How can the study of action kinematics inform our understanding of human social interaction?

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ABSTRACT

The kinematics of human actions are influenced by the social context in which they are performed. Motion-capture technology has allowed researchers to build up a detailed and complex picture of how action kinematics vary across different social contexts. Here we review three task domains—point-to-point imitation tasks, motor interference tasks and reach-to-grasp tasks—to critically evaluate how these tasks can inform our understanding of social interactions. First, we consider how actions within these task domains are performed in a non-social context, before highlighting how a plethora of social cues can perturb the baseline kinematics. We show that there is considerable overlap in the findings from these different tasks domains but also highlight the inconsistencies in the literature and the possible reasons for this. Specifically, we draw attention to the pitfalls of dealing with rich, kinematic data. As a way to avoid these pitfalls, we call for greater standardisation and clarity in the reporting of kinematic measures and suggest the field would benefit from a move towards more naturalistic tasks.

1. Introduction

How an action is performed can differ significantly based on context; a simple reaching action such as picking up a pen to sign one's name could be performed with a victorious flourish, or shaky reluctance. Thus, we can infer a lot about the emotional and social context in which an action is undertaken from just the kinematic features of movement. A growing number of studies are now using motion capture and detailed kinematic analyses to examine questions relating to social interaction. In the present paper, we review studies of the kinematics of hand and arm movements in various social contexts to understand how we can learn about human social behaviour from the examination of movement parameters. We focus on the different methods that have been used and the ways in which kinematic data can be interpreted to evaluate social interaction. In particular we consider how action kinematics *change* depending on social context.

This paper reviews three major task domains where kinematic measures have been used to address social questions: (1) simple point-to-point movement tasks which are used to study imitative behaviour, (2) motor interference tasks and (3) reach-to-grasp tasks. For each, we first review the characteristics of typical, non-social actions to set a baseline comparison. We place this within the framework of optimal control theory (Franklin and Wolpert, 2011; Wolpert et al., 1995) as a

way to understand motor parameters. We then review the various studies which have examined each action in a social context, and finally we consider what the findings mean and where the field can go next.

2. Imitation of simple point-to-point movements

Traditionally, copying behaviours have been studied in terms of imitation of complex hand actions, scored from video recordings or live performance. For example, categorical criterion have been used to assess imitation performance developmentally (Stone et al., 1997), and, within the mimicry literature, human video coders count the frequency of particular behaviours (e.g. foot shaking) to establish whether mimicry has taken place (Chartrand and Bargh, 1999). An alternative approach is to use simpler movements such as pointing, in combination with motion capture to parameterise behaviour in much greater detail. This allows researchers to analyse which specific aspects of the observed behaviour were copied, when the copying occurred, and the fidelity of the copying. For example, it is feasible to track the extent to which participants imitate the kinematics of others' movements, such as movement height or velocity, under different experimental conditions. Here we review some recent studies using these methods to illustrate the advantages and disadvantages of the approach. We focus particularly on imitation of simple pointing movements using a single

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finger.

To understand imitation of action kinematics, it is helpful to start with knowledge of the kinematics of the same actions in a non-social context. A fundamental problem for the human motor system is the degrees-of-freedom problem (Bernstein, 1967). Consider the simple task of pointing to a location in space (x, y and z coordinates) using the 90 muscles which control the right hand and arm. There are an infinite number of possible patterns of muscle activation that can place the fingertip at the desired location, which may suggest that there are a multitude of ways in which people achieve this task. However, in reality, people perform planar pointing actions in a very similar fashion, moving their hand in a near-straight trajectory from the starting point to the target (Abend et al., 1982). The existence of a stereotypical pattern of hand movement—where a single action is repeatedly chosen from the infinitely many available patterns—is commonly explained in terms of optimal control models. This theory suggests that out of the many possible actions only a small number are optimal—using either less energy than others, generating less discomfort or accompanied by a lower risk of failure (Harris and Wolpert, 1998; Todorov and Jordan, 2002). Under the optimal feedback solution for a particular movement, some motor parameters may be carefully controlled to achieve the task, while others may be allowed to vary. This flexibility could allow for the variable parameters to convey additional information—including social cues—depending on the context. Here we review what is known about the stereotypical optimal trajectory for each movement type before considering how it may vary depending on social context.

One of the first studies to examine imitation kinematics in detail was conducted by Wild et al. (2010). They showed participants videos of a hand pointing to a sequence of three locations (out of a possible four different locations) with either a 'fast' or 'slow' velocity. In some videos there were visual targets (goal directed condition) at the four different locations whilst in others there were no visual targets (non-goal directed condition). The results showed that participants imitated the velocity of the actor's movements when these were non-goal directed but not when these were goal directed. In a follow up study, they found autistic participants did not imitate the velocity of the observed action in either condition (Wild et al., 2012). These studies demonstrated the value of precisely tracking action kinematics to uncover subtle features of imitation in simple movements.

Hayes et al. (2016) extended this work by investigating whether participants imitated cursor movements with atypical velocity profiles, and if this behaviour changed in the presence of action goals. Typical pointing actions have a bell-shaped velocity profile with the peak velocity at around 50% of the total movement time. Such actions are recognised as 'human' by neurotypical participants (Cook et al., 2009; Florendo et al., 2014) and may have privileged brain processing (Tai et al., 2004). Hayes et al. generated dots moving with atypical movement profiles where the peak velocity occurred much earlier, at 17% or 26% of the total movement time, rather than at the typical mid-point of the movement (i.e. roughly 50% of the movement time). Participants were instructed to imitate the dot motion. Peak velocity occurred significantly earlier in participants' movements after the observation of such motion profiles compared to the observation of movements with constant velocity. Thus, participants imitated the atypical kinematic profiles. However, whilst the presence of goals influenced imitation accuracy, as demonstrated by shorter movement times, the atypical kinematics (i.e. the earlier peak velocity) were unaffected by the presence or absence of goals. This suggests that whilst atypical kinematics can be imitated (i.e. earlier peak velocities), only certain kinematic aspects of movement are sensitive to the presence and absence of goals.

One important question for these studies of kinematic imitation is whether this effect is mandatory and impervious to outside influence, or whether it can be modulated according to social and contextual factors. The former implies a robust and automatic mechanism which
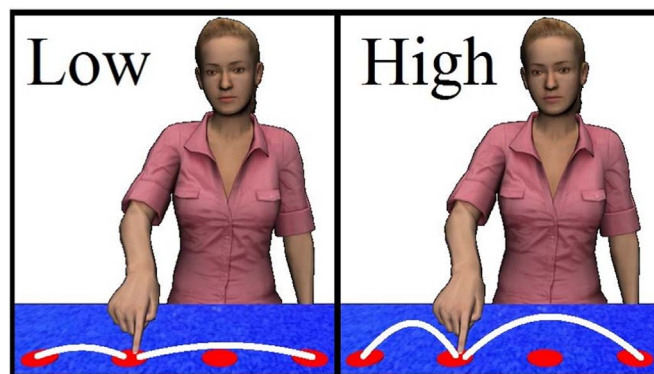

Fig. 1. The point-point imitation paradigm (Wild et al., 2010). Participants' own movements are sensitive to the kinematics of the model's actions, such as peak height (Forbes et al., 2016).

translates observed actions to performed actions without outside influence (Heyes, 2011). The latter theory has been formalised in the social top-down response modulation (STORM) model (Wang and Hamilton, 2012). STORM suggests that imitation can have a social—communicative function and can be modulated by social contexts such as gaze and prosocial priming. Some studies have examined this idea directly. Using the same paradigm as Wild et al. (2010, 2012) and Bek et al. (2016) investigated the influence of attention and motor imagery on imitation. Participants who had been told to attend closely to the movement or imagine performing the movement themselves matched the duration, peak velocity and amplitude of the observed movements more closely compared to a control group. Bek et al. suggest these results show that kinematic imitation is modulated by task context.

