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Joint action: bodies and minds moving together

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The ability to coordinate our actions with those of others is crucial for our success as individuals and as a species. Progress in understanding the cognitive and neural processes involved in joint action has been slow and sparse, because cognitive neuroscientists have predominantly studied individual minds and brains in isolation. However, in recent years, major advances have been made by investigating perception and action in social context. In this article we outline how studies on joint attention, action observation, task sharing, action coordination and agency contribute to the understanding of the cognitive and neural processes supporting joint action. Several mechanisms are proposed that allow individuals to share representations, to predict actions, and to integrate predicted effects of own and others' actions.

Introduction

Watching a fast pass in a basketball game, listening to a sophisticated piano duet, or observing a couple glide effortlessly along the dancefloor, we often marvel at how people manage to coordinate their actions so swiftly and accurately. Yet, engaging in joint action is by no means just a speciality of experts in domains like sports or art. Rather, we coordinate our actions with others all the time, be it washing the dishes with our partner or helping a child to get dressed. As Allport observed more than 80 years ago [1], even seemingly simple joint actions like carrying a heavy object together are challenging in that two individual bodies and minds must be coordinated. How is this actually achieved?

In this article, we review recent findings from developmental psychology, cognitive psychology and cognitive neuroscience that contribute to the understanding of the mechanisms underlying joint action. A lot of progress has been made by studying language as a form of joint action [2,3], but it is also vital to gain an understanding of how individuals coordinate actions in situations where verbal communication is either impractical or impossible. Only few studies have directly addressed this issue so far. However, recent studies investigating perception and action in social context have revealed cognitive and neural processes that might provide crucial building blocks for joint action. The aim of this article is to demonstrate in what ways recent studies enhance the understanding of joint action, and to draw attention to mechanisms that appear to be crucial for the successful coordination of actions. We believe it is time for a first synthesis of this kind, as researchers are just beginning to acknowledge that to reach a more comprehensive understanding of the processes underlying social interaction, one needs to move on from studying the processing of social stimuli towards investigating real-time social interactions. Moreover, studies on joint action challenge the assumption traditionally held in cognitive psychology that perception, action, and higher-level cognitive processes can be understood by investigating individual minds in isolation (see also [4,5]).

As a working definition, joint action can be regarded as any form of social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment. We propose that successful joint action depends on the abilities (i) to share representations, (ii) to predict actions, and (iii) to integrate predicted effects of own and others' actions. In the following, we discuss several mechanisms through which this could be achieved.

Joint attention: knowing what others perceive (and don't perceive)

Studies on joint attention suggest that the ability to direct one's attention to where an interaction partner is attending provides a basic mechanism for sharing representations of objects and events [6,7]. Thus, joint attention creates a kind of 'perceptual common ground' in joint action, linking two minds to the same actualities. This can serve two functions, one being the initiation of coordinated action (as when one individual follows another's gaze to an object to be manipulated), the other being coordination once individuals are already engaged in a joint action (as when two people jointly attend to an obstacle while carrying an object together).

In infants, joint attention develops around the age of 12–18 months [8,9]. At this time, children also start to engage intensively in joint action, for example, building castles with others or playing ball. Initiating and engaging in such joint actions is possible despite the fact that children's theory of mind is far from fully developed at this age, questioning the view held by some philosophers that joint action depends on shared 'we' intentions [6]. Rather, imitation and joint action seem to rely on the ability to

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Box 1. Social learning: from imitation to joint action

One of the crucial precursors to social learning in human development is the ability to selectively attend to an object of mutual interest. Humans have a large repertoire of social cues such as gaze direction, pointing gestures and postural cues, all of which indicate to an observer which object is currently under consideration. Imitation plays an important role in transferring the meaning of objects. Caregivers show infants objects all the time, and try to transfer knowledge via imitation games, such as the name and function of an object. For example, the caregiver might shake a rattle and then look at the infant while signifying 'can you do the same?'

