with least absolute shrinkage and selection operator (SVM-LASSO). In order to maintain the same number of trials in each SVM-LASSO model of each condition, for each of the 100 iterations we randomly selected 480 trials (i.e., 30 trials per participant: 15 *congruent* trials and 15 *incongruent* trials). Data splitting was then performed by employing a 15-fold cross-validation procedure. K-fold cross-validation involves splitting the dataset into equally sized folds. During each iteration, the model is trained on k-1 folds, and then tested on the fold left out. We repeated this procedure 15 times, each time using a different fold as the testing dataset, and the other 14 folds as the training dataset. Each of the 15 folds contained 32 trials (i.e., 2 trials per participant: 1 *congruent trial* and 1 *incongruent trial*). Hyper-parameter was recursively tuned on all but one fold of the training set by implementing a nested 14-fold cross-validation procedure. Classification accuracy was used as a measure of classification performance. To test whether the classification accuracy significantly exceeded chance level, we randomly permuted the *congruent/incongruent* labels (100 permutations per condition) and recomputed the classification accuracy after each permutation. This allowed us to obtain an empirical null distribution of *random*

classification accuracies. The p-values were then determined as the proportion of times that the classification accuracy obtained from the random permutations exceeded the average classification accuracy obtained from the original classifiers.

To test the difference in classification accuracy between experimental conditions, we computed empirical p-values, which were determined as the proportion of times that the classification accuracy obtained from the classifiers of one condition was lower than the average classification accuracy obtained from the classifiers of another condition. Holm-Bonferroni correction was applied to correct for multiple pairwise comparisons.

The level of significance, α, was set at 0.05 for all statistical comparisons.

4.2.9. Quantification of visuo-motor interference in single kinematic features across conditions

To investigate whether each kinematic feature encoded information about the action performed by the confederate, we performed 100 repetitions of five separate SVM-LASSO models for each experimental condition. Each model was trained and tested using only one kinematic feature at a time (i.e., WV, WA, WJ, GA and WH). For each model, we reproduced the same k-fold cross-validation procedure described above (i.e., 15 folds; 32 trials per fold; in each fold, 2 trials per participant: 1 *congruent*, 1 *incongruent*). Hyper-parameter was recursively tuned on all but one fold of the training set by implementing a nested 14-fold cross-validation procedure. To test whether the classification accuracy significantly exceeded chance level, we randomly permuted the *congruent/incongruent* labels (100 permutations per kinematic feature per condition) and recomputed the classification accuracy after each permutation. The p-values were determined

as the proportion of times that the classification accuracy obtained from the random permutations exceeded the average classification accuracy obtained from the original classifiers.

The difference in classification accuracy between experimental conditions was tested, for each kinematic feature, by computing empirical p-values, determined as the proportion of times that the classification accuracy obtained from the classifiers of one condition was lower than the average classification accuracy obtained from the classifiers of another condition. Holm-Bonferroni correction was applied to correct for multiple pairwise comparisons.

The level of significance, α, was set at 0.05 for all statistical comparisons.

4.2.10.   Embodiment of confederate's kinematic parameters through time

To gain further understanding on whether and how the spatio-temporal kinematic parameters expressed by the confederate were embodied by participants through time, we computed, only for the kinematic features that were found significantly discriminative, a measure of *kinematic distance* between the participants and the confederate. For each *incongruent* trial of the *Non Interactive* condition, we measured the Euclidean distance between the kinematic profile displayed by the participant and the average kinematic profile displayed by the confederate in that particular action sequence. Each kinematic profile was expressed in 10 time intervals (from 10% to 100% of the movement time). Each *kinematic distance* was thus computed as the Euclidean distance between two 10-value vectors. We focused on the *Non Interactive* condition as it was the one in which the effect of visuo-motor interference was significantly more pronounced. For each kinematic feature, we conducted a repeated measures ANOVA with 'trials' (2 levels: first half, second half) and 'action' (i.e. action performed by the participant; 2 levels: PG, WHP) as within-

79

subject factors. For each kinematic feature, we expected the kinematic distance to decrease between the first half and the second half of the trials.

4.3. Results

Data for this study consisted of 3349 motor sequences recorded from 16 pairs of agents involved in the sequential motor task. The agent who always started the sequence was a confederate, while the agent who completed the sequence was a participant. A near-infrared camera motion-capture system was used to record movement kinematics of both agents. Kinematic features of interest (N = 5, see 'Kinematic data processing', in 'Methods' section) were computed only throughout the reach-to-grasp phase of the movement, at intervals of 10% of the normalized movement time. The 50 resulting features (5 features x 10 intervals) obtained from each participant's actions were used as predictors for the classification analyses. The first classification analysis aimed to test the hypothesis of a modulation of visuo-motor interference depending on the experimental condition. This was done by testing whether, in each condition, it was possible to classify what action the confederate had performed based on the whole pattern of the participants' kinematic features, and whether there were differences in classification performance between conditions. The follow-up analysis aimed to explore the contribution of each feature to these classifications. An additional analysis was performed to test the hypothesis of kinematic similarity to the observed movement (i.e., visuo-motor interference effect). This was done by computing a measure of *kinematic distance* between the participants' kinematic profiles and the

confederate's kinematic profiles, and by looking at whether this distance decreased during the course of the experiment.

Analyses were performed separately on participants' PG actions and on participants' WHP actions. We expected the same pattern of results from both datasets. Here, we will present the results obtained using participants' PG actions as predictors. The results obtained using participants' WHP actions as predictors can be accessed in the supplementary results (see Appendix B).

4.3.1. Catch trials

To ascertain whether the quantitative differences of visuo-motor interference were not due to explicit differences in the level of attention paid by the participants in the three conditions, experimental trials were randomly interspersed with catch trials. A catch trial appeared identical to an experimental trial, up until the moment the confederate grasped his object. At that point, the participant was visually signaled not to perform the movement, but to inform the experimenter on what action the confederate had performed. The average response accuracy was 0.97 (SEM = 0.007). There was no difference between the response accuracies of the *Non Interactive*, the *Joint*, and the *Joint Outcome* conditions (ps ranging from 0.40 to 0.90, sign tests).

4.3.2. Quantification of visuo-motor interference during Non Interactive, Joint and Joint Outcome conditions

To quantify the amount of visuo-motor interference, and to investigate its modulation between the *Non Interactive*, the *Joint*, and the *Joint Outcome* conditions, we trained, validated and tested 100 support vector machines regularized with least absolute shrinkage and selection operator (SVM-LASSO). For each SVM-LASSO model, we randomly selected 30 trials per participant (15 *congruent* trials and 15 *incongruent* trials), and then employed a 15-fold cross-validation procedure (32 trials per fold, i.e., 2 trials per participant: 1 *congruent*, 1 *incongruent*). For each of the three conditions, we attempted to classify the confederate's action (i.e., *congruent/incongruent*), using, as predictors, the reach-to-grasp features of the PG movements performed by the participants. To test whether the classification accuracy significantly exceeded chance level, we randomly permuted the *congruent/incongruent* labels and recomputed the classification accuracy after each permutation. P-values were determined as the proportion of times that the classification accuracy obtained from the random permutations exceeded the average classification accuracy obtained from the original classifiers. To test the difference in classification accuracy between experimental conditions, we computed empirical p-values, determined as the proportion of times that the classification accuracy obtained from the classifiers of one condition was lower than the average classification accuracy obtained from the classifiers of another condition.

Classification results revealed that participants' kinematics encoded the action performed by the confederate (i.e., *congruent/incongruent*) significantly above the level of chance in all three conditions (*Non Interactive* mean $\pm$ SEM $= 0.62 \pm 0.001$, p $= 0.01$, permutation test; *Joint* mean $\pm$ SEM $= 0.59 \pm 0.002$, p $= 0.01$, permutation test; *Joint Outcome* mean $\pm$ SEM $= 0.55 \pm 0.002$, p $=$

