Coordinating Joint Action

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1. Introduction

It is often necessary that agents' actions are coordinated if they are to successfully exercise collective (or 'shared') intentionality in acting together. An eloping couple clink plastic beakers of cheap wine together to toast their escape, sharing a smile of achievement; on the beach in front of them a small group of roadies are putting up a marquee outside for a concert later that evening while the musicians, having been made to wait while the audio technicians replace a cable, playfully improvise on stage. In cases like these, successfully exercising collective intentionality involves coordinating actions precisely in space and time. Such precise coordination is not, or not only, a matter of having intentions and knowledge, whether individual or collective. Intentions and knowledge states may play a role in long-term coordination—they may explain, for instance, why the couple's both being on the beach tonight is no accident. But they cannot explain how the precise coordination needed to clink beakers or to share a smile is achieved. Given that is not only intention or knowledge, what does enable two or more agents' actions to be coordinated and so enables exercises of collective intentionality such as these?

Much psychological and neuroscientific research bears directly on this question. This chapter introduces that research: it outlines some of the key findings and describes a minimal theoretical framework, identifying along the way issues likely to be of interest to researchers studying collective intentionality.

2. Joint Action

Where philosophers tend to focus on notions such as collective intentionality and shared agency, scientific research on coordination mechanisms is usually interpreted in terms of a broader and simpler notion of joint action. This is standardly defined by appeal to Sebanz, Bekkering and Knoblich's working definition 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' (Sebanz, Bekkering and Knoblich 2006, p. 70).

Although widely used, this working definition has some drawbacks. It requires that joint actions should be 'social interactions', thereby raising tricky issues about which interactions are social. The working definition also appears to require that coordinating their actions is something the individuals involved in joint action do, perhaps even requiring that this is done with the end of bringing about a change. As we will see, there are reasons to consider the possibility actions can be coordinated without both (or even either) requirements being met. We can avoid the drawbacks while remaining true to the implicit conception underlying scientific research with a simpler and even broader definition:

> A *joint action* is an event grounded[1] by two or more agents' actions.

This definition of joint action, like Sebanz, Bekkering and Knoblich's working definition, is neutral on representations and processes. So when two people swing their arms in synchrony, the event of them swinging their arms is a joint action. Likewise, if fish are agents then the movements of a shoal are joint actions.[2]

How does research on coordination in joint action bear on the question about collective intentionality? Not all joint actions involve exercising collective

[1] Events D_1, ... D_n *ground* E just if: D_1, ... D_n and E occur; D_1, ... D_n are each part of E; and every event that is a part of E but does not overlap D_1, ... D_n is caused by some or all of D_1, ... D_n. (This is a generalisation of the notion specified by Pietroski 1998.)

[2] Note that what follows is neutral on whether joint actions are actions. As a terminological stipulation, I shall say that an individual is an *agent of a joint action* just if she is an agent of an action which, together with some other events, grounds this joint action. (Depending on your views about events, causation and agents, getting some edge cases right may require adding that for this individual to be an agent of this joint action, this particular plurality of grounding events—her action and the other events—must include actions with agents other than her.)

intentionality, but some or all exercises of collective intentionality are, or involve, joint actions. It is reasonable to conjecture that what enables the actions of agents exercising collective agency to be precisely coordinated are mechanisms of coordination common to many different forms of joint action. To illustrate, consider entrainment.

3. Entrainment

Entrainment, the process of synchronizing two or more rhythmic behaviours with respect to phase, is a feature of everyday life. People walking side by side may fall into the same walking patterns (Ulzen et al. 2008; Nessler and Gilliland 2009), conversation partners sometimes synchronize their body sway (Shockley, Santana and Fowler 2003) and gaze (Richardson, Dale and Kirkham 2007), clusters of male fiddler crabs wave their claws synchronously to attract mates (Backwell et al. 1998; Merker, Madison and Eckerdal 2009), and an audience will sometimes briefly synchronise its clapping (Néda et al. 2000).

As these examples suggest, entrainment enables the coordination of a wide range of joint actions, not all of which involve collective intentionality. In fact interpersonal entrainment is sometimes treated as a special case of a process by which sequences of actions can be synchronised with sequences of environmental stimuli such as a metronome (e.g. Konvalinka et al. 2010; Repp and Su 2013), and, more boldly, sometimes even as just one instance of what happens when oscillators are coupled (e.g. Shockley, Richardson and Dale 2009, p. 314). Some also compare the entrainment of two agent's actions with the entrainment of two actions performed by a single agent; thus, for instance, Ulzen et al. (2008, p. 92) compare patterns in the coordination of two walker's limbs with patterns in how a single walker's two legs are coordinated, and Harrison and Richardson (2009) compare spontaneous coordination in two people mechanically coupled to create something like a pantomime horse with the way a quadruped's leg movements are coordinated. So entrainment is plausibly important for the coordination not just of joint actions but also of many individual actions too.

Which exercises of collective intentionality might entrainment enable? Entrainment allows for extremely precise coordination of movements and is probably essential for joint actions involving rhythmic music, dance, drill, and some martial arts. For a sense of just how precise the coordination achieved through entrainment can be, consider what happens when expert musicians are instructed to synchronise a button press with a sequence of tones. Repp (2000) introduced minute perturbations in the otherwise equal intervals between successive tones, increasing or decreasing one inter-tone interval by amounts so small (between 10 and 4ms) that the discrepancy would not be detectable by the subjects. (That is, people encountering two sequences of events where one lagged the other by such a small amount would be unable determine which event came first.) Subjects nevertheless rapidly corrected for these perturbations, and did so in much the way that they would correct larger, readily detectable perturbations.

