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Co-actors represent the order of each other's actions

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ABSTRACT

Previous research has shown that people represent each other's tasks and actions when acting together. However, less is known about how co-actors represent each other's action *sequences*. Here, we asked whether co-actors represent the order of each other's actions within an action sequence, or whether they merely represent the intended end state of a joint action together with their own contribution. In the present study, two co-actors concurrently performed action sequences composed of two actions. We predicted that if co-actors represent the order of each other's actions, they should experience interference when the order of their actions differs. Supporting this prediction, the results of six experiments consistently showed that co-actors moved more slowly when performing the same actions in a different order compared to performing the same actions in the same order. In line with findings from bimanual movement tasks, our results indicate that interference can arise due to differences in movement parameters and due to differences in the perceptual characteristics of movement goals. The present findings extend previous research on co-representation, providing evidence that people represent not only the elements of another's task, but also their temporal structure.

1. Introduction

Human motor behavior relies on precise action planning and control. We need to decide which button in the elevator to press, when and how far to jump over a puddle, and we need to coordinate our left and right limb during a dance routine. When acting jointly with others, coordination is not only required within an individual's motor system but also between the independent motor systems of two (or more) individuals (e.g., Knoblich & Jordan, 2003; Wolpert, Doya, & Kawato, 2003), such as when two dance partners coordinate their steps, or when pianists play a duet together (e.g., Keller, Knoblich, & Repp, 2007).

Previous research has suggested that the coordination of actions within and between individuals may rely on similar processes (e.g., Fine & Amazeen, 2011; Richardson, Marsh, & Baron, 2007; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt & Richardson, 2008). For instance, when performing repetitive, rhythmic movements, a tendency to entrain to the same movement rhythm was observed between individuals in a group (e.g., Fine & Amazeen, 2011; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt et al., 1990) as well as between the limbs of one individual acting bimanually (e.g., Heuer, 1996; Heuer & Klein, 2005; Kelso, Southard, & Goodman, 1979; Mechsner, Kerzel, Knoblich, & Prinz, 2001).

Further similarities between intra- and interpersonal processing have been found at the level of task and action representation. When tasks are distributed between two co-actors, similar response selection conflicts (Atmaca, Sebanz, & Knoblich, 2011; Sebanz, Knoblich, & Prinz, 2003), attention allocation processes (Böckler, Knoblich, & Sebanz, 2012; Kourtis, Knoblich, Wozniak, & Sebanz, 2014; Welsh et al., 2005), lexical processes (Hoedemaker, Ernst, Meyer, & Belke, 2017; Kuhlen & Abdel Rahman, 2017), and motor priming effects (Griffiths & Tipper, 2009; Welsh, McDougall, & Weeks, 2009) occur as when one individual performs the whole task alone. Further evidence comes from interpersonal movement coordination tasks. When two co-actors concurrently perform movements of different difficulty, they make similar adjustments in action execution (Fine & Amazeen, 2011; Vesper, van der Wel, Knoblich, & Sebanz, 2013) as one individual performing movements of different difficulty with her two limbs (Fowler, Duck, Mosher, & Mathieson, 1991; Kelso et al., 1979; Marteniuk, MacKenzie, & Baba, 1984). Moreover, van der Wel and Fu (2015; see also Schmitz, Vesper, Sebanz, & Knoblich, 2017) demonstrated that when only one of two co-actors needs to move over an obstacle, the actor without obstacle also increases her movement amplitude. Again, this result pattern resembles findings earlier obtained in a bimanual version of the same task in which the limb without obstacle moved as if it were also clearing an obstacle (Kelso, Putnam, &

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Goodman, 1983). Finally, della Gatta et al. (2017) showed that when one person draws a line while the other draws a circle, the line trajectories tend to become ovalized. This corresponds to findings from the bimanual literature showing that the same interference occurs when drawing a circle with one hand while drawing a line with the other (Franz, Zelaznik, & McCabe, 1991), indicating that the action representations of line and circle interfere with one another.

Taken together, the research so far indicates that similar mechanisms operate in intrapersonal and interpersonal action planning and action coordination. In particular, people's tendency to represent a co-actor's part of a task (e.g., Sebanz et al., 2003) often leads to similar interferences as when one individual performs the whole task alone. This co-representation tendency has been mainly observed in studies where co-actors in a joint action performed *discrete, individual* actions such as pressing a response button or performing a goal-directed forward jump or an aiming movement. However, in everyday life, people often perform *multiple* actions in a sequence. Therefore, the present study asked how co-actors represent each other's actions when they perform *sequences* of actions to achieve temporal coordination at the end. We examined whether similarities between intra- and interpersonal coordination can be observed.

To illustrate, consider two dancers who perform a dance move that requires them to approach each other so that they arrive synchronously at the center of the dance floor. The male dancer performs a long step followed by a short step whereas the female dancer performs a short step followed by a long step. Our question is whether the two dancers represent the order of actions within each other's action sequence, or whether they merely represent the end state that the two action sequences produce, together with their own contribution. Does the male dancer represent the female dancer's sequence of a short step followed by a long one, or does he merely represent her meeting him at the center, while ignoring the specifics of how she is going to get there? Abstracting from the example, we consider a situation where two co-actors perform the same actions in a different order (i.e., B-A vs. A-B), with the joint goal of synchronized arrival at a pre-defined position (see Fig. 1). Reaching a synchronized end state in this type of situation does not necessarily require co-actors to take into account each other's actions because synchronization can be based on the overall duration of the sequence which is not affected by the order of actions within the sequence (on anticipatory temporal prediction and sensorimotor synchronization, see e.g., Repp & Su, 2013; van der Steen & Keller, 2013).