Interestingly, recent theories about imitation have stressed the fact that from 14-months of age infants only imitate the modelled action if they consider it to be the most rational alternative [56]. Most probably, imitation is a selective, goal-directed process, rather than a simple re-enactment of actions perceived [57,58]. Such a selective action interpretation process might also be crucial for eliciting engagement in joint action. For example, when we observe somebody dragging a large table with their hands behind the back we will understand that this person only drags it in such an awkward way to avoid obstacles. Having identified the other's goal, we can act according to our perception of it, thereby establishing a joint goal (Figure I).

A process of selective goal-directed action interpretation might not only affect whether we decide to engage in a joint action, but also help to suppress dysfunctional tendencies to imitate observed actions. Although joint action sometimes requires imitative kinds of movement (e.g. 'you make the same movement to balance the table'), in other circumstances the goal can only be accomplished by making complementary movements (e.g. 'you grasp the table with your hands in front of you to help avoiding obstacles'). This can only be achieved if activation of motor representations following observation [59,60] is suppressed by a joint goal representation, so that one can perform actions dissimilar from those observed. It is likely that similar neurocognitive mechanisms govern goal-directed imitation and the selection of appropriate actions to achieve joint goals.

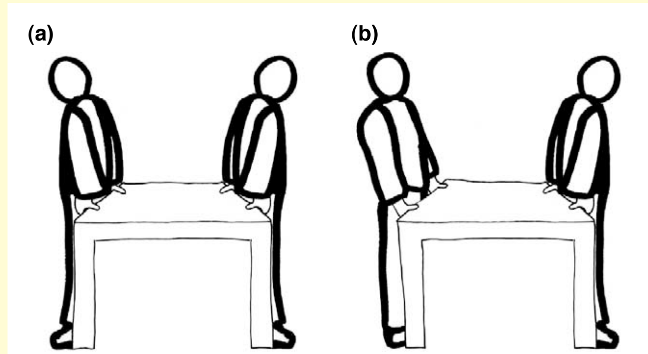

Figure I. Goal-directed joint action. Rather than imitating the other's actions **(a)**, people must sometimes perform complementary actions **(b)** to reach a common goal. Drawing by Ellie Langenhuizen.

infer action goals (see Box 1). Knowing what the other is attending to in a particular action context provides important cues about the other's action goals [10] and can elicit complementary actions in the observer.

Further evidence that sharing representations of objects and events is important for joint action comes from studies involving verbally mediated coordination [11]. The use of gesture during speech suggests that people are highly sensitive to shared space, adjusting their gestures depending on where an interaction partner is positioned [12]. Clark and Krych showed that joint action performance deteriorates when interaction partners cannot jointly attend to the same objects and events [13]. In this study, pairs of participants built lego models together, with one person giving instructions and the other assembling. Pairs took longer and made more errors when the participant giving instructions could not see the builder's workspace. Presumably, they were partially able to compensate by explicitly referring to objects and events through the use of language. Impairments in performance due to a lack of shared perceptual space are especially likely to occur when a range of different objects or events could be in the focus of the other's attention, and when actors need to adjust their actions jointly to sudden changes in the environment.

Action observation: knowing what others will do

Although joint attention can support the understanding of others' action goals to some extent, a more direct mechanism is provided by action observation. A multitude of studies has shown that during observation of an action, a corresponding representation in the observer's action system is activated (e.g. [14]; for a review see [15]). It has been suggested that such 'motor resonance' supports action understanding [16]. This claim is supported by findings showing that actions are not purely coded in terms of visual properties of the observed movement, but rather in terms of action goals [17–19]. This could help to establish procedural common ground in joint action [2]. Without relying on symbolic communication, individuals could be 'on the same page' action-wise by sharing representations of actions and their underlying goals. The similarity between an observer's and an actor's action representations might determine the degree to which resonance occurs in the observer. For instance, resonance is higher when one has a high level of expertise at performing the observed actions [20,21], or perceives one's own previously performed actions [22,23].

However, to interact successfully with others, it is often not sufficient to understand what they are doing at a given moment in time. Instead, being able to predict outcomes of others' actions and knowing what others are going to do next is crucial [24]. Several findings suggest that motor resonance also supports action prediction [25,26]. For instance, a recent study on patterns of eye–hand coordination showed that when individuals observed a person stacking blocks, their gaze preceded the action and predicted a forthcoming grip, just like when they performed the block-stacking task themselves [27].