0.03, permutation test). This indicates that, in all conditions, the action performed by the confederate was interfering with the participants' movement kinematics. However, visuo-motor interference was significantly more pronounced in the *Non Interactive* condition, as compared to both the *Joint* condition (p = 0.04, corrected empirical p-value) and the *Joint Outcome* condition (p = 0.03, corrected empirical p-value). Classification accuracy was also significantly higher in the *Joint* condition, compared to the *Joint Outcome* condition (p = 0.04, corrected empirical p-value; Fig. 4.2).
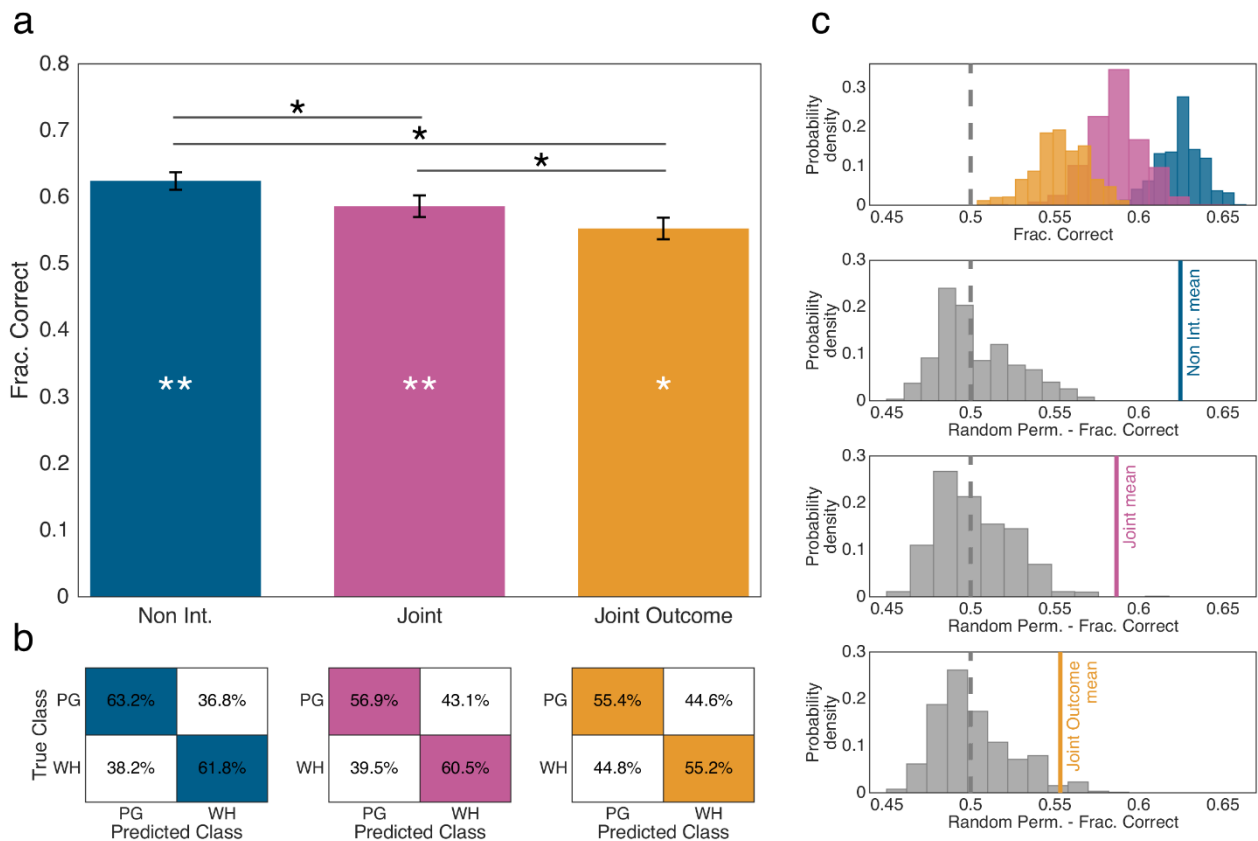
Figure 4.2

Classification accuracy during Non Interactive, Joint, and Joint Outcome conditions. Panel (a) shows a bar plot representing the mean classification accuracies of the 100 SVM-LASSO models performed for each condition. Bars indicate standard deviation (SD). White asterisks denote significant (i.e., above chance) classification accuracies (* p < 0.05; ** p < 0.01). Black asterisks denote significant differences between conditions (* p <

0.05). Panel (b) shows the confusion matrices corresponding to each condition (rows are the true classes). The upper histogram in panel (c) represents the empirical distributions of the classification accuracies obtained from the 100 SVM-LASSO models of each condition. The dashed line indicates 0.5 chance level. The other three histograms of panel (c) represent, for each condition, the empirical distribution of the classification accuracies obtained from the 100 SVM-LASSO models computed after the random permutation of labels. For each of the three histograms, the solid line represents the mean classification accuracy obtained from the original models of the corresponding condition. The dashed line indicates 0.5 chance level.

4.3.3. Quantification of visuo-motor interference in single kinematic features across conditions

To investigate how each kinematic feature was affected by the actions performed by the confederate, we performed 100 SVM-LASSO models for each of the five kinematic features, in each of the three conditions. For each model, we used a single kinematic feature to classify the action performed by the confederate (i.e., *congruent/incongruent*). . In each SVM-LASSO model, we reproduced the same k-fold cross-validation procedure described above (i.e., 15 folds; 32 trials per fold; in each fold, 2 trials per participant: 1 *congruent*, 1 *incongruent*). The significance of the classification accuracy of each model and the difference between conditions were assessed using the same methods described above.

Results of models performed using participants' PG movements revealed that, during the *Non Interactive* condition, the kinematic features that could significantly encode the confederate's action were *Wrist Velocity* (*WV*; mean $\pm$ SEM = 0.57 ± 0.001, p = 0.01, permutation test), *Wrist Acceleration* (*WA*; mean $\pm$ SEM = 0.57 ± 0.002, p = 0.01, permutation test), *Grip Aperture* (*GA*; mean $\pm$ SEM = 0.57 ± 0.001, p = 0.01, permutation test), and *Wrist Height* (*WH*; mean $\pm$ SEM = 0.59 ± 0.001, p = 0.01, permutation test). Similar results were obtained during the *Joint* condition, where *WV* (mean $\pm$ SEM = 0.55 ± 0.001, p = 0.02, permutation test), *WA* (mean $\pm$ SEM = $0.56 \pm$

0.002, p = 0.01, permutation test), *GA* (mean ± SEM = 0.56 ± 0.001, p = 0.02, permutation test), and *WH* (mean ± SEM = 0.55 ± 0.001, p = 0.02, permutation test) significantly encoded the confederate's action. During the *Joint Outcome* condition, only the model that used *GA* could significantly predict the actions performed by the confederate (mean ± SEM = 0.54 ± 0.002, p = 0.05, permutation test). The other kinematic features were not found to be significantly discriminative during this condition (*WV* mean ± SEM = 0.51 ± 0.002, p = 0.25, permutation test; *WA* mean ± SEM = 0.51 ± 0.002, p = 0.31, permutation test; *WH* mean ± SEM = 0.52 ± 0.002, p = 0.51, permutation test). For all conditions, the models that used *Wrist Jerk (WJ)* as predictor did not perform above chance level (p_s ranging from 0.06 to 0.53, permutation tests).

Classification accuracy of models trained on single kinematic features was then compared between conditions. As shown in Fig. 4.3a, with the exception of *GA*, the classification accuracy was systematically higher in the *Non Interactive* compared to *Joint Outcome* condition (all p_s = 0.03, corrected empirical p-values), and in the *Joint* compared to the *Joint Outcome* condition (p_s ranging from 0.02 to 0.03, corrected empirical p-values). Significant differences were also found between the *Non Interactive* and the *Joint* condition. For both *WV* and *WH,* the classification accuracy was higher in the former (p_s = 0.05 and 0.03, respectively, corrected empirical p-values).
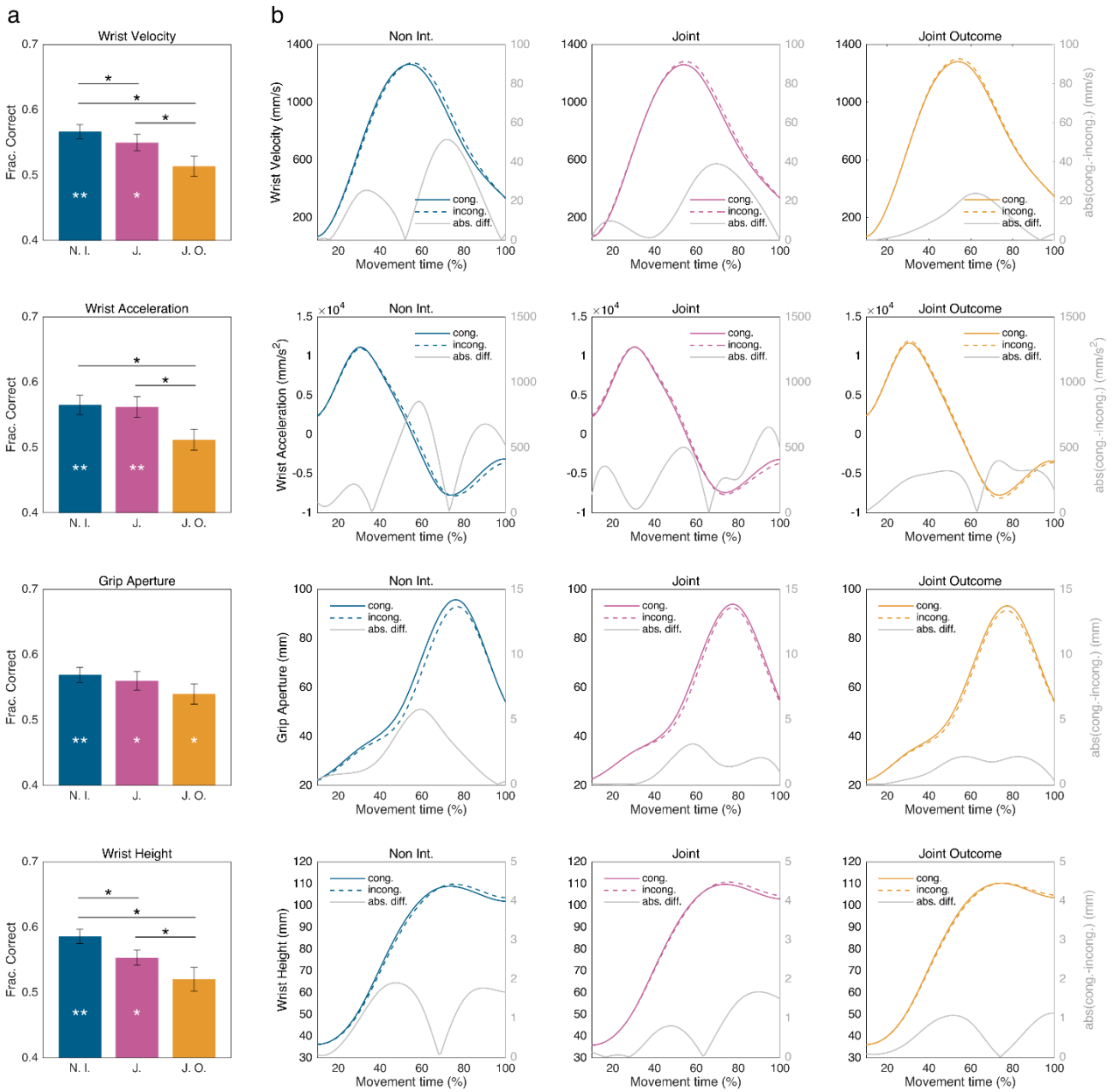
Figure 4.3

Classification accuracy and kinematic profiles of single kinematic features during each condition. Panel (a) shows, for each of the four relevant (i.e., significantly discriminative) kinematic features, a bar plot representing the mean classification accuracies of the 100 SVM-LASSO models performed for each condition. Bars indicate standard deviation (SD). White asterisks denote significant (i.e., above chance) classification accuracies (* $p <$ 0.05; ** $p <$ 0.01). Black asterisks denote significant differences between conditions (* $p <$ 0.05). Panel (b) represents, for each of these kinematic features, the mean kinematic profiles displayed by participants while performing PG actions on congruent and incongruent trials, during the Non Interactive, the Joint, and the Joint Outcome conditions. In each plot, the grey line represents the absolute difference between the mean kinematic

profile displayed during congruent trials and the mean kinematic profile displayed during incongruent trials. For each kinematic feature, the kinematic difference between congruent and incongruent trials is visibly higher during the Non Interactive condition, compared to the Joint and the Joint Outcome conditions.