Forbes et al. (2016) recently devised a virtual reality version of Wild et al. (2010, 2012) paradigm to test STORM in a richer social context. In this task participants observed an avatar point to a sequence of three targets and were then required point to the same targets. On half the trials the avatar moved with a high trajectory between the targets and on the other half with a low trajectory (see Fig. 1). Participants played the game twice, once with a "socially engaged" avatar who smiled at and looked at the participant, and once with a "social disengaged" avatar who looked away from the participant during the response period. They found that both autistic and neurotypical participants copied the height of the avatar's movements but the autistic participants did so to a lesser extent. Social engagement did not modulate mimicry, contrary to the predictions of STORM. It remains to be seen if this is a limitation of the level of social engagement which can be obtained in virtual reality, or if the same applies in live interaction contexts. At present, it is clear that some top-down factors (e.g. the presence of goals, motor imagery, and attention) modulate the imitation of action kinematics, but other top-down factors (e.g. social engagement) may not.

The majority of the imitation studies outlined above used magnetic or camera-based motion tracking systems to analyse participants' kinematics. However, these are not always suitable for children or for neuroimaging environments. Culmer et al. (2009), therefore, developed a touchscreen-computer based system, the Kinematic Assessment Tool (KAT), to measure human movement kinematics. Williams et al. (2013) exploited the portability of this system to measure imitation accuracy in primary school children. Children observed videos clips of an actor drawing with a stylus on a touchscreen-computer and were when asked to try and copy the drawing actions as closely as possible. By measuring the path-length, duration and speed of the participants' movements, Williams et al. showed high correlations between the kinematics of the child and those of the actor, particularly in older children. So, studying the kinematics of copying behaviours enables researchers to establish not only whether a participant imitated but also how well they imitated.

Stewart et al. (2013) used the same touchscreen approach to investigate imitation differences in autistic children. Their primary aim was to determine the extent to which differences in imitative performance were due to self-other mapping deficits (i.e. being able to map the actions of others onto one's own motor system) rather than due to general differences in motor, memory or attentional abilities. To do this they compared the participants' kinematics in an imitative condition, where participants observed an actor drawing shapes with a stylus on a touchscreen computer, to a 'ghost control' condition, during which the actor simply watched a black dot moving on the touchscreen computer producing the same shapes. However, the dot's movements were based on those of the actor's stylus tip during the imitative condition. As before, they found reduced imitation accuracy on both tasks in autism as demonstrated by lower path length error in the neurotypical sample (Wild et al., 2012). Crucially, there was an interaction between group and condition, whereby the autistic sample showed greater path length error in the imitative condition compared to the 'ghost control' condition but this was not the case for the neurotypical group. This demonstrates that poor performance in the autism group was not due to poor motor control in general, but was specific to imitation of human hand actions.

2.1. Conclusion

Many of our actions take place in a social context, so understanding what factors influence the kinematics of our imitative movements is important for theories of both motor control and social cognition (Wolpert et al., 2003). The studies above all demonstrate that participants have a tendency to copy the kinematics of actions they see, even when these may take the action trajectory further from the optimal trajectory. Two major theories can account for this. First, common coding theory claims that action perception and action production are closely linked (Prinz, 1990), and is made more explicit in the associative sequence learning theory (Heyes, 2011) which posits learnt associations between perception and action that are not modulated by outside factors. These theories focus on the direct link between perception and action, and consider any modulation of this link must reflect either changes to the input or output systems outside the core perception-action link. Thus, copying of basic kinematic features is plausible but the modulation of copying by social context falls outside the scope of the theory. The second theory is the STORM model (Wang and Hamilton, 2012) which focuses on the social modulation of imitation, beyond simple perception-action links. This theory suggests that imitation has a social function, and is controlled according to the social need for imitation.

The data reviewed above shows that several features of an imitation task can modulate the level of imitation. The presence of goals (Wild et al., 2010), the nature of the observed movement kinematics (Hayes et al., 2016), attention (Bek et al., 2016), motor imagery (Bek et al., 2016) as well as the age (Williams et al., 2013) and clinical diagnosis of the participant (Forbes et al., 2016; Stewart et al., 2013; Wild et al., 2012) all determine whether or not the kinematics of others' movements are copied, and, if so, which kinematic features are copied and how accurately. However, modulation of the kinematics of point-to-point actions by social cues such as gaze or group membership, as predicted by the STORM model, has yet to be fully tested or demonstrated.

Future research in this area can examine how a range of social cues modulate kinematic imitation. New touchscreen systems also now allow detailed kinematics to be studied developmentally in both neurotypical (Williams et al., 2013) and autistic children (Stewart et al., 2013), and, also in combination with neuroimaging techniques (Braadbaart et al., 2012). One potential direction for future work is to test whether the predominance of the basic, kinematic priming effects disguise the impact of more subtle social manipulations during imitative point-to-point movements. This is likely to require the development of robust paradigms that can reliably distinguish between social and non-social conditions via the manipulation of factors such as gaze while also allowing for imitative behaviour to be generated in more naturalistic settings.

3. Motor interference

In contrast to imitation, motor interference typically occurs when a participant performs an action that is different to the action they observe. It could be considered as a counterpart to imitation. In typical studies of motor interference, participants observe an action that is either similar to or different from the one they perform, and any difference in performance between these two is considered an interference effect. The existence of action interference effects was postulated as part of the common coding model (Prinz, 1990) because observing an action excites the motor programs used to execute that same action (James M Kilner et al., 2009). So if the observed action is incongruent to the action being performed, for example if it is in a different plane, then interference occurs and execution of the action is perturbed. Motor interference can be seen as a measure of visuomotor mapping – the extent to which we map observed movements onto our own motor systems.

Motor interference was first demonstrated for simple finger actions (Brass et al., 2000). The first study using kinematically richer measures of motor interference asked participants to make continuous sinusoidal hand movements in either the horizontal or vertical plane (Kilner et al., 2003). The simultaneous observation of a similar movement in the orthogonal plane interfered with the execution of that movement compared to the observation of the movement in the same plane. The extent of this motor interference (or 'motor contagion'; Blakemore and Frith, 2005) was measured as the variance in the whole motion trajectory or in the endpoint locations, in the axis orthogonal to the axis in which participants were instructed to move (see Fig. 2). Various aspects of this motor inference task have been manipulated, such as the nature of the observed action (e.g. biological vs. non-biological movements), the agent performing the observed action (e.g. robot vs. human) and the events occurring before or during the observed action (e.g. social priming). We review results in each of these areas below.
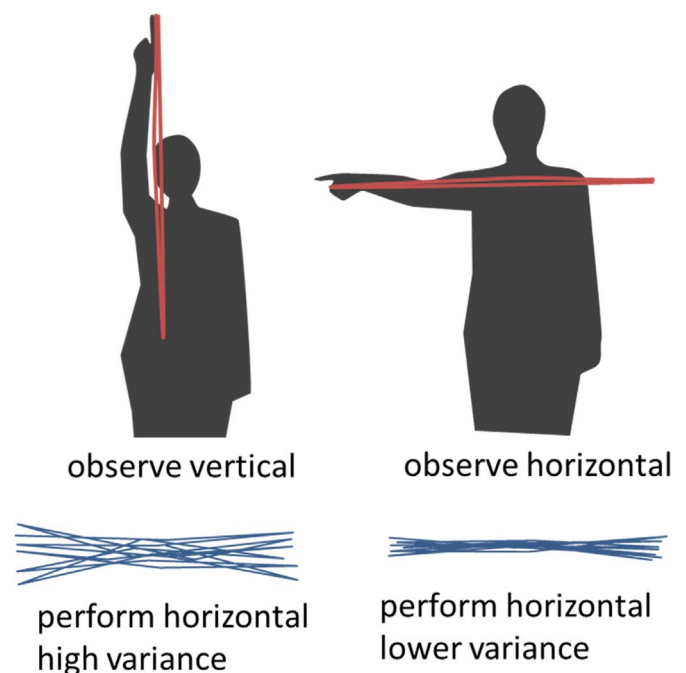

observe vertical   observe horizontal

perform horizontal   perform horizontal
high variance   lower variance

Fig. 2. Interference in continuous movements.