Entrainment probably matters for coordination even where precision is not important and may facilitate coordination in many exercises of collective intentionality other than those involving rhythmic music, dance or drill. While relatively little is yet understood about the broader roles of entrainment,[3] there are hints that it may facilitate exercises of collective intentionality in ways that are currently not fully understood. To mention just one intriguing finding, Richardson and Dale (2005) did an experiment with adult humans in which each participant heard a pre-recorded monologue about Friends, a soap opera. In front of the participant was a static display comprising silhouettes of the six main characters. This was all the participant saw: the speaker of the monologue was never present. Richardson and Dale found that the more closely a participant's gaze followed that of the speaker's, the better the participant understood the monologue. By itself, this is unsurprising. But then, in a further experiment, Richardson and Dale manipulated participant's gaze using subtle cues. They found that artificially making participants' gazes more closely follow the speaker's gaze improved their comprehension. This intriguing finding is a hint that entrainment may facilitate interpersonal understanding.

How is entrainment related to agents' intentions concerning coordination or the lack thereof? Entrainment of two or more agents' actions can occur without any intention concerning coordination (e.g. Varlet et al. 2015), and without the agents being aware of the coordination of their actions (Richardson, Marsh and Schmidt 2005). Further, although subjects can sometimes intentionally prevent entrainment, entrainment and related forms of coordination do sometimes occur even despite individuals attempting not to coordinate their actions (e.g. Issartel, Marin and Cadopi 2007; Ulzen et al. 2008). So whether two agents' actions become entrained is not always, and perhaps not typically, something which they do or could control.

This is not to say that entrainment is always independent of agents' intentions, however. Whether spontaneous entrainment occurs can depend on agents'

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[3] For relatively speculative discussions, see Richardson, Schockley and Kevin (2008), Merker, Madison and Eckerdal (2009) and Keller, Novembre and Hove (2014, §4).

attitudes to each other, as shown by an experiment in which participants' actions showed greater entrainment with the actions of a punctual than a late confederate (Miles et al. 2010). Nessler and Gilliland (2009) observe that 'intentional entrainment promotes greater synchronization between participants than conditions where unintentional entrainment is likely to occur.' But given that entrainment appears to involve mechanisms that can operate without awareness, how could agents' intending to entrain facilitate tighter coordination?

One possibility is that intention influences a certain kind of monitoring and control. Because no one can perform two actions without introducing some tiny variation between them, entrainment of any kind depends on continuous monitoring and ongoing adjustments (Repp 2005, p. 976). One kind of adjustment is a phase shift, which occurs when one action in a sequence is delayed or brought forwards in time. Another kind of adjustment is a period shift; that is, an increase or reduction in the speed with which all future actions are performed, or in the delay between all future adjacent pairs of actions. These two kinds of adjustment, phase shifts and period shifts, appear to be made by mechanisms acting independently, so that correcting errors involves a distinctive pattern of overadjustment.[4] Repp (2005, p. 987) argues, further, that while adjustments involving phase shifts are largely automatic, adjustments involving changes in frequency are to some extent controlled. One possibility is that period adjustments can be made intentionally (as Fairhurst, Janata and Keller 2013, p. 2599 hint); another is that there are a small number of 'coordinative strategies' (Repp and Keller 2008) between which agents with sufficient skill can intentionally switch in something like the way in which they can intentionally switch from walking to running. However exactly it works, it seems that intentions concerning coordination can influence how tightly agents synchronise their actions.

Entrainment is clearly necessary for coordination in many joint actions requiring precise synchronisation such as those involving rhythmic music or dance. Entrainment may be important in ways as yet barely understood for a much wider range of joint actions in which such precise synchronisation initially appears unnecessary. But, equally clearly, there must be more to coordinating joint actions than entrainment. After all entrainment depends on repetition whereas many joint actions are one-off events, as when the a couple clink plastic beakers. Which forms of coordination enable one-off joint actions?

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[4] See Schulze, Cordes and Vorberg (2005, pp. 474–6). Keller, Novembre and Hove (2014) suggest, further, that the two kinds of adjustment involve different brain networks. Note that this view is currently controversial: Loehr and Palmer (2011) could be interpreted as providing evidence for a different account of how entrainment is maintained.

4. Motor Simulation

Many one-off joint actions—those which do not depend on repetition or rhythm—do require precise coordination. In clinking beakers, swinging a toddler between our arms, and executing a pass in football, the window for success may be fractions of a second in duration and but millimetres wide. One way—perhaps the only way—of achieving such precise coordination depends on the existence of a phenomenon often called 'motor simulation' or 'mirroring'. What is this?

To understand motor simulation it is necessary first to get a rough fix on the idea that motor processes and representations are involved in performing ordinary, individual actions. Preparing for, and performing, bodily actions involves not only intentions and practical reasoning but also motor representations and processes. To illustrate, consider a cook who has grasped an egg between her finger and thumb and is now lifting it from the egg box. She will typically grip the egg just tightly enough to secure it. But how tightly she needs to grip it depends in part, of course, on the forces to which she will subject the egg in lifting it. The fact that she grips eggs just tightly enough throughout such action sequences which vary in how she lifts the egg implies that how tightly she grips the egg depends on the path along which she will lift it. This in turn indicates (along with much other evidence) that information about her anticipated future hand and arm movements appropriately influences how tightly the cook initially grips the egg (Kawato 1999). This fine-grained, anticipatory control of grasp, like many other features of action performance (see Rosenbaum 2010, chapter 1 for more examples), is not plausibly a consequence of mindless physiology, nor of intention and practical reasoning. The processes and representations it depends on are motoric.