4.3.4. Embodiment of the confederate's kinematic profile through time

To explore the effect of visuo-motor interference in participants' movement kinematics, and to address whether participants were incorporating the kinematic properties of the confederate's movements, we computed the Euclidean distance between the participants' movements and the confederate movements (i.e., *kinematic distance*) during the incongruent trials of the *Non Interactive* condition. For each kinematic feature, we conducted a repeated measures ANOVA with 'trials' (2 levels: first half, second half) and 'action' (i.e. action performed by the participant; 2 levels: PG, WHP) as within-subject factors. The ANOVAs on *WV* and *WA* revealed a significant main effect of 'trials' (*WV*: $F_{(1,15)} = 7.36$; $p < .05$; partial $\eta^2 = .329$; *WA*: $F_{(1,15)} = 9.83$; $p < .01$; partial $\eta^2 = .396$). For both variables, *kinematic distance* was lower in the second half of the trials (*WV* Distance mean $\pm$ SEM $= 649.37 \pm 30.06$; *WA* Distance mean $\pm$ SEM $= 12778.05 \pm 554.88$), compared to the first half (*WV* Distance mean $\pm$ SEM $= 700.97 \pm 26.97$; *WA* Distance mean $\pm$ SEM $= 13826.61 \pm 663.42$). No other effects were found to be significant. These two kinematic features thus displayed a pattern of increased similarity to the kinematics of the confederate (Fig 4.4a and 4.4b). Instead, *GA* and *WH* revealed no such modulation. Indeed, the ANOVA on *GA* did not reveal any significant effects. The ANOVA on *WH* revealed instead only a significant main effect of 'action' ($F_{(1,15)} = 268.32$; $p < .001$; partial $\eta^2 = .947$). These two kinematic features thus displayed a pattern that was not modulated in relation to the kinematics of the confederate (Fig. 4.4c and 4.4d).
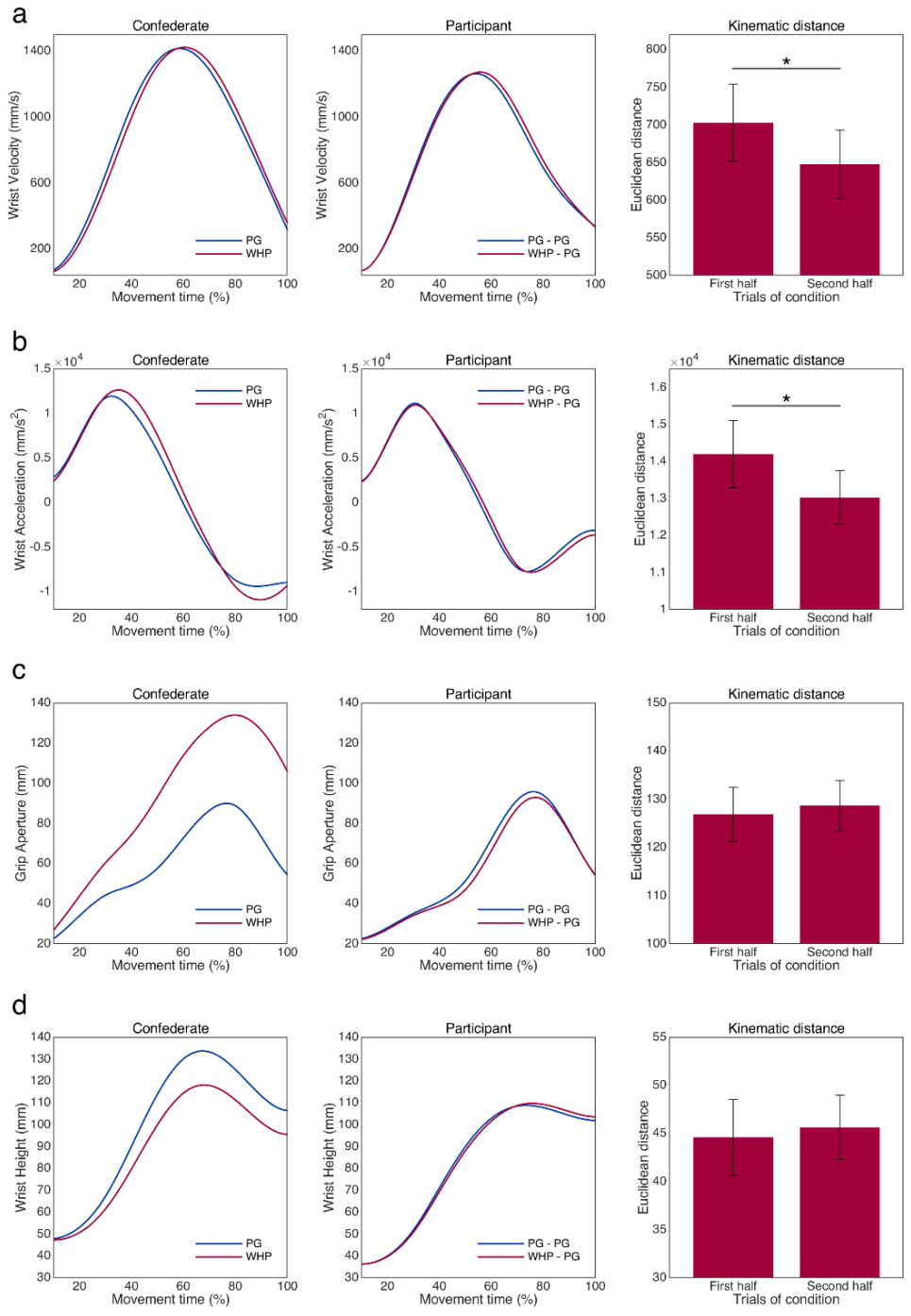
Figure 4.4

Kinematic distance between confederate and participant. The graphs in the first column represent the kinematic profiles of Wrist Velocity (a), Wrist Acceleration (b), Grip Aperture (c) and Wrist Height (d), displayed by the confederate while performing PG or WHP actions during the Non Interactive condition. The graphs in the second

column represent, for each kinematic feature, the kinematic profile displayed by participants while performing PG actions during congruent trials (PG-PG motor sequence) or during incongruent trials (WHP-PG motor sequence) of the Non Interactive condition. The bar plots in the third column represent, for each kinematic feature, the Euclidean distance between the participants' and the confederate's kinematic profiles, during the first half and the second half of the incongruent PG trials of the Non Interactive condition (WHP-PG motor sequence). Bars indicate standard error (SE). Asterisks denote significant differences (* $p < 0.05$).

4.4. Discussion

In the present study, we aimed at investigating whether and how interactivity modulates the effect of visuo-motor interference. Using a machine-learning approach, we assessed the presence of visuo-motor interference in the kinematics of reach-to-grasp movements performed by participants in three different interactive conditions, in which the action of the other could be (i) irrelevant, to achieve an individual goal (*Non Interactive* condition), (ii) relevant, in terms of the performed movement, to achieve a common goal, (*Joint* condition), or (iii) relevant, in terms of the performed movement and the produced sensory outcome, to achieve a common goal, (*Joint Outcome* condition).

Results show that the effect of visuo-motor interference is present in both interactive and non-interactive contexts, but that the effect is smaller in interactive contexts. Indeed, compared to the *Non Interactive* condition, the effect of visuo-motor interference was reduced in both joint action conditions (*Joint* and *Joint Outcome*; Fig. 4.2). This suggests that, when we share a goal with the other, observing his/her actions is less disruptive to us, compared to a non-interactive scenario. This finding is consistent with previous studies that have shown that the visuo-motor interference effect disappears when the action of the other is performed within a joint action setting (Clarke et

al., 2019; Sacheli et al., 2018, 2019). The present study replicates and extends these findings, by showing that the reduction in visuo-motor interference is indeed present, and explicitly visible in the kinematic unfolding of reach-to-grasp movements.

The above-mentioned studies employed joint action conditions in which the common goal, shared with the other, was to produce a sensory outcome in the environment, generated by the two actions involved (e.g. a light switch, in Clarke et al., 2019; a melody, in Sacheli et al., 2018). The effect was then explained by suggesting that, during joint actions, we shift from the automatic simulation of an observed action to the active prediction of the consequences of a partner's action, by forming a *dyadic motor plan*, in which both our own and our partner's actions are represented in terms of their predicted effects in the environment (Sacheli et al., 2018). In our study, visuo-motor interference was reduced not only when the movement of the other was relevant in terms of what it would have produced in the environment (*Joint Outcome* condition), but also when the movement of the other was just relevant 'per se' to achieve the common goal (*Joint* condition). This suggests that, in order to form a dyadic motor plan, it may not be necessary to represent the actions in terms of their predicted sensory outcomes in the environment, but it may be sufficient to represent them as pure motor contributions to achieve the desired shared goal. This interpretation does not deny the predictive nature that these action representations might have. On the contrary, our results support the idea that, during joint actions, the action performed by the other is indeed processed in predictive terms. However, these predictions may not be contingent upon the *production* of an outcome in the environment. Instead, the predictive activity may just regard the movement per se, so that, during joint action, what we actually predict is the *movement* performed by the other, and not only what this movement will produce (see also Pesquita et al., 2018).

