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Imitation from a joint action perspective

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Imitation research has focused on turn-taking contexts in which one person acts and one person then copies that action. However, people also imitate when engaging in joint actions, where two or more people coordinate their actions in space and time in order to achieve a shared goal. We discuss how the various constraints imposed by joint action modulate imitation, and the close links between perception and action that form the basis of this phenomenon. We also explore how understanding imitation in the context of joint action yields new insights into cultural phenomena such as teaching and innovation.

KEYWORDS
cultural transmission, imitation, improvisation, interpersonal coordination, joint action, teaching

1 | INTRODUCTION

Imitation plays a central role in human sociality, and is ubiquitous in social interactions. It is one of the driving forces behind cultural evolution due to its importance for the sharing of cultural knowledge and skills (Tomasello, 1994). It features prominently in parent–child interactions (Csibra & Gergely, 2009) and cultural practices such as music and dance (Blackmore, Dugatkin, Boyd, Richerson & Plotkin, 2000) and has even been described as a “social glue” due to the various prosocial and affiliative effects it yields (Dijksterhuis, 2005). Despite its documented importance to sociality, the investigation of behavioural, cognitive, and neural mechanisms of imitation has largely been restricted to contexts in which one person acts and then subsequently another person copies (henceforth referred to as “classical imitation”). Although these classical imitation contexts have been invaluable in informing our understanding of imitation, they are just a small subset of the types of social interactions that we engage in during our daily lives.

Many of our interactions with others involve joint action, which can be defined in a broad way as “two or more people coordinating their actions in space and time in order to bring about a change in the environment” (Sebanz, Bekkering & Knoblich, 2006; for a discussion of other definitions and a useful minimalist definition, see Butterfill, 2016). Whether it be dancing the tango, carrying a sofa, or even just passing a pen to that one person in your class who never has his/her own stationery, coordinating our actions with other people is a huge part of our everyday lives. Importantly, imitation is also often observed in the context of joint action, for example, two dancers trying to synchronize the same movement, a musician in a jazz band copying another's improvised tune, or a child and a parent taking turns in feeding the ducks.

Some of the processes underlying our ability to imitate others' actions are thought to also play an important role for joint action. In particular, close links between perception and action allow not only for the copying of observed actions but for making predictions about others' actions that are crucial for joint action coordination. At the same time, joint action coordination places additional requirements on the cognitive systems of human co-actors. These requirements are not accounted for by theories of classical imitation and offer routes to learning and cultural transmission that may deviate from the ones identified in studies of classical imitation. Therefore, one aim of the present paper is to spell out implications from joint action studies that provide a deeper embedding of imitation in the context of real-time reciprocal interactions.

A second aim is to consider the role of imitation and learning in joint action. Much of the joint action literature has focused on temporal coordination, at times neglecting questions about the role of similarity between different co-actors' actions, questions about transmission of skills and practices, and the mapping of observed actions onto one's own body. We will specifically review joint action studies that shed light on these processes, demonstrating how questions that stem from the study of imitation gain new relevance when applied to the context of joint action.

The paper is organized as follows. We will first briefly review the role of close links between perception and action for imitation and joint action. We will then discuss how the operations of these close links are modulated by joint action goals, by representations of the group one is part of, and by bodily relations between co-actors. Next, we will discuss how dynamics between co-actors are affected by the reciprocity of information flow that is a core characteristic of joint action, spelling out implications for synchronized imitative joint actions like the mirror game. Finally, we will take a look at the opportunities for information exchange, teaching and learning of skills, and innovations that arise by participating in joint action, arguing that there is more to cultural transmission processes than suggested by imitation research.

2 | PERCEPTION–ACTION LINKS

Imitation is a broad phenomenon that includes behaviours such as non-conscious mimicry (Chartrand & Bargh, 1999), stimulus–response compatibility (Brass, Bekkering & Prinz, 2001), automatic imitation (Heyes, 2011), and intentional and goal-directed copying (Fridland & Moore, 2015). A basic principle that can be used to explain the wide range of imitation behaviours that people engage in relies on the premise that perception and action share a common representational code. Given the tight coupling between perception and action, visual representations of an observed action can activate motor representations of that action in an observer (Prinz, 1997).

