

CO-REPRESENTATION AND COMMUNICATION IN JOINT ACTION

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*In partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Cognitive Science*

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Budapest, Hungary

2017

Declaration of Authorship

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or which have been accepted for the award of any other degree or diploma at Central European University or any other educational institution, except where due acknowledgment is made in the form of bibliographical reference.

The present thesis includes work that appears in the following articles:

Schmitz, L., Vesper, C., Sebanz, N., & Knoblich, G. (2017). Co-representation of others' task constraints in joint action. *Journal of Experimental Psychology. Human Perception and Performance*, 43(8), 1480-1493.

Schmitz, L., Vesper, C., Sebanz, N., & Knoblich, G. (accepted). When height carries weight: Communicating hidden object properties for joint action. *Cognitive Science*.

Schmitz, L., Vesper, C., Sebanz, N., & Knoblich, G. (under review). Co-actors represent the order of each other's actions.

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Abstract

Humans constantly coordinate their actions with those of others, ranging from a handshake to the building of a house. What are the processes enabling individuals to perform such *joint actions*? The present work targets this question by investigating to what extent individuals integrate others' constraints into their own actions when acting together. The first study explored whether individuals represent and adapt to a co-actor's environmental constraint to achieve temporal coordination, even if this implies compromising the efficiency of their own movements. The results showed that unconstrained individuals represented the obstacle obstructing their co-actor's movement path such that they moved *as if* an obstacle was obstructing their own path as well. A second study investigated whether co-actors represent the temporal structure of each other's actions. Co-actors experienced interference when performing the same actions in a different order, indicating that they represented the order of each other's actions although this was not necessary for joint task performance. A third study asked whether and how co-actors create novel communication systems to overcome knowledge constraints that impede coordination. Depending on situational factors, informed actors communicated by engaging in novel forms of sensorimotor communication or of symbolic communication. In sum, these studies show that individuals possess a distinct tendency to take others' constraints into account when faced with the challenges of real-time action coordination. Specifically, individuals represent others' environmental constraints, others' task-specific constraints in the form of the temporal structure of their actions, and the knowledge others do (or do not) possess – and they integrate these constraints into their own actions even if this compromises individual efficiency. If overcoming another's constraint requires an active transfer of information, individuals flexibly create novel communication systems. Taken together, the work presented in this thesis contributes to a better understanding of the processes underlying joint action and it provides further evidence of the human predisposition to act with others in mind.

Acknowledgements

Writing a dissertation is a journey one does not undertake alone. I am thankful to the following people for accompanying me on this journey with their help and support.

First and foremost, I would like to thank Günther and Natalie, who sparked my interest in joint action in the first place and who continue to inspire me. Thank you for your guidance and support throughout the years; I feel fortunate having been able to work with and learn from you. Secondly, I would like to thank Cordula – for being my mentor, academic role model, collaborator, and friend at the same time. Thank you for all the advice, constructive criticism, and encouragement you provided me with whenever needed. I cannot imagine this journey without you.

Next, I would like to thank all members of the Social Mind and Body Group, for valuable feedback and inspiring discussions, and for making work so much more enjoyable. Special thanks go to Martin for always being a step ahead and showing me how things are done; to Thomas for his readiness to help, for his enthusiasm, and for his mix of creativity, genius, and craziness; to Gina and Simily for joining the Sombies with fresh ideas and good vibes; to Tiffany for her positive perspective on (academic) life; to Dimi for keeping up the traditions; and to Arianna and Luke for being such awesome summer school companions. Not to forget, heartfelt thanks go to Ivana and Vero, whose presence during the beginnings of my PhD made all the difference. Another heartfelt thank you goes to April, my favorite Somby intern, who has become a dear friend and colleague. And another one goes to Basil, not a Somby himself but a converted joint action enthusiast, for his support in statistics and in similarly vital matters.

I would also like to thank all PhD students and all faculty from the Cognitive Science Department at CEU for providing such a friendly, open-minded, and diverse working environment. In particular, I would like to mention Eszter, Johannes, Lenka, Luke, and Nazli, with whom I entered the PhD program and thanks to whom the first year of the PhD will remain

unforgettable. Thanks also to Denis for contributing to the adventures of the first year. Moreover, I would like to thank Francesca for bringing new life into our office and Otávio for those regular and cheerful window visits. Finally, very special thanks go to Nazli, for having been there from day one, putting a smile on my face – and for continuing to do so no matter what. Thank you also for having such a big heart for homeless PhD students.

Another huge thank you goes to Réka, Andi, and Eszter, whose work in the background is simply irreplaceable. Thank you for taking care of everything, for being extremely patient and seemingly all knowing – and last but not least, for always making the visits to your office a pleasant experience. For a different kind of work in the background I would like to thank Annamaria, Fruzsí, and Dávid whose help in the lab has been invaluable. Thanks also to all the participants who took part in my studies.

Moreover, I would like to thank the group at the Institute of Philosophy in London, especially Ophelia, for the warm welcome and for letting me be part of an incredibly creative, productive, and enthusiastic working atmosphere.

My thanks also go to all the different people from all over the world whom I had the chance to meet at conferences and workshops. In particular, thanks to all JAM participants for those intense and inspiring meetings, and thanks to all participants at *the* (one and only) summer school for those yearly island reunions full of exceptionally stimulating academic and social exchange.

Thank you, Budapest, and thank you, London – for the hot summers, cold winters, and mild springs; for the blue skies, the rivers and bridges, the parks and the pools; for the coffee, the chickpeas, the ginger and mint – and for being those special places during special times.

And last but certainly not least, thank you to my family for the constant and unconditioned support.

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Chapter 1. Introduction

Coordinating our actions with the actions of others is one of our most fundamental abilities, crucial not only for our individual success but also for the success of the human species (Sebanz, Bekkering, & Knoblich, 2006). Yet, there is a large discrepancy between the degree of importance of *joint action* (Sebanz et al., 2006) for human life and the degree to which the cognitive and neural processes underlying this ability are understood. This is because cognitive psychologists and cognitive neuroscientists have traditionally studied the mind and brain of isolated individuals, ignoring the social context in which human cognition is typically embedded. These traditional approaches have merely scratched on the surface of *social* cognition by looking at how individuals passively process static images with social content. However, during the past two decades, scientists have begun to go beyond the classical “isolation paradigm” (Becchio, Sartori, & Castiello, 2010), acknowledging the importance of studying real-time social interactions (e.g., Becchio et al., 2010; Knoblich, Butterfill, & Sebanz, 2011; Schilbach et al., 2013; Sebanz et al., 2006). Since then, an increasing amount of research has been addressing the perceptual, cognitive, and motor processes that enable us to coordinate our actions with others, and major advances in understanding these processes have been made (for reviews, see Knoblich et al., 2011; Sebanz et al., 2006; Vesper & Sebanz, 2016).

The work I present in this thesis aims to contribute to the growing field of joint action research by further exploring the processes underlying real-time action coordination. To this end, it investigates to what extent individuals integrate others’ constraints into their own actions when acting together. Specifically, this thesis focusses on how individuals co-represent each other’s actions (Chapters 2-3) and on how they create non-conventional communication systems (Chapter 4). Chapter 1 provides an overview of the current state of the art in joint action research, serving as a backdrop for my own research that is presented subsequently.

1.1 Approaches to joint action

Joint action, broadly defined 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 et al., 2006, p. 70), encompasses a wide range of coordination phenomena, from ordinary everyday activities such as passing someone a bottle of water or having a conversation, to expert skills such as playing a piano duet or performing acrobatic dives in perfect synchrony. As diverse as the instances of joint action, as diverse are the approaches taken in the study of joint action. Initially, it was philosophers’ curiosity about the nature of joint intentionality that sparked scientists’ interest in joint action. Philosophers generally agreed that *shared* intentions are required to plan and engage in joint actions, yet there is an ongoing debate pertaining to the nature of these shared intentions. Some hold that shared intentions are fundamentally different from individual intentions because they imply a distinct psychological attitude, a so-called we-intention or we-mode (e.g., Gallotti & Frith, 2013; Searle, 1990; Sellars, 1986; Tuomela & Miller, 1988; for neurophysiological evidence, see Becchio & Bertone, 2004). Others argue that shared intentions come about in a different way than individual intentions (Gold & Sugden, 2007), or that they entail a special kind of commitment to others (Gilbert, 1992; Roth, 2004). In opposition to these views, Bratman argues that shared intentions can be reduced to individual intentions that interlock in particular ways (Bratman, 1992, 2009).

The philosophical explorations of joint intentionality served as guidance for conceptual and empirical work on a specific case of joint action, namely on language use (e.g., Brennan & Clark, 1996; Brennan & Hanna, 2009; Clark, 1996; Shintel & Keysar, 2009). The use of language is seen as a case of joint action (Clark, 1996) where meaning is coordinated between interlocutors (e.g., Barr & Keysar, 2007; Shintel & Keysar, 2009). Notably, this type of coordination in conversation seems to be supported by similar mechanisms as coordination in

nonverbal forms of joint action (Garrod & Pickering, 2009; Pickering & Garrod, 2013). Not only does verbal communication constitute a case of joint action in and of itself, but it also functions as a coordination device, helping to establish common ground between co-actors (Clark, 1996). This function is particularly crucial when external common ground is limited, e.g., because agents do not share a visual context (Brennan, 2005; Clark & Krych, 2004; Duff, Hengst, Tranel, & Cohen, 2006). Furthermore, language can be used to plan joint activities and to coordinate actions online. During online coordination, joint action partners can greatly benefit from language use: If given the opportunity to communicate, two co-actors can jointly outperform an individual actor (e.g., Bahrami et al., 2010; Brennan & Enns, 2015). Whether such a collective benefit is achieved depends on the specifics of co-actors' language use. In some tasks, such as perceptual decision-making, co-actors benefit from aligning on a shared task-relevant vocabulary (Fusaroli et al., 2012) whereas in other tasks, such as abstract category formation and transfer, a high diversity in co-actors' linguistic contributions has proven beneficial (Tylén, Fusaroli, Smith, & Arnoldi, 2017). However, there are also coordination tasks where language use cannot function as a coordination device because verbal communication is not practical or even impossible, as for instance when time is limited (e.g., Brennan, Chen, Dickinson, Neider, & Zelinsky, 2008). In cases where conventional communication is not possible, humans have been shown to spontaneously invent novel communication systems (Galantucci, 2009).