It is important to underline that we did not expect to find a reduced visuo-motor interference effect in the *Joint* condition, compared to the *Non Interactive* condition. These two conditions were designed to differ only within the cooperative framework given to participants. In line with previous studies, we expected this manipulation to result in an enhanced interference during the *Joint* condition. Indeed, it has been suggested that, when the action performed by the other is part of a shared common goal, action observation would lead to a higher motor activation, and consequently to a higher visuo-motor interference effect, because, compared to a non-interactive scenario, the other's action needs to be represented and monitored (della Gatta et al., 2017). Our results however do not support this argument. Instead, they show that observing actions that are part of a joint action reduces detrimental effects on motor execution, compared to observing actions within a non-interactive scenario.

These results cannot be simply explained by an attentional difference between conditions. In fact, during each condition, experimental trials were randomly interspersed with catch trials, which were designed to maintain the participants' attention focused on the movement performed by the confederate. The response accuracy derived from the analysis of catch trials allows us to exclude the presence of any difference in attentional focus between conditions.

The methodology used in the present study also aimed at investigating the visuo-motor interference effect in a comprehensive manner. The fine-grained analysis of movement kinematics allowed us to examine the behavior of different kinematic features, and to compare the kinematic profiles of the participants with those of the confederate. In line with the existing literature, we expected participants to show kinematic profiles similar to those of the confederate, as a result of visuo-motor interference (Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011). When looking at the *kinematic distance* between the

91

participants and the confederate in the first and in the second half of the trials, our results show that, within Wrist Velocity and Wrist Acceleration, the similarity between the two agents increased over the course of the experiment (Fig. 4.4a and 4.4b). This supports the idea of an interference driven by the kinematics of the observed action, by which participants were increasingly converging towards the kinematic profile displayed by the confederate (see also Rocca & Cavallo, 2020). This result was however not replicated on Grip Aperture and Wrist Height, which thus showed a kinematic modulation that was unrelated to the kinematics displayed by the confederate (Fig. 4.4c and 4.4d).

Overall, these results suggest that, when we are engaged in joint actions with others, observing their actions is not distracting for us, as it is observing them in a non-interactive scenario. This might be due to the fact that during joint actions, we shift from the automatic simulation to the active prediction of the movement that we observe, by forming a *dyadic motor plan*, in which both our own and our partner's actions are represented in predictive terms, with respect to the common goal that should be achieved (Pesquita et al., 2018; Sacheli et al., 2018). These predictive representations regard what *movement* the other will perform, regardless of whether this movement will indeed produce a concrete sensory outcome in the environment.

Observing others' movements affects us deeply, and this effect is mediated by the significance and the relevance that the observed action has to our social interaction. Actions are processed and produce a motor response that varies as a function of the social context in which they are embedded.

5. General discussion

The studies included in the present thesis aimed at advancing the current knowledge about how we represent other people's actions when we engage in social interactions with them. This was done by investigating detailed aspects of upper-limb movement kinematics in pairs of agents involved in real-time dyadic joint actions.

5.1. Representing *how* our partner will move

The aim of the first study (Chapter 2) was to present an alternative method, based on the analysis of movement kinematics, to investigate the content of the motor representations we form about the other's action when we are involved in a joint action. The proposed method was implemented in the second study (Chapter 3). The results of this study suggest that, during joint actions, we represent not only the goal of our partner's action, but also how our partner will achieve this goal. Indeed, during the sequential motor task that participants performed, the movements of the first agents of each pair were influenced by the anticipation of the action that the second agents would have performed after them. However, the kinematic modulation exhibited by the first agents was not only related to the task that the second agents had to perform, but also to the specific kinematics that each second agent would have displayed while performing the task. Indeed, a high kinematic similarity was found between the agents of each pair, and this kinematic similarity was

highest only when computed with the real pairs of agents, rather than when computed with random pairs, created artificially after data collection.

These findings suggest that the motor representations we form about a partner's action when we are involved in a joint action might be more detailed than previously thought. We represent not only *what* our partner will do, but also *how* our partner will do it. This specificity might be the result of time and practice, which evolve *during* the course of an interaction. This idea is supported by the findings of this study, which also reveal the presence of what appears to be a *learning process*, through which the first agents may have incorporated the specific kinematics displayed by the second agents, and thus refined their motor representation of the action that the second agents would have performed after them.

5.2.   Representing the *joint* action

The third study (Chapter 4) aimed at investigating whether and how being engaged in a joint action changes the way other people's actions affect us. This was done by assessing the presence of visuo-motor interference in the kinematics of reach-to-grasp movements performed by participants engaged in a sequential motor task with a confederate. Under three different conditions, the confederate's action could be either (i) irrelevant, to achieve an *individual* goal, (ii) relevant, in terms of the performed movement, to achieve a *common* goal, or (iii) relevant, in terms of the performed movement and the produced sensory outcome, to achieve a *common* goal. The results of this study show that the presence of a common goal reduces the detrimental effect of a partner's action on motor execution, regardless of whether the other's action produces a concrete

sensory outcome in the environment. Indeed, visuo-motor interference was reduced in both conditions in which there was a common goal, shared with the other. This suggests that, during a joint action, the action performed by the other is indeed processed differently, compared to a non-interactive context. In particular, these results support the idea that during joint actions we shift from the *automatic imitation* of the action that we observe, to the *active prediction* of the consequences of a partner's action (Sacheli et al., 2018). As it has recently been proposed, during joint actions the action performed by our partner might in fact be processed in a *predictive* manner, as it becomes part of an overarching joint motor plan in which the contribution of both our own and our partner's actions to achieve the desired common goal are represented (Pesquita et al., 2018; Sacheli et al., 2018, 2019). The action performed by the other is thus not *distracting*, because it is accurately predicted in the joint motor plan, with respect to the common goal to be achieved. The findings of this study suggest that these predictive representations may regard not only the outcome produced by the other's movement, but also the unfolding of the movement itself.

5.3. *Learning* to represent others

The third study presented in this thesis also aimed at investigating, at a detailed level, *how* the observation of the action performed by another influences our own movement kinematics. Indeed, the existing literature suggests that the visuo-motor interference effect might be the result of a *contagion* effect, whereby the action performed by the other is automatically *incorporated* into the performed movement (Blakemore & Frith, 2005). Several studies have shown that when we perform an action after having observed someone else performing a different action, our

movements display kinematic aspects that are specific to the action that has been observed (Dijkerman & Smit, 2007; Forbes & Hamilton, 2017; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011). In line with the existing literature, in this study the participants' kinematic profiles of velocity and acceleration showed a modulation consistent with a *contagion* behavior. Velocity and acceleration displayed in fact a pattern of similarity to the action performed by the confederate, which increased over the course of the interaction, as evidenced by a reduced kinematic distance between the participants and the confederate during the second half of the trials. This result supports the idea, already suggested by the findings of the second study presented in this thesis, that when acting with another person a *learning process* might be involved, which allows the observer to refine, through time and practice, their motor representations about their specific partner's actions.

5.4. Conclusion and future directions

The studies included in the present thesis allow us to expand the current understanding of how we represent the actions of others when we actively interact with them. An extensive literature suggests that we represent and code other people's actions similarly to our own actions (Sommerville & Decety, 2006). Recently, due to the growing interest in the *social* and *interactive* aspects of cognition, researchers have started to investigate how we represent other people's actions when we are engaged in social interactions with them (Sebanz et al., 2006). However, several aspects remain unclear: what is the specific *content* of the motor representations that we

form when we interact with others? How does the presence of a common goal affect the way we perceive other people's actions, compared to a non-interactive scenario?

Overall, the results of the studies presented in this thesis suggest that when we interact with others, we form *detailed* motor representations that relate to *the way* our partner moves. These representations allow us to carefully *predict* (and not carelessly *imitate*) the actions of our interaction partner, in order to successfully coordinate with the other and monitor the achievement of the desired common goal, shared with the other.

Future studies should investigate whether these motor representations also have a *long-term* effect on how we perform our own actions. Indeed, acting together with a partner might change the way we move even after the interaction has ended (e.g. Oullier et al., 2008). A long-term effect might allow us to successfully engage in future interactions with the same partner, in order to 'start where we left off', without the need to re-learn how our partner moves.

Another important aspect to explore in future studies is how motor representations might differ when interacting with different individuals. Several studies suggest that each individual has its own idiosyncratic motor style, and this unique style is reflected in the way we perform our movements (Koul et al., 2016; Ting et al., 2015). Recent studies have shown that people who have similar motor styles perform better in coordination tasks (Słowiński et al., 2016). But how does the similarity or dissimilarity between individuals affect the way we represent others when we interact with them to achieve a common goal? It has recently been suggested that motor recruitment might be higher when we observe someone performing movements with a motor style that is different from ours (Hilt et al., 2020). It could thus be possible that this motor involvement might be more pronounced if the person we are observing is an interaction partner. Indeed, if social

interactions between *similar* individuals are more successful, this mechanism could lead one to

become more similar to the other, in order to enhance the interaction success.