Behavioural evidence supporting this theory comes, for example, from a study by Brass et al. (2001). They investigated whether a stimulus response arrangement with high or low ideomotor similarity between observed and executed actions could lead to compatibility effects, with observed actions facilitating or interfering with the executed action. Participants were required to make simple finger movements (lifting or tapping) and were presented with an actor carrying out either compatible or incompatible movements. They found that observing the action to be performed facilitated responses, while observing the opposite action interfered. Moreover, their control experiments ruled out alternative explanations of general spatial compatibility or movement direction, suggesting that this effect of perceived actions on performance is indeed due to the overlap between visual and motor representations of actions. Neurophysiological evidence of the common coding theory comes in the form of "mirror neurons," which fire both when executing and when observing the same action (Rizzolatti & Craighero, 2004), as well as from numerous brain imaging studies demonstrating that perception and action are coupled on the neural level (Iacoboni, 2009).

Common representations of perceived actions and performed actions are also thought to underlie the ability to accurately predict the actions of a co-actor, which is central for joint action coordination. It has been proposed that predicting the outcome of another's actions largely relies on the same mechanisms that allow one to predict the outcome of one's own actions. The motor system uses predictive internal models in order to predict the sensory consequences of an executed action. The motor system then matches the predicted sensory consequences with the actual consequences of the action, with any error propagating back through the system in order to update the internal model (Wolpert & Flanagan, 2001). This same mechanism has been proposed to be responsible for predicting the actions of an interaction partner. We use internal models from our own motor system in order to predict the sensory consequences of others' actions by matching these predictions to the actual consequences of others' actions (Wolpert, Doya & Kawato, 2003). Thus, close perception action links may not only be useful for imitating previously observed actions, but they may also help with preparing the actions that observed actors are expected to perform.

2.1 | Goal representations modulating imitative tendencies

Common representations of perceived and performed actions imply that observing (or imagining) a particular action elicits a covert, and occasionally even an overt, tendency to perform the same action (Cook, Bird, Lünser, Huck & Heyes, 2011; Fadiga et al., 1998). This can be helpful for imitation, where an observer's goal is to reproduce an observed action. Although co-actors engaging in a joint action can have the same goals (i.e., produce the same actions), typically, they will have a joint goal and individual sub-goals that they will need to carry out in order to achieve the joint goal. In this type of scenario, people have to complete complementary rather than identical actions. The challenge that joint action poses here concerns how to perform complementary actions given the tendency to automatically imitate.

There is indeed evidence that when trying to coordinate complementary actions, people have a tendency to automatically imitate their co-actors, which impedes their joint performance. Sacheli, Tidoni, Pavone, Aglioti and Candidi (2013) designed a task in which a leader and a follower were instructed to grasp a bottle in synchrony. The leader was instructed to grasp the bottle either with a power or precision grip, with the follower being required to either carry out an imitative action or a complementary action. They found that the most coordinated trials (marked by low asynchrony between the two actors) were characterized by the absence of automatic imitation as quantified by a large difference between the leader's and followers' maximum grip aperture and a large difference between their wrist height. In the least coordinated trials, automatic imitation was present as quantified by a small difference between the leader's and follower's maximum grip aperture and wrist height. Moreover, the magnitude of the automatic imitation was correlated with asynchronies, suggesting that automatic imitation impeded joint performance. This demonstrates that the close links between perception and action that facilitate imitation can get in the way of joint action performance. However, the study also demonstrates that the ability to inhibit the tendency to imitate a co-actor can lead to successful coordination.