Philosophers' theoretical work on joint intentionality has also served as inspiration for empirical studies on the phylogenetic and ontogenetic development of joint action abilities (Call, 2009; Carpenter, 2009; Tomasello, 2009). These studies have shown that chimpanzees, and even elephants, are capable of initiating coordinated action with a conspecific (Melis, Hare, & Tomasello, 2006; Plotnik, Lair, Suphachoksahakun, & de Waal, 2011), reflecting some basic abilities for joint action in non-human animals. In contrast to other primates, however, human

infants seem “ultrasocial” (Tomasello, 1999, p. 59), equipped with a natural aptitude for collaboration (Boyd & Richerson, 1996; Tomasello, Carpenter, Call, Behne, & Moll, 2005). From very early on, infants eagerly participate in dyadic interactions with caregivers (Reddy, 2008; Stern, 2002; Trevarthen, 1979), and soon start to engage in shared attention (Barresi & Moore, 1996). At an early age, they still have difficulties coordinating their actions with others and depend on a caregiver’s scaffolding, but their coordination abilities rapidly develop during the first three years of life (Brownell, 2011). By the age of one, infants show signs of prosocial motivation, helping others to attain a goal (Warneken & Tomasello, 2007) and providing helpful information (Liszkowski, Carpenter, & Tomasello, 2008). By the age of two, children engage in simple coordination games with adults (Warneken, Chen, & Tomasello, 2006) and peers (Brownell, Ramani, & Zerwas, 2006), and by the age of three do they succeed in more complex coordination tasks (e.g., Meyer, Bekkering, Paulus, & Hunnius, 2010). It remains to be shown which are the crucial abilities that need to develop before joint action proper can emerge (e.g., Meyer, Bekkering, Haartsen, Stapel, & Hunnius, 2015), and in turn, whether and how performing joint actions may contribute to development.

By focusing on action plans and intentions, on language use, and on the phylo- and ontogenetic trajectory of joint action abilities, philosophers, psycholinguists, and developmental/comparative psychologists have all contributed to a better understanding of joint action. The present thesis focuses on a related but slightly different approach, i.e., the one taken by cognitive psychologists, who empirically study the basic processes enabling adult humans to perform actions together. In the remainder of this chapter, I will outline previous work on these basic processes, thereby laying the foundation for my own empirical research that will be presented in the subsequent three chapters. Prior to addressing the processes and mechanisms underlying interpersonal coordination, I will provide a short overview of the different types of coordination that have been identified in previous research. This serves to illustrate and

structure the wide variety of coordination phenomena, while at the same time providing the broader context for the particular types of coordination of interest in this thesis.

1.2 Types of coordination

As interpersonal coordination comes in a multitude of forms – from a handshake over rhythmical chants to the building of a house –, it is helpful to distinguish different types of coordination on the basis of a few important dimensions. A first crucial distinction is between emergent and planned coordination (Knoblich et al., 2011). *Emergent* coordination between individuals occurs spontaneously and the individuals involved do not necessarily have any prior plans, shared intentions, or common knowledge. Due to perception-action couplings (and often without any direct mechanical coupling), agents become ‘entrained’ and start acting in similar ways, such as when pedestrians fall into synchronized walking patterns (Van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008), when two people in rocking chairs involuntarily start rocking in synchrony (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007), or when interlocutors synchronize their body sway (Shockley, Santana, & Fowler, 2003). This emergent process of entrainment is often conceptualized as a coupling of rhythmic oscillators and can be observed in mechanical as well as in biological systems (e.g., Schmidt & Richardson, 2008; for a recent review, see Shockley & Riley, 2015).

In contrast, coordination is *planned* when agents intend to act towards a joint goal, i.e., towards a desired outcome of their coordinated actions. Within the domain of planned coordination, a number of further distinctions can be made (cf. Vesper, 2013). First of all, planned coordination can be subdivided in terms of its temporal and spatial properties. Regarding the temporal dimension, coordination can happen either in real-time where agents coordinate their actions with fine-grained temporal precision – often involving adaptations in the range of (milli-)seconds such as when two people perform synchronized finger-tapping

(Konvalinka, Vuust, Roepstorff, & Frith, 2010) –, or it can last over a longer period of time, such as when co-authors work on a manuscript together. In the case of real-time coordination, actions can be coordinated either continuously, e.g., when dancing a tango together, or at discrete points in time, e.g., when clinking glasses with someone (Kourtis, Knoblich, Wozniak, & Sebanz, 2014). Regarding the spatial dimension, co-actors can either act in a shared physical space, e.g., when playing football together, or they can coordinate their actions remotely, e.g., when jointly playing a multiplayer game over the internet.

Finally, an important distinction is to be made between symmetric and asymmetric coordination scenarios. Symmetry can be defined with respect to co-actors' tasks, to the task difficulty, and to the amount of information co-actors receive. For instance, when two people lift a two-handled basket together (Knoblich & Sebanz, 2008), coordination is symmetric with respect to co-actors' tasks and to the task difficulty, as both co-actors lift one handle of the basket, distributing the weight of the basket equally. On the contrary, coordination is asymmetric with respect to task difficulty when one co-actor performs a more difficult task than the other, e.g., when one person needs to jump farther than the other (Vesper, van der Wel, Knoblich, & Sebanz, 2013). Moreover, an asymmetry is often created because information is distributed unequally between co-actors such that one actor has task-relevant knowledge that the other lacks (e.g., Sacheli, Tidoni, Pavone, Aglioti, & Candidi, 2013; Vesper & Richardson, 2014; Vesper, Schmitz, & Knoblich, 2017). As an exemplary case of asymmetric knowledge distribution, consider two friends who jointly bake a birthday cake while only one of them knows the recipe, or consider the same friends jointly walking to the birthday party while only one of them knows where the party takes place. Furthermore, co-actors may also have asymmetric access to each other's actions, e.g., such as when only one co-actor hears or sees the other (e.g., Clark & Krych, 2004; Konvalinka et al., 2010; Vesper & Richardson, 2014). Especially in cases of asymmetric knowledge distribution or when perceptual access to each

other's actions is restricted, coordination largely depends on information exchange between co-actors. Co-actors may exchange information by relying on conventional, verbal communication (see section above on language use) or by developing novel, non-verbal communication systems (see section below on coordination processes and mechanisms).

To sum up, coordination can be classified as either emergent or planned. In the present thesis, I will focus on planned coordination. Specifically, I will focus on real-time, non-verbal interactions between two agents who coordinate their actions at discrete points in time in a shared physical space. Which coordination processes do co-actors in these and in other types of joint actions rely on?

1.3 Coordination processes and mechanisms

When acting alone, individuals plan, control, and coordinate their own actions internally, within their own action system. For instance, when an individual passes a ball from her left to her right hand, she will specify for the left hand when to release the ball and into which direction, and she will activate the corresponding catching action for the right hand at the appropriate point in time. Precise intrapersonal coordination is achieved through a process known as motor simulation, whereby internal models in the individual's motor system generate predictions about the unfolding of an action and its sensory consequences (Wolpert, Doya, & Kawato, 2003). This enables the individual to correct her movements online in case an error signal is detected, for instance when the predicted position of the ball does not intersect with the predicted trajectory of the right hand.

What happens when the same task of passing a ball is shared by two people, with one of them passing and the other catching the ball? In this case of interpersonal coordination, co-actors face the challenge of not being able to access each other's internal models. How do they manage to coordinate their actions in space and time, despite this lack of shared internal

processes? At first glance, an option might be to simply observe another person's action and then react to it. However, this strategy is likely to fail, especially in time-critical interactions. If the ball moves quickly, it will have touched the ground before the catcher is able to react. Instead, what is needed is anticipatory coordination: Rather than responding to a co-actor's observed action, one needs to plan and execute one's own action in response to the predicted effects of a co-actor's action (e.g., Knoblich & Jordan, 2003; Sebanz et al., 2006). Thus, the question becomes: How do co-actors predict each other's actions?

1.3.1 Prediction through observation

Previous research has shown that common representations and processes underlie the execution of own actions and the perception of others' actions (Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Jeannerod, 2001; Prinz, 1997). Specifically, when observing another's action, the same motor commands are activated in the observer that she would use to execute, plan, or imagine the same action herself (e.g., Decety & Grèzes, 1999; for a meta-analysis, see Grèzes & Decety, 2001; for a comprehensive review, see Rizzolatti & Sinigaglia, 2010). Relying on this common representational format, observers are able to predict the unfolding of another's observed action by using the same processes as for planning their own actions (Grush, 2004; Knoblich & Flach, 2001; Wilson & Knoblich, 2005; Wolpert et al., 2003). This ability is modulated by an observer's own familiarity with the observed action such that observers are more accurate at predicting actions they are familiar with (e.g., Aglioti, Cesari, Romani, & Urgesi, 2008; Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Sebanz & Shiffrar, 2009). Consequently, prediction is best when it is based on perceptual input that reflects one's own previously performed actions. This was demonstrated in a study where pianists played more synchronously with the recordings of their own compared to others' earlier performance (Keller, Knoblich, & Repp, 2007).