References

Adolphs, R. (1999). Social cognition and the human brain. *Trends in Cognitive Sciences*, *3*(12), 469–479. https://doi.org/10.1016/S1364-6613(99)01399-6

Alaerts, K., Senot, P., Swinnen, S. P., Craighero, L., Wenderoth, N., & Fadiga, L. (2010). Force requirements of observed object lifting are encoded by the observer's motor system: A TMS study. *European Journal of Neuroscience*, *31*(6), 1144–1153. https://doi.org/10.1111/j.1460-9568.2010.07124.x

Ansuini, C., Cavallo, A., Koul, A., Jacono, M., Yang, Y., & Becchio, C. (2015). Predicting object size from hand kinematics: a temporal perspective. *PloS One*, *10*(3), e0120432. https://doi.org/10.1371/journal.pone.0120432

Astolfi, L., Toppi, J., Ciaramidaro, A., Vogel, P., Freitag, C. M., & Siniatchkin, M. (2020). Raising the bar: Can dual scanning improve our understanding of joint action? *NeuroImage*, *216*(March), 116813. https://doi.org/10.1016/j.neuroimage.2020.116813

Atmaca, S., Sebanz, N., & Knoblich, G. K. (2011). The joint flanker effect: Sharing tasks with real and imagined co-actors. *Experimental Brain Research*, *211*(3–4), 371–385. https://doi.org/10.1007/s00221-011-2709-9

Atmaca, S., Sebanz, N., Prinz, W., & Knoblich, G. K. (2008). Action co-representation: The joint SNARC effect. *Social Neuroscience*, *3*(3–4), 410–420. https://doi.org/10.1080/17470910801900908

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Becchio, C., Koul, A., Ansuini, C., Bertone, C., & Cavallo, A. (2018). Seeing mental states: An experimental strategy for measuring the observability of other minds. *Physics of Life Reviews*, *24*, 67–80. https://doi.org/10.1016/j.plrev.2017.10.002

Becchio, C., Sartori, L., & Castiello, U. (2010). Toward You: The Social Side of Actions. *Current Directions in Psychological Science*, *19*(3), 183–188. https://doi.org/10.1177/0963721410370131

Bekkering, H., De Bruijn, E. R. A., Cuijpers, R. H., Newman-Norlund, R., Van Schie, H. T., & Meulenbroek, R. (2009). Joint Action: Neurocognitive Mechanisms Supporting Human Interaction. *Topics in Cognitive Science*, *1*(2), 340–352. https://doi.org/10.1111/j.1756-8765.2009.01023.x

Blakemore, S. J., & Frith, C. D. (2005). The role of motor contagion in the prediction of action. *Neuropsychologia*, *43*(2), 260–267. https://doi.org/10.1016/j.neuropsychologia.2004.11.012

Bolt, N. K., & Loehr, J. D. (2021). The motor-related brain activity that supports joint action: A review. *Acta Psychologica*, *212*, 103218. https://doi.org/10.1016/j.actpsy.2020.103218

Bootsma, R. J., Marteniuk, R. G., MacKenzie, C. L., & Zaal, F. T. J. M. (1994). The speed-accuracy trade-off in manual prehension: effects of movement amplitude, object size and object width on kinematic characteristics. *Experimental Brain Research*, *98*(3), 535–541. https://doi.org/10.1007/BF00233990

Bozzacchi, C., Spinelli, D., Pitzalis, S., Giusti, M. A., & Di Russo, F. (2014). I know what i will see: Action-specific motor preparation activity in a passive observation task. *Social Cognitive and Affective Neuroscience*, *10*(6), 783–789. https://doi.org/10.1093/scan/nsu115

Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, *106*(1–2), 3–22. https://doi.org/10.1016/S0001-6918(00)00024-X

Brass, M., Bekkering, H., Wohlschläger, A., & Prinz, W. (2000). Compatibility between Observed and Executed Finger Movements: Comparing Symbolic, Spatial, and Imitative Cues. *Brain and Cognition*, *44*(2), 124–143. https://doi.org/10.1006/brcg.2000.1225

Brothers, L. (1990). The social brain: a project for integrating primate behaviour and neurophysiology in a new domain. *Concepts Neurosci*, *1*, 27–51.

Casartelli, L., & Chiamulera, C. (2016). The motor way : Clinical implications of understanding and shaping actions with the motor system in autism and drug addiction. *Cogn Affect Behav Neurosci*, *16*, 191–206. https://doi.org/10.3758/s13415-015-0399-7

Casartelli, L., Federici, A., Biffi, E., Molteni, M., & Ronconi, L. (2018). Are We "Motorically" Wired to Others? High-Level Motor Computations and Their Role in Autism. *The Neuroscientist*, *24*(6), 568–581. https://doi.org/10.1177/1073858417750466

Casartelli, L., Molteni, M., & Ronconi, L. (2016). So close yet so far: Motor anomalies impacting on social functioning in autism spectrum disorder. *Neuroscience and Biobehavioral Reviews*, *63*, 98–105. https://doi.org/10.1016/j.neubiorev.2016.02.001

Castiello, U. (1996). Grasping a fruit: Selection for action. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(3), 582–603. https://doi.org/10.1037/0096-1523.22.3.582

Castiello, U. (1999). Mechanisms of selection for the control of hand action. *Trends in Cognitive Sciences*, *3*(7).

Castiello, U. (2003). Understanding other people's actions: Intention and attention. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 416–430. https://doi.org/10.1037/0096-1523.29.2.416

Castiello, U. (2005). The neuroscience of grasping. *Nature Reviews. Neuroscience*, *6*(9), 726–736. https://doi.org/10.1038/nrn1744

Castiello, U., Bennett, K. M. B., & Paulignan, Y. (1992). Does the type of prehension influence the kinematics of reaching. *Behavioural Brain Research*, *50*(1–2), 7–15. https://doi.org/10.1016/S0166-4328(05)80283-9

Castiello, U., Bennett, K. M., & Mucignat, C. (1993). The reach to grasp movement of blind subjects. *Experimental Brain Research*, *96*(1), 152–162. https://doi.org/10.1007/BF00230448

Catmur, C., Walsh, V., & Heyes, C. (2009). Associative sequence learning: The role of experience in the development of imitation and the mirror system. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1528), 2369–2380. https://doi.org/10.1098/rstb.2009.0048

Cavallo, A., Koul, A., Ansuini, C., Capozzi, F., & Becchio, C. (2016). Decoding intentions from movement kinematics. *Scientific Reports*, *6*, 37036. https://doi.org/10.1038/srep37036

Cavallo, A., Romeo, L., Ansuini, C., Podda, J., Battaglia, F., Veneselli, E., Pontil, M., & Becchio, C. (2018a). Prospective motor control obeys to idiosyncratic strategies in autism. *Scientific Reports*, *8*(1), 13717. https://doi.org/10.1038/s41598-018-31479-2

Cavallo, A., Romeo, L., Ansuini, C., Podda, J., Battaglia, F., Veneselli, E., Pontil, M., & Becchio, C. (2018b). Prospective motor control obeys to idiosyncratic strategies in autism. *Scientific Reports*, *8*(1), 13717. https://doi.org/10.1038/s41598-018-31479-2

Clark, A. (1998). Embodied, Situated, and Distributed Cognition. In *A Companion to Cognitive Science* (pp. 506–517). Blackwell Publishing Ltd. https://doi.org/10.1002/9781405164535.ch39

Clark, A. (1999). An embodied cognitive science? *Trends in Cognitive Sciences*, *3*(9), 345–351. https://doi.org/10.1016/S1364-6613(99)01361-3

Clarke, S., McEllin, L., Francová, A., Székely, M., Butterfill, S. A., & Michael, J. (2019). Joint action goals reduce visuomotor interference effects from a partner's incongruent actions. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-52124-6

Crippa, A., Salvatore, C., Perego, P., Forti, S., Nobile, M., Molteni, M., & Castiglioni, I. (2015). Use of Machine Learning to Identify Children with Autism and Their Motor Abnormalities. *Journal of Autism and Developmental Disorders*, *45*(7), 2146–2156. https://doi.org/10.1007/s10803-015-2379-8

Csibra, G. (2007). Action mirroring and action understanding: an alternative account. In P. Haggard, Y. Rosetti, & M. Kawato (Eds.), *Sensorimotor Foundations of Higher Cognition. Attention and Performance* (pp. 435–459). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199231447.003.0020

Davison, A. C., & Hinkley, D. V. (1997). *Bootstrap Methods and their Application*. Cambridge University Press. https://doi.org/10.1017/CBO9780511802843

De Jaegher, H. (2009). Social understanding through direct perception? Yes, by interacting. *Consciousness and Cognition*, *18*(2), 535–542. https://doi.org/10.1016/j.concog.2008.10.007

De Jaegher, H., Di Paolo, E., & Gallagher, S. (2010). Can social interaction constitute social cognition? *Trends in Cognitive Sciences*, *14*(10), 441–447. https://doi.org/10.1016/j.tics.2010.06.009

della Gatta, F., Garbarini, F., Rabuffetti, M., Viganò, L., Butterfill, S. A., & Sinigaglia, C. (2017). Drawn together: When motor representations ground joint actions. *Cognition*, *165*, 53–60. https://doi.org/10.1016/j.cognition.2017.04.008

Dijkerman, H. C., & Smit, M. C. (2007). Interference of grasping observation during prehension, a behavioural study. *Experimental Brain Research*, *176*(2), 387–396. https://doi.org/10.1007/s00221-006-0627-z

Dolk, T., Hommel, B., Colzato, L. S., Schuetz-Bosbach, S., Prinz, W., & Liepelt, R. (2014). The joint Simon effect: a review and theoretical integration. *Frontiers in Psychology*, *5*, 974. https://doi.org/10.3389/fpsyg.2014.00974

Dolk, T., Hommel, B., Colzato, L. S., Schütz-Bosbach, S., Prinz, W., & Liepelt, R. (2011). How "social" is the social Simon effect? *Frontiers in Psychology*, *2*, 84. https://doi.org/10.3389/fpsyg.2011.00084