There is a large body of behavioural and neurophysiological evidence suggesting that motor processes and representations lead a double life: they occur not only in performing actions but also observing them. For instance, in someone observing the cook gripping and lifting the egg, there may be motor processes and representations related to those which would occur in her if she, the observer, were performing this action herself. One dramatic piece of evidence for this claim comes from a study in which activity in an observer's motor cortex was artificially boosted with transcranial magnetic stimulation (TMS). This caused minute patterns of activation (specifically, motor-evoked potentials) to occur in a muscle of the observer at just the times the agent being observed used the corresponding muscle.[5] As this illustrates, motor processes in an observer can carry detailed information about the timing of components of actions. *Motor simulation* is the occurrence of motor processes and representations in an observer concerning an action which she is observing or imagining and which are driven by observing or imagining that action.[6]

Motor simulation enables observers to anticipate how others' actions will unfold and the likely outcomes the actions will achieve (Wolpert, Doya and Kawato 2003; Wilson and Knoblich 2005). Such anticipation is reflected both in explicit judgements (e.g. Aglioti et al. 2008) and in spontaneous eye movements (e.g. Flanagan and Johansson 2003; Rotman et al. 2006; Ambrosini, Costantini and Sinigaglia 2011; Costantini et al. 2014).[7]

How does any of this bear on the coordination of joint action? If motor simulation is to play a role in coordinating joint actions, it is not enough that its occurrence enables actions to be anticipated. The agents of a joint action are not mere observers but have to perform actions, and these actions typically differ from those they observe. So for motor simulation to underpin coordination for joint action, agents must be capable of using anticipation based on motor simulation in preparing and performing actions different from those simulated. Is there any evidence that this is possible?

Kourtis, Sebanz and Knoblich (2013) used neural markers of motor activity to show that motor simulation can occur in joint action even where agents are performing different actions in close succession. To show, further, that motor simulation in joint action can facilitate coordination, Vesper et al. (2013) instructed pairs of people to jump and land at the same time. Each member of a pair was told how far to jump, and the distances varied so that sometimes one member of a pair had to jump 35cm, 70cm, or 105cm further than the other. Although individuals could not see or hear each other, there was a start signal which both could hear and each could see lights marking how far she and her

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5 Gangitano, Mottaghy and Pascual-Leone (2001); see further Fadiga, Craighero and Olivier (2005) and Ambrosini, Sinigaglia and Costantini (2012). For a review of evidence that, when observing an action, motor processes and representations occur in the observer like those which would occur if she were performing an action of the kind observed rather than merely observing it, see Rizzolatti and Sinigaglia (2010).

6 Philosophers sometimes use the term 'simulation' in such a way that motor simulation is not simulation. Although nothing that follows depends on whether motor simulation is simulation, for convenience I occasionally use the term 'simulation' to describe it.

7 That motor representations have a double life which involves their playing roles in both performing and anticipating actions can initially seem incoherent because it appears to entail that a single attitude simultaneously has two directions of fit. In fact this is not entailed.

partner were supposed to jump. Vesper et al. found that jumps were coordinated by means of several adjustments. One is most relevant here and concerns effects on the time it takes to perform a jump. The person with the shorter jump would extend the time her jump took: she would jump longer, higher and further as the difference between her jump and her partner's jump lengthened. Since the minute adjustments to jump duration varied with the difference between the two partner's jump lengths, and since these appeared from the first trial without learning, it is reasonable to conjecture that these are a consequence of motor simulation (see further Vesper, Knoblich and Sebanz 2014; Ramenzoni et al. (2008) provide related evidence that estimating another's maximum jump-height involves your own motor abilities). So in the member of a pair with a shorter jump, there is a motor simulation of her partner's jump which influences how she herself jumps and so enables precise coordination in landing together. This is one example of how motor simulation may enable coordination in joint action.[8]

How, if at all, does coordination driven by motor simulation depend on intentions concerning coordination? We saw that entrainment can occur independently of, and even contrary to, intentions concerning coordination (see section 3). Since the effects of motor simulation on performing an action are often automatic (e.g. Brass et al. 2000), it is plausible that its effects on joint action resemble entrainment in occurring independently of intentions concerning coordination. In fact, it may be possible to disentangle the effects of motor simulation from the effects of intentions concerning coordination in Vesper et al.'s jumping study (introduced just above). We have just seen that participants in the jumping study achieved coordination in part by adjusting the time it took them to perform a jump (for example, jumping higher would make performing the jump take longer). In addition to this adjustment, the person in a pair who had the shorter jump would typically delay initiating her jump; and the greater the difference in length between her jump and her partner's, the longer she would delay her jump. Meanwhile the person in a pair who had the longer jump would jump as quickly as possible after the start signal, thereby making her more predictable to her partner. Interestingly, subjects interviewed after the experiment did report intentionally delaying initiating jumps, but none mentioned performing a jump that would take longer (by jumping higher, for example). Further, Vesper et al. found that these two types of adjustment—taking

[8] For evidence that motor simulation also enables coordination in musical performances, see Keller, Knoblich and Repp (2007), Loehr and Palmer (2011) and Novembre et al. (2013). For evidence on development, see Meyer et al. (2011)'s investigation of motor processes and coordination in three-year-old children.

longer to jump vs delaying the initiation of a jump—were not correlated; for instance, for a fixed difference in how far members of a pair were instructed to jump, the jumps longer in duration were not compensated for by shorter delays. Delaying and speeding up the initiation of a jump may have been driven by intentions concerning coordination, whereas the effects of motor simulation on the time taken to perform a jump were probably not so driven. This suggests that, like entrainment, coordination underpinned by motor simulation can occur independently of intentions concerning coordination.

The form of coordination underpinned by motor simulation is not specifically linked to collective intentionality. It can occur in joint actions without there being any exercise of collective intentionality. Consider, for instance, passengers entering a terminal building through a narrow tunnel. One passenger deftly overtakes another, weaving around her just before she draws level with a third passenger. Where such precise coordination is not merely luck it plausibly depends on motor simulation. There is (surely) no collective intentionality here. So motor simulation, like entrainment, supports the view that many exercises of collective agency are made possible by forms of coordination which can occur in a wide range of joint actions. Motor simulation is relevant not because of any intrinsic connection to collective intentionality but because it is probably indispensable for many exercises of collective intentionality which do not involve repetition or rhythm but do require precise bodily coordination.