Besides brain areas in premotor and parietal cortex, pertaining to the 'mirror system', the superior temporal sulcus (STS) seems to be involved in action prediction, and in particular in the updating of predictions after a violation has occurred. Activation in this area was observed when participants' expectation about a walker appearing behind an occluder was violated [28], and when they watched an actor lifting a box the weight of which differed from what the actor expected [29]. Interestingly, deafferented patients are not able to identify such expectations, which points to a possible role of peripheral sensory information in action prediction [30].

Task-sharing: knowing what others should do

An efficient means to predict others' actions that is not based on action observation is knowing what another's task is – that is, knowing the stimulus conditions under which an individual will perform a certain action [31,32]. For example, when a pedestrian sees a red traffic light, he can predict that it is likely that cars will stop. Three different kinds of studies have provided evidence that individuals form shared task representations. Firstly, in experiments by Kilner *et al.* [26] and van Schie *et al.* [33], participants observed actions that were performed only under certain conditions. Both studies found evidence for motor activation *in advance* of action observation, suggesting that participants generated a representation of the appropriate action following stimulus presentation (see also [34]). Van Schie *et al.*'s study showed that activation either continued to develop or decreased depending on whether the observed actor's response to a stimulus was correct or not. Observing an error elicited medial frontal activity similar to that elicited by making an error oneself, suggesting that similar neural mechanisms are involved in monitoring one's own and others' task performance.

Secondly, in a study by Ramnani and Miall, participants acquired stimulus–response mappings, and were then presented with stimuli indicating whether they should respond, a co-actor in another room should respond, or a computer should respond [35]. Although the other's actions could not be observed, participants anticipated the co-actor's actions. This was associated with activity in motor areas, including ventral premotor cortex, as well as areas typically involved in mentalizing. These results suggest that predictive mechanisms in the human action system, as well as mechanisms supporting mental state attribution, can be triggered by shared task representations [31].

Finally, a series of recent studies has shown that individuals form shared representations of tasks quasi-automatically, even when it is more effective to ignore one another. In these studies, pairs of participants performed a 'go–nogo' task sitting alongside each other with no interpersonal coordination being required. Surprisingly, each actor integrated the co-actor's action alternative in his or her action planning, even when the other's actions could not be observed [36–38]: an action selection conflict occurred when a stimulus required an action from both actors, each of whom acted according to a different stimulus–response mapping. This suggests that (i) each person knew what the other should do, and (ii) the other's task was represented in a functionally equivalent way to one's own [32]. ERP measurements on nogo trials showed increased response inhibition when a stimulus required the other's response compared with trials where no response was required [39,40] (see Figure 1). This indicates that a representation of the action to be