3.1. Agent appearance and motion

The first study of motor interference with arm movements contrasted a human moving with a natural, biological motion trajectory with a robot moving with a robotic, linear trajectory (Kilner et al., 2003). Studies since have tried to distinguish the impact of form and motion factors. Kilner et al. (2007) showed that videos of biological human movements, but not non-biological human movements, caused motor interference. Videos of a ball moving incongruently interfered with executed arm movements regardless of whether its motion was biological or non-biological. Kilner et al. (2007) suggested that there may not have been enough information within the ball videos for observers to distinguish biological from non-biological motion. The videos displayed just one dot moving across the screen, rather than point-light displays.

Cook et al. (2014) supported the findings of Kilner et al. (2007) by showing that the form of the agent matters for interference effects. Neurotypical participants displayed an interference effect when observing real and virtual human movements but not virtual robot movements. Autistic participants did not show an interference effect when observing any of the agents (Cook et al., 2014). However, Oztop et al. (2005) found that motor interference was induced by a robot with human-like appearance and human-like movements, in contrast to the findings of Kilner et al. (2003) and Cook et al. (2014) who found no interference for real or virtual robot movements, respectively. Oztop and colleagues note that Kilner et al. used an industrial robot which was not human-like in either its movements or appearance. Together these findings suggested that motor inference could be dependent on the observed agent appearing and moving like a human. This was supported by Marshall et al. (2010) who adapted the motor interference paradigm so that it could be performed on a tablet computer using a stylus. Four-year-old children were instructed to move the stylus "side to side" or "up and down" on the tablet whilst observing a background video of an actor moving in either the congruent or incongruent plane. Motor interference was greater when the observed actor was a peer compared to an adult. Kupferberg et al. (2012), however, have argued that it is not the nature of the agent's movements nor their appearance which are key in determining motor interference, but rather the motility, specifically the joint configuration, of the observed agent. If an industrial robot arm had a human-like joint-configuration and moved with quasi-biological motion this resulted in motor interference. But this did not occur when the robot arm made the same movements with its standard industrial configuration (Fig. 3).

In sum, these studies would appear to suggest that the correspondence between the observed agent and participant, in terms of their appearance, movement profile, age and even the joint configuration, are important in determining extent of motor interference for neurotypical participants. Autistic participants appear to be immune to the effects of this type of motor interference. Yet, the finding that a moving ball regardless of its movement trajectory results in motor interference in neurotypical participants (Kilner et al., 2007) suggests that the similarity between the observed agent and participant cannot by itself explain the extent of motor interference.

3.2. Belief about the actions

Prior information about the social status of stimuli may also be able to influence the motor interference effect. In a study by Stanley et al. (2007), participants who were told that they were observing a moving dot generated from human movements showed greater motor interference than those told the moving dot was computer generated, regardless of whether the dot was moving with a biological or non-biological movement profile. The intriguing interplay between the basic kinematics features of the action and 'top down' social factors was further demonstrated in a study with four to five year old children. Saby et al. (2011) familiarised children with either an "animate bear" or "inanimate bear" during classroom story reading – the animated bear was treated as a hand puppet so would respond to and follow the story, conversely, the inanimate bear lay on the lap of the experimenter during the story. The results showed that motor interference occurred when a previously animated toy bear was seen moving with non-biological motion, and when a previously inanimate lifeless bear was seen moving with biological motion. Saby et al. suggested that the mismatch between an expected and observed movement profile results in increased activation of brain areas involved in action processing and hence more motor interference. For example, seeing a previously inanimate bear move with a biological movement profile violated the children's expectations as did the previously animate bear moving non-biologically. Saby et al. also proposed that the intransitive nature of the movements may have also accounted for the lack of a main effect of either movement profile or animacy. For example, Bekkering et al. (2000) showed that children are especially sensitive to goals during imitation task, and, Bouquet et al. (2011) found greater motor interference for goal-directed as opposed to non-goal directed sinusoidal movements. Hence, the motor interference tasks could provide a useful tool for exploring the role of goals in imitative behaviours across childhood and in autistic individuals (Stanley et al., 2007).

3.3. Social priming and group membership

Other social factors also influence the extent of motor interference. For example, van Schaik et al. (2016) assigned four to six year old children to a group based on their colour preference of a vest. Participants performed a tablet-based motor interference task (Marshall et al., 2010) but the observed agent wore either the same (in-group) or a different (out-group) coloured vest to that preferred and worn by the participant. Motor interference occurred only for the out-group not for the in-group. Similarity between the observed agent and participant resulted in an absence of motor interference, whilst the explicit dissimilarity between the observed agent (e.g. wearing a blue vest) and the participant (e.g. wearing a red vest) resulted in motor interference. Van Schaik et al. (2016) proposed that there is increased
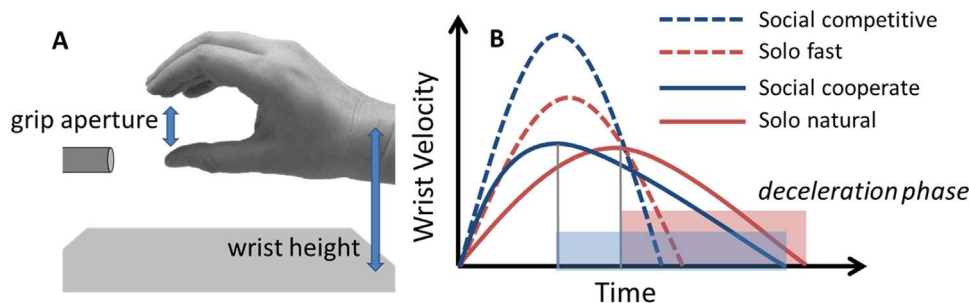

Fig. 3. Reach-to-grasp tasks. A. These tasks typically measure grip aperture, wrist height, wrist velocity and hand trajectory features as a participant grasps an object. B. A stylised velocity profile of wrist trajectory in single-agent (fast and natural speed) conditions and in cooperative and competitive social conditions as observed in Experiment 1 in Georgiou et al. (2007).

attention towards the out-group model resulting in increased motor interference. However, van Shaik et al. suggested that this heightened attention could be driven by a motivation to overcome intergroup differences to promote affiliation (Miles et al., 2011), appease threat (Rauchbauer et al., 2015), or increased monitoring of the out-group to try and predict dangerous behaviour (Cikara et al., 2014). The effect of biological compared to non-biological movements on motor interference was minimal; van Schaik et al. argue that the saliency of social manipulation may have reduced the impact of any movement profile differences on motor interference.

The effect of social priming on the motor interference has also been investigated. In a slight variation of the original motor interference task Roberts et al. (2015) asked participants to execute horizontal arm movements whilst observing videos of a human agent performing biological horizontal (congruent) or curvilinear (incongruent) movements. This adaptation of the original task ensured the end-points of both the congruent and incongruent movements were in the same spatial location (Roberts et al., 2014). Three seconds before the model started moving, a pro-social (e.g. friend, group) or anti-social (e.g. alone, self) prime appeared in each of the four corners of the screen and remained there for the duration of the trial. Anti-social priming led to higher motor interference than pro-social priming. Analogous to the findings of van Schaik et al. (2016), who found increased motor interference towards the out-group, the anti-social prime may have been interpreted as a threat to the social encounter resulting in increased attention to the model's movements. Similar results have been found in finger movement tasks (Wang and Hamilton, 2013). In sum, anti-social primes and out-group membership both result in increased motor interference compared to pro-social primes and in-group membership, respectively. Future work should explicitly test what is driving this increased motor interference, for example, whether this results from a need to promote affiliation or appease threat.

3.4. Other methods for studying interference

The studies reviewed above, which used kinematics measures to assess motor interference, are broadly consistent with reaction times studies which also tap into an interference effect. For example, in the widely used "finger tapping" paradigm (Brass et al., 2000) participants must make index or middle finger movements in response to a number appearing on the screen (e.g. 1=move index finger, 2=move middle finger); the simultaneous observation of a task-irrelevant congruent finger movement enhances reaction times whilst the observation of a task-irrelevant incongruent finger movement slows reaction times. The difference in reaction times between congruent trials (e.g. observe index finger movement, perform index finger movement) and incongruent trials (e.g. observe middle finger movement, perform index finger movement) has been called the motor priming effect (or congruency effect). This congruency effect, like the motor interference effect, is similarly susceptible to top-down social modulation. For example, Liepelt and Brass (2010) manipulated participants' beliefs about the animacy of observed hand during a finger tapping paradigm. All participants saw a hand wearing a leather glove. However, those participants who believed this hand belonged to a human showed a larger congruency effect than those who believed it was a wooden hand. As outlined above, comparable effects of animacy have been demonstrated in motor interference tasks (Stanley et al., 2007). Similarly, Rauchbauer et al. (2015), also using a finger tapping paradigm, showed that participants demonstrated larger congruency effects to a racial out-group compared to a racial in-group. Again, as outlined above, comparable effects of out-group membership have been found in motor interference tasks (van Schaik et al., 2016).