Findings by van Schie, van Waterschoot and Bekkering (2008) provide evidence for people's ability to override imitative tendencies when executing actions that are complementary to the actions that they observe. Participants were presented with an actor grasping an object either with a power or precision grip whilst completing an imitation task (e.g., carry out a power grip in response to observing a power grip) or a “joint action task” (e.g., carry out a precision grip in response to observing a power grip). For the test trials, participants were instructed to carry out either a power grip or a precision grip, regardless of the actor's grasp, leading to congruent and incongruent actions. As expected, van Schie et al. found a congruency effect in the imitation condition, with participants being quicker to execute imitative actions. However, for the test trials, in the joint action condition, the congruency effect was reversed, with participants being quicker to respond to complementary grasps. The instruction to complement the co-actor in this condition seemed to be sufficient to reverse the congruency effect, suggesting that the mapping between observed actions and executed actions is flexible and can be modulated by context-specific joint action goals.

A later study by Sartori, Bucchioni and Castiello (2012) investigated how the tendency to imitate or to perform complementary actions unfolds over time, using a task in which participants watched an actor carrying out social or non-social actions. Participants watched a video of an actor making coffee, in which the actor either intended to pour sugar (with a precision grip) or coffee (with a power grip) into a mug that was aligned with the participant. Crucially, these actions were either shown in a social context, in which the actor intended to put sugar or coffee in the participant's mug, or a non-social context, in which the actor never intended to interact with the participant's mug. The experimenter recorded motor-evoked potentials (MEPs; an indicator of muscular activity) in the arms and hands at five time points and found that initially MEPs were the strongest for the imitative response. However, at a later stage of the action, the MEPs became stronger for the complementary response but only in the social condition, where the actor would interact with the participant's cup. This study demonstrates that the motor system can flexibly switch between imitative and complementary modes of action: an early tendency to automatically imitate can be reversed in later processing when a co-actor has a social intention.

Taken together, the above studies demonstrate that people can effectively override the tendency to automatically imitate when in a joint action context. This occurs when they know in advance that a complementary action is required (as in Sacheli et al., 2013, Van Schie et al., 2008) but also when they infer the necessity for complementary action from observed kinematics during early stages of observing another's action (as in Sartori et al., 2012). As suggested by Sacheli et al. (2013), failure to inhibit automatic imitation is likely due to the failure to successfully incorporate a co-actor's actions into a joint action plan. Successful joint action planning allows us to incorporate our co-actor into our own action planning, similar to intrapersonal coordination where relations between different parts of a coordinated action (e.g., actions performed by the left and right hand) are represented in a single plan (Kourtis, Knoblich, Woźniak & Sebanz, 2014).

2.2 | Individual versus group representations

If observing an action performed by another individual activates corresponding motor representations, what happens when we observe joint actions? This question is relevant for joint actions where multiple groups of individuals coordinate with each other, as well as for joint action imitation, where one group of co-actors is trying to perform the same actions as another group. For example, take a pair of tango novices trying to perform a figure that they have just observed being performed by an expert couple. If each of the novices only tried to copy one part (one trying to do the leader's part, the other the follower's), their coordination might suffer because—as we discussed earlier—successful joint action relies on plans that specify relations between different actions. If observing joint actions triggered corresponding joint action plans, this might facilitate the imitation of joint actions.

To investigate this hypothesis, Ramenzoni, Sebanz and Knoblich (2014) employed an experimental task in which dyads were instructed to tap in synchrony with the index fingers of an observed pair of hands. The hands were shown on a screen from an allocentric point of view, as if one or two people were facing the participants. Crucially, the observed hands belonged either to one actor tapping bimanually or to two actors tapping together with one hand each. The index fingers of the hands moved in alternation, and the instruction for participants was to synchronize with each tap using the corresponding hand (so, e.g., when the hand on the left side of the screen moved, the participant sitting on the left would try to respond in synchrony with it). The results showed that participants' spatio-temporal matching of the actions was more accurate when they observed joint actions, compared to observing identical actions being performed by a single individual. The authors explained this by suggesting that it is easier to map representations of joint action outcomes onto a joint internal model, thus allowing participants engaging in joint actions to more effectively imitate groups than individuals.