Moreover, by simulating and integrating own and other's actions in real time, co-actors can monitor the progress towards their joint goal. When the simulated outcome and the intended outcome mismatch, co-actors can flexibly adjust their own actions. This monitoring process has been examined by a recent electrophysiological study on duet music performance. The study showed that duetting pianists do not only process their own and their partner's errors but are especially sensitive to errors affecting the overall musical outcome, i.e., the harmony produced by their combined pitches (Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013). Findings from this and other studies suggest that co-actors rely on the same mechanisms to monitor (errors in) own and other's action outcomes (Schuch & Tipper; 2007; van Schie, Mars, Coles, & Bekkering, 2004; de Bruijn, de Lange, von Cramon, & Ullsperger, 2009; Picton, Saunders, & Jentzsch, 2012) while at the same time also monitoring the combined action outcome (Loehr et al., 2013; Radke, de Lange, Ullsperger, & de Bruijn, 2011).

1.3.2 Prediction through task co-representation

How is prediction achieved when co-actors cannot see or hear each other's actions? It has been shown that merely knowing what another person is going to do is sufficient to trigger corresponding motor simulations of another's action. This was demonstrated in a study where pairs of participants performed forward jumps of different distances with the joint goal of landing at the same time, while not being able to observe each other's actions (Vesper, van der Wel, et al., 2013). Results showed that participants with the shorter jump systematically adjusted the time before initiating their jump and the height of their jump as a function of the difference between their own and their co-actor's jumping distance. Specifically, they took longer to initiate their jumps and jumped higher the larger the distance difference between co-actors was, thereby facilitating synchronous landing. This finding indicates that even without perceptual information, and merely based on the knowledge of each other's tasks, participants

were able to predict and integrate each other's actions into their own action planning and execution (Vesper, van der Wel, et al., 2013).

Additionally, there is evidence suggesting that people simulate others' actions not only online during action performance but also offline in the action preparation phase, i.e., before movement initiation. When planning to hand over objects or clink glasses with a co-actor, participants showed neural activations suggesting that they represented their co-actor's upcoming action in addition to their own (Kourtis, Sebanz, & Knoblich, 2013; Kourtis et al., 2014). Moreover, people are able to engage in predictive motor simulations even when merely imagining to perform a joint action (Vesper, Knoblich, & Sebanz, 2014). Together, these findings suggest that in addition to direct observation, mental representations of others' tasks can serve as the basis for action prediction, thereby supporting coordination in real time.

1.3.3 Task co-representation: a pervasive tendency

Another line of research has revealed that people also represent each other's tasks when interpersonal coordination is not required. When acting alongside another person with information about the other's task being available, people have a quasi-automatic tendency to take this information into account, even if it is not relevant or in fact detrimental to their own performance. This was first suggested by studies showing that when two-choice tasks are distributed between two co-actors, similar response conflicts (evidenced by slower and less accurate performance) occur as when one individual performs the whole task alone (Sebanz, Knoblich, & Prinz, 2003, 2005). This has been taken to indicate that people represent others' tasks in a functionally equivalent way to their own, i.e., they represent two stimulus-response mappings even though only one of the responses is at their own disposal. Accordingly, it takes participants increased effort to inhibit their own action when it is the co-actor's turn to act, as compared to when it is nobody's turn (Baus et al., 2014; de Bruijn, Miedl, & Bekkering, 2008;

Sebanz, Knoblich, Prinz, & Wascher, 2006; Tsai, Kuo, Jing, Hung, & Tzeng, 2006; Tsai, Kuo, Hung, & Tzeng, 2008).

Importantly, this tendency for co-representation is invoked by knowledge alone, as perceptual access to a co-actor's actions is not necessary (Sebanz et al., 2003) and the mere belief about an unseen co-actor seems sufficient for the effect to occur (Atmaca, Sebanz, & Knoblich, 2011; Tsai et al., 2008; Ruys & Aarts, 2010; but see Welsh, Higgins, Ray, & Weeks, 2007). Replicated in many variations in adults (e.g., Atmaca, Sebanz, Prinz, & Knoblich, 2008; Böckler, Knoblich, & Sebanz, 2012; Wenke et al., 2011; Welsh, 2009; for a review, see Dolk et al., 2014) as well as in children (Milward, Kita, & Apperly, 2014; Saby, Bouquet, & Marshall, 2014), the 'co-representation effect' has been shown to be robust and reliable.

Notably, the strength of the effect is modulated by social factors, with stronger effects found for co-actors who have agentive features (Atmaca et al., 2011; Müller et al., 2011a; Tsai & Brass, 2007; Tsai et al., 2008), who belong to the ingroup (Constantini & Ferri, 2013; He, Lever, & Humphreys, 2011; McClung, Jentsch, & Reicher, 2013; Müller et al., 2011b), who appear likeable rather than hostile (Hommel, Colzato, & van den Wildenberg, 2009), and who behave cooperatively rather than competitively (Iani, Anelli, Nicoletti, Arcuri, & Rubichi, 2011; Iani, Anelli, Nicoletti, & Rubichi, 2014). These modulations point to the deeply social nature of co-representation. In line with this social account, it has been found that the ability to co-represent other's tasks is impaired in neuropsychological patients with deficits in mental state attribution (Humphreys & Bedford, 2011; Liepelt et al., 2012).

As research on task co-representation has mostly employed simple reaction time tasks involving arbitrary stimulus-response rules, it remains to be further explored which aspects of a co-actor's task, besides stimulus-response mappings, may be co-represented. A few studies have addressed this question, showing that people actively engage with a co-actor's task rather than just representing the conditions under which it is a co-actor's turn to act. For instance, it

was found that participants exhibited higher recall performance for stimuli relevant to a co-actor (Elekes, Bródy, Halász, & Király, 2016; Eskenazi, Doerrfeld, Logan, Knoblich, & Sebanz, 2013) and that they engaged in lexical processing when it was a co-actor's turn to name an object (Baus et al., 2014).

Why do humans exhibit this unintentional, quasi-automatic tendency to represent others' tasks in the first place? It has been suggested that the strong inclination to take others into account may reflect the way in which the human cognitive system has been shaped to meet the demands of joint action (Sebanz et al., 2005). By forming representations of others' action goals and intentions even in contexts where coordination is not required, people are always prepared to predict others and to engage in joint action should the situation arise, as if they were “constantly carrying an umbrella that is big enough for two” (Sebanz et al., 2005, p. 1245).

1.3.4 Coordination without prediction?

In certain situations, predicting others' actions is not possible because co-actors receive only minimal or no information about each other, or because they cannot simulate the unfolding of an observed action because they lack the skill to perform this action themselves, and therefore they lack the corresponding motor program. In these cases, individuals can rely on so called coordination smoothers, i.e., they can modulate their own behavior in ways that reliably simplify coordination (Vesper, Butterfill, Knoblich, & Sebanz, 2010). For instance, people can make their own behavior more predictable by reducing the variability of their actions (Roberts & Goldstone, 2011; Vesper, van der Wel, Knoblich, & Sebanz, 2011; Vesper, Schmitz, Safra, Sebanz, & Knoblich, 2016) or by converging on external conventions (Schelling, 1960). Another type of coordination smoother is to structure the task in a way that reduces coordination demands, e.g., by moving away from shared task space and potential areas of collision (Richardson, Harrison, May, Kallen, & Schmidt, 2011; Richardson et al., 2015; Vesper,

Soutschek, & Schubö, 2009) or by distributing the task efficiently (Brennan et al., 2008; Wahn, Kingstone, & König, 2017). Moreover, coordination can be simplified by using objects that afford a particular task distribution (Gibson, 1977), such as a heavy bag with two handles that affords being carried by two people with their left and right hand, respectively.

1.3.5 From coordination to communication

Another way to solve coordination problems, especially when task information is limited or distributed asymmetrically, is to use communicative signals (Clark, 1996; Vesper et al., 2010). Verbal communication is an instance of a conventional signal that can be used to achieve coordination, and a very powerful one at that (see section above on language use). It has been suggested that language might have evolved precisely for that purpose, i.e., for facilitating joint action coordination. Indeed, previous research has demonstrated that communication naturally emerges out of the need to interact and coordinate actions with others (Clark, 1996; Galantucci, 2005). To study how novel communication systems emerge in the face of coordination demands, researchers used games in which participants needed to coordinate their actions but could not rely on conventional language or other pre-established common ground, as the medium through which they could interact prevented the use of pictorial representations and of standard symbols (de Ruiter, Noordsij, Newman-Norlund, Hagoort, & Toni, 2007; Galantucci, 2005; Scott-Phillips, Kirby, & Ritchie, 2009). These studies have shown that despite the lack of pre-established common ground, participants tend to succeed in coordinating their actions by inventing a shared set of novel symbols.

Instead of developing shared symbol systems, actors may also reliably simplify coordination by producing subtle kinematic modulations that carry information for their co-actors. In particular, if one actor systematically modulates her instrumental movements, it will be easier for her co-actor to discriminate between different movement trajectories and to predict

the actor's movement goals and intentions (e.g., Pezzulo, Donnarumma, & Dindo, 2013; Sacheli et al., 2013; Vesper & Richardson, 2014). For instance, lifting one's fingers higher during a piano duet can facilitate temporal coordination, especially when auditory feedback is reduced (Goebel & Palmer, 2009). Or when reaching for a bottle, moving lower and opening one's hand more widely can communicate the intention to grasp the bottle around its body rather than around its neck (Sacheli et al., 2013). To understand this type of sensorimotor signals, observers can use their own motor system to predict the other's unfolding action (Wilson & Knoblich, 2005; Wolpert et al., 2003). By detecting systematic deviations from the predicted movements, observers may understand the actor's communicative intention and the meaning conveyed by the deviations (Pezzulo et al., 2013). This way, the mechanism of motor simulation, normally employed to plan one's own and to predict others' actions, can be exploited for communicative purposes.