Whilst motor interference studies are generally consistent with reaction time studies used to assess social modulators of visuomotor mapping, Roberts et al. (2015) have highlighted the advantages that motor interference tasks may have over these reaction time methods

(Roberts et al., 2015). Reaction time tasks, such as the "finger tapping" paradigm, typically involve displaying isolated hand stimuli performing discrete actions (Brass et al., 2000). However, Roberts et al. (2015) suggested that the continuous biological movements observed and executed in motor interference tasks are more akin to what occurs during naturalistic social interactions. Additionally, they argue that reaction time measures are limited in establishing whether social modulators of visuomotor mapping are due to their regulation of the action goal or the kinematics of the action. Motor interference tasks enable researchers to disentangle these two processes (Bouquet et al., 2011; Marshall et al., 2010; Roberts et al., 2015). Finally, motor interference tasks, particularly those implemented using tablet computers (Marshall et al., 2010), enable changes in the social modulation of visuomotor mapping to be assessed developmentally in both neurotypical children (Saby et al., 2011; van Schaik et al., 2016) as well as those diagnosed with neurodevelopmental disorders. Relatively, few studies have explored developmental differences in visuomotor priming using reaction time tasks (Grecucci et al., 2013).

3.5. Conclusion

Motor interference during the observation of continuous sinusoidal actions provides a useful and flexible method for measuring the extent to which we map observed movements onto our own motor systems (Kilner et al., 2003; Prinz, 1997). Various aspects of the motor interference task have been manipulated, including the nature of the observed action and agent the action is performed by. Findings investigating the modulation of motor interference are largely consistent with findings from reaction times paradigms used to explore visuomotor priming (Brass et al., 2000). Both reaction time paradigms and whole arm movement paradigms show a variety of social factors can influence the level of interference found. This is in contrast to point-to-point imitation tasks reviewed above, where features of the action as well as the action goal primarily influence kinematics; the social factors which have been tested so far do not seem to change imitation. Understanding the differences between these paradigms will be important in the future. One possible difference is that motor inference tasks examine continuous movements, while pointing tasks examine discrete movements. Continuous movements might give a better model of real-world social interactions (Roberts et al., 2015) and might thus tap into social modulations better. Another important future direction is the use of computer tablet-based motor interference tasks which will allow the modulation of visuomotor mapping to be assessed developmentally in both neurotypical and autistic children. This has remained relatively unexplored using standard reaction time paradigms, such as the "finger tapping" paradigm.

4. Reach-to-grasp movements

Many studies of motor control have described the everyday action of reaching to pick up an object such as a mug or a pen. These reaching movements typically involve two phases: a "reach-to-grasp" phase during which an agent moves from a resting position to pick up an object, and a "placing phase" when the agent moves the object to a final target location. The key parameters that specify the kinematic profile of this movement include the grip aperture (the width of the fingers when grasping the object), the reaction time, overall movement time, length of the movement, maximum height reached by the wrist, peak velocity, the time taken to reach peak velocity and the deceleration time. The kinematics of reach-to-grasp movements have been shown to be affected by a number of physical factors including the characteristics of the target object, the near-term goal of the movement, and the intention behind the movement, including any communicative intent (Jacob and Jeannerod, 2005; Marteniuk et al., 1987; Patel et al., 2012; Quesque and Coello, 2015; Sartori et al., 2009a).

The kinematics of these movements have also been shown to be

affected by sudden changes, or perturbations, that occur during the performance of the task (Haggard, 1994) such as a change in the target object, or the goal. In this section we review how the kinematics of reach-to-grasp movement are affected in particular by social factors and perturbations and the extent to which social context can be perceived through the observation of kinematics.

Broadly, the inclusion of social factors leads to movements that are slower and have a higher trajectory (see also Becchio et al. (2010) and Quesque and Coello (2015)) than non-social movements. Previous research has shown that when compared with non-social movements, social movements—such as when a participant is asked to place an object on the hand of another person rather than place it on a stand— are slower, incorporating an exaggerated movement trajectory with a greater maximum height (Becchio et al., 2008b); a similar slowing down and exaggeration of movement trajectory was observed when the eye level of an observer was varied (Quesque and Coello, 2014) and when an action was undertaken with communicative intent in the presence of an observer (Sartori et al., 2009a).

In addition, the deceleration phase was found to be longer in the social condition when compared with the single-agent condition. In a study by Sartori et al. (2009b), participants performed a reach-to-grasp movement during which the agent picked up an object and moved it to an intermediate target, and a place movement where the object was then moved to a final location (a container towards the right of the agent). The reach-to-grasp movement was perturbed in 20% of the trials by an observer who reached out her hand as if to request the object, and this perturbation led to a dramatic deviation in the agent's trajectory towards the observer as early as 165–171 ms after the onset of movement. The presence of such a social request also influenced movement in the final place phase (despite the agent being explicitly instructed to place the object only in the inanimate container), where perturbed movements reached higher maximum wrist heights and took longer to reach these peak heights.

In contrast to the explicit inclusion of social context above, Quesque et al. (2013) tested a paradigm in which the social context was made implicit and found a similar effect. This involved a preparatory action (always performed by the agent) and a main action (which was sometimes performed by the experimenter, and other times by the agent). In the social certainty condition, the experimenter always performed the main action, and here it was observed that the agent's movements in the preparatory phase were slower and smoother with a higher peak wrist height. In the social uncertainty condition the experimenter performed the main action in about 30% of the trials and this led to agents adopting a more competitive kinematic profile, with shorter movement times and jerkier movements. Thus, even in a preparatory phase of movement where there is no difference in actor, source or target between the social and non-social conditions, agents make slower movements with higher trajectories and longer reaction times when these movements are made with social rather than non-social intent.

Another factor that appears to influence movement kinematics is gaze providing further support for the view that movement kinematics and social intent are related bi-directionally. As mentioned previously, a confederate's eye level can influence the curvature of the trajectory modelled by a participant (Quesque and Coello, 2014), and gaze can interfere with motor kinematics in neurotypical children (Becchio et al., 2007) although autistic children do not appear to show this effect. Other studies have shown that participants appear to be able to draw inferences about intent from the gaze of the demonstrator (Castiello, 2003). Taken together, these suggest that the mere inclusion of social context (say via the presence of an observer or co-actor) does not change an action in a uniform fashion. Rather, context and task constraints act differently in different studies. In the remainder of this section we distinguish between four kinds of movements where kinematic patterns may change based on social context, including (1) cooperative movements and (2) competitive movements; (3) move-

ments requiring a high degree of precision; and (4) movements intended to serve a communicative purpose.

A broad distinction can be drawn between factors that lead to a competitive social context and factors that lead to more cooperative movements (Fig. 3). Georgiou et al. (2007) compared the kinematic profile of an agent's movements when they were asked to move an object under time constraints but on their own (single-agent-fast) to movements in a competitive context, and solo movements without time constraints (single-agent-normal) to cooperative movements. Trivially, single-agent-fast and competitive movements were much faster than cooperative and single-agent-natural movements. However, competitive movements reached a higher peak velocity than even single-agent-fast movements; cooperative movements meanwhile, reached the same peak velocity as single-agent-natural movements but reached that peak faster than both single-agent movements as well as the competitive social movement, resulting in a longer deceleration phase.