Generally, this study indicates that the notion of common representations of perceived and performed actions is not sufficient for explaining joint action imitation and coordination between groups of individuals. Rather, one needs to consider the role of top–down influences of joint action representations specifying joint action outcomes; these representations constrain how we employ internal models to map observed actions onto our own motor system. This seems to hold true not only for continuous action sequences as in the tapping task described above but also for imitation of discrete actions (Tsai, Sebanz & Knoblich, 2011).

2.3 | Bodily representations

Spatial and bodily relations between interacting individuals can also modulate imitative tendencies that action observation induces for performance. It has been demonstrated that similarity between the spatial configuration of observed and performed actions can provide a source of facilitation or interference, with people mapping the spatial characteristics of the observed movements onto their own movements (Brass et al., 2001). For example, consider two people lifting a box together whilst facing each other; their hands are spatially aligned but not topologically aligned because they are lifting with different hands. It has been shown that topological similarity between the observed and performing effectors can provide a source of facilitation or interference, with people mapping the observed body parts onto their own body parts (Catmur et al., 2008; Tsakiris, 2010). An example of this can come from capoeira: when demonstrating techniques, experts will match the bodily orientation of the student to make it easier for the student to map the observed movements onto their own body (Downey, 2008).

Imitation research on spatial and topological relations has focused on discrete actions, in which one person is required to imitate the actions of another. In this context, spatial mappings appear to dominate over topological mappings. However, joint actions are often continuous, with actors coordinating sequences of actions in synchrony. Do the real-time constraints of joint action coordination affect the operation of spatial and topological mappings? If action prediction mechanisms based on internal models in the motor system are involved in continuous imitation, then topological mappings are likely to play a greater role because internal models rely on bodily representations.

In a recent study addressing this question (Ramenzoni, Sebanz & Knoblich, 2015), participants were presented with a model tapping her left and right index fingers in alternation at increasing speeds. Participants were instructed to imitate the model by always tapping with the corresponding hand, which requires applying spatial mappings. They were also instructed to tap in synchrony with the model, keeping to the same tempo. Crucially, the stimuli were presented from either an egocentric or an allocentric perspective so that the model's hands were either topologically congruent or incongruent with the participants' hands. For example, making a left tap from the egocentric perspective involved using one's left hand in response to the model's left hand movement, while from the allocentric perspective, performing a left hand movement was required in response to the model's right hand movement.

It was found that topological incongruence interfered with the maintenance of spatial mappings. Even though participants were instructed to always tap with the spatially corresponding hand, they had a tendency to synchronize with the anatomically matching hand of the model. Interestingly, the topological interference effect was particularly strong in musicians who have extensive experience from their training in matching others' body movements onto their own. This suggests that people use topological mappings to imitate continuous action sequences and that their ability to predict the co-actor's actions depends on these topological mappings. Generally, these findings demonstrate that, for a comprehensive understanding of the processes involved in imitation, it may be important to consider real-time constraints of social interaction.

3 | DYNAMICS OF IMITATIVE JOINT ACTIONS

Many joint actions provide the opportunity for a bidirectional flow of information, with both members of a dyad influencing each other's behaviour reciprocally. This stands in contrast to classical imitation scenarios that are typically unidirectional; a demonstrator will produce an action to be imitated by an observer who has no influence over the demonstrator's actions. However, there are also cases of imitative interactions where two individuals mutually adjust to each other in order to perform the same actions in synchrony. This can be seen in the mirror game, an exercise used widely in improvisation training where two or more people try to spontaneously perform the same movements in synchrony, "mirroring" each other as closely as possible. Research on joint action and on the mirror game as a special, improvised form has started to address the question of how the dynamics of information flow and the assignment of roles affect coordination. Is it beneficial to have a clear leader and a follower, akin to the role distribution in classical imitation, or do people achieve better coordination when they mutually predict and adapt to each other?