1.3.6 Summary

To summarize, previous research has identified different coordination processes that enable joint action partners to coordinate their actions successfully in space and time, while overcoming the challenge of not having direct access to each other's internal models. For instance, this challenge can be overcome by monitoring and predicting others' observed actions, relying on simulations in one's own motor system (e.g., Knoblich & Jordan, 2003). Another means to predict others' actions is based on representations of others' tasks rather than on direct observation (e.g., Vesper, van der Wel, et al., 2013). Constantly prepared for joint action, individuals also form representations of others' tasks when coordination is not required (e.g., Sebanz et al., 2003). When there is no possibility to predict others' actions, individuals can apply general heuristics to simplify coordination, e.g., by making themselves predictable (e.g., Vesper et al., 2011) or by structuring the task in a way that reduces coordination demands (e.g.,

Richardson et al., 2011). Finally, language use is a powerful way to solve coordination problems (e.g., Clark, 1996). As verbal communication is often not feasible during fast online interactions, co-actors may resort to non-conventional forms of communication, e.g., by systematically modulating their movement kinematics (e.g., Pezzulo et al., 2013).

Taken together, there is not one way of achieving interpersonal coordination, but there are many. What is common to all is that co-actors rely on some form of shared information, or common ground (see Clark & Carlson, 1982; Clark & Marshall, 1981; Lewis, 1969; Schelling, 1969). Minimally, co-actors share information about the joint goal (see Vesper et al., 2010). In addition, co-actors may share more detailed information about each other's tasks and actions, either because they have access to mutually available task knowledge or because they can observe each other acting (or a combination of the two). Moreover, co-actors can share information by means of communication (e.g., Brennan & Clark, 1991).¹ Broadly speaking, there are two ways of how information can become shared between co-actors – what one may call a 'passive' and an 'active' way of sharing. Accessing mutually available task knowledge and observing each other's actions are 'passive' ways of sharing information. Individuals can rely on this shared information and accordingly adjust their own actions to those of a co-actor – by planning ahead and/or by monitoring the co-actor's action and flexibly adjusting as the joint action unfolds. In contrast, information is shared in an 'active' way when co-actors communicate with one another. By actively transmitting (and receiving) information, co-actors make this information part of their common ground. This allows them to eliminate knowledge asymmetries that impede coordination.

What are the factors that determine which coordination process co-actors rely on? One factor is whether co-actors have perceptual access to each other, as this determines whether

¹ Not to forget, co-actors often share a vast amount of background knowledge about the world, about cultural conventions and norms, etc., as well as knowledge based on a shared personal history (see Clark, 1996, for a comprehensive account). This type of shared advance knowledge, however, is beyond the present focus.

communication is possible (e.g., Vesper et al., 2016). Another factor is the amount of knowledge co-actors possess about each other's tasks, as this determines whether they can represent each other's tasks and generate predictions about each other's actions. A third factor is the distribution of knowledge between co-actors (e.g., whether one co-actor possesses task knowledge the other lacks), as this determines whether the active exchange of information is required for successful coordination.

How do these factors interact with the different ways of sharing information between co-actors? For instance, when perceptual access is restricted but mutual task knowledge is available, co-actors can plan and adapt their own actions based on shared representations of each other's tasks. Conversely, when perceptual access is available but task knowledge is distributed asymmetrically between co-actors, the need for coordination drives the more knowledgeable actor to actively communicate the required information to her naïve co-actor.

1.4 Research aims

The work presented in this thesis aims to contribute to a better understanding of the processes underlying real-time action coordination. To this end, it investigates to what extent individuals integrate others' constraints into their own actions when acting together. Specifically, I will present three empirical studies that focus on how individuals co-represent each other's actions (Chapters 2-3) and on how they create non-conventional communication systems (Chapter 4). The following three central questions will be addressed.

In **Chapter 2**, I ask whether actors **represent and adapt to a co-actor's environmental constraint** to achieve temporal coordination *even if* other coordination processes imply less movement effort. To examine this question, I employed a temporal movement coordination task with asymmetric constraints. In this task, pairs of participants performed reaching movements back and forth between two targets, with the aim of synchronizing their landing times. One of

the participants needed to move over an obstacle while the other had no obstacle. To achieve temporal coordination, the unconstrained actor could either represent her co-actor's environmental constraint (i.e., the obstacle) at the cost of performing more effortful movements or slow down her own actions only based on feedback about the co-actor's movement tempo. To illustrate, consider two people walking alongside each other trying to synchronize their steps. As it happens, one person needs to step over heaps of snow that are in her way while the other person's path is unconstrained. Thus, in order to keep the same tempo, the unconstrained person needs to adjust to her partner's constraint. Will the unconstrained person adjust her action solely based on perceiving the duration of her partner's movements? Or will she adjust her action based on representing the obstacles in her partner's way, modulating her own movement amplitude *as if* obstacles were obstructing her way as well? By addressing this question, I will contribute to previous research on co-representation in a decisive way, exploring which aspects of a co-actor's task, besides stimulus-response mappings, may be co-represented. In particular, I will test whether the tendency to take others' environmental constraints into account and to thereby compromise one's own movement efficiency prevails over alternative coordination strategies that would require less movement effort.

In **Chapter 3**, I extend previous research on the co-representation of individual actions to action *sequences*, asking whether co-actors **represent the order of actions within each other's action sequence** even if doing so is not necessary for joint task performance. To address this question, I used a joint movement task where two participants concurrently performed *sequences* of actions to achieve temporal coordination at the end. 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. Will the two dancers represent the order of actions within each other's action sequence? Or will they

merely represent the end state that the two action sequences produce, together with their own contribution? In other words, will the male dancer represent the female dancer's sequence as a short step followed by a long one, or will he merely represent her meeting him in the middle, while ignoring the specifics of how she is going to get there? Note that reaching a synchronized end state in this type of joint action situation does not 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. Will co-actors still represent each other's actions, even if doing so is not necessary and might even interfere with individual performance? By addressing this question, I will determine whether people take into account not only the elements of another's task, but also their temporal structure.

In **Chapter 4**, I address the interface between coordination and communication, looking at how communication emerges out of the need to coordinate in a situation where knowledge is distributed asymmetrically between co-actors. Extending previous research which has shown that co-actors systematically modulate kinematic parameters of their movements to communicate spatial target locations, I ask whether sensorimotor communication also provides an effective means for **communicating non-spatial, hidden object properties**. To test this question, I created a task where two participants needed to select objects of the same weight. Crucially, there was a knowledge asymmetry between co-actors such that only one actor knew the correct weight in advance. As co-actors could not rely on any pre-established conventions (such as language), the only way to overcome this knowledge asymmetry was to invent a novel communication system. To illustrate, imagine two people about to lift a box together while only one of them knows the weight of the box. Will the informed person modulate her movements in a communicative way, e.g., by grasping the box from below to signal that it is heavy? What if there was a small sticker on the side of the box, with an icon suggesting 'Caution: heavy' – will the informed person point to the sticker rather than modulating her grasping movements?

In other words, when do co-actors prefer to rely on sensorimotor communication to solve coordination problems, and under which conditions do they switch to symbolic forms of communication? By addressing this question, I will provide a significant contribution to the current state of research on sensorimotor communication, probing whether its scope extends from conveying information about spatial locations to hidden object properties, and if so, whether this way of communicating is preferred over using symbolic forms of communication. More generally, by exploring how communication emerges out of the need to interact and coordinate actions with others, this study will provide novel insights into the processes leading to the successful bootstrapping of communication systems.

Finally, after having presented the empirical evidence informing my three research questions, I will provide a summary of the findings and discuss theoretical implications and possible applications, as well as directions for future research.

Chapter 2. Co-representing Others' Task Constraints

2.1 Introduction

Previous research has shown that when performing independent tasks alongside each other, humans have a tendency to represent each other's tasks even if there is no joint goal. This was first indicated by a joint interference task in which a conflict between participants' own response and their task partner's response detrimentally affected participants' response speed (Sebanz et al., 2003, 2005). Such interference has been taken to indicate that people represent their own and a task partner's actions in a functionally equivalent way such that the action at the other's disposal (including task rules governing this action) is represented in addition to one's own action (Sebanz et al., 2003). While the effect has been replicated reliably in different variations (e.g., Atmaca et al., 2008; Böckler et al., 2012; Tsai et al., 2006; Welsh, 2009), its interpretation has been critically discussed, with a focus on *what* task partners actually co-represent (Dolk & Prinz, 2016; Liepelt, Wenke, Fischer, & Prinz, 2011; Liepelt, Wenke, & Fischer, 2013; Prinz, 2015; Wenke et al., 2011).

One way to gain better insight into the mechanisms behind task co-representation is to use different types of tasks and more interactive settings. To date, most of the research on task co-representation has used joint interference tasks that require two task partners to take turns in performing one or the other of two complementary responses. Particular stimulus-response incompatibilities then elicit response selection conflicts. A few studies have gone beyond this type of task, showing that co-representation also occurs in tasks without systematic stimulus-response incompatibilities (Elekes et al., 2016; Eskenazi et al., 2013) and during lexical processing in a picture-naming task (Baus et al., 2014). Furthermore, a recent study provided first evidence for task co-representation in a movement task where participants moved between different target locations: When two individuals performed independent movements next to

each other, representing the co-actor's movement constraints (an obstacle in her way) affected the movement amplitude of an unconstrained actor (van der Wel & Fu, 2015).

The motivation for the present study was twofold: Firstly, we aimed to further investigate task co-representation in a task in which no direct conflict between own and other's actions exists, in contrast to the traditionally employed interference tasks. Secondly, we were interested in the role of task co-representation in a social interactive setting in which individuals are required to coordinate their actions in real time, rather than performing independent tasks side by side in a turn-taking fashion as it is the case in interference tasks.

Regarding our second aim, previous research has already shown that individuals engaged in joint action often form detailed representations not only of the joint goal and their own task but also of task partners' contributions, especially when precise interpersonal coordination is required. A number of findings indicates that such representations facilitate interpersonal coordination by guiding motor simulations of a partner's actions (Kourtis et al., 2013; Kourtis et al., 2014; Novembre, Ticini, Schütz-Bosbach, & Keller, 2014; Vesper, van der Wel, et al., 2013).