Reflecting on entrainment and coordination driven by motor simulation, it is striking that one-off motor simulation allows greater flexibility at the cost of some precision. Is there a more general trade-off between flexibility and precision in mechanisms underpinning coordination? If so, what might this tell us about the nature of mechanisms underpinning coordination for joint action and their relations to each other?

5. Flexibility vs Precision

Consider two ways of partially ordering mechanisms underpinning coordination. The first is precision: How precise, in space and time, is the coordination they underpin in the best cases? For instance, mechanisms underpinning entrainment enable expert musicians to coordinate their actions to within tens of milliseconds, whereas one-off motor simulation permits coordination of actions to within larger fractions of a second.[9] A second partial ordering is flexibility: How wide is the range of situations in which this mechanism can underpin coordination? For instance, motor simulation can underpin coordination whether or not repetition or rhythm is involved, unlike entrainment. Thinking just about motor simulation and mechanisms underpinning entrainment, there appears to be a trade-off between precision and flexibility. This appears to generalise to other forms of coordination too, such as forms of coordination driven by shared intention. Gains in flexibility seem to come at the cost of precision.

Why? Before attempting to answer this question, it is useful to fix terminology with some stipulations. A *goal* of an action or behaviour is an outcome to which it is directed. Relative to a particular action or behaviour, goals can be partially ordered by the means-end relation. In saying that one goal is more *abstract* than another relative to a behaviour or action, I shall mean that the latter is linked to the former by a chain of outcomes ordered as means to ends. A *goal-state* is a mental state (or a structure of mental states) which represents, or otherwise specifies, an outcome and is the kind of thing in virtue of which some actions or behaviours can be directed to certain outcomes. Given that intentions are mental states, they are paradigmatic goal-states. But intentions are not the only goal-states: as we have seen, some motor representations are also goal-states. For instance, in Vesper et al.'s jumping experiment, subjects represented the goal of jumping a certain distance motorically (see section 4).[10]

So why might flexibility in a mechanism underpinning coordination come at the cost of precision? One possibility involves two conjectures. First, achieving flexibility generally depends on representing goals, and the more abstract the goals that can be represented, the greater the flexibility. To illustrate, entrainment can occur without any representations of goals at all, whereas motor simulation involves motor representations which are goal-states. But relative to intentions or knowledge states, motor representations are limited with respect to how abstract the outcomes they can specify are. Motor representations can specify outcomes such as grasping or transporting a fragile object, and even sequences of such outcomes (see, e.g., Fogassi et al. 2005). But they cannot specify outcomes such as selecting an organic egg or testing for freshness: motor processes and

9 As far as I know, there is no published investigation of the limits of precision of one-off motor simulation underpinning coordination. However several studies show, or depend on, split-second synchronisation; for example, in Vesper et al. (2013), pairs of jumpers landed within less than 200 milliseconds of each other.

10 For arguments that some motor representations are goal-states, see Prinz (1997, pp. 143–6), Pacherie (2008) and Butterfill and Sinigaglia (2014).

representations are mostly blind to things so distantly related to bodily action. Intentions and knowledge states underpinning coordination are more flexible than motor representations, enabling us to coordinate on, say, whether to use organic eggs or not. This is consistent with the first conjecture: relying on kinds of representation capable of specifying more abstract goals allows greater flexibility. A further conjecture is that processes involving more abstract goal representations typically (but not necessarily always) place greater demands on cognitive resources, which typically (but not necessarily always) results in lower precision. This conjecture is suggested by an analogy with the physiological. Because physiological processes are a source of variability, coordinating with a given degree of precision should get harder as the duration and complexity of the actions to be coordinated increases. Given that cognitive processes, like physiological processes, are a source of variability, increasing cognitive demands by relying on representations of more abstract goals should likewise increase variability and so limit precision.

In short, flexibility may come at the cost of precision because increasing flexibility requires representations of more abstract goals, which in turn imposes greater cognitive demands and thereby increases variability, so reducing how precise in space and time the coordination underpinned by the mechanism can be in the best cases. This may be why forms of coordination such as entrainment and motor representation can occur independently of, and even contrary to, intentions concerning coordination: precision requires such independence.

In thinking about mechanisms underpinning coordination for joint action, it is useful to order them according to how abstract the goals represented in them are. Doing so makes it clear that there is a gap between motor simulation and intentions or shared intentions. To see why, contrast two situations. In the first you, are at a wedding and invited to raise your glass in a toast by the bride's wife. Since there is a leader—the bride's wife—who initiates the toast by reaching for and starting to lift her glass, it is plausible that you can coordinate by motor simulation. But now consider the situation of a couple alone on a beach. Having filled plastic beakers with wine, they spontaneously and fluidly clink them together in a toast without spilling a drop of wine. Here there is no leader and the clinking is triggered by an event, the filling of the beakers, which has not routinely preceded clinking in the couple's past. To explain how they are able to coordinate so precisely we cannot appeal to motor simulation alone; but it would be no less plausible to appeal only to practical deliberation involving intentions or other propositional attitudes. We need something more flexible than motor simulation and more precise than practical deliberation.

6. Task Co-representation

Consider individual agents acting alone for a moment. A *task representation* links an event to an outcome in such a way that, normally, the event's actual or expected occurrence would trigger motor preparation for actions that should realise the outcome. Why do we need task representations? Imagine yourself cycling up to a crossroad. Even if you are concentrating hard on dodging potholes without being hit by the rapidly approaching car behind you (will it slow down or should you risk going through this hole?), it is likely—hopefully—that the traffic light's turning red will cause you to brake. The connection between red light events and braking actions can be hardwired and need not require thought, thanks to task representations.