While Georgiou et al. (2007) explicitly generated competitive and cooperative contexts via the demands of the task itself, others have demonstrated that these dynamics can also be induced implicitly. One study showed a congruency effect between the agent's kinematic profile and the attitude adopted by a co-actor (Becchio et al., 2008a); in ostensibly cooperative trials, for example, when the co-actor adopted a competitive attitude the agent's kinematic profile soon shifted to a competitive pattern. The nature of the co-actor and their position in the shared space has also been shown to influence movement kinematics: a study by Gianelli et al. (2013) involved agents performing tasks in a shared space with either friends or strangers, who were either in a position where they could easily reach out to disrupt task performance, or were too far to be able to do so. It was seen that the presence of a second person in the shared space led to agents adopting a more competitive kinematic profile, with faster movements and tighter grips on the object; however, while this occurred for strangers in all positions, when the co-actor was a friend, the kinematic profile grew more competitive only when the friend was near the agent, and not when the friend was too far to disrupt movement. This suggests that the agent's threshold for viewing the friend as 'a threat to my movement' is higher than it is for strangers.

Apart from competitive and cooperative contexts, another reason why movement kinematics may vary could be the demand for task accuracy. Studies of how physical factors affect kinematics have suggested that the demand for task accuracy is proportional to the length of the deceleration phase (Marteniuk et al., 1987); i.e. handling a more fragile object or having to execute a more precise task (such as place an object at a specific spot, rather than point in a certain direction) results in movement trajectories that have a significantly longer deceleration phases. This is likely to give time for visual feedback to be used to increase accuracy. In a similar vein, when it comes to social context, we hypothesise that the need to cooperate increases the social complexity of the task, resulting in these longer reported deceleration phase (Becchio et al., 2008b; Georgiou et al., 2007). Support for this can be found in studies that compare kinematic profiles between scenarios where agents are asked to feed a conspecific (reach-to-feed) and where agents are asked to place food in a mouth-like aperture (reach-to-place) (Ferri et al., 2010, 2011). It is observed that agent's movements are slower, with longer deceleration times, in the reach-to-feed condition when compared with the reach-to-place condition. Agents also took longer to place the food in the agent's mouth versus placing food elsewhere on the agent's face or in a mouth-like aperture, illustrating the more deliberate kinematic profile adopted in the reach-to-feed condition.

The speed versus accuracy trade-off is easy to understand; however, the deliberate, almost exaggerated, kinematic profile adopted in social conditions suggests that it may be signalling intent to observers or co-actors. Indeed, previous work has shown that observers can use the kinematic profile of an agent's movements to make inferences about the physical characteristics of the target object. These include studies

that show how observers can use an agent's kinematics to successfully predict the weight of an object being lifted by an agent (Hamilton et al., 2007), whether this weight has changed since the observer last lifted the object (Meulenbroek et al., 2007) or whether the actor is reaching for a large or small (hidden) object (Ansuini et al., 2016). In one intriguing study conducted among professional poker players, naïve observers were able to judge the quality of the poker players hands better than chance merely by observing the smoothness of their arm movements (Slepian et al., 2013). These studies showcase the two-way nature of the interaction between physical and social factors, such as gaze, and movement kinematics. They also suggest that kinematics can be used to infer intent, at least in terms of the *physical* characteristics of the object and the purpose of the movement.

Whether one can similarly infer *social* intent from kinematics remains an active area of research. A seminal paper by Jacob and Jeannerod (2005) suggested that merely observing and understanding the kinematics of an action is insufficient to infer social intent. In their now famous Jekyll & Hyde formulation they suggested that watching a man grasp a scalpel and make an incision on a prone person does not distinguish between a murderer committing a crime and a surgeon operating to cure a patient. However, more recent work has suggested that people can nevertheless infer social information from movements in some contexts (Becchio et al., 2012). Indeed, it appears that observers are able to distinguish between agent's moving to cooperate or compete by merely viewing points-of-light representations of their kinematics in the preparatory phase (when the source and target are the same across conditions) (Manera et al., 2011). However, as Obhi (2012) has noted, these studies involve forced-choice paradigms where the observer's range of possible responses are experimentally constrained, and as such may not be reflective of real-world dynamics.

There is one demonstration of participants distinguishing social conditions (cooperation versus competition) using movement kinematics, with observers utilising this knowledge even when they are not explicitly aware of doing so (Quesque et al., 2015). In this study Quesque et al. (2015) showed that an agent's kinematics in a preparatory phase differ depending on whether the agent is aware of who is to undertake the motion in the subsequent phase (the agent or the co-actor). In the condition where the agent is aware that it will be the co-actor's turn next (but the co-actor is still naïve as to whose turn is next) merely observing the agent's kinematics facilitates a faster response time by the co-actor. This perhaps implicit inference of social intent promises to be an exciting line of inquiry, although it is subject to between-subject heterogeneity and may depend on empathic abilities (Lewkowicz et al., 2015). Finally, further to anticipating social intent, it has been suggested that kinematics may also allow an observer to infer higher-order cognitive functioning, such as inferring an agent's subjective confidence level (Patel et al., 2012).

4.1. Conclusion

The studies reviewed here show that a large number of social factors can influence the kinematics of reach to grasp actions. While the field uses a wide variety of paradigms which are not always comparable (see Methods section below), broadly, the kinematics of actions undertaken in a social context appear to be slower with a more exaggerated movement profile, when compared with actions undertaken in non-social contexts (Becchio et al., 2008b, 2010; Quesque and Coello, 2015). Rather than having a universal effect on kinematics, social context appears to influence kinematics to varying extents depending on whether the movement is being undertaken in a competitive (or cooperative) context (Georgiou et al., 2007), the demand for accuracy when performing the movement (Marteniuk et al., 1987) and whether or not the movement is intended to signal intent to observers and co-actors (Becchio et al., 2012; Manera et al., 2011). However, it remains unclear which effects are driven primarily by task constraints (e.g. competitive actions must be fast in order to

win) and which effects reflect the use of kinematics to perform a social-communicative function. Certain paradigms have addressed this issue specifically, such as Quesque et al. (2015) where all elements of the task were kept identical with only the social intention being varied between conditions. This shows that social context matters; however such rigour is not universal in the field and other paradigms do include confounds owing to differences in task constraints between conditions.

When considering the factors which influence the kinematics of reach to grasp actions, it is useful to make some important distinctions. Firstly, we must distinguish between the social context – the simple absence or presence of a conspecific (Becchio et al., 2010) – and the social intention within this social context – whether the action is being performed with the aim of influencing some else's movements (Quesque et al., 2013). Next, when performing movements within a social context actors may have a particular motor intention, for example, placing an object on a stand or in the hand of another person (Becchio et al., 2010), but this must be separated from the social intention of their movements, whether their actions aim to influence the movements of a co-actor (Quesque et al., 2013). Finally, the social intention can be either implicitly (Quesque et al., 2015) or explicitly (Sartori et al., 2009b) processed by the co-actor. The development of more standardised paradigms to tap these dissociations and to examine these actions in atypical and developing populations, are interesting future directions.

5. Methods for the study of social kinematics

The studies reviewed above have used a range of methods to examine the influence of social contexts on kinematic action parameters. We have reviewed imitation studies, motor interference studies and reach-to-grasp actions, as these three areas cover the majority of the literature. In the case of imitation of pointing actions, it seems that participants regularly copy the kinematic features of the movement they observe but evidence for social factors adding to this imitation are limited. In motor interference studies, there is a robust interference effect which is modulated by both the appearance and motion of the stimulus and participant's prior beliefs about the social context. Finally, the kinematics of reach-to-grasp actions vary according to the task context and trade-offs between speed and accuracy, but may also convey social information. Unifying these results remains challenging, because different methods and paradigms are used in each case. For example, stimuli used include videos of humans, moving dots, virtual reality and live social interactions, but these might induce different levels of social presence or impose different demands for interactive behaviour. Rich ecologically valid studies of grasping kinematics in the presence of a live co-actor may not engage the same cognitive processes as rather minimal studies of observing a moving dot and pointing to a blank table. Further exploration of the role of social engagement and the importance of realistic stimuli in studies of action kinematics in social contexts would be useful.