However, other findings show that interpersonal coordination can also be achieved without representing a partner's task, either because interpersonal coordination spontaneously emerges from the behavioral interaction dynamics such as when people fall into synchrony during walking (Romero, Kallen, Riley, & Richardson, 2015; Richardson, Marsh, Isenhower, et al., 2007; Schmidt, Carello, & Turvey, 1990) or because task representations only specify a joint goal and an actor's own task but not the partner's contribution to the joint goal (Vesper et al., 2010). Findings in comparative research suggest that chimpanzees and elephants can successfully perform joint actions without representing each other's tasks by using the partner as a "social tool" (Melis et al., 2006; Plotnik et al., 2011).

Taken together, an extensive amount of studies has found evidence for task co-representation in minimally social settings using interference tasks where co-actors perform complementary action alternatives. Despite the robustness of this evidence, its interpretation and generalizability remains limited as research has been constrained to one type of paradigm only and not much is known about the effects of task co-representation in other types of tasks. Furthermore, it has been shown that task partners in a joint action represent each other's tasks when it is essential for the coordination success. However, individuals can also jointly bring about a goal by using coordination processes that do not require representing another's task. It has not yet been systematically investigated whether joint action partners engage in co-representation if the joint goal can also be attained without representing the partner's task.

Addressing these gaps in the two lines of research, we aimed to explore task co-representation in a real-time coordination task in which co-actors' actions are not conflicting and in which co-actors may or may not rely on task co-representation. More specifically, the aim of the present study was to examine whether actors rely on task co-representation to achieve temporal coordination with a co-actor even if other coordination processes imply less movement effort. To this end we devised a joint movement task where co-actors could either represent their partner's task constraint at the cost of performing more effortful movements or slow down their own actions only based on feedback about the partner's movement tempo.

To illustrate, consider two people walking on a narrow sidewalk during winter, with the joint goal of keeping the same tempo. On one side of the sidewalk, small heaps of snow are piled up in front of every house's driveway. Person A, walking on the snowy side, needs to step over these heaps of snow. Person B has no such obstructions in her way. If B just continued in her regular walking tempo, she would end up walking faster than A who needs to cover more distance due to the snow heaps. Our question is whether B's adjustments will be solely based

on perceiving the duration of A's movements or whether B will adjust her action based on representing the obstacles in A's way.

Generally, when two individuals' tasks differ in terms of movement constraints, successful temporal synchronization requires co-actors to adjust the timing of their individual actions. A straightforward way to do this is adjusting one's own movement speed to match the predicted duration of a co-actor's movement based on sampling the duration of her previous movements (Loehr, Large, & Palmer, 2011; van der Steen & Keller, 2013) while ignoring the specifics of her task. Alternatively, an unconstrained actor may represent a co-actor's task constraint and predict the duration of the other's movement based on motor simulation that takes into account the task-relevant features of the other's constraint (Vesper, van der Wel, et al., 2013; Wilson & Knoblich, 2005; Wolpert et al., 2003). This motor simulation process may lead unconstrained actors to adjust their movements in a way that increases movement effort and makes their own movements resemble those of the constrained co-actor. The actors' own motor experience with the task-relevant features may facilitate this strategy.

Experiment 1 was conducted as a first test of the prediction that co-actors will rely on task co-representation to achieve coordination even if this implies increased movement effort for an unconstrained actor. In Experiment 2, we examined whether amplified coordination demands lead to larger effects of task co-representation. In Experiment 3, we addressed the potential influence of co-actors' visuospatial perspective on co-representation. Finally, in Experiment 4, we tested whether actors represent their co-actor's constraint or parameters of their co-actor's movements.

2.2 Experiment 1

To test whether joint action partners rely on task co-representation for coordination, we adapted a task previously used to investigate task co-representation in uncoordinated action

(van der Wel & Fu, 2015). In van der Wel and Fu's study, two actors performed reaching movements back and forth between two targets in time with an auditory metronome. They were not required to coordinate their actions, i.e., they performed their movements independently while sitting next to each other. One of the actors had to move over an obstacle to reach the far target while the other actor did not have an obstacle. The results showed that the unconstrained actor's movements were affected by the co-actor's constraint such that the unconstrained actor moved higher when the co-actor was required to move over the obstacle. Importantly, this also happened when the movements of the co-actor were not visible. This indicates that unconstrained actors co-represented the co-actor's task constraint which made them move higher themselves.

For the present study we modified van der Wel and Fu's (2015) task so that co-actors were required to synchronize the landing times of their movements. So instead of acting independently next to each other, co-actors had the joint goal to coordinate their actions. We predicted that the peak height of the unconstrained actor's movements should be higher in trials where the co-actor's movement is constrained by an obstacle than in trials where the co-actor's movement is not constrained by an obstacle. This would indicate an effect of representing the co-actor's constraint on the unconstrained actor's movements. A second prediction was that the peak height of the unconstrained actor's movements should be higher in trials where the co-actor has an obstacle than in trials where the unconstrained actor *individually* performs unconstrained reaching movements. This is because co-representing a co-actor's constraint in the joint condition should lead to a deviation from the most efficient movement path that actors produce when acting alone.

For the present task it is important to consider that a modulation in movement amplitude could be induced by mere action observation. If co-actors observe each other moving, they may automatically adapt to each other's movements due to visuomotor interference (Brass,

Bekkering, Wohlschläger, & Prinz, 2000; Kilner, Paulignan, & Blakemore, 2003; Sacheli, Candidi, Pavone, Tidoni, & Aglioti, 2012), dynamic entrainment (Richardson et al., 2007; Richardson, Campbell, & Schmidt, 2009), automatic imitation (Heyes, 2011; Naber, Eijgermans, Herman, Bergman, & Hommel, 2016; Wang & Hamilton, 2012), or motor priming (Griffiths & Tipper, 2009). We followed van der Wel & Fu's (2015) lead in separating effects of action observation from effects of task co-representation by comparing a condition where co-actors could observe each other moving to a condition where they could not observe each other moving. If co-representing a partner's task constraint leads to movement modulations, then these effects should also be present when the co-actor's movements cannot be observed.

In order to determine how successfully co-actors coordinated their movements, we compared asynchrony in landing times in the joint condition with asynchrony derived from the two actors' independent individual performances of the same task where they had no instruction to coordinate their movements with someone else. The asynchronies in the joint condition should be significantly smaller than the asynchronies of two actors who perform their tasks independently.

2.2.1 Method

Participants. Twelve pairs of individuals (13 female, $M_{age} = 24.3$ years, $SD = 3.61$ years) participated in the study. The members in each pair did not know each other prior to participation. All participants were right-handed and had normal or corrected-to-normal vision. They signed prior informed consent and received monetary compensation. The study was performed in accordance with the Declaration of Helsinki.

Apparatus and procedure. The two participants were seated opposite each other at the long sides of a table (110 cm, short side 55 cm). Each person sat close to the right edge of their side of the table (see Figure 1A). Participants' task was to each move a wooden dowel rod

(height: 20 cm, diameter: 2.5 cm, weight: 50 g) back and forth between two circular targets (5 cm diameter; felt material with cardboard surface) on the table. The two targets for each participant were positioned such that the ‘close target’ was 5 cm away and the ‘far target’ was 45 cm away from the edge of the table, such that the distance between the two target centers was 40 cm. Participant A’s far target and participant B’s close target (and vice versa) were aligned along the table’s long side and were 40.5 cm apart (see Figure 1A). A Polhemus G4 electro-magnetic motion capture system (www.polhemus.com) was used to record participants’ movement data at a constant sampling rate of 120 Hz. For that purpose, a motion capture sensor was attached to the top of each dowel rod. Data recording was controlled by MATLAB (2014a).

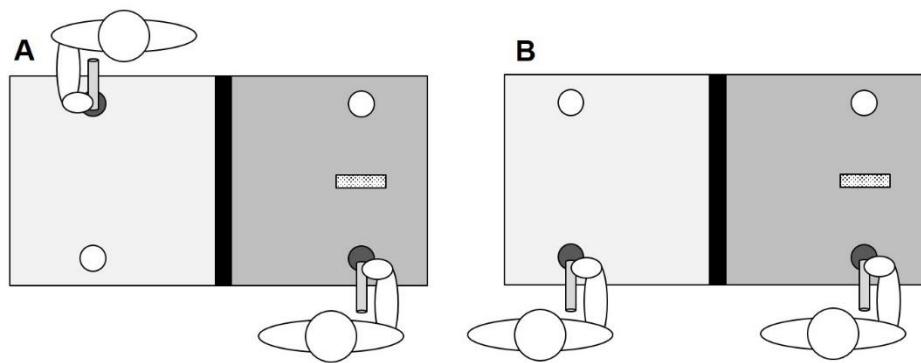


Figure 1. Experimental setup. Panel A: In Experiments 1 and 2, co-actors were seated opposite each other at a table and performed arm movements back and forth between the close and far targets on their side of the table (dark and light circles, respectively). Co-actors were instructed to synchronize their landing times on the targets. The black vertical bar in the middle of the table represents the partition in the ‘No Vision’ condition which prevented co-actors from seeing each other’s movements. The small horizontal bar represents the obstacle. In the ‘No Obstacle’ condition the obstacle was absent for both co-actors while in the ‘Co-actor Obstacle’ condition the obstacle was present for one of the actors and absent for the other actor. Panel B: Parallel seating in Experiments 3 and 4.

Both participants were instructed to hold the dowel rod in their right hand with a power grip and to move it once from the close to the far target and back in each trial. The joint goal

was to synchronize landing times, i.e., to hit one's target at the same time as the co-actor. Touching the target with the dowel rod resulted in a clearly audible natural sound at the respective target location. Thus, the sounds resulting from the two actors landing at their respective target locations reflected the asynchrony between the two actors' landing times. Participants could distinguish self- and other- produced sounds based on the temporal correspondence between arriving at the target and hearing a sound, and because the sounds varied in terms of loudness (depending on the speed of the dowel rod at impact) and spatial origin. In order to prescribe a general movement tempo, three auditory cues (440 Hz, 100 ms) were played indicating two equal intervals of 850 ms for the forward and backward movement (van der Wel & Fu, 2015). A pause of 2 s followed while participants rested the dowel rod on the close target; then the next back-and-forth movement started. The short pause served to ensure discrete instead of continuous action (van der Wel & Fu, 2015). One back-and-forth movement constituted one trial and 20 such trials were grouped into a mini-block.