Task representations are not intentions, although the two are related. When things go well, for many of an agent's intentions there will be corresponding task representations which persist only as long as the intention does. But task representations are not related to practical reasoning in the ways that intentions are standardly held to be. For instance, they neither set problems for practical reasoning nor require the formation of further intentions (on intention, see Bratman 1987). Task representations also differ from intentions in their representational format. Whereas intentions are standardly considered to be propositional attitudes, the contents of task representations can be individuated by event–outcome pairs, where the outcomes are all ones the agent can represent motorically. One consequence is that for many intentions there cannot be a corresponding task representation. These are reasons, not decisive but compelling, for treating task representations and intentions as distinct.

How is task representation relevant to coordinating joint actions? Sebanz, Bekkering and Knoblich (2006) suggest that one form of coordination for joint actions is underpinned by task co-representations (see also Sebanz, Knoblich and Prinz 2003). In the simplest case of task co-representation, there is one task (specifiable by an event–outcome link) and two individuals each have a task representation of that task. In general, some individuals have a *task co-representation* in a situation just if there are one or more tasks performing which would reliably involve the same actions in this situation and each agent has a task representation of one or another of these tasks. But why care about task co-representation? Sebanz, Bekkering and Knoblich claim that the agents of a joint action can have a task co-representation concerning a task which only one of them is actually supposed to perform. This, they suggest, would enable the agents whose task it is to exploit motor simulation prior to, and independently of, observing the any actual actions. Thus task co-representation could in principle greatly extend the range of situations in which motor simulation could underpin coordination in joint action. To illustrate, consider again the couple on the beach filling beakers with wine and then clinking them together. As noted earlier (in section 5), their doing this spontaneously, fluidly and with precision could not be explained by motor simulation alone when neither of them plays the role of leader. But it could be explained by Sebanz et al's proposal about task co-representation. If the couple expect to clink beakers after the wine is poured and have task co-representations concerning each's task in the clinking, then they will be able to use motor simulation to anticipate each other's actions in advance of starting to act. This is one illustration of how task co-representation might underpin coordination for one-off joint actions where agents have to respond to events in ways they have never done before.

The task co-representation hypothesis—agents involved in a joint action can have a task co-representation concerning a task that only one of them is supposed to perform—generates a variety of predictions. It predicts interference and facilitation effects: when acting together with another, your performance of your task will be affected by facts about which task the other is performing, and your performance will be impaired or enhanced in ways analogous to those in which it would be affected if you were performing both tasks alone. This prediction has been confirmed for a variety of tasks (Sebanz, Knoblich and Prinz 2005; Atmaca, Sebanz and Knoblich 2011; Böckler, Knoblich and Sebanz 2012; Vesper et al. 2013; Wel and Fu 2015).[11] The task co-representation hypothesis also predicts that, in some situations when you are acting with another, events linked to the other's task will trigger some preparation (but not necessarily full preparation) in you for a task which is actually supposed to be performed by the other. Evidence in support of this prediction includes signs that agents of a joint action sometimes inhibit tendencies to act when another, rather than she herself, is supposed act (Sebanz et al. 2006; Tsai et al. 2008), as well as signs that agents of a joint action are sometimes preparing for, or even covertly performing, actions that another is supposed to perform (e.g. Kourtis, Sebanz and Knoblich 2013; Baus et al. 2014).[12]

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[11] Vesper et al. (2013)'s experiment—the one with the jumping—was already mentioned in section 4 to illustrate motor simulation. Because subjects were required to jump in response to an event which would not ordinarily cue jumping, their findings bear not only on motor simulation but also on task co-representation.

[12] Wenke et al. (2011) and Dolk et al. (2011, 2014) have defended hypotheses which, if true, would enable some of the evidence for these predictions to be explained without accepting the task

Task co-representation is valuable in coordinating joint actions at least in part because it is more flexible than bare motor simulation while also more precise than practical reasoning. But there is a limit to what can be explained with either motor simulation or task co-representation, at least as we have conceived of them so far. Suppose motor simulation (whether or not triggered by a task co-representation) enables agents of a joint action to anticipate each other's actions. How could these anticipations inform preparation for their own actions, and, in particular, how could they do so without requiring cognitive processes inimical to precision? To offer even a candidate answer to this question requires going beyond motor simulation and task co-representation as we have so far conceived them.

7. Emergent vs Planned Coordination

In thinking about coordination for joint action it is useful to have plural counterparts of the notions of goal and goal-state introduced earlier (in section 4 on page 6). To say of an outcome that it is a *collective goal* of some actions or behaviours is to say that they are collectively directed to this outcome—that is, they are directed to this outcome and their being so directed is not, or not only, a matter of each action or behaviour being individually directed to that outcome. This is a broad notion: raising a brood can be a collective goal of some eusocial insects' behaviours,[13] and repairing a broken fence can be a collective goal of some neighbours' actions. A *collective goal-state* is a mental state or, more likely, a structure of mental states, which specifies an outcome and is the kind of thing in virtue of which some pluralities of actions or behaviours can be collectively directed to certain outcomes. While there is currently much controversy on the nature of collective goal-states, many agree both that they exist and that there are intention-like states or structures which are goal-states specifying collective goals. For instance, Searle's discussion of 'we-intentions' is an attempt to characterise the individual components of a collective goal-state (see Searle 1990), and

co-representation hypothesis. Neither approach can yet provide an alternative explanation for the full range of evidence in support of the co-representation hypothesis, however. In particular, no published research has yet tested (or even formulated) an alternative explanation for evidence of motor activity related to outcomes specified by others' tasks (e.g. Kourtis, Sebanz and Knoblich 2013; Vesper et al. 2013; Wel and Fu 2015).