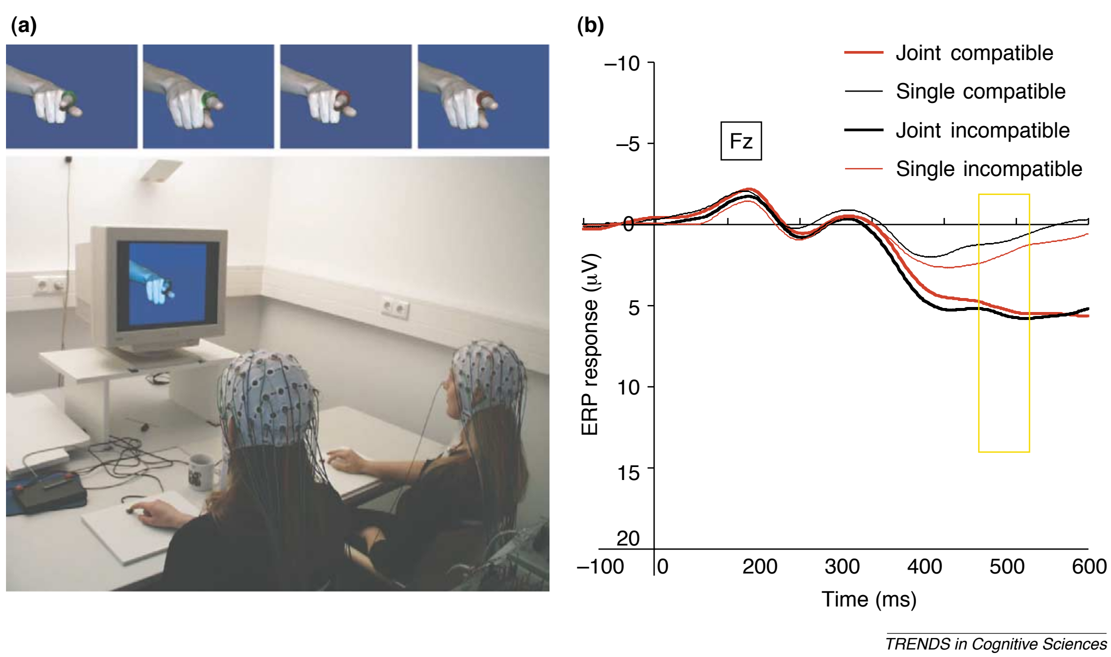

Figure 1. Response inhibition while another person is acting. **(a)** Participants saw pictures of a hand pointing left and right and responded to the color of the ring on the index finger (see top). One participant responded only to red, the other only to green (joint condition, as shown below). Thus, on each trial, one participant responded ('go') and the other did not ('nogo'). The same go–nogo task was also performed alone, with no response given on nogo trials (individual condition). **(b)** Measurements of event-related potentials showed that the nogo-P3, a component reflecting response inhibition, was more pronounced on nogo trials in the joint condition than in the individual condition, regardless of pointing direction (bold lines: joint condition, fine lines: individual condition; red: finger points at participant, black: finger points away). These results suggest that when participants saw a stimulus that required the other's response, a representation of the action to be performed was activated, because the other's task was known. This activation was however suppressed to avoid responding when it was the other's turn. (Data redrawn from [40].)

performed was activated following stimulus presentation, and was then suppressed to avoid acting when it was the other's turn.

In the light of these findings, it is tempting to speculate that the ability to form shared representations of tasks is a cornerstone of social cognition. It allows individuals to extend the temporal horizon of their action planning, acting in anticipation of others' actions rather than simply responding. Whereas predictions based on action observation are simple and immediate, predictions based on known associations between certain events in the environment and others' actions allow one to prepare actions in response to events that will only occur a considerable time ahead.

Action coordination: attuning to make common cause

Perhaps the most important feature of joint action to be understood is how individuals adjust their actions to those of another person in time and space (see also Boxes 1 and 2). Clearly, this cannot be explained just by the assumption that representations are shared. Although motor resonance and task sharing allow individuals to predict others' actions, it remains unclear how they would go from predicting another's action to choosing an appropriate complementary action at an appropriate time. Recent studies have advanced our knowledge about the processes integrating self and other by revealing how individuals incorporate others' action capabilities into their own action planning, and how temporal feedback about others' actions is used in anticipatory action control.

In an intriguing series of experiments, Richardson and colleagues asked pairs of participants to lift wooden planks off a conveyer belt [41,42]. The planks could only be touched at the ends, and they varied in length such that they could be lifted by a single person, or only by two individuals. The planks were presented in ascending or descending order of length. It was expected that participants would successively lift small planks, and would switch to joint lifting at some point as the planks got longer. This transition point is informative because it reflects to what extent co-actors – whose arms spans can vary considerably – take each other's action capabilities into account. It was found that the transition point varied as a function of a pair's mean arm span: pairs with large mean arm spans made the transition from taking turns to lifting jointly at a longer plank length than pairs with small mean arm spans. This finding provides evidence that the perceived affordance of objects is governed not only by what individuals believe they can do, but also by what they believe they can do with others. More generally, this suggests that the way members of a group perceive the environment might be a function of the resources and action capabilities that are inherent to the group.

Box 2. Minds make bodies synchronize

When we engage in cooperative tasks with others, our bodies seemingly come to help. Recent studies have shown that individuals working on mental tasks together non-consciously mimic each other's actions and synchronize rhythmical movements. Non-conscious mimicry of gestures, postures, and mannerisms has been shown to enhance the smoothness of interactions and foster liking [61]. People with an affiliation goal [62] or interdependent self-construal [63] are especially prone to mimicking others.