Participants completed two joint blocks that consisted of three mini-blocks each. Visibility of the co-actor varied between the two blocks: In the 'Vision' block, co-actors could see each other and each other's movements. In the 'No Vision' block, visual access was prevented by a partition (styrofoam material on wooden mount; height: 55 cm, width: 65 cm, depth: 0.5 cm) placed on the table between the participants (see Figure 1). The order of Vision and No Vision blocks was counterbalanced across pairs. Additionally, it was varied whether one of the two actors needed to move the dowel rod over an obstacle (cardboard; height: 20 cm, width: 10 cm, depth: 0.2 cm) that was placed mid-way between the close and far target. In the 'No Obstacle' condition the obstacle was absent for both actors and in the 'Co-actor Obstacle' condition the obstacle was present for one of the actors and absent for the other actor. Within each block ('Vision'/'No Vision'), there was one mini-block in which the obstacle was absent for both actors ('No Obstacle') and two mini-blocks in which the obstacle was present for one

actor but not for the other ('Co-actor Obstacle'). The order of mini-blocks was the same for both blocks but counterbalanced across pairs. In the No Vision block, the experimenter shortly lifted the partition before the start of each mini-block such that actors could see whether the obstacle was placed on the co-actor's side. Thus, when visual access was restricted in the Co-actor Obstacle condition, the unconstrained actor (i.e., the actor *without* obstacle) did not only receive auditory feedback from her co-actor's target landing, but she also had additional knowledge about her co-actor's task constraint (i.e., she knew that there was an obstacle and what the obstacle looked like).

Before and after the joint blocks an individual baseline was collected where participants performed the same task as in the joint condition but without a partner. While participant A's baseline was collected, participant B waited outside of the testing room and then they switched roles. Each baseline contained two mini-blocks consisting of 20 trials each. Mini-block 1 was performed with the obstacle absent and mini-block 2 was performed with the obstacle present. Participants were instructed to perform their movements naturally and to adhere to the tempo prescribed by the auditory cues.

Before the main experiment started, the experimenter verbally explained and shortly demonstrated the task. Then each of the two participants performed three short practice rounds (each consisting of six back-and-forth movements). The first round served to familiarize them with the task as such. In the second and third round, participants were instructed to move the dowel rod over (and not around) the obstacle. After the main experiment, participants were debriefed and asked to indicate how they had tried to achieve the coordination goal (i.e., whether they had relied on a certain strategy). The whole experiment lasted about 60 minutes.

Data preparation. Data preparation was conducted using MATLAB (2013b) and statistical analyses were performed in IBM SPSS 22. Prior to data analysis, the movement data were corrected for slight spatial distortions in the vertical dimension that linearly increased with

horizontal distance (the correction parameters were calculated using the two target locations as reference points). All data was then filtered using a 4th-order two-way low-pass Butterworth filter with a cutoff at 20 Hz. Data from the first and last trial in each mini-block were not included in the analysis due to potential starting and stopping effects (see Smits-Engelsman, Van Galen, & Duysens, 2002).

We derived the movement trajectories' peak height for each participant, separately for forward and backward movements in each trial. As a measure of coordination in each pair, we calculated the mean absolute asynchrony between co-actors' landing times on the far target. The absolute asynchronies in the Co-actor Obstacle condition were obtained by averaging mean absolute asynchrony from the mini-block where participant A had an obstacle and mean absolute asynchrony from the mini-block where participant B had an obstacle.

2.2.2 Results

Only trials where both forward and backward movement had a horizontal movement length of at least 80 % of the Euclidean distance between close and far target (= 32 cm) were included. Using this criterion for minimal horizontal movement distance, we excluded trials where movements were not properly completed (0.4 % in the individual and 0.2 % in the joint condition), e.g., because a participant hit the obstacle. Two repeated measures 2x2 ANOVAs with the factors Vision (No Vision, Vision) and Obstacle (No Obstacle, Co-actor Obstacle) were conducted, separately for the peak height of the forward movement and the peak height of the backward movement to assess whether effects of Vision and Obstacle were present in both movement directions. A further 2x2 ANOVA with the same factors was conducted for the asynchrony.

Peak height. Movements in which peak height deviated more than two standard deviations from a participant's mean in a mini-block were excluded. We removed 3.1 % of

forward and 4.1 % of backward movements in the individual condition and 3.7 % of forward and 3.9 % of backward movements in the joint condition.

The results showed that unconstrained actors moved higher when their co-actor moved over an obstacle (see Figure 2). Accordingly, the ANOVA for the unconstrained actors' peak height forward showed a significant main effect of Obstacle, $F(1,23) = 8.37, p = .008, \eta_p^2 = .267$. The main effect of Vision was not significant ($F(1,23) = 3.66, p = .068, \eta_p^2 = .137$), although, numerically, unconstrained actors' peak height was slightly higher in the Vision condition. There was no significant interaction effect between Vision and Obstacle, $F(1,23) = 1.71, p = .204, \eta_p^2 = .069$. The analysis for peak height backward also yielded a significant main effect of Obstacle, $F(1,23) = 11.40, p = .003, \eta_p^2 = .331$. The main effect of Vision was significant as well, $F(1,23) = 5.83, p = .024, \eta_p^2 = .202$, indicating that unconstrained actors moved higher backwards when they saw their co-actor's movements. There was no significant interaction effect, $F(1,23) = 1.74, p = .200, \eta_p^2 = .070$.

In the next step, we tested whether the unconstrained actor's peak height in the joint condition where the co-actor had an obstacle was different from an individual baseline where the unconstrained actor performed the same task individually before the joint part of the experiment (see dashed horizontal lines in Figure 2)². Note that the number of trials in these two conditions was the same ($n = 20$).

² There was no difference between individual baselines recorded before and after the joint condition, all $p \geq .61$.

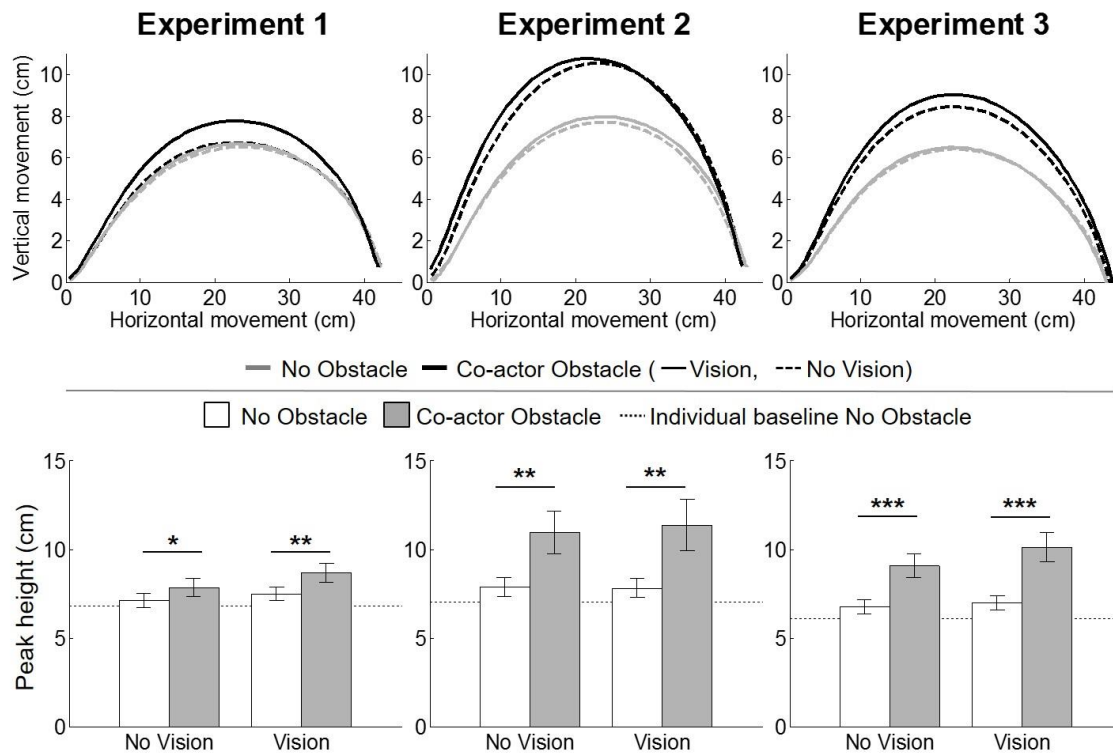
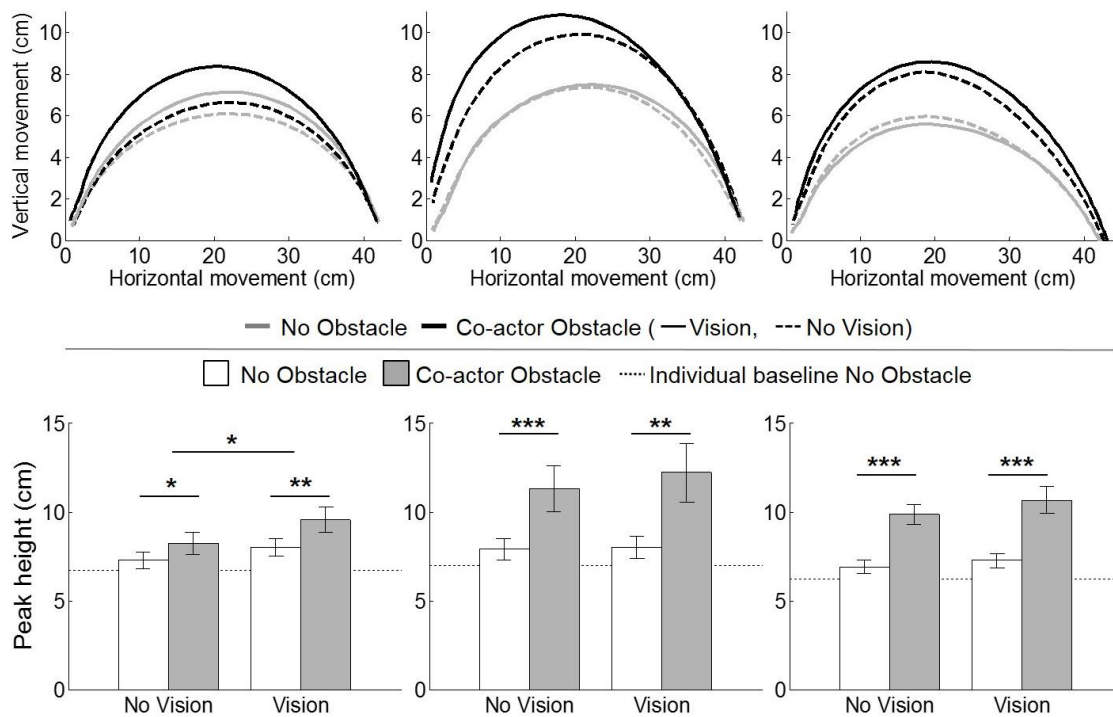
A: forward →**B: backward ←**