It has been argued that, in order to achieve effective temporal synchrony, we employ both reactive and predictive processes (van der Steen, Jacoby, Fairhurst & Keller, 2015). People are adaptive to their partners, employing phase and period correction in order to maintain temporal synchrony with their partners. As discussed earlier, people also employ predictive internal models in order to anticipate the timing of their partner's actions (Repp & Keller, 2008; Wolpert et al., 2003). How the directionality of the information flow between co-actors affects these predictive and adaptive processes underpinning temporal coordination was addressed in a study by Konvalinka, Vuust, Roepstorff and Frith (2010). Participants were required to synchronize the timing of tapping movements with a co-actor. They completed a unidirectional coupling condition, in which only one of the two co-actor's taps was audible, and a bidirectional coupling condition, in which each participant could hear the other's taps.

There was evidence of a clear leader–follower relationship in the unidirectional condition, as evidenced by the fact that the non-audible participant's inter-tap intervals (ITIs) oscillated around the audible participant's ITIs, demonstrating that the "leader" was unresponsive, and the "follower" was continuously trying to adapt. In the bidirectional condition, participants' ITIs oscillated around each other, which demonstrated that both participants were trying to mutually predict and adapt to each other, a behaviour the authors termed “hyper-following”. Interestingly, coordination performance in terms of asynchronies was better in the bidirectional condition than in the unidirectional condition, demonstrating that successful interpersonal coordination relies on mutual prediction and adaptation.

Findings by Noy and colleagues suggest that bidirectionality is also crucial for synchronization of actions in imitative interactions (Noy, Dekel & Alon, 2011). They transformed the mirror game into a one-dimensional coordination game in which two participants would stand opposite one another, each moving a slider that recorded movement data as participants were moving left and right. Participants were instructed to imitate and synchronize with each other in order to create interesting patterns together. In some rounds of the game, roles were assigned, designating one participant as the leader and the other as a follower, whereas in other rounds, participants played the game without role assignment. Leader–follower interactions were characterized by velocity profiles that were smooth and “confident” for leaders but not for followers, who jittered around the leader's trajectory, overshooting and undershooting as they were trying to track and follower the leader's movements. In contrast, interactions without role assignment yielded movement trajectories in which both participants' movements were smooth and confident; this was labelled “co-confident motion.” The authors argued that, when jointly improvising in a successful way, people enter a state of mutual agreement, which allows them to share the leader role. In terms of underlying mechanisms, co-confident motion can be modelled and explained by coupled predictive models where the output of one controller is the input for the other (Noy et al., 2011).

The benefits of coordinating without role assignment were only observed in participants with musical or theatre improvisation experience, raising questions about the conceptual and procedural expertise required to engage in co-confident motion. In a later study using the same one-dimensional movement task, Hart, Noy, Feniger-Schaal, Mayo and Alon (2014) showed that during joint improvisation, participants move in ways that make their actions easier to predict. In particular, the velocity profiles of participants when engaged in co-confident motion were characterized by very low skewness (implying symmetry of acceleration and deceleration phase of the movement) and low kurtosis (implying gentle acceleration and deceleration). Interestingly, participants displayed low skewness and low kurtosis movements when in co-confident motion regardless of their movement characteristics when moving alone.

These findings are important for our understanding of imitative joint actions for a number of reasons. They demonstrate that the interactional roles that participants are engaged in affect their ability to imitate each other under specific timing constraints (synchrony). The jittery movements in followers' non-confident movements could be taken as evidence that followers do not make the best imitators, at least in improvised joint actions. Another interesting point is that movements produced in highly coordinated joint actions can be qualitatively different from movements produced alone, and even different from movements produced in leader–follower interactions. Whether this imbues these movements with particular aesthetic qualities is an interesting question for future research.