Unintentional synchronization of movements has been observed for postural sway [64], and the swinging of hand-held pendulums [65,66] by pairs of participants while engaged in verbal problem solving tasks. A recent study investigated unintentional synchronization by asking pairs of participants sitting side-by-side in rocking chairs to rock independently and at their own preferred pace [67]. Both the visual information available about the other person and the natural rocking frequency of the chairs was manipulated. Participants unintentionally adopted the same rocking frequency when they visually attended to each other. Most surprisingly, synchronization occurred even when participants rocked two chairs with different eigenfrequencies. Thus, they unintentionally acted against the natural tendency of these chairs to de-synchronize. It remains to be investigated to what extent non-conscious mimicry and unintentional synchronization facilitate joint action.

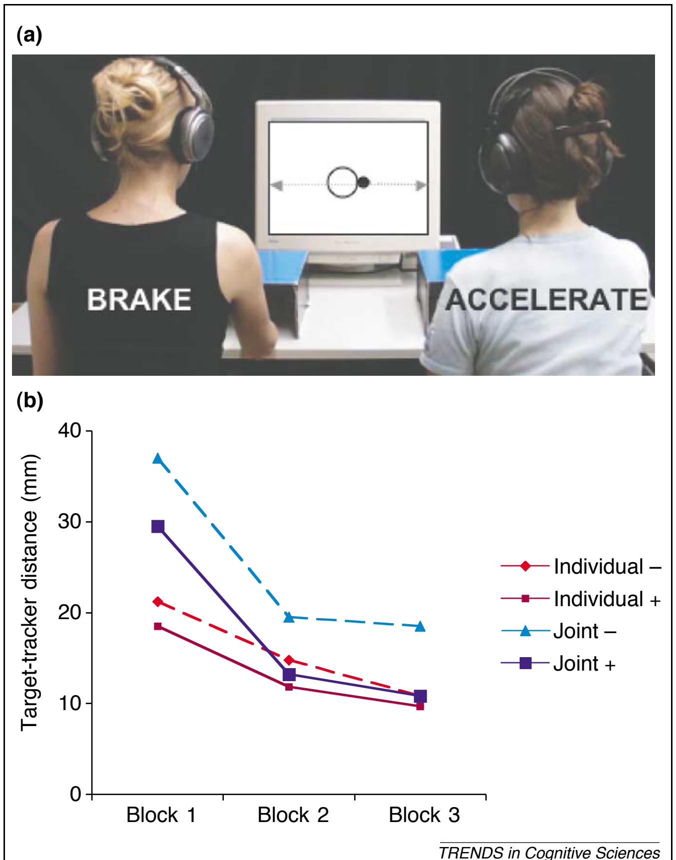

Figure 2. Anticipatory action control. **(a)** The participants task was to keep a tracker (depicted by the circle on the screen) on top of a horizontally moving dot (depicted by the black dot next to the circle). In the individual condition, one participant was in charge of two buttons, one for acceleration, the other for deceleration. In the joint condition (as illustrated), one participant was in charge of acceleration, and the other was in charge of deceleration. The dot turned abruptly at the borders of the screen, making it a better strategy to wait for it to turn by stopping the tracker some way before the border and then catching up with it again, rather than trying to track the dot's turning (the grey arrows illustrate the horizontal movement of the dot). Button presses either resulted in a tone, providing auditory feedback about the timing of the actions (Individual +, Joint +), or were not followed by a tone (Individual −, Joint −). **(b)** The results showed that participants in the joint conditions gradually learned to minimize distance between target and tracker by anticipating each other's actions. However, pairs reached the same level of performance as individuals only when they received feedback about the timing of each other's actions. (Data redrawn from [43].)