[13] The insects' behaviours cannot be regarded as directed to raising a brood just in virtue of each individual insect behaviour being so directed because there is (typically, at least) a division of labour.

Bratman's account of shared intention aims to describe one kind of collective goal-state which functions as a collective counterpart of ordinary, individual intentions (see Bratman 1993).

Following Knoblich, Butterfill and Sebanz (2011), we can distinguish between emergent and planned coordination. *Planned coordination* is coordination driven by a collective goal-state,[14] whereas *emergent coordination* is coordination not so driven. Planned coordination is familiar from philosophical discussions of shared intention, one of the functions of which is to coordinate agents' actions (Bratman 1993, p. 99). By contrast, all the forms of coordination discussed in this chapter so far—entrainment as well as coordination driven by action and task co-representations—are naturally thought of as forms of emergent coordination insofar as it seems they could occur independently of the agents having any collective goal-state.

There is a complication, however. As we saw in section 3, entrainment can occur independently of, or even contrary to, any goal-states, whether individual or collective. In such cases entrainment is emergent coordination. But a qualification is necessary: as we also saw in section 3, the precision with which entrained actions are synchronised can be influenced by the agents' intentions concerning coordination and therefore probably also by collective goal-states. This suggests that it is a mistake to think of all entrainment as emergent coordination. But even where agents' intentions influence the degree of synchronisation in entrainment, it is likely that many of the processes critical for entrainment are not driven by intentions or any other goal-states. Reflection on entrainment therefore indicates that it may be necessary to recognise hybrid forms of coordination which are part emergent and part planned. Investigating such hybrid cases may be particularly important for understanding how largely isolated mechanisms for coordination can, in at least a limited range of situations, reliably have synergistic rather than discordant effects.

So far we have focussed on emergent forms of coordination. But there is also a growing body of evidence about the existence of planned coordination for joint action.

8. Collective Goal-States

Two pianists are producing tones in the course of playing a duet. Consider one of the pianists. There is an outcome to which her action is directed, the

[14] Note that, despite the name, planned coordination does not by definition involve planning.

production of a tone or melody; and there is an outcome to which her and her partner's actions are collectively directed, the production of a combination of pitches or harmony. As noted earlier (in footnote 8 to page 8), dueting pianists can use motor simulation to coordinate. This implies that in each pianist there are motor representations of the outcomes (i.e. tones or melodies) to which the other pianist's actions are directed. Do dueting pianists also represent collective goals, that is, outcomes to which their actions are collectively directed?

One way to investigate this question involves covertly introducing errors. Loehr et al. (2013) contrasted two kinds of error: those which were errors relative to the goal of an individual pianist's actions (the pitch) but not relative to the collective goal of the two pianists' actions (the harmony); and those which were errors relative to both. They found neural signatures for both kinds of errors in expert pianists. This is evidence that dueting pianists do indeed represent collective goals. But what is the nature of this representation? Is it, for instance, a knowledge state, a motor representation, or what?

Consider what happens when a someone who has learnt to play a duet is now tasked with playing just her part. Whether or not collective goals are represented motorically in her determines whether this task is more like performing a new action or repeating one she has already rehearsed. If collective goals are represented motorically in her, then, from her point of view, the task will involve actions different from those she has rehearsed. But if collective goals are not represented motorically in her, then the task involves repeating the very performance she rehearsed while dueting. To work out which possibility obtains, Loehr and Vesper (2015) compared novice pianists who had learned to play a duet ('the duetists', Experiment 1) with novices who had learned to play a melody while a computer filled in the sounds that the other duetist would have made ('the soloists', Experiment 2). Idealising, the duetists' and soloists' bodily movements and perceptual experiences were equated during the learning phase. After learning, each member of the two groups was then tasked with playing just her part in one of two conditions: either she played and heard only her own part, or else she played and heard both parts. If collective goals are not represented motorically in the former duetists, then their performances on this task should not differ from the former soloists' performances. But Loehr and Vesper found that the former duetists were unlike the former soloists: in performing the task while hearing only their part they made more errors than in performing the task while hearing the duet. This is evidence that duetists represent collective goals of their actions.

There are several sources of evidence for the further claim that representations of collective goals in the agents of a joint action sometimes include motor representations. One such source depends on the fact that how an agent represents her actions motorically reliably affects her tendencies to imitate observed actions. In particular, if there is no motor representation of a collective goal in an agent, then she should not have any tendency to imitate observed joint actions over and above possibly having a tendency to imitate individual actions which are components of a joint action. Using ingeniously contrived situations, Tsai, Sebanz and Knoblich (2011) and Ramenzoni, Sebanz and Knoblich (2014) have shown that agents involved in a joint action do indeed have tendencies to imitate observed joint actions, implying that they represent collective goals motorically. There is also some evidence from an innovative dual-EEG paradigm suggesting that agents acting together can represent collective goals motorically (Ménoret et al. 2014), and from a behavioural investigation of an interpersonal analogue of the end-state comfort effect (Meyer, Wel and Hunnius 2013).

How might motor representations of collective goals underpin coordination for joint action? One possible answer is suggested by Gallotti and Frith (2013) who, in discussing the research on imitating joint actions just mentioned, propose that a 'we-mode' is required. They explain:

> 'The central idea of the we-mode is that interacting agents share their minds by representing their contributions to the joint action as contributions to something that they are going to pursue together, as a 'we'. […] To represent things in the we-mode is for interacting individuals to have the content of their individual actions specified by representing aspects of the interactive scene in a distinct psychological attitude of intending-together, believing-together, desiring-together, etc' (p. 163).