The type of data collected in kinematic studies of imitation also presents both advantages and challenges to researchers. Kinematic data is typically very rich, with 100s of data points in each trial and many different movement parameters which can be extracted in different studies – reaction time, movement time, peak height, peak velocity, wrist height, grip aperture, end point variance and more. This richness gives the data much more detail than simple reaction time studies, but brings some caveats. First, many studies report different measures, which makes it hard to compare between studies. Second, rich data allows some potential for researcher-degrees-of-freedom, which can lead to high levels of false positives (Simmons et al., 2011). Third, the movement parameters extracted are highly correlated with each other. Whilst, the relationship between certain parameters, such as movement duration and velocity, may be obvious, the relationship between less well-known parameters can be less clear. Future kinematic studies reporting multiple dependent measures should

clearly state the relationship between these different measures.

Bearing these limitations in mind it would be very valuable to see more standardisation of measures and reproducibility in this area. Developing a set of standardised measures that are universally reported would enable a productive comparison of results across experiments and would greatly further progress in this field. Full reporting of all results and effect sizes are also key in reducing false positives.

6. Future directions

Evidence from imitation tasks, motor interference tasks and reach-to grasp tasks has consistently demonstrated that the social context influences the kinematics of participants' movements. However, there are differences between these tasks in terms of how the social context influences participants' kinematics. During the imitation tasks outlined above the basic kinematics properties of the observed movement seem to have the greatest impact on participant's own movements. For example, whilst participants copy the height and velocity of the observed movement (Forbes et al., 2016; Wild et al., 2010), they also copy atypical movement profiles, such as the earlier peak velocity of an observed movement (Hayes et al., 2016). Yet, compared to motor interference tasks, the movements recorded during imitation tasks seem to be more resistant to the effects of other types of social manipulations, such as the characteristics of the model (Forbes et al., 2016). Results from motor interference tasks has shown that beliefs about the animacy of the model (Stanley et al., 2007) and their group membership (van Schaik et al., 2016) can override, or at least interact with (Saby et al., 2011), the influence of the basic kinematics aspects of the observed movement, such as whether it is biological or non-biological motion. Comparable to participants' performance during motor interference tasks, during reach-to-grasp tasks, movement kinematics are also modulated by the particular characteristics of the co-actor, such as whether she is a friend or stranger (Gianelli et al., 2013). In addition to the characteristics of the co-actor, the demands of the task also modulate the effect of the social context in reach-to-grasp tasks. For example, whether the task is competitive or cooperative can affect the degree to which the kinematics of the movement differ between a social and non-social context (Georgiou et al., 2007).

A fruitful avenue for future research would be to establish what accounts for the differences between these tasks. One possibility is that timing between the observed action, the social manipulation and the executed action is important in imitation and motor interference tasks. In kinematic imitation tasks there is typically a delay between the observed and executed movement, this may place memory demands on the participant as they try to remember the model's movement. This could nullify the impact of any social effects (Forbes et al., 2016). Conversely, during motor interference tasks the observed and executed movement are occurring concurrently which may increase the impact of any social manipulation.

Another avenue for further study may be to consider how social modulation of kinematics fits with the optimal control framework for motor control. There may be some tasks where the social modulation of kinematics falls within the natural variability of the movement, and does not make overall task performance suboptimal. For example, if participants are instructed to point to particular dots, moving with a higher trajectory might not reduce accuracy and so is not suboptimal with respect to the instructed task. Such modulation might be accounted for by a low-level priming effect. However, there may be other social tasks where the kinematics of an action in a social context might deviate substantially from the kinematics of the equivalent non-social action, suggesting that a different control mechanism might be in use. In such cases, it would be useful to test if kinematic features are being used as a social/communicative signal, or if another factor reduces the optimality of social movements.

The ecological validity of both the movement and environment are likely to account for some of the differences between these tasks

(Reader and Holmes, 2016). Arguably, reach-to-grasp tasks are more naturalistic when compared to imitation studies and motor interference tasks. This may explain why even subtle social manipulations are detectable during reach-to-grasp actions. However, it remains to be seen whether it is the nature of the interaction partner (e.g. live vs. video: Reader and Holmes, 2015) and/or the nature of the movement (e.g. sinusoidal vs. reach-to-grasp) that is driving the differences between these tasks.

7. Conclusion

Human actions are influenced by the social context in which they are performed. The advent of motion capture technology has enabled us to build up a detailed and complex picture of how the kinematics of our actions vary across different social contexts. Our review has focused on three task domains: point-to-point imitation tasks, motor interference tasks and reach-to-grasp tasks. Results from these tasks have revealed that a plethora of social factors can influence the kinematics of our actions. These findings have important implications for both theories of both social cognition and motor control. Future studies examining the neural basis of these kinematic differences as well as studies investigating children and autistic individuals, will further inform these theories. However, the findings from these task domains are not always consistent and are often hard to compare. We call for greater standardisation and clarity in the reporting of kinematic measures and a move towards more naturalistic tasks. This will give us a better understanding of any differences we see across these studies and thereby further this intriguing field.

Acknowledgments

References

Abend, W., Bizzi, E., Morasso, P., 1982. Human arm trajectory formation. Brain 105 (2), 331–348 ⟨http://doi.org/10.1093/brain/105.2.331⟩.

Ansuini, C., Cavallo, A., Koul, A., D'Ausilio, A., Taverna, L., Becchio, C., 2016. Grasping others' movements: rapid discrimination of object size from observed hand movements. J. Exp. Psychol.: Hum. Percept. Perform. 42 (7), 918–929 ⟨http://doi.org/10.1037/xhp0000169⟩.

Becchio, C., Manera, V., Sartori, L., Cavallo, A., Castiello, U., 2012. Grasping intentions: from thought experiments to empirical evidence. Front. Hum. Neurosci. 6, 1–6 , (May)⟨http://doi.org/10.3389/fnhum.2012.00117⟩.

Becchio, C., Pierno, A., Mari, M., Lusher, D., Castiello, U., Cognitiva, S., Generale, P., 2007. Motor contagion from gaze: the case of autism. ⟨http://doi.org/10.1093/brain/awm171⟩

Becchio, C., Sartori, L., Bulgheroni, M., Castiello, U., 2008a. Both your intention and mine are reflected in the kinematics of my reach-to-grasp movement. Cognition 106 (2), 894–912 ⟨http://doi.org/10.1016/j.cognition.2007.05.004⟩.

Becchio, C., Sartori, L., Bulgheroni, M., Castiello, U., 2008b. The case of Dr. Jekyll and Mr. Hyde: a kinematic study on social intention. Conscious. Cogn. 17 (3), 557–564 ⟨http://doi.org/10.1016/j.concog.2007.03.003⟩.

Becchio, C., Sartori, L., Castiello, U., 2010. Toward you: the social side of actions. Curr. Dir. Psychol. Sci. 19 (3), 183–188 ⟨http://doi.org/10.1177/0963721410370131⟩.

Bek, J., Poliakoff, E., Marshall, H., Trueman, S., Gowen, E., 2016. Enhancing voluntary imitation through attention and motor imagery. Exp. Brain Res. 234 (7), 1–10 ⟨http://doi.org/10.1007/s00221-016-4570-3⟩.

Bekkering, H., Wohlschläger, A., Gattis, M., 2000. Imitation of gestures in children is goal-directed. Q. J. Exp. Psychol. A Hum. Exp. Psychol. 53 (1), 153–164 ⟨http://doi.org/10.1080/713755872⟩.

Bernstein, N.A., 1967. The Co-ordination and Regulation of Movements. Pergamon Press, Oxford, UK.

Blakemore, S.J., Frith, C., 2005. The role of motor contagion in the prediction of action. Neuropsychologia 43, 260–267 , (2 SPEC. ISS)⟨http://doi.org/10.1016/j.neuropsychologia.2004.11.012⟩.

Bouquet, C.A., Shipley, T.F., Capa, R.L., Marshall, P.J., 2011. Motor contagion: goal-directed actions are more contagious than non-goal-directed actions. Exp. Psychol. 58 (1), 71–78 ⟨http://doi.org/10.1027/1618-3169/a000069⟩.

Braadbaart, L., Waiter, G.D., Williams, J.H.G., 2012. Neural correlates of individual differences in manual imitation fidelity. Front. Integr. Neurosci. 6, 91 , (October) ⟨http://doi.org/10.3389/fnint.2012.00091⟩.