4 | TEACHING AND LEARNING IN THE CONTEXT OF JOINT ACTION

Social learning is a key route through which we acquire knowledge, including knowledge about objects and practices. Research on teaching and learning about objects and actions has largely focused on the classical imitation context, in which a teacher demonstrates to a student, who then reproduces what has been observed. There are several ways in which teachers can support learning in this context. The theory of natural pedagogy proposes that experts use ostensive communication in order to signal to a novice their intention to teach. Cues such as direct eye gaze and pointing signal that the expert is about to communicate something which is learning-relevant and generalizable (Csibra & Gergely, 2009). Ostensive communication helps to maintain learners' attention and may bias their memory towards generic information (Yoon, Johnson & Csibra, 2008).

There is evidence that experts not only add ostensive signals but also modulate specific parameters of their instrumental actions in order to support learning through demonstration. This type of communication, labelled “motionese,” consists of experts exaggerating movement parameters such as movement height or movement punctuality (Brand, Baldwin & Ashburn, 2002). This allows the experts to highlight parts of an action sequence that are most relevant for learning (Brand & Shallcross, 2008; Koterba & Iverson, 2009). Moreover, it also allows for the novice to more easily parse an action sequence into sub-goals, thus understanding the overall structure of the action (Nagai & Rohlfing, 2008). Motionese differs from ostensive communication because, here, experts do not signal an intention to teach but rather use parameters of their instrumental actions to bias the observer's attention to the most learning-relevant part of an action sequence. This can facilitate the novice's processing of what is being demonstrated.

Although there is no doubt that observing others and imitating them plays a very large role in social learning, interaction between novices and experts is highly variable and dynamic and includes many coordinated joint actions. For example, a child learning how to play the xylophone from an adult will not only watch and then try to imitate but might try to play in synchrony with the adult. The remainder of this section will explore some of the ways in which people can learn through participating in joint action. Firstly, we will focus on the overlap of the communicative signals involved in teaching and joint action coordination, exploring the possibility that sensorimotor communication in joint action can also provide learning-relevant information. We will then discuss some of the ways in which learning can arise by being haptically coupled with another person.

4.1 | Teaching and learning: Sensorimotor communication

During recent years, several studies have provided evidence that people adjust the kinematic parameters of their movements not only during demonstration but also in order to support joint action coordination. This has been labelled sensorimotor communication, which includes modulations of instrumental actions like exaggerating the spatial trajectory or slowing down of the movements. These kinematic adjustments allow a co-actor to more effectively disambiguate and predict the actions of their partners (Pezzulo, Donnarumma & Dindo, 2013). An example comes from Vesper and Richardson (2014), who investigated the performance of a joint task in which two participants had to coordinate a sequence of taps towards different spatial locations, with either full, partial, or no vision of their co-actor. They found that participants exaggerated the maximum height of their movements selectively when their partner could see them, suggesting that this exaggeration was used in order to support the predictions of their co-actor. Exaggerating kinematic parameters can support joint action coordination by allowing one to more quickly and effectively select the most appropriate internal model in order to predict the actions of one's co-actor.

A recent study (McEllin, Knoblich & Sebanz, in press) directly compared the movement kinematics people produced when they were demonstrating how to play specific melodies on a virtual xylophone to a novice and when they were playing in synchrony with the novice. Compared to a baseline of individual performance, similar exaggerations of movement height were observed in both social contexts. Given that people modulate their actions in similar ways when demonstrating an action to a novice and when coordinating with a task partner, it is plausible that the kinematic cues produced to facilitate prediction in joint action coordination could also provide learning-relevant cues. An expert's way of acting during joint action coordination may bias the attention of a less expert co-actor to the learning- relevant parts of an action sequence and better allow the novice to understand the structure of the action, even in the absence of any explicit intention to teach or learn. Further studies are needed to determine whether being engaged in a joint action indeed provides an alternative route to learning that depends on coordination constraint, and whether it can be as effective or even more effective than demonstration.