An alternative possible answer is suggested by what Vesper et al. (2010) call a 'minimal architecture for joint action'. They propose to start by attempting to characterise joint action and its coordination without postulating distinct psychological attitudes and without invoking representations of interacting agents as comprising a 'we'. Instead their proposal is that some or all of the representations underpinning coordination for joint action are ordinary motor representations, task representations and other representations that are also involved in the coordination of ordinary, individual action. Relatedly, in at least some cases, coordination is driven by representations which are *agent-neutral*, that is, which do not specify any particular agent or agent. This proposal is consistent with evidence for the roles of motor simulation and task co-representation in coordinating joint action (see section 4 and section 6): anticipating another's actions and their effects involves much the same agent-neutral motor and task representations which would be involved if one were actually performing those actions oneself. (Of course, motor and task representations concerning actions others will eventually perform must ultimately have effects different from those concerning actions the agent will perform; but this is necessary for both observation and joint action and need not involve a novel kind of attitude.)

But how, given Vesper et al.'s 'minimal architecture' proposal, could motor representations of collective goals underpin coordination for joint action? In each agent of a joint action, the motor representations of collective goals trigger preparation for action in just the way any motor representations do. This has the effect that each agent is preparing to perform all of the actions comprising a joint action, although not necessarily in much detail (compare Loehr and Vesper 2015). Now this may appear wasteful given that each agent will only perform a subset of the actions prepared for. But it is not. One agent's preparing (to some extent) to perform all of the actions that will comprise a joint action ensures that the resulting motor plan for her actions will be constrained by her motor plan for the others' actions. And, given that she is sufficiently similar to the others and that the possibilities for action are sufficiently constrained in their situation, her motor plan for the others' actions will reliably match their motor plans for their actions. So one agent's preparing to perform all of the actions has the effect that her motor plan for her actions is indirectly constrained by the others' motor plans for their actions. In this way motor representations of collective goals could in principle underpin coordination for joint action by enabling agents to meet relational constraints on their actions (see further Butterfill, forthcoming).

One prediction of this hypothesis about how motor representations of collective goals could underpin coordination for joint action is that, where such representations are involved, an agent performing a joint action and an agent performing an individual action corresponding to the whole joint action should resemble each other motorically to some degree. To illustrate, compare two agents clinking a plastic beakers together (the joint action) with one agent clinking two plastic beakers together bimanually (the individual action). Motorically, the agent in the joint action should resemble the agent performing this individual action; and she should differ from an agent performing one part of the joint action alone by raising a single plastic beaker. Kourtis et al. (2014) used EEG to make just this comparison. One component of their study concerns a signal of motor preparation called the CNV, which is short for 'contingent negative variation'. This signal typically marks the onset of your own actions, but in prior research Kourtis, Sebanz and Knoblich (2013) showed that, for agents performing a joint action, the CNV also can also mark the onset of another's action. Comparing agents performing the joint action with agents acting individually by either performing the whole thing bimanually or performing just one part of the joint action indicates that in agents performing the joint action there is motor preparation concerning the whole joint action. While these findings might be interpreted in several ways, they are neatly explained by the hypothesis that motor representations of collective goals can underpin coordination by triggering preparation for all of the actions comprising a joint action.

The conjecture that motor representations of collective goals underpin coordination for joint action provides one response to a question raised at the end of section 6. The question was how anticipations concerning another's actions arising from motor simulation (whether bare motor simulation or occurring as a consequence of task co-representation) feed into preparing and monitoring your own actions. When coordination depends on motor representations of collective goals, the presupposition this question makes is incorrect. There are not two processes but one. Anticipation of another's actions and preparation for your own are not two separate things. They are parts of a single process in the same sense that, in preparing to perform a bimanual action, preparation for the actions to be performed by the left hand and anticipation of the movements of the right hand are parts of a single process. So where motor simulation and task co-representation involve collective goals to which a joint action is directed, motor processes themselves can ensure the integration of anticipations concerning another's actions with preparation for your own.

What can we conclude? Much is uncertain because the existence of collective goal-states and their possible roles in coordinating joint action is a relatively new area of scientific research. But it is striking that research using a variety of methods and paradigms all points to the existence of motor representations of collective goals in the agents of joint actions. Planned coordination is unlikely to be exclusively involved in exercises of collective intentionality.

This is not quite the end of the story about collective goals. Research on perceiving joint affordances points to a second way in which motor representations of collective goals may underpin coordination in joint action.

9. Joint Affordances

A *joint affordance* is an affordance for the agents of a joint action collectively—that is, it is an affordance for these agents and this is not, or not only, a matter of its being an affordance for any of the individual agents. Perceiving (or otherwise detecting) joint affordances is critical for many mundane joint actions such as appropriately gripping objects and applying the right force in moving them together, and crossing a busy road while holding hands. It is possible that motor representations of collective goals enable the agents of some joint actions to perceive joint affordances, or so I will suggest in this section.[15] But first, what grounds are there for supposing that joint affordances even exist?

Doerrfeld, Sebanz and Shiffrar (2012, p. 474) argue that 'the joint action abilities of a group shape the individual perception of its members.' In their experiment, perceptual judgements of weight were affected by whether the perceiver was about to lift the box alone or with another. Others have investigated different situations in which performing actions independently or as part of a joint action can affect how you perceive affordances. For instance, consider two individuals walking through a doorway. How wide must the doorway be for them to walk though it without rotating their shoulders? Davis et al. (2010, Experiment 1) show that the answer cannot be obtained simply by adding the minimum widths for each individual, and (in Experiments 2–4) that people can perceive whether doorway-like openings will allow a particular pair of walkers to pass through comfortably.[16] Importantly, people can perceive what openings afford people walking together not only when they are one of those walking but also when they are merely observing others walking (Experiment 4). This suggests that the perceptual capacity does not depend on the perceiver's own current possibilities for action. So what makes perception of joint affordances possible?