Dolk, T., Hommel, B., Prinz, W., & Liepelt, R. (2013). The (Not So) social Simon effect: A referential coding account. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(5), 1248–1260. https://doi.org/10.1037/a0031031

Dunbar, R. I. M. (1998). The social brain hypothesis. *Evolutionary Anthropology*, *6*(5), 178–190. https://doi.org/10.1002/(SICI)1520-6505(1998)6:5<178::AID-EVAN5>3.0.CO;2-8

Edwards, M. G., Humphreys, G. W., & Castiello, U. (2003). Motor facilitation following action observation: A behavioural study in prehensile action. *Brain and Cognition*, *53*(3), 495–502. https://doi.org/10.1016/S0278-2626(03)00210-0

Elekes, F., Bródy, G., Halász, E., & Király, I. (2016). Enhanced encoding of the co-actor's target stimuli during a shared non-motor task. *The Quarterly Journal of Experimental Psychology*, *69*(12), 2376–2389. https://doi.org/10.1080/17470218.2015.1120332

Era, V., Aglioti, S. M., Mancusi, C., & Candidi, M. (2018). Visuo-motor interference with a virtual partner is equally present in cooperative and competitive interactions. *Psychological Research*, *0*(0), 0. https://doi.org/10.1007/s00426-018-1090-8

Fadiga, L., Craighero, L., & Olivier, E. (2005). Human motor cortex excitability during the perception of others' action. *Current Opinion in Neurobiology*, *15*(2), 213–218. https://doi.org/10.1016/j.conb.2005.03.013

Fitts, P. M., & Peterson, J. R. (1964). Information Capacity of Discrete Motor Responses. *Journal of Experimental Psychology*, *67*(2), 103–112.

Forbes, P. A. G., & Hamilton, A. F. de C. (2017). Moving higher and higher: imitators' movements are sensitive to observed trajectories regardless of action rationality. *Experimental Brain Research*, *235*(9), 2741–2753. https://doi.org/10.1007/s00221-017-5006-4

Freeman, J. B., Dale, R., & Farmer, T. A. (2011). Hand in motion reveals mind in motion. *Frontiers in Psychology*, *2*, 59. https://doi.org/10.3389/fpsyg.2011.00059

Frith, U., & Frith, C. (2010). The social brain: Allowing humans to boldly go where no other species has been. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1537), 165–175. https://doi.org/10.1098/rstb.2009.0160

Gallese, V. (2007). Before and below "theory of mind": Embodied simulation and the neural correlates of social cognition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1480), 659–669. https://doi.org/10.1098/rstb.2006.2002

Gallese, V., Rochat, M. J., & Berchio, C. (2013). The mirror mechanism and its potential role in autism spectrum disorder. *Developmental Medicine and Child Neurology*, *55*(1), 15–22. https://doi.org/10.1111/j.1469-8749.2012.04398.x

Gallotti, M., Fairhurst, M. T., & Frith, C. D. (2017). Alignment in social interactions. *Consciousness and Cognition*, *48*, 253–261. https://doi.org/10.1016/j.concog.2016.12.002

Gergely, G., Bekkering, H., & Király, I. (2002). Rational imitation in preverbal infants. *Nature*, *415*(6873), 755–755. https://doi.org/10.1038/415755a

Gibson, J. J. (1969). The Senses Considered as Perceptual Systems. *Journal of Aesthetic Education*, *3*(1), 142. https://doi.org/10.2307/3331482

Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica*, *37*(3), 424. https://doi.org/10.2307/1912791

Griffiths, D., & Tipper, S. P. (2009). Priming of reach trajectory when observing actions: Hand-centred effects. *Quarterly Journal of Experimental Psychology*, *62*(12), 2450–2470. https://doi.org/10.1080/17470210903103059

Hardwick, R. M., & Edwards, M. G. (2011). Observed reach trajectory influences executed reach kinematics in prehension. *Quarterly Journal of Experimental Psychology*, *64*(6), 1082–1093. https://doi.org/10.1080/17470218.2010.538068

Hasson, U., & Frith, C. D. (2016). Mirroring and beyond: coupled dynamics as a generalized framework for modelling social interactions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1693), 20150366. https://doi.org/10.1098/rstb.2015.0366

Heyes, C. (2011). Automatic imitation. *Psychological Bulletin*, *137*(3), 463–483. https://doi.org/10.1037/a0022288

Hilt, P. M., Cardellicchio, P., Dolfini, E., Pozzo, T., Fadiga, L., & D'Ausilio, A. (2020). Motor recruitment during action observation: Effect of interindividual differences in action strategy. *Cerebral Cortex*, *30*(7), 3910–3920. https://doi.org/10.1093/cercor/bhaa006

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*(5), 849–878. https://doi.org/10.1017/S0140525X01000103

Hurley, S. (2001). Perception and Action : Alternative Views. *Synthese*, *129*(1), 3–40.

Hutto, D. D. (2004). The limits of spectatorial folk psychology. *Mind and Language*, *19*(5), 548–573. https://doi.org/10.1111/j.0268-1064.2004.00272.x

Jackson, P. L., & Decety, J. (2004). Motor cognition: A new paradigm to study self-other interactions. *Current Opinion in Neurobiology*, *14*(2), 259–263. https://doi.org/10.1016/j.conb.2004.01.020

James, W. (1890). *The principles of psychology, Vol. 2*. Henry Holt and Company.

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences*, *17*(2), 187–202. https://doi.org/10.1017/S0140525X00034026

Jeannerod, M. (2001). Neural Simulation of Action: A Unifying Mechanism for Motor Cognition. *NeuroImage*, *14*(1), S103–S109. https://doi.org/10.1006/nimg.2001.0832

Jeannerod, M., Arbib, M. A., Rizzolatti, G., & Sakata, H. (1995). Grasping objects: the cortical mechanisms of visuomotor transformation. *Trends in Neurosciences*, *18*(7), 314–320. https://doi.org/10.1016/0166-2236(95)93921-J

Keller, P. E., Novembre, G., & Hove, M. J. (2014). Rhythm in joint action: psychological and neurophysiological mechanisms for real-time interpersonal coordination. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1658), 20130394. https://doi.org/10.1098/rstb.2013.0394

Kilner, J. M., Friston, K. J., & Frith, C. D. (2007). Predictive coding: an account of the mirror neuron system. *Cognitive Processing*, *8*(3), 159–166. https://doi.org/10.1007/s10339-007-0170-2

Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An Interference Effect of Observed Biological Movement on Action. *Current Biology*, *13*(6), 522–525. https://doi.org/10.1016/S0960-9822(03)00165-9

Kilner, J. M., Vargas, C., Duval, S., Blakemore, S. J., & Sirigu, A. (2004). Motor activation prior to observation of a predicted movement. *Nature Neuroscience*, *7*(12), 1299–1301. https://doi.org/10.1038/nn1355

Knoblich, G., Butterfill, S., & Sebanz, N. (2011). Psychological Research on Joint Action. In B. Ross (Ed.), *The Psychology of Learning and Motivation* (Vol. 54, pp. 59–101). Academic Press. https://doi.org/10.1016/B978-0-12-385527-5.00003-6

Knoblich, G., & Jordan, J. S. (2002). *The mirror system and joint action* (pp. 115–124). https://doi.org/10.1075/aicr.42.10kno

Koul, A., Cavallo, A., Ansuini, C., & Becchio, C. (2016). Doing It Your Way: How Individual Movement Styles Affect Action Prediction. *PLOS ONE*, *11*(10), e0165297. https://doi.org/10.1371/journal.pone.0165297

Kourtis, D., Sebanz, N., & Knoblich, G. K. (2010). Favouritism in the motor system: Social interaction modulates action simulation. *Biology Letters*, *6*(6), 758–761. https://doi.org/10.1098/rsbl.2010.0478

Kourtis, D., Sebanz, N., & Knoblich, G. K. (2013). Predictive representation of other people's actions in joint action planning: An EEG study. *Social Neuroscience*, *8*(1), 31–42. https://doi.org/10.1080/17470919.2012.694823

Krishnan-Barman, S., Forbes, P. A. G., & Hamilton, A. F. de C. (2017). How can the study of action kinematics inform our understanding of human social interaction? *Neuropsychologia*, *105*, 101–110. https://doi.org/10.1016/j.neuropsychologia.2017.01.018

Laurens van der Maaten, & Geoffrey E., H. (2008). Visualizing Data using t-SNE. *Journal of Machine Learning Research*, *164*(2210), 10.

Lotze, R. H. (1852). *Medicinische Psychologie oder Physiologie der Seele*. Leipzig, Germany: Weidmann'sche Buchhandlung.