Before asking whether co-actors represent the discrete actions that make up *each other's* action sequences, we briefly consider the question of how co-actors plan and execute *their own* action sequences. Prior research has shown that when performing a sequence of two consecutive movements, people do not plan and parametrize each of the movements separately. Rather, both movement segments are planned in advance and stored in a "buffer" such that the second movement can be read from this buffer while the first movement is being executed ("movement integration hypothesis"; Adam et al., 2000). This online preparation of the second movement during the execution of the first movement has the effect of slowing down the first movement: Completing a movement that is followed by a second movement will take longer than completing the same movement on its own – an effect known as the "one-target advantage" (for a recent review, see Bested, de Grosbois, & Tremblay, 2018). In the context of the present research, we assume that even though movement sequences are typically planned in an integrated fashion, the order in which the movement segments are to be executed must surely be part of this plan. Thus, when it comes to co-representing *others'* action sequences, we ask whether people represent others' actions as an *ordered* sequence or whether they merely take into account the other's sequence as a whole. An ordered sequence may be represented either in terms of two separate movement segments or as one complex movement with two pre-planned stages.

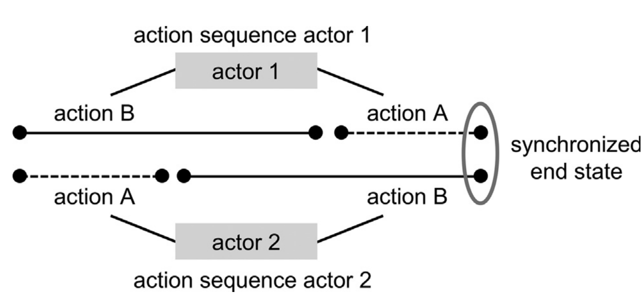

Fig. 1. Schematic depiction of a joint action situation in which two co-actors perform the same actions in a different order (i.e., B-A vs. A-B), with the joint goal of synchronizing the end state of their action sequences.

To test whether co-actors represent the order of actions within each other's action sequence, we designed a novel joint movement task where two co-actors performed sequences of goal-directed, speeded aiming movements towards targets on a table (Fig. 2). The sequences consisted of two movements of differing distances such that each actor performed a short movement followed by a long one or a long movement followed by a short one. Their joint goal was to synchronize arrival times at the endpoint of the sequence. One way to facilitate synchronization is to make the overall duration of one's own action sequence as invariant, and thus predictable, as possible (Vesper, Schmitz, Safra, Sebanz, & Knoblich, 2016; Vesper, van der Wel, Knoblich, & Sebanz, 2011). This strategy does not require representing the order of a co-actor's actions.

However, if co-actors represent the order of actions within each other's action sequence, they may experience interference when the order of their own actions differs from the order of their co-actor's actions. This hypothesis follows from the assumption that behavior within and between individuals is organized by similar mechanisms (e.g., Schmidt et al., 1990). In particular, the present interpersonal task relates to studies on bimanual motor control showing that people encounter intermanual interference when trying to simultaneously perform movements of differing spatial characteristics. Interference is reflected in longer initiation times (Diedrichsen, Grafton, Albert, Hazletine, & Ivry, 2006; Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, 2003; Heuer & Klein, 2006; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997) and longer movement times (Albert, Weigelt, Hazeltine, & Ivry, 2007; Diedrichsen, Hazeltine, Kennerly, & Ivry, 2001; Heuer & Klein, 2006) for movements of differing distances or directions.

Two distinct sources for this intermanual interference have been identified in the motor control literature. On the one hand, interference can occur at the level of motor representations, where different movement parameters for left and right hand need to be concurrently specified during motor programming (Diedrichsen et al., 2006; Heuer & Klein, 2006; Heuer, 1993; Spijkers et al., 1997). On the other hand, interference can also occur at a higher cognitive level of goal-selection, where different movement goals are selected and assigned to left and right hand (Diedrichsen et al., 2001, 2003, 2006; Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004; Kunde & Weigelt, 2005; Mechsner & Knoblich, 2004; Mechsner et al., 2001; Weigelt, 2007; Weigelt, Rieger, Mechsner, & Prinz, 2007).

For the present interpersonal task, these findings imply that co-actors may show similar interference – at a motor and/or cognitive level – when they represent the actions within each other's action sequence. At the motor level, actors might be unable to plan and execute their own movements independently of a co-actor's movements such that interference occurs when a co-actor's movements differ in crucial movement parameters. In contrast to bimanual aiming movements where this type of movement-related interference is attributed to interhemispheric communication (Diedrichsen et al., 2006; Franz, Eliassen, Ivry, & Gazzaniga, 1996; Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002), interpersonal interference would arise from motor simulation processes whereby co-actors use their own motor systems to simulate and predict each other's actions (e.g., Wilson & Knoblich, 2005;