Figure 2. Grand averaged trajectories (upper panels) and peak height (lower panels) depicted for all three experiments for forward movements (A) and backward movements (B). In all experiments, unconstrained actors moved significantly higher when their co-actor moved over an obstacle; this effect was significantly larger in Experiment 2 and 3 compared to Experiment 1. Error bars reflect Standard Errors. (* $p < .05$, ** $p < .01$, *** $p < .001$)

Paired-samples t-tests showed that the peak height of the unconstrained actor's forward and backward movements was significantly larger in the joint Vision and No Vision conditions compared to the individual baseline (Vision condition: peak height forward: $t(23) = 4.09$, $p < .001$, Cohen's $d = 0.83$; peak height backward: $t(23) = 4.23$, $p < .001$, Cohen's $d = 0.86$; No Vision condition: peak height forward: $t(23) = 2.63$, $p = .015$, Cohen's $d = 0.54$; peak height backward: $t(23) = 3.69$, $p = .001$, Cohen's $d = 0.75$).

Mean absolute asynchrony. Trials in which mean absolute asynchronies deviated more than two standard deviations from a pair's mean in a mini-block were excluded (4.2 %). Asynchronies did not differ significantly across the different joint conditions (see Figure 3). The main effect of Obstacle did not reach significance, $F(1,11) = 4.65$, $p = .054$, $\eta_p^2 = .297$, although asynchronies were numerically larger when the obstacle was present. There was no main effect of Vision, $F(1,11) = 0.21$, $p = .655$, $\eta_p^2 = .019$, and no significant interaction effect, $F(1,11) = 0.92$, $p = .357$, $\eta_p^2 = .077$.

In the next step, we tested whether participants were more synchronized during joint performance (averaged across all conditions) compared to a baseline that was calculated from the individual performances of the two participants in a pair. We computed the mean absolute asynchrony between participant A's and B's trials from the individual baseline recorded before the joint condition to obtain an estimate of the synchronization that would result from independently performing the same task³. A paired-samples t-test confirmed that asynchronies were significantly smaller when the two participants in a pair interacted in the joint condition than when they acted independently, $t(11) = 2.71$, $p = .020$, Cohen's $d = 0.78$ ($M_{joint} = 65$ ms, $SD_{joint} = 32$ ms; $M_{individual} = 92$ ms, $SD_{individual} = 41$ ms); see dashed horizontal line in Figure 3.

³ Estimates derived from the individual baseline before and after the joint condition did not differ; $t(11) = 0.29$, $p = .778$, Cohen's $d = 0.08$.

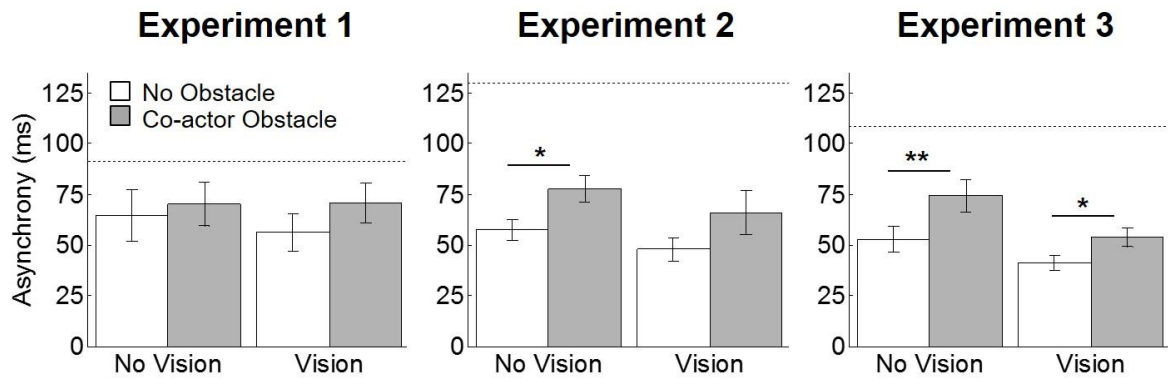


Figure 3. Mean absolute asynchronies for Experiments 1-3. Obstacle presence led to higher asynchronies. In Experiment 3, co-actors were significantly better synchronized when they could see each other. There were no asynchrony differences between experiments. Dashed horizontal lines show that asynchronies were significantly larger when participants performed the task independently than jointly. Error bars reflect Standard Errors. (* $p < .05$, ** $p < .01$)

2.2.3 Discussion

The results of Experiment 1 show that unconstrained actors co-represented their co-actor's task constraint such that they increased their own movement height when their co-actor moved over an obstacle. The unconstrained actor's movements were also significantly higher when acting jointly with a co-actor who had an obstacle than when performing the same task individually. Thus, co-representing the co-actor's task constraint led to deviations from the movement path chosen in the individual setting, thereby increasing movement effort.

Unconstrained actors increased movement height irrespective of whether they could observe their co-actor moving over an obstacle or not. This provides further support for the assumption that unconstrained actors represented the co-actor's task constraint because the unconstrained actor's increase in peak height in the No Vision condition cannot be explained by purely perceptual processes such as visuomotor interference or automatic imitation. Finally, the results of Experiment 1 confirmed that pairs of participants successfully coordinated their movements. Interpersonal synchronization during joint performance was significantly better than would be expected if two actors perform the task independently.

Although the results of Experiment 1 provide clear evidence for the hypothesis that unconstrained actors co-represent their co-actor's task constraint, unconstrained actors increased the peak height of their movements only to a small extent (slightly more than 1 cm; obstacle height was 20 cm). This could be due to the fact that the three auditory cues prescribing the general movement tempo might have substantially reduced the demands on interpersonal coordination. Potentially, co-actors could have independently synchronized their movements with the external auditory cues, thereby supporting interpersonal synchronization without needing to predict each other's actions.

2.3 Experiment 2

Experiment 2 tested whether increasing interpersonal coordination demands would increase the influence of task co-representation on the unconstrained actor's movements. To increase coordination demands, we reduced the amount of external timing information available for synchronization. Specifically, participants in Experiment 2 received only two auditory cues to specify the movement tempo for the whole back-and-forth movement. They no longer received the auditory cue that defined the middle of the interval. If increased coordination demands lead to a more pronounced influence of task co-representation on the unconstrained actor's movements, then unconstrained actors should show a larger increase in peak height when their co-actor moves over an obstacle than in Experiment 1.

2.3.1 Method

Participants. Twelve pairs of individuals (16 female, $M_{age} = 25.8$ years, $SD = 4.39$ years) participated in the study. The members of one pair knew each other prior to participation. All participants were right-handed and had normal or corrected-to-normal vision. They signed

prior informed consent and received monetary compensation. The study was performed in accordance with the Declaration of Helsinki.

Apparatus and procedure. Apparatus and procedure were the same as in Experiment 1, except that the movement tempo for one back-and-forth movement was prescribed by only two instead of three auditory cues. As in Experiment 1, the first tone indicated the start of a movement interval. The second tone was played after 1700 ms to indicate the end of the interval so that the prescribed overall movement tempo was the same as in Experiment 1.

2.3.2 Results

We excluded trials where movements were not properly completed (0.7 % in the individual and 1.0 % in the joint condition).

Peak height. Movements in which peak height deviated more than two standard deviations from a participant's mean in a mini-block were excluded. We removed 4.1 % of forward and 3.7 % of backward movements in the individual condition and 3.7 % of forward and 3.8 % of backward movements in the joint condition.

Replicating the main finding of Experiment 1, the results showed that peak height of unconstrained actors' movements was significantly higher when their co-actor moved over an obstacle (see Figure 2). A significant main effect of Obstacle was found both for peak height forward, $F(1,23) = 10.90, p = .003, \eta_p^2 = .322$, and backward, $F(1,23) = 15.48, p = .001, \eta_p^2 = .402$. There were no other significant main effects or interaction effects (all $p > .14$). To test whether the magnitude of the unconstrained actors' movement adaptation increased with higher coordination demands, we compared the peak height data from Experiment 1 and Experiment 2 by conducting a 2 X 2 X 2 ANOVA with Experiment, Vision, and Obstacle as factors. In line with our prediction, we found a significant interaction effect of Obstacle X Experiment for both movement directions (forward: $F(1,46) = 4.87, p = .032, \eta_p^2 = .096$; backward: $F(1,46) = 5.99,$

$p = .018$, $\eta_p^2 = .155$). This interaction effect indicates that the magnitude of the increase in movement height by unconstrained actors in response to the co-actor's obstacle was significantly larger in Experiment 2 than in Experiment 1.