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology*, *41*(3), 365–378. https://doi.org/10.1037/h0084157

McGuigan, N., Makinson, J., & Whiten, A. (2011). From over-imitation to super-copying: Adults imitate causally irrelevant aspects of tool use with higher fidelity than young children. *British Journal of Psychology*, *102*(1), 1–18. https://doi.org/10.1348/000712610X493115

McKinstry, C., Dale, R., & Spivey, M. J. (2008). Action dynamics reveal parallel competition in decision making. *Psychological Science*, *19*(1), 22–24. https://doi.org/10.1111/j.1467-9280.2008.02041.x

Naish, K. R., Houston-Price, C., Bremner, A. J., & Holmes, N. P. (2014). Effects of action observation on corticospinal excitability: Muscle specificity, direction, and timing of the

mirror response. *Neuropsychologia*, *64*, 331–348. https://doi.org/10.1016/j.neuropsychologia.2014.09.034

Oullier, O., de Guzman, G., Jantzen, K. J., Lagarde, J., & Scott Kelso, J. A. (2008). Social coordination dynamics: Measuring human bonding. *Social Neuroscience*, *3*(2), 178–192. https://doi.org/10.1080/17470910701563392

Pesquita, A., Whitwell, R. L., & Enns, J. T. (2018). Predictive joint-action model: A hierarchical predictive approach to human cooperation. *Psychonomic Bulletin and Review*, *25*(5), 1751–1769. https://doi.org/10.3758/s13423-017-1393-6

Pezzulo, G., Donnarumma, F., & Dindo, H. (2013). Human Sensorimotor Communication: A Theory of Signaling in Online Social Interactions. *PLoS ONE*, *8*(11), e79876. https://doi.org/10.1371/journal.pone.0079876

Press, C., Cook, J., Blakemore, S. J., & Kilner, J. M. (2011). Dynamic Modulation of Human Motor Activity When Observing Actions. *Journal of Neuroscience*, *31*(8), 2792–2800. https://doi.org/10.1523/JNEUROSCI.1595-10.2011

Prinz, W. (1990). A Common Coding Approach to Perception and Action. *Relationships Between Perception and Action*, 167–201. https://doi.org/10.1007/978-3-642-75348-0_7

Prinz, W. (1997). Perception and Action Planning. *European Journal of Cognitive Psychology*, *9*(2), 129–154. https://doi.org/10.1080/713752551

Puffe, L., Dittrich, K., & Klauer, K. C. (2017). The influence of the Japanese waving cat on the joint spatial compatibility effect: A replication and extension of Dolk, Hommel, Prinz, and Liepelt (2013). *PLoS ONE*, *12*(9), e0184844. https://doi.org/10.1371/journal.pone.0184844

Ramnani, N., & Miall, R. C. (2004). A system in the human brain for predicting the actions of others. *Nature Neuroscience*, *7*(1), 85–90. https://doi.org/10.1038/nn1168

Rizzolatti, G., & Sinigaglia, C. (2016). The mirror mechanism: a basic principle of brain function. *Nature Reviews Neuroscience*, *17*(12), 757–765. https://doi.org/10.1038/nrn.2016.135

Rocca, M., & Cavallo, A. (2018). What's Shared in Movement Kinematics: Investigating Co-representation of Actions Through Movement. *Frontiers in Psychology*, *9*, 1578. https://doi.org/10.3389/fpsyg.2018.01578

Rocca, M., & Cavallo, A. (2020). Wired actions: Anticipatory kinematic interference during a dyadic sequential motor interaction task. *Journal of Experimental Psychology: General*. https://doi.org/10.1037/xge0001003

Rosenbaum, D. A. (2005). The Cinderella of Psychology. *American Psychologist*, *60*(4), 308–317. https://doi.org/10.1037/0003-066X.60.4.308

Sacheli, L. M., Arcangeli, E., & Paulesu, E. (2018). Evidence for a dyadic motor plan in joint action. *Scientific Reports*, 1–12. https://doi.org/10.1038/s41598-018-23275-9

Sacheli, L. M., Verga, C., Arcangeli, E., Banfi, G., Tettamanti, M., & Paulesu, E. (2019). How task interactivity shapes action observation. *Cerebral Cortex*, *29*(12), 5302–5314. https://doi.org/10.1093/cercor/bhz205

Savelsbergh, G. J. P., Steenbergen, B., & Van Der Kamp, J. (1996). The role of fragility information in the guidance of the precision grip. *Human Movement Science*, *15*(1), 115–127. https://doi.org/10.1016/0167-9457(95)00039-9

Schall, J. D., Palmeri, T. J., & Logan, G. D. (2017). Models of inhibitory control. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1718). https://doi.org/10.1098/rstb.2016.0193

Schilbach, L. (2010). A second-person approach to other minds. *Nature Reviews Neuroscience*, *11*(6), 449. https://doi.org/10.1038/nrn2805-c1

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., & Vogeley, K. (2013). Toward a second-person neuroscience. *Behavioral and Brain Sciences*, *36*(04), 393–414. https://doi.org/10.1017/S0140525X12000660

Schmitz, L., Vesper, C., Sebanz, N., & Knoblich, G. K. (2017a). Co-representation of others' task constraints in joint action. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(8), 1480–1493. https://doi.org/10.1037/xhp0000403

Schmitz, L., Vesper, C., Sebanz, N., & Knoblich, G. K. (2017b). Co-Representation of Others' Task Constraints in Joint Action Co-Representation of Others' Task Constraints in Joint Action. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(8), 1480–1493. https://doi.org/10.1037/xhp0000403

Sebanz, N., Bekkering, H., & Knoblich, G. K. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences*, *10*(2), 70–76. https://doi.org/10.1016/j.tics.2005.12.009

Sebanz, N., & Knoblich, G. K. (2009). Prediction in Joint Action: What, When, and Where. *Topics in Cognitive Science*, *1*(2), 353–367. https://doi.org/10.1111/j.1756-8765.2009.01024.x

Sebanz, N., & Knoblich, G. K. (2021). Progress in Joint-Action Research. *Current Directions in Psychological Science*. https://doi.org/10.1177/0963721420984425

Sebanz, N., Knoblich, G. K., & Prinz, W. (2003). Representing others' actions: just like one's own? *Cognition*, *88*(3), B11–B21. https://doi.org/10.1016/S0010-0277(03)00043-X

Sebanz, N., Knoblich, G. K., & Prinz, W. (2005). How two share a task: Corepresenting stimulus-response mappings. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(6), 1234–1246. https://doi.org/10.1037/0096-1523.31.6.1234

Semin, G. R., & Cacioppo, J. T. (2008). From Embodied Representation to Co-regulation. *Mirror Neuron Systems*, 107–120. https://doi.org/10.1007/978-1-59745-479-7_5

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review*, *91*(4), 417–447. https://doi.org/10.1037/0033-295X.91.4.417

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science*, *22*(11), 1359–1366. https://doi.org/10.1177/0956797611417632

Słowiński, P., Zhai, C., Alderisio, F., Salesse, R., Gueugnon, M., Marin, L., Bardy, B. G., Di Bernardo, M., & Tsaneva-Atanasova, K. (2016). Dynamic similarity promotes interpersonal coordination in joint action. *Journal of the Royal Society Interface*, *13*(116). https://doi.org/10.1098/rsif.2015.1093

Sommerville, J. A., & Decety, J. (2006). Weaving the fabric of social interaction: Articulating developmental psychology and cognitive neuroscience in the domain of motor cognition. *Psychonomic Bulletin & Review*, *13*(2), 179–200. https://doi.org/10.3758/BF03193831

Song, J.-H., & Nakayama, K. (2008). Numeric comparison in a visually-guided manual reaching task. *Cognition*, *106*(2), 994–1003. https://doi.org/10.1016/j.cognition.2007.03.014

Song, J.-H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Sciences*, *13*(8), 360–366. https://doi.org/10.1016/j.tics.2009.04.009

Sperry, R. W. (1952). *NEUROLOGY AND THE MIND BRAIN PROBLEM*. *40*(2), 291–312.

Spivey, M. J., & Dale, R. (2004). On the Continuity of Mind: Toward a Dynamical Account of Cognition. *Psychology of Learning and Motivation - Advances in Research and Theory*, *45*, 87–142. https://doi.org/10.1016/S0079-7421(03)45003-2

Springer, A., de Hamilton, A. F. C., & Cross, E. S. (2012). Simulating and predicting others' actions. *Psychological Research*, *76*(4), 383–387. https://doi.org/10.1007/s00426-012-0443-y

Steel, K., Ellem, E., & Baxter, D. (2014). The application of biological motion research: biometrics, sport, and the military. *Psychonomic Bulletin and Review*, *22*(1), 78–87. https://doi.org/10.3758/s13423-014-0659-5

Thompson, J., & Parasuraman, R. (2012). Attention, biological motion, and action recognition. *NeuroImage*, *59*(1), 4–13. https://doi.org/10.1016/j.neuroimage.2011.05.044

Ting, L. H., Chiel, H. J., Trumbower, R. D., Allen, J. L., McKay, J. L., Hackney, M. E., & Kesar, T. M. (2015). Neuromechanical Principles Underlying Movement Modularity and Their

Implications for Rehabilitation. *Neuron*, *86*(1), 38–54. https://doi.org/10.1016/j.neuron.2015.02.042

Ting, L. H., Chvatal, S. A., Safavynia, S. A., & McKay, J. L. (2012). Review and perspective: neuromechanical considerations for predicting muscle activation patterns for movement. *International Journal for Numerical Methods in Biomedical Engineering*, *28*(10), 1003–1014. https://doi.org/10.1002/cnm.2485

Tipper, S. P., Howard, L. A., & Jackson, S. R. (1997). Selective Reaching to Grasp: Evidence for Distractor Interference Effects. *Visual Cognition*, *4*(1), 1–38. https://doi.org/10.1080/713756749

Vesper, C., Abramova, E., Bütepage, J., Ciardo, F., Crossey, B., Effenberg, A., Hristova, D., Karlinsky, A., McEllin, L., Nijssen, S. R. R., Schmitz, L., & Wahn, B. (2017). Joint action: Mental representations, shared information and general mechanisms for coordinating with others. *Frontiers in Psychology*, *7*(JAN), 1–7. https://doi.org/10.3389/fpsyg.2016.02039

Vesper, C., Butterfill, S., Knoblich, G. K., & Sebanz, N. (2010). A minimal architecture for joint action. *Neural Networks*, *23*(8–9), 998–1003. https://doi.org/10.1016/j.neunet.2010.06.002

Vesper, C., Schmitz, L., Safra, L., Sebanz, N., & Knoblich, G. K. (2016). The role of shared visual information for joint action coordination. *Cognition*, *153*, 118–123. https://doi.org/10.1016/j.cognition.2016.05.002

Viviani, P., & Flash, T. (1995). Minimum-jerk, two-thirds power law, and isochrony: converging approaches to movement planning. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 32–53. https://doi.org/10.1037/0096-1523.21.1.32

Weir, P. L., Mac Kenzie, C. L., Marteniuk, R. G., & Frazer, S. L. (1991). Is object texture a constraint on human prehension?: kinematic evidence. *Journal of Motor Behavior*, *23*(3), 205–210. https://doi.org/10.1080/00222895.1991.10118363

Whiten, A., & Byrne, R. W. (Eds.). (1997). *Machiavellian Intelligence II*. Cambridge University Press. https://doi.org/10.1017/CBO9780511525636

Wild, K. S., Poliakoff, E., Jerrison, A., & Gowen, E. (2010). The influence of goals on movement kinematics during imitation. *Experimental Brain Research*, *204*(3), 353–360. https://doi.org/10.1007/s00221-009-2034-8

Wilson, M. (2002). Six views of embodied cognition. *Psychometric Bulletin & Review*, *9*(4), 625–636.