Brass, M., Bekkering, H., Wohlschläger, A., Prinz, W., 2000. Compatibility between observed and executed finger movements: comparing symbolic, spatial, and imitative

cues. Brain Cogn. 44 (2), 124–143 ⟨http://doi.org/10.1006/brcg.2000.1225⟩.

Castiello, U., 2003. Understanding other people's actions: intention and attention. J. Exp. Psychol. Hum. Percept. Perform. 29 (2), 416–430 ⟨http://doi.org/10.1037/0096-1523.29.2.416⟩.

Chartrand, T.L., Bargh, J. a., 1999. The chameleon effect: the perception-behavior link and social interaction. J. Personal. Soc. Psychol. 76 (6), 893–910 ⟨http://doi.org/10.1037/0022-3514.76.6.893⟩.

Cikara, M., Van Bavel, J.J., 2014. The neuroscience of intergroup relations: an integrative review. Perspect. Psychol. Sci. 9 (3), 245–274 ⟨http://doi.org/10.1177/1745691614527464⟩.

Cook, J., Saygin, A.P., Swain, R., Blakemore, S.-J., 2009. Reduced sensitivity to minimum-jerk biological motion in autism spectrum conditions. Neuropsychologia 47 (14), 3275–3278 ⟨http://doi.org/10.1016/j.neuropsychologia.2009.07.010⟩.

Cook, J., Swapp, D., Pan, X., Bianchi-Berthouze, N., Blakemore, S.-J., 2014. Atypical interference effect of action observation in autism spectrum conditions. Psychol. Med. 44 (4), 731–740 ⟨http://doi.org/10.1017/S0033291713001335⟩.

Culmer, P.R., Levesley, M.C., Mon-Williams, M., Williams, J.H.G., 2009. A new tool for assessing human movement: the kinematic assessment tool. J. Neurosci. Methods 184 (1), 184–192 ⟨http://doi.org/10.1016/j.jneumeth.2009.07.025⟩.

Ferri, F., Campione, G.C., Volta, R.D., Gianelli, C., Gentilucci, M., 2010. To me or to you? When the self is advantaged. Exp. Brain Res. 203 (4), 637–646 ⟨http://doi.org/10.1007/s00221-010-2271-x⟩.

Ferri, F., Campione, G.C., Volta, R.D., Gianelli, C., Gentilucci, M., 2011. Social requests and social affordances: how they affect the kinematics of motor sequences during interactions between conspecifics. PLoS One 6 (1)⟨http://doi.org/10.1371/journal.pone.0015855⟩.

Florendo, M., Miller, L.E., Cook, J., Saygin, A.P., 2014. The Influence of (biological) form on the perception of biological motion. J. Vis. 14 (10), (1008–1008)⟨http://doi.org/10.1167/14.10.1008⟩.

Forbes, P.A.G., Pan, X., de C. Hamilton, A.F., 2016. Reduced mimicry to virtual reality avatars in autism spectrum disorder. J. Autism Dev. Disord.⟨http://doi.org/10.1007/s10803-016-2930-2⟩.

Franklin, D.W., Wolpert, D.M., 2011. Computational mechanisms of sensorimotor control. Neuron⟨http://doi.org/10.1016/j.neuron.2011.10.006⟩.

Georgiou, I., Becchio, C., Glover, S., Castiello, U., 2007. Different action patterns for cooperative and competitive behaviour. Cognition 102 (3), 415–433 ⟨http://doi.org/10.1016/j.cognition.2006.01.008⟩.

Gianelli, C., Scorolli, C., Borghi, A.M., 2013. Acting in perspective: the role of body and language as social tools. Psychol. Res. 77 (1), 40–52 ⟨http://doi.org/10.1007/s00426-011-0401-0⟩.

Grecucci, A., Brambilla, P., Siugzdaite, R., Londero, D., Fabbro, F., Rumiati, R.I., 2013. Emotional resonance deficits in autistic children. J. Autism Dev. Disord. 43 (3), 616–628 ⟨http://doi.org/10.1007/s10803-012-1603-z⟩.

Haggard, P., 1994. Chapter 8 perturbation studies of coordinated prehension. Adv. Psychol. 105, 151–170 ⟨http://doi.org/10.1016/S0166-4115(08)61277-7⟩.

Hamilton, A.F.D.C., Joyce, D.W., Flanagan, J.R., Frith, C.D., Wolpert, D.M., 2007. Kinematic cues in perceptual weight judgement and their origins in box lifting. Psychol. Res. 71 (1), 13–21 ⟨http://doi.org/10.1007/s00426-005-0032-4⟩.

Harris, C.M., Wolpert, D.M., 1998. Signal-dependent noise determines motor planning. Nature 394 (6695), 780–784 ⟨http://doi.org/10.1038/29528⟩.

Hayes, S.J., Dutoy, C.A., Elliott, D., Gowen, E., Bennett, S.J., 2016. Atypical biological motion kinematics are represented by complementary lower-level and top-down processes during imitation learning. Acta Psychol. 163, 10–16 ⟨http://doi.org/10.1016/j.actpsy.2015.10.005⟩.

Heyes, C., 2011. Automatic imitation. Psychol. Bull. 137 (3), 463–483 ⟨http://doi.org/10.1037/a0022288⟩.

Jacob, P., Jeannerod, M., 2005. The motor theory of social cognition: a critique. Trends Cogn. Sci. 9 (1), 21–25 ⟨http://doi.org/10.1016/j.tics.2004.11.003⟩.

Kilner, J., Paulignan, Y., Blakemore, S., 2003. An interference effect of observed biological movement on action. Curr. Biol. 13.

Kilner, J., Hamilton, A.F.D.C., Blakemore, S., 2007. Interference effect of observed human movement on action is due to velocity profile of biological motion. Soc. Neurosci. 2 (3–4), 158–166 ⟨http://doi.org/10.1080/17470910701428190⟩.

Kilner, J.M., Neal, A., Weiskopf, N., Friston, K.J., Frith, C.D., 2009. Evidence of mirror neurons in human inferior frontal gyrus. J. Neurosci. 29 (32), 10153–10159 ⟨http://doi.org/10.1523/JNEUROSCI.2668-09.2009.Evidence⟩.

Kupferberg, A., Huber, M., Helfer, B., Lenz, C., Knoll, A., Glasauer, S., 2012. Moving just like you: Motor interference depends on similar motility of agent and observer. PLoS One 7 (6), 1–8 ⟨http://doi.org/10.1371/journal.pone.0039637⟩.

Lewkowicz, D., Quesque, F., Coello, Y., Delevoye-Turrell, Y.N., 2015. Individual differences in reading social intentions from motor deviants. Front. Psychol. 6, 1–12 , (August)⟨http://doi.org/10.3389/fpsyg.2015.01175⟩.

Liepelt, R., Brass, M., 2010. Top-down modulation of motor priming by belief about animacy. Exp. Psychol. 57 (3), 221–227 ⟨http://doi.org/10.1027/1618-3169/a000028⟩.

Manera, V., Becchio, C., Cavallo, A., Sartori, L., Castiello, U., 2011. Cooperation or competition? Discriminating between social intentions by observing prehensile movements. Exp. Brain Res. 211 (3–4), 547–556 ⟨http://doi.org/10.1007/s00221-011-2649-4⟩.

Marshall, P.J., Bouquet, C.A., Thomas, A.L., Shipley, T.F., 2010. Motor contagion in young children: exploring social influences on perception-action coupling. Neural Netw. 23 (8–9), 1017–1025 ⟨http://doi.org/10.1016/j.neunet.2010.07.007⟩.

Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., Dugas, C., 1987. Constraints on human arm movement trajectories. Can. J. Psychol. 41 (3), 365–378 ⟨http://doi.org/10.1037/h0084157⟩.

Meulenbroek, R.G.J., Bosga, J., Hulstijn, M., Miedl, S., 2007. Joint-action coordination

in transferring objects. Exp. Brain Res. 180 (2), 333–343 ⟨http://doi.org/10.1007/s00221-007-0861-z⟩.

Miles, L.K., Lumsden, J., Richardson, M.J., Neil Macrae, C., 2011. Do birds of a feather move together? Group membership and behavioral synchrony. Exp. Brain Res. 211 (3–4), 495–503 ⟨http://doi.org/10.1007/s00221-011-2641-z⟩.