Another interesting question that sensorimotor communication in joint action raises is how "rational" (effective) people are when imitating a co-actor (Gergely, Bekkering & Király, 2002) and whether they engage in any over-imitation (McGuigan, Makinson & Whiten, 2011). It could be construed as irrational to exactly imitate the way in which the co-actor performed an action when this deviated from the most effective trajectory for communicative purposes. However, if one is learning how to perform the other's part of a joint action, then faithfully copying the other's trajectory and timing may turn out to be optimal for subsequent joint actions. Thus, it would be interesting to investigate in future research if over-imitation depends on whether the imitator intends to later carry out the action alone or with another person.

4.2 | Teaching and learning: Haptic information sharing

Often, people are haptically coupled in joint actions and can use the haptic channel as a means to share information. An example of this is two people carrying a table around a corner whilst facing each other. The person walking forward can see what direction to turn the table; however, the person walking backward does not have access to this information. This can be resolved by the person facing forward applying more force in the correct direction, thus signalling which way to turn.

It has been shown that people exploit the haptic channel when coupled in order to support joint action coordination. van der Wel, Knoblich and Sebanz (2011) asked participants to move a pole from left to right by pulling cords attached to either side of the pole; the cords measured the amount of force that each participant pulled with. The participants' task was to move the pole between two targets at different frequencies and amplitudes, either bimanually or together with another participant. They found more force overlap between the two cords in participants who were performing the task together compared to participants performing the same task bimanually, with the highest force overlap during difficult joint coordination points. Importantly, participants acting together achieved the same level of performance as participants acting bimanually. The authors suggested that applying more force in the joint condition was used as a haptic communication channel in order to support interpersonal coordination.

Given that haptic coupling can facilitate coordination, it may also allow experts to guide a novice through an action sequence and scaffold his/her learning. An example of this comes from Mead and Bateson (1942) who studied teaching and learning in a Balinese society. When first learning how to play particular musical instruments, a teacher will stand behind the student, guiding her through the action to be performed by directly applying pressure to the relevant limbs. This type of teaching requires no verbal instruction or face-to-face visual demonstration; rather, the teacher uses haptic coupling in order to provide the student with direct motor experience of the action.

Haptic coupling could support skill learning in a number of ways. One possibility is that it may allow an expert to constrain the novice's action exploration space (Newell, 1991). Indeed, at the very early stages of learning a motor skill, people are faced with the "motor equivalence problem," which describes the large number of degrees of freedom we face when first carrying out a motor task. A partial solution to this problem is a "locking out" of degrees of freedom in one's movements in order to make them more controllable (Bernstein, 1967). Haptic coupling could provide the expert with a way of systematically constraining the novice's degrees of freedom, thereby reducing his/her action exploration space (Bosga & Meulenbroek, 2007).

Moreover, haptic coupling may allow experts to provide novices with very accurate feedback that they can use to fine-tune their forward models. Haptic coupling provides a scaffold within which experts and novices can exchange information at high temporal and spatial resolution; the expert can continuously feel whether the novice is executing the action correctly and can continuously adjust to provide fine-grained feedback, guiding the novice's movements with high spatial and temporal precision. In a study by Feygin, Keehner and Tendick (2002), participants learned and reproduced complex motions whilst undergoing different trainings: haptic guidance, visual guidance, or haptic and visual guidance. Interestingly, visual guidance yielded more accurate reproductions of the spatial trajectory of the movement, while haptic guidance yielded more accurate reproduction of the timing of the action. Moreover, participants performed best overall when guided both haptically and visually. These findings indicate that haptic coupling as a form of joint action may provide a unique route to learning that complements other forms of social learning, being particularly suited for teaching fine-grained timing aspects of actions and action sequences.

4.3 | Cultural transmission and innovation through joint action

Understanding how people transform their actions for coordinative purposes may also contribute to our understanding of cultural transmission. Two key questions here are how the relative stability of cultural traditions can be explained (Sperber & Hirschfeld, 2004) and how innovation is brought about (Legare & Nielsen, 2015). Traditionally, imitation has been considered the main or even sole mechanism of transmission (Heyes, Huber, Gergely & Brass, 2009). However, joint action may contribute to increasing the fidelity of transmission as well as creating unique opportunities for innovation.