Wilson, M., & Knoblich, G. K. (2005). The case for motor involvement in perceiving conspecifics. *Psychological Bulletin*, *131*(3), 460–473. https://doi.org/10.1037/0033-2909.131.3.460

Yamaguchi, M., Wall, H. J., & Hommel, B. (2018). Sharing tasks or sharing actions? Evidence from the joint Simon task. *Psychological Research*, *82*(2), 1–10. https://doi.org/10.1007/s00426-016-0821-y

Appendix A – Supplementary material to Chapter 3

A1. Table 1

Measure: % of movement to peak velocity

Tests of Within-Subjects Effects

Source	df				F		Sig.		Partial Eta Squared	
	Second agent		First agent		Second agent	First agent	Second agent	First agent	Second agent	First agent
session	**1.00**	**19.00**	**1.00**	**19.00**	**34.36**	**4.95**	**0.000**	**0.038**	**0.644**	**0.207**
target distance	1.46	27.66	1.50	28.55	7.64	0.38	0.005	0.625	0.287	0.020
target size	1.00	19.00	1.00	19.00	41.06	0.01	0.000	0.930	0.684	0.000
session * target distance	1.52	28.92	1.95	36.99	4.28	3.10	0.033	0.058	0.184	0.140
session * target size	**1.00**	**19.00**	**1.00**	**19.00**	**18.65**	**9.89**	**0.000**	**0.005**	**0.495**	**0.342**
target distance * target size	1.90	36.19	1.97	37.51	0.07	0.65	0.927	0.524	0.004	0.033
session * target distance * target size	1.48	28.05	1.59	30.23	1.41	4.67	0.256	0.024	0.069	0.197

Results of the within-subjects repeated measures ANOVA on the % of movement to peak velocity of the first and of the second agent. The effects that were found significant for both agents are highlighted in bold. Greenhouse-Geisser correction was applied to the degrees of freedom when needed.

A2. Table 2

Measure: % of movement to peak deceleration

Tests of Within-Subjects Effects

Source	df				F		Sig.		Partial Eta Squared	
	Second agent		*First agent*		*Second agent*	*First agent*	*Second agent*	*First agent*	*Second agent*	*First agent*
session	**1.00**	**19.00**	**1.00**	**19.00**	**249.53**	**7.85**	**0.000**	**0.011**	**0.929**	**0.292**
target distance	1.24	23.59	1.83	34.77	2.39	0.44	0.131	0.627	0.112	0.023
target size	1.00	19.00	1.00	19.00	28.08	0.91	0.000	0.353	0.596	0.046
session * target distance	1.25	23.70	1.86	35.26	2.71	3.02	0.106	0.065	0.125	0.137
session * target size	**1.00**	**19.00**	**1.00**	**19.00**	**28.99**	**9.79**	**0.000**	**0.006**	**0.604**	**0.340**
target distance * target size	1.54	29.33	1.82	34.53	0.58	2.97	0.521	0.069	0.030	0.135
session * target distance * target size	1.86	35.32	1.64	31.14	1.66	0.91	0.206	0.396	0.080	0.046

Results of the within-subjects repeated measures ANOVA on the *% of movement to peak deceleration* of the first and of the second agent. The effects that were found significant for both agents are highlighted in bold. Greenhouse-Geisser correction was applied to the degrees of freedom when needed.

A3. Table 3

Measure: Velocity

Tests of Within-Subjects Effects

Source	df		F		Sig.		Partial Eta Squared	
	Second agent	*First agent*	*Second agent*	*First agent*	*Second agent*	*First agent*	*Second agent*	*First agent*
session	1.00, 19.00	1.00, 19.00	0.04	11.68	0.835	0.003	0.002	0.381
target distance	1.69, 32.11	1.75, 33.27	458.03	1.08	0.000	0.343	0.960	0.054
target size	1.00, 19.00	1.00, 19.00	19.73	4.17	0.000	0.055	0.509	0.180
% of movement	**2.16, 41.13**	**1.61, 30.53**	**302.44**	**200.01**	**0.000**	**0.000**	**0.941**	**0.913**
session * target distance	1.31, 24.80	1.68, 32.01	197.93	2.36	0.000	0.119	0.912	0.110
session * target size	**1.00, 19.00**	**1.00, 19.00**	**15.82**	**7.23**	**0.001**	**0.015**	**0.454**	**0.276**
target distance * target size	1.84, 34.96	1.68, 31.93	1.51	1.15	0.236	0.321	0.073	0.057
session * target distance * target size	1.88, 35.72	1.94, 36.85	4.12	3.23	0.027	0.052	0.178	0.145
session * % of movement	1.30, 24.75	1.66, 31.51	52.56	3.25	0.000	0.060	0.735	0.146
target distance * % of movement	2.15, 40.87	2.46, 46.83	105.57	0.66	0.000	0.552	0.847	0.034
session * target distance * % of movement	2.49, 47.33	2.61, 49.65	89.03	1.67	0.000	0.190	0.824	0.081
target size * % of movement	2.02, 38.39	1.74, 33.01	20.13	2.30	0.000	0.122	0.514	0.108
session * target size * % of movement	**1.74, 33.12**	**1.88, 35.79**	**14.36**	**4.17**	**0.000**	**0.025**	**0.431**	**0.180**
target distance * target size * % of movement	3.70, 70.34	3.52, 66.91	2.76	0.91	0.038	0.456	0.127	0.045
session * target distance * target size * % of movement	**3.87, 73.47**	**2.72, 51.59**	**3.68**	**3.58**	**0.009**	**0.023**	**0.162**	**0.158**

Results of the within-subjects repeated measures ANOVA on the *wrist velocity* of the first and of the second agent. The effects that were found significant for both agents are highlighted in bold. Greenhouse-Geisser correction was applied to the degrees of freedom when needed.

Appendix B – Supplementary material to Chapter 4

B1. Quantification of visuo-motor interference during Non Interactive, Joint and Joint Outcome conditions - WHP dataset

Results of SVM-LASSO models performed using WHP actions as predictors:

condition	mean ± SEM	p-value (permutation test)
Non Interactive	0.59 ± 0.001	0.01**
Joint	0.56 ± 0.001	0.01**
Joint Outcome	0.55 ± 0.001	0.01**

$(*p < 0.05; **p < 0.01)$

Comparison between conditions:

condition(1)	condition(2)	Holm-Bonferroni corrected empirical p-value
Non Interactive	*Joint*	0.04*
Non Interactive	*Joint Outcome*	0.03*
Joint	*Joint Outcome*	0.38

$(*p < 0.05; **p < 0.01)$

B2. Quantification of visuo-motor interference in single kinematic features across conditions – WHP dataset

Results of SVM-LASSO models performed using single kinematic features of WHP actions as predictors:

condition	kinematic feature	mean ± SEM	p-value (permutation test)
Non Interactive	*Wrist Velocity*	0.60 ± 0.001	0.01**
	Wrist Acceleration	0.59 ± 0.001	0.01**
	Wrist Jerk	0.57 ± 0.002	0.02*
	Grip Aperture	0.52 ± 0.002	0.19
	Wrist Height	0.54 ± 0.001	0.03*
Joint	*Wrist Velocity*	0.55 ± 0.002	0.02*
	Wrist Acceleration	0.54 ± 0.001	0.02*
	Wrist Jerk	0.54 ± 0.001	0.07
	Grip Aperture	0.51 ± 0.002	0.27
	Wrist Height	0.53 ± 0.001	0.05*
Joint Outcome	*Wrist Velocity*	0.55 ± 0.001	0.02*
	Wrist Acceleration	0.55 ± 0.001	0.01**
	Wrist Jerk	0.55 ± 0.002	0.02*
	Grip Aperture	0.50 ± 0.002	0.36
	Wrist Height	0.54 ± 0.001	0.03*

($*p < 0.05; **p < 0.01$)

Comparison between conditions:

kinematic feature	condition(1)	condition(2)	Holm-Bonferroni corrected empirical p-value
Wrist Velocity	*Non Interactive*	*Joint*	0.03*
	Non Interactive	*Joint Outcome*	0.03*
	Joint	*Joint Outcome*	0.45
Wrist Acceleration	*Non Interactive*	*Joint*	0.03*
	Non Interactive	*Joint Outcome*	0.04*
	Joint	*Joint Outcome*	0.81
Wrist Jerk	*Non Interactive*	*Joint*	0.09
	Non Interactive	*Joint Outcome*	0.14
	Joint	*Joint Outcome*	0.74
Grip Aperture	*Non Interactive*	*Joint*	0.62
	Non Interactive	*Joint Outcome*	0.62
	Joint	*Joint Outcome*	0.53
Wrist Height	*Non Interactive*	*Joint*	0.51
	Non Interactive	*Joint Outcome*	0.55
	Joint	*Joint Outcome*	0.66

($*p < 0.05$; $**p < 0.01$)