Obhi, S.S., 2012. The amazing capacity to read intentions from movement kinematics. Front. Hum. Neurosci. 6, 162 ⟨http://doi.org/10.3389/fnhum.2012.00162⟩.

Oztop, E., Franklin, D.W., Chaminade, T., 2005. Human − Humanoid Interaction : Is a Humanoid, 2(4), 537–559.

Patel, D., Fleming, S.M., Kilner, J.M., 2012. Inferring subjective states through the observation of actions. Proc. Biol. Sci./R. Soc. 279 (1748), 4853–4860 ⟨http://doi.org/10.1098/rspb.2012.1847⟩.

Prinz, W., 1990. A common coding approach to perception and action. Relatsh. Percept. Action, 167–201 ⟨http://doi.org/10.1007/978-3-642-75348-0_7⟩.

Prinz, W., 1997. Perception and action planning. Eur. J. Cogn. Psychol. 9, 129–154 ⟨http://doi.org/10.1080/713752551⟩.

Quesque, F., Coello, Y., 2014. For your eyes only: effect of confederate's eye level on reach-to-grasp action. Front. Psychol. 5, 1–7 ⟨http://doi.org/10.3389/fpsyg.2014.01407⟩.

Quesque, F., Coello, Y., 2015. Perceiving what you intend to do from what you do: evidence for embodiment in social interactions. Socio. Neurosci. Psychol. 5, 28602 ⟨http://doi.org/10.3402/snp.v5.28602⟩.

Quesque, F., Delevoye-Turrell, Y., Coello, Y., 2015. Facilitation effect of observed motor deviants in a cooperative motor task: Evidence for direct perception of social intention in action. Q. J. Exp. Psychol. 218, 1–13 ⟨http://doi.org/10.1080/17470218.2015.1083596⟩.

Quesque, F., Lewkowicz, D., Delevoye-Turrell, Y., Coello, Y., 2013. Effects of social intention on movement kinematics in cooperative actions. Front. Neurorobotics 7, 1–10 ⟨http://doi.org/10.3389/fnbot.2013.00014⟩.

Rauchbauer, B., Majdandžić, J., Hummer, A., Windischberger, C., Lamm, C., 2015. Distinct neural processes are engaged in the modulation of mimicry by social group-membership and emotional expressions. Cortex 70, 49–67 ⟨http://doi.org/10.1016/j.cortex.2015.03.007⟩.

Reader, A.T., Holmes, N.P., 2015. Video stimuli reduce object-directed imitation accuracy: a novel two-person motion-tracking approach. Front. Psychol. 6, 644 ⟨http://doi.org/10.3389/fpsyg.2015.00644⟩.

Reader, A.T., Holmes, N.P., 2016. Examining ecological validity in social interaction: problems of visual fidelity, gaze, and social potential. Cult. Brain⟨http://doi.org/10.1007/s40167-016-0041-8⟩.

Roberts, J.W., Bennett, S.J., Hayes, S.J., 2015. Top-down social modulation of interpersonal observation???execution. Psychol. Res., 487–495 ⟨http://doi.org/10.1007/s00426-015-0666-9⟩.

Roberts, J.W., Hayes, S.J., Uji, M., Bennett, S.J., 2014. Motor contagion: the contribution of trajectory and end-points. Psychol. Res. 79 (4), 621–629 ⟨http://doi.org/10.1007/s00426-014-0589-x⟩.

Saby, J.N., Marshall, P.J., Smythe, R., Bouquet, C.A., Comalli, C.E., 2011. An investigation of the determinants of motor contagion in preschool children. Acta Psychol. 138 (1), 231–236 ⟨http://doi.org/10.1016/j.actpsy.2011.06.008⟩.

Sartori, L., Becchio, C., Bara, B.G., Castiello, U., 2009a. Does the intention to communicate affect action kinematics? Conscious. Cogn. 18 (3), 766–772 ⟨http://doi.org/10.1016/j.concog.2009.06.004⟩.

Sartori, L., Becchio, C., Bulgheroni, M., Castiello, U., 2009b. Modulation of the action control system by social intention: unexpected social requests override preplanned action. J. Exp. Psychol. Hum. Percept. Perform. 35 (5), 1490–1500 ⟨http://doi.org/10.1037/a0015777⟩.

Simmons, J.P., Nelson, L.D., Simonsohn, U., 2011. False-positive psychology: undisclosed flexibility in data collection and analysis allows presenting anything as significant. Psychol. Sci. 22 (11), 1359–1366 ⟨http://doi.org/10.1177/0956797611417632⟩.

Slepian, M.L., Young, S.G., Rutchick, A.M., Ambady, N., 2013. Quality of Professional Players' Poker Hands Is Perceived Accurately From Arm Motions. ⟨http://doi.org/10.1177/0956797613487384⟩

Stanley, J., Gowen, E., Miall, R.C., 2007. Effects of agency on movement interference during observation of a moving dot stimulus. J. Exp. Psychol. Hum. Percept. Perform. 33 (4), 915–926 ⟨http://doi.org/10.1037/0096-1523.33.4.915⟩.

Stewart, H.J., Mcintosh, R.D., Williams, J.H.G., 2013. A specific deficit of imitation in autism spectrum disorder. Autism Res. 6 (6), 522–530 ⟨http://doi.org/10.1002/aur.1312⟩.

Stone, W.L., Ousley, O.Y., Littleford, C.D., 1997. Motor imitation in young children with autism: what's the object? J. Abnorm. Child Psychol. 25 (6), 475–485 ⟨http://doi.org/10.1023/A:1022685731726⟩.

Tai, Y.F., Scherfler, C., Brooks, D.J., Sawamoto, N., Castiello, U., 2004. The human premotor cortex is "mirror" only for biological actions. Curr. Biol. 14 (2), 117–120 ⟨http://doi.org/10.1016/j.cub.2004.01.005⟩.

Todorov, E., Jordan, M.I., 2002. Optimal feedback control as a theory of motor coordination. Nat. Neurosci. 5 (11), 1226–1235 ⟨http://doi.org/10.1038/nn963⟩.

van Schaik, J.E., Endedijk, H.M., Stapel, J.C., Hunnius, S., 2016. Young children's motor interference is influenced by novel group membership. Front. Psychol. 7⟨http://doi.org/10.3389/fpsyg.2016.00321⟩.

Wang, Y., Hamilton, A.F.D.C., 2012. Social top-down response modulation (STORM): a model of the control of mimicry in social interaction. Front. Hum. Neurosci. 6, 153 ⟨http://doi.org/10.3389/fnhum.2012.00153⟩.

Wang, Y., Hamilton, A.F. de C., 2013. Understanding the role of the "self" in the social priming of mimicry. PLoS One 8 (4)⟨http://doi.org/10.1371/journal.pone.0060249⟩.

Wild, K.S., Poliakoff, E., Jerrison, A., Gowen, E., 2010. The influence of goals on

movement kinematics during imitation. Exp. Brain Res. 204 (3), 353–360 ⟨http://doi.org/10.1007/s00221-009-2034-8⟩.

Wild, K.S., Poliakoff, E., Jerrison, A., Gowen, E., 2012. Goal-directed and goal-less imitation in autism spectrum disorder. J. Autism Dev. Disord. 42 (8), 1739–1749 ⟨http://doi.org/10.1007/s10803-011-1417-4⟩.

Williams, J.H.G., Casey, J.M., Braadbaart, L., Culmer, P.R., Mon-Williams, M., 2013. Kinematic measures of imitation fidelity in primary school children. J. Cogn. Dev.

8372, (null-null)⟨http://doi.org/10.1080/15248372.2013.771265⟩.

Wolpert, D.M., Doya, K., Kawato, M., 2003. A unifying computational framework for motor control and social interaction. Philos. Trans. R. Soc. Lond. B Biol. Sci. 358 (1431), 593–602 ⟨http://doi.org/10.1098/rstb.2002.1238⟩.

Wolpert, D.M., Ghahramani, Z., Jordan, M.I., 1995. An internal model for sensorimotor integration. Science 269, 1880–1882 ⟨http://doi.org/10.1126/science.7569931⟩.