Consider the conjecture that joint affordances are perceived as a consequence of motor simulation (this is one of two possibilities discussed by Doerrfeld, Sebanz and Shiffrar 2012). This conjecture is made plausible by independent evidence for two hypotheses. First, motor representations can modulate perceptual experience; for instance, how an event is represented motorically can affect how a pair of tones are perceived with respect to pitch (Repp and Knoblich 2007, 2009; for

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[15] The notion of a collective goal was introduced in section 7; evidence for the existence of motor representations of collective goals was discussed in section 8.

[16] See Richardson, Marsh and Baron (2007) for a further study involving jointly lifting planks.

discussion, see Sinigaglia and Butterfill 2015). Second, perceiving another's affordance involves motor activity (Cardellicchio, Sinigaglia and Costantini 2012). These two findings make it plausible that, in general, perceiving some affordances is facilitated or even enabled by motor simulation. The findings just discussed suggest that the same may be true for joint affordances, that is, affordances for agents involved in one or another kind of joint action. But of course this is possible only given that there are motor representations of collective goals. After all, perceiving joint affordances requires motor simulation concerning the joint action, which would be triggered by a motor representation of a collective goal of the actions grounding the joint action; merely having separate motor simulations of each agent's actions could not underpin the identification of a joint affordance. This is why motor representations of collective goals may facilitate coordination in joint actions not only by enabling the agents to meet relational constraints on their actions (see section 8) but also by enabling them to perceive joint affordances.

10. Conclusion

I started from the observation that some exercises of collective intentionality depend on coordination too precise to be explained merely by appeal to knowledge states and intentions. What forms of coordination for joint action enable humans to exercise collective intentionality in doing things such as clinking beakers, sharing smiles, erecting marquees, or producing rhythmic music? We have seen that there is much diversity. Coordination for joint action includes not only emergent varieties such as entrainment (see section 3) and the forms underpinned by motor simulation (see section 4) and task co-representation (see section 6), but also planned coordination underpinned by motor representations of collective goals (see section 8).[17]

This diversity in forms of coordination may exist in part because, in general, there is a trade-off between flexibility and precision for individual mechanisms underpinning coordination (see section 5). Having multiple mechanisms is useful in part because each makes a different trade-off between flexibility and precision.

Many exercises of collective intentionality appear both to rely on highly flexible mechanisms and also to require extremely precise coordination in space or time. Improvising musicians ideally achieve temporal synchrony without

[17] This is not a comprehensive list. Relevant reviews include Marsh, Richardson and Schmidt (2009), Knoblich, Butterfill and Sebanz (2011) and Keller, Novembre and Hove (2014).

becoming enslaved to a rhythm. How is this possible? It might seem that this question arises only because we have been artificially considering forms of coordination in isolation from each other, as progress in experimental research often also requires. In practice, many exercises of collective intentionality depend on multiple forms of coordination, of course. To illustrate, fluid conversational exchanges may depend on a combination of entrainment, motor simulation and intentions to cooperate. Individual mechanisms underpinning coordination may be constrained by the precision–flexibility trade-off, but this constraint does not apply to a diversity of mechanisms considered in aggregate. So there is no theoretical obstacle to relying on highly flexible mechanisms yet achieving extremely precise coordination. This requires only that diverse mechanisms can have synergistic effects on coordination.

Just here a challenge arises, call it the *synergy challenge*. Achieving precise coordination in space and time probably demands that mechanisms underpinning different forms of coordination are to a significant degree independent of each other (see section 5), while acting flexibility requires that the different mechanisms sometimes nonaccidentally operate synergistically—the shared intention, the task co-representation, and the motor representation of the collective goal cannot all be pulling in different directions. The challenge is to understand how, in some situations, mechanisms underpinning different forms of coordination and which are driven by largely independent representational structures can nevertheless nonaccidentally have synergistic effects. Meeting this challenge may require attention to differences between novices and experts, to why practice is sometimes necessary, to the effects of common knowledge on moment-by-moment coordination (see, for example, Richardson, Dale and Kirkham 2007), and to phenomenal aspects of coordination (as Keller, Novembre and Hove 2014 hint), among other things. The synergy challenge is a significant obstacle to progress is understanding how high degrees of flexibility and precision can be combined in the coordination of joint actions.

Another issue likely to demand future discussion concerns which, if any, forms of coordination require postulating novel kinds of representations or processes specific to collective intentionality (see section 8). Although scientists sometimes adopt terms from philosophical discussions of collective intentionality such as 'shared' and 'we-' representations, the discoveries about the representations and processes underpinning coordination reviewed in this chapter do not require representations to be shared. Or at least they do not require representations to be 'shared' other than in the sense in which barrel organ aficionados share a taste in music. In line with Vesper et al. (2010)'s proposal, it is possible to understand much about coordination for joint action without relying on notions more sophisticated than those of agent-neutrality, co-representation and collective goal-state.

One theme in this chapter was that much coordination of joint action appears to involve not fully distinguishing others' actions from your own. Take motor simulation, task co-representation and motor representation of collective goals. In each case, coordination involves motor or task representations of actions, tasks or goals that relate primarily to another's part in the joint action. This is not a matter of representing another's goals or plans as an observer: it is a matter of preparing actions and representing tasks she will perform in ways that would also be appropriate if it were you, not her, who was about to perform them. To a limited but significant extent, then, coordination involves representing both another's actions and your own in ways that would also be appropriate if you were going to perform all these actions. The existence of such a perspective on the actions grounding a joint action might just turn out to matter not only for coordination but also for other aspects of collective intentionality such as commitment and cooperation.[18]

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[18] Acknowledgements. I have benefitted immeasurably from extended collaborations with Natalie Sebanz, Guenther Knoblich and Corrado Sinigaglia as well as from shorter (so far) collaborations with Cordula Vesper and Lincoln Colling. I am also indebted to many people for discussion. Thank you!

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