Joint action also requires that individuals incorporate the timing of others' actions in their own action planning, as when two people are juggling together. Interacting partners must plan and execute their actions in relation to what they predict the other will do rather than respond to observed actions. Knoblich and Jordan investigated the mechanisms underlying such anticipatory coordination with a tracking paradigm, where participants kept a circle on a moving target jointly or individually [43–45] (see Figure 2). The task required the participants to anticipate sudden target turns. The results demonstrate that feedback about the timing of another's actions can become as effective for anticipatory action control as internal signals about one's own actions. Receiving unambiguous feedback about each other's timing enabled participants in the group to plan ahead, because each member learned to predict the timing of the other's actions. Importantly, action planning was ultimately based on a prediction of what the joint effects of one's own and the other's action would be.

Box 3. From spatial coordination to symbolic interaction

Verbal communication is a powerful means to solve coordination problems that arise in joint action [2,3]. Could language have evolved as a consequence of interpersonal coordination demands? A recent study by Galantucci examined how communication systems emerge in the context of joint activities [68]. The findings impressively showed how interpersonal coordination demands can drive the creation of symbolic communication systems that help to establish common ground between co-actors (see Figure I). In principle, such systems are not tied to a specific medium. Currently, there is a heated debate about what form human language took in its beginnings – was it a verbal or a manual communication system [69]? It has been argued that human language might have evolved out of a gestural communication system, supported by the mirror system for grasping and later by extensions that allowed for imitation [70]. It could be fruitful to unite this approach with empirical data on the emergence of communication systems in the face of coordination demands imposed by joint action.