A study by Herrmann, Legare, Harris and Whitehouse (2013) showed that children imitated an observed action more faithfully when they observed two actors performing the same action in synchrony, compared to observing the two actors performing the action in succession or observing only a single model. The finding that not simply the number of observed models but their interaction with each other boosted imitation indicates that interpersonal coordination can take on a stabilizing function in the transmission of skills and practices. The authors suggested that seeing two people performing the same actions at the same time highlights the conventionality of the observed actions, which increases the motivation to imitate these actions as closely as possible. Furthermore, joint actions may lead to more stable transmission as they often require reducing the variability of one's actions (Vesper, Schmitz, Safra, Sebanz & Knoblich, 2016).

Joint action may also create opportunities for creativity and innovation. The need to adjust to different partners in real time comes with constraints that may foster the emergence of new action patterns and create a wider space of exploration (Wilf, 2013). For example, trying to communicate information to a partner or trying to adapt to a partner's action outcomes could lead one to carry out an action or action sequence differently than if that same action was carried out alone. Different ways of doing things may also be taken up more readily if one needs to achieve coordination. Interactions between partners who are quite different from each other may be particularly fruitful in fostering creativity (Canonne & Aucouturier, 2016). A special case of this is the interaction between humans and robot partners. For example, it has been suggested that, in jazz improvisation, humans can be inspired by a robot partner by drawing on unexpected contributions produced by computer algorithms (Hoffman & Weinberg, 2011; Wilf, 2013).

5 | CONCLUSIONS

Imitation and joint action are not entirely separate phenomena that can be understood in isolation from each other. Rather, we may gain a deeper understanding of the processes involved in imitation when considering its embedding in social interactions that are characterized by joint goals and the need to achieve temporal coordination. At the same time, imitation research with its focus on questions of bodily mapping and social learning mechanisms offers new perspectives on joint action as a tool for cultural learning and innovation. In concluding, we would like to highlight three points that follow from our review of the literature.

First, joint action goals play an important role in modulating the links between perception and action that underlie our tendency to imitate observed actions. People can effectively override the tendency to automatically imitate when in a joint action context. This demonstrates that imitation is not necessarily our default mode; joint action planning allows us to incorporate complementary actions into our action plans. Furthermore, we are sensitive to the individual or joint goals underlying observed actions, leading to a greater tendency to imitate joint actions when we are with a task partner than when we are by ourselves. This finding points to the important role of top–down influences of joint action representations that specify joint action outcomes: these joint representations constrain how we map observed actions onto our own motor system.

Second, considering real-time constraints of social interaction and interaction dynamics between co-actors is important for a comprehensive understanding of the processes sub-serving imitation. The timing constraints involved in concurrently imitating continuous action sequences create a tendency to rely on topological mappings, where actions of corresponding body parts are matched in the process of generating predictions about observed actions. This stands in contrast to studies on imitation of discrete actions where spatial mappings have been found to dominate. In imitative interactions like the mirror game where two individuals mutually adjust to each other in order to perform the same actions in synchrony, the interactional roles that participants are engaged in affect their ability to imitate each other. Shared leadership and unique movement patterns allow individuals to imitate each other in synchrony.

Finally, recent findings on joint action performance suggest that people might learn from each other not only through imitation but by participating in joint actions. Using sensorimotor communication, the more skilled individual in a dyad modulates her actions in ways that may not only facilitate prediction but also provide learning-relevant cues. Haptic communication may allow experts to guide novices through an action sequence and scaffold their learning by constraining their action space and by providing fine-grained feedback during performance. Key questions for future research are whether and how constraints of joint action can stabilize the transmission of skills and practices and how dynamics of joint action coordination create unique opportunities for innovation.

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