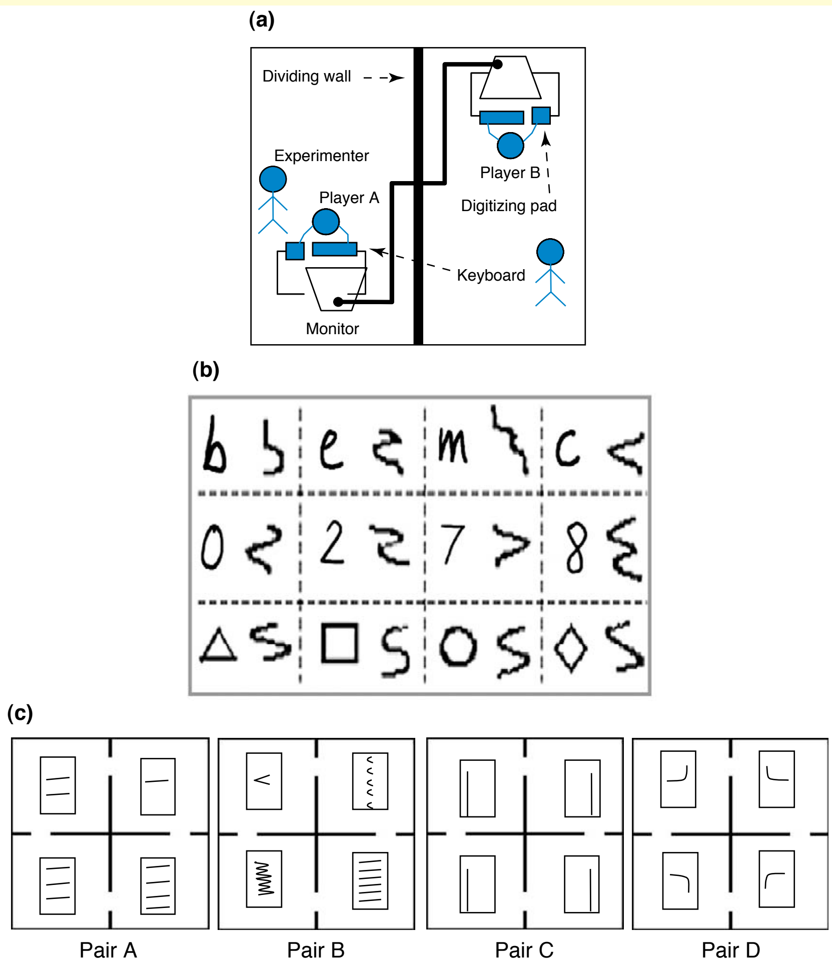

Figure I. Emerging communication systems. **(a)** Pairs of participants played a real-time videogame, in which each player controlled one agent. The virtual environment contained four rooms. Each participant could see only the room in which her player was located. The joint goal was to have the agents meet in the same room. During each game, a player could move her agent to an adjacent room or have the agent stay put. Participants could not see each other, and the only means of communication was to write with a stylus on a digitizing pad. However, the use of common graphic symbols like letters and numbers was not possible, because the writing trajectories were systematically distorted on the communication panel, as in **(b)**. Participants created communication systems that allowed them to solve the task by agreeing on what to code and how to do so. Communication systems emerged through explicit naming strategies as well as trial-by-error learning. **(c)** Interestingly, different pairs of participants coded the same task environment in very different ways (each sign is presented in the room it stands for). The pattern of sign forms suggests that successful signs were perceptually distinct, easy to produce and tolerant to variations. Figure courtesy of Bruno Galantucci, and reproduced from [68] by permission of the Cognitive Science Society.

Agency in joint action: uncertain selves

It is precisely this close link between actions performed by oneself and actions performed by others that sometimes leads to confusion as to who caused a particular action effect [46]. This anecdote illustrates what happens when the connection between one's own and others' actions and their consequences is ambiguous: On a bad hunting day, Carl Rogers, the founder of client-centered therapy, shot at a duck just as another man aimed at it. As they met on their way to retrieve the duck, Rogers voiced what probably applied to both of them: '*You feel this is your duck*'. In joint action, such problems of agency arise when one's own and others' actions are carried out at approximately the same time and result in similar effects [47]. When individuals act alone, agency is experienced when predicted sensory effects occur in a timely manner after the action has been performed [48–50]. Such effects do not help to determine whether an action was caused by oneself or the other in joint action, when the effects predicted for one's own actions can also be produced by the other.

Furthermore, studies by Wegner have shown that post-hoc judgments of agency can be distorted in situations where the source of actions is ambiguous [51,52]. In particular, in social interactions where two agents can be the source of an action, people can be fooled into attributing actions to themselves that they actually never performed. Participants were likely to believe they had performed an action that was brought about by a confederate when they had had action-relevant thoughts before the action effect was observed [51]. The opposite error, where actions performed by oneself are wrongly ascribed to others, has also been observed [52].

Although a lack of differentiation between self- and other-generated actions sometimes constitutes a problem to be overcome, it can also be a desired characteristic of certain kinds of joint action that involve experiences of synergy and flow [53]. For example, musicians in a band might strive to experience a sense of agency that transcends individual boundaries, which is based on what it feels like to produce action effects as a group. It remains a challenge for future studies to determine how agency experiences of the 'multiple bodies, one mind' sort arise.

Conclusions and future directions

Individuals possess a remarkable ability to coordinate their actions with others to reach common goals. Several mechanisms can be identified that are involved in joint action. First, joint attention provides a mechanism for sharing the same perceptual input and directing attention to the same events. Second, a close link between perception and action allows individuals to form representations of others' action goals and to predict action outcomes. Third, by forming shared task representations, it is possible to predict actions based on certain events in the environment, independent of action observation. Fourth, action coordination is achieved by integrating the 'what' and 'when' of others' actions in one's own action planning. This affects the perception of object affordances, and permits joint anticipatory action control. Finally, the ability to distinguish between effects of one's own and others' actions might be reduced in joint actions where the combined outcome of one's own and others' actions is more important than the results of individual actions.

Many questions remain to be addressed in future research, as the study of joint action has only recently started to gain broader attention (see Boxes 3 and 4). Most importantly, future studies should investigate the mechanisms whereby individuals coordinate their actions online. This is particularly challenging, because the mutual influences of two or more actors on each other must be assessed. However, it will help to fill a gap in current theorizing about the social nature of cognition, which so far has drawn mainly on studies that have investigated how solitary individuals respond to static stimuli with social content. Together with research on cooperation [54,55], studies of joint action will contribute to the understanding of how bodies and minds move together.

Box 4. Questions for future research

- How does acting together shape the perception of object affordances?
- What are the mechanisms supporting precise temporal coordination of actions?
- What are the parallels between nonverbal forms of joint action and language?
- To what extent does joint action rely on theory of mind?
- What are the neural correlates of acting together?

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