In the next step, we tested whether the unconstrained actor's peak height in the joint condition where the co-actor had an obstacle was different from the individual baseline recorded before the joint condition (see dashed horizontal lines in Figure 2)⁴. Paired-samples t -tests showed that the peak height of the unconstrained actor's forward and backward movements was significantly larger in the joint condition compared to the individual baseline (forward: $t(23) = 3.76$, $p = .001$, Cohen's $d = 0.77$; backward: $t(23) = 4.17$, $p < .001$, Cohen's $d = 0.85$).

Mean absolute asynchrony. Trials in which mean absolute asynchronies deviated more than two standard deviations from a pair's mean in a mini-block were excluded (4.7 %). Asynchronies were significantly higher when one of the co-actors moved over an obstacle, leading to a main effect of Obstacle ($F(1,11) = 7.25$, $p = .021$, $\eta_p^2 = .397$); see Figure 3. There were no other significant main effects or interaction effects (both $p > .17$). A comparison between Experiment 1 and 2 yielded no significant differences in asynchronies between experiments and no significant interaction effects involving the factor Experiment (all $p > .30$).

Next, we tested whether participants were more synchronized during joint performance (averaged across all conditions) compared to a baseline estimate calculated from the individual performances of the two participants in a pair that was recorded before the joint condition⁵. A paired-samples t -test confirmed that asynchronies were significantly smaller when the two participants in a pair interacted in the joint condition than when they acted independently, $t(11) = 4.23$, $p = .001$, Cohen's $d = 1.22$ ($M_{joint} = 62$ ms, $SD_{joint} = 17$ ms; $M_{individual} = 130$ ms, $SD_{individual}$

⁴ There was no difference between individual baselines recorded before and after the joint condition, all $p > .25$.

⁵ Estimates derived from the individual baseline before and after the joint condition did not differ; $t(11) = 1.00$, $p = .339$, Cohen's $d = 0.29$.

= 61 ms); see dashed horizontal line in Figure 3. As the presence of the obstacle significantly increased asynchronies in the joint condition, we conducted a baseline comparison separately for the No Obstacle and Co-actor Obstacle conditions. Paired-samples t-tests confirmed that participants were better coordinated when acting jointly than independently, irrespective of obstacle presence (No Obstacle condition vs. the individual baseline without obstacle, $t(11) = 3.95$, $p = .002$, Cohen's $d = 1.14$; Co-actor Obstacle condition vs. the corresponding individual baseline, $t(11) = 4.38$, $p = .001$, Cohen's $d = 1.26$).

2.3.3 Discussion

The results of Experiment 2 demonstrate that unconstrained actors co-represented their co-actor's spatial task constraint, moving higher themselves when their co-actor moved over an obstacle than when the co-actor did not have an obstacle. Unconstrained actors also moved higher when acting jointly with a constrained co-actor than when performing individual movements and did so irrespective of whether the co-actor's movements over the obstacle were visible or not. The increase in peak height observed in Experiment 2 was substantially larger than in Experiment 1, confirming our prediction that higher coordination demands would increase the influence of task co-representation on the unconstrained actor's movements.

The results of Experiment 2 further show that it was more difficult for co-actors to coordinate their movements if one of them moved over an obstacle. This suggests that the obstacle condition became more difficult when external information that could support interpersonal coordination was reduced. Nevertheless, participants were quite successful in coordinating their movements. Interpersonal synchronization during joint performance was considerably better than during independent performance of the task.

2.4 Experiment 3

With Experiment 3 we aimed to further generalize the role of co-representation of a partner's task constraint in interpersonal coordination. In particular, we tested the prediction that task co-representation should be unaffected by the particular orientation of the two co-actors towards each other and by the visuospatial perspective from which they observe each other's movements. Although visuospatial perspective clearly plays an essential role in processes of social perception and social cognition (see for instance Beveridge & Pickering, 2013; Creem-Regehr, Gagnon, Geuss, & Stefanucci, 2013; Fini, Brass, & Committeri, 2015; Hamilton, Kessler, & Creem-Regehr, 2014), it should not affect co-representation of another's task constraint.

To determine whether the effects of task co-representation observed in Experiment 2 can be replicated across different interpersonal orientations affecting the co-actors' visuospatial perspective, participants performed the same task sitting next to each other and sharing the same visuospatial perspective. We predicted that unconstrained actors would move higher when their co-actor moves over an obstacle just as in Experiment 2.

2.4.1 Method

Participants. Twelve pairs of individuals (11 female, $M_{age} = 24.7$ years, $SD = 4.53$ years) participated in the study. The members of two pairs knew each other prior to participation. All but three participants were right-handed. (Two of the left-handed individuals performed the experiment with their left hand and one individual used her right hand.) All had normal or corrected-to-normal vision. Participants signed prior informed consent and received monetary compensation. The study was performed in accordance with the Declaration of Helsinki.

Apparatus and procedure. Apparatus and procedure were the same as in Experiment 2, except that participants were not seated opposite each other but side by side (see Figure 1B). Participants' close and far targets were located on the same side of the table, respectively. The distance between close and far targets was the same as in the previous experiments (40 cm). Due to the parallel seating, the distance between the close/far target of participant A and the close/far target of participant B was slightly larger (62.5 cm) compared to the previous setup to give participants enough space to move. This difference regarding participants' peripersonal space should not affect performance, as indicated by findings by van der Wel and Fu (2015).

2.4.2 Results

We excluded trials where movements were not properly completed (1.0 % in the individual and 0.2 % in the joint condition).

Peak height. Movements in which peak height deviated more than two standard deviations from a participant's mean in a mini-block were excluded. We removed 3.9 % of forward and 3.5 % of backward movements in the individual condition and 3.4 % of forward and 3.7 % of backward movements in the joint condition. The results of Experiment 3 showed that unconstrained actors moved significantly higher when their co-actor moved over an obstacle (see Figure 2). There was a significant main effect of Obstacle for both movement directions (forward: $F(1,23) = 41.62, p < .001, \eta_p^2 = .644$; backward: $F(1,23) = 82.68, p < .001, \eta_p^2 = .782$) and no other significant main effects or interaction effects (all $p > .12$). To test whether visuospatial perspective affected the magnitude of the unconstrained actor's increase in peak height, we compared the peak height data from Experiment 2 and Experiment 3 by conducting a 2 X 2 X 2 ANOVA with Experiment, Vision, and Obstacle as factors. There was no significant main effect of Experiment and no significant interaction effects involving the factor Experiment (all $p > .21$).

In the next step, we tested whether the unconstrained actor's peak height in the joint condition where the partner had an obstacle was different from an individual baseline where the unconstrained actor performed the same task individually before the joint condition (see dashed horizontal lines in Figure 2)⁶. Paired-samples t-tests showed that the peak height of the unconstrained actor's forward and backward movements was significantly larger in the joint condition compared to the individual baseline (forward: $t(23) = 6.32, p < .001$, Cohen's $d = 1.29$; backward: $t(23) = 7.59, p < .001$, Cohen's $d = 1.55$).

Mean absolute asynchrony. Trials in which mean absolute asynchronies deviated more than two standard deviations from a pair's mean in a mini-block were excluded (3.9 %). As in Experiment 2, the presence of an obstacle led to larger asynchronies, as indicated by a significant main effect of Obstacle, $F(1,11) = 14.49, p = .003, \eta_p^2 = .568$ (see Figure 3). A significant main effect of Vision ($F(1,11) = 8.82, p = .013, \eta_p^2 = .445$) showed that asynchronies were smaller when co-actors could observe each other moving. There was no significant interaction effect, $F(1,11) = 1.52, p = .244, \eta_p^2 = .121$.

Next, we tested whether participants were more synchronized during joint performance (averaged across all conditions) compared to a baseline estimate calculated from the individual performances of the two participants in a pair that was recorded before the joint condition⁷. A paired-samples t-test confirmed that asynchronies were significantly smaller when pairs interacted in the joint condition compared to when they acted independently, $t(11) = 4.24, p = .001$, Cohen's $d = 1.22$ ($M_{joint} = 56$ ms, $SD_{joint} = 15$ ms; $M_{individual} = 108$ ms, $SD_{individual} = 38$ ms); see dashed horizontal line in Figure 3. Because obstacle presence as well as visibility of the co-

⁶ For the backward movements, peak height differed between the baselines recorded before and after the joint condition, possibly due to carry-over effects (forward: $t(23) = -1.94, p = .065$, Cohen's $d = -0.40$; backward: $t(23) = -2.96, p = .007$, Cohen's $d = -0.60$; backward $M_{diff} = 0.97$ cm). The peak height of the individual backwards movement recorded *after* the joint condition was also significantly smaller than in the joint condition where the co-actor had an obstacle, $t(23) = 5.87, p < .001$, Cohen's $d = 1.20$.

⁷ Estimates derived from the individual baseline before and after the joint condition did not differ; $t(11) = -0.95, p = .363$, Cohen's $d = -0.27$.

actor's movements significantly affected asynchronies during joint performance, we conducted the baseline comparison separately for the four experimental conditions. Paired-samples t-tests (Bonferroni-corrected with $\alpha = .0125$) confirmed that participants were better coordinated when acting jointly (Vision No Obstacle vs. the individual baseline without obstacle, $t(11) = 3.92$, $p = .002$, Cohen's $d = 1.13$; Vision Co-actor Obstacle vs. the corresponding individual baseline, $t(11) = 5.76$, $p < .001$, Cohen's $d = 1.66$; No Vision No Obstacle vs. the individual baseline without obstacle, $t(11) = 2.77$, $p = .018$, Cohen's $d = 0.80$; No Vision Co-actor Obstacle vs. the corresponding individual baseline, $t(11) = 3.46$, $p = .005$, Cohen's $d = 1.00$).

2.4.3 Discussion

Experiment 3 shows that unconstrained actors increased peak height in response to a co-actor's task constraint, irrespective of whether they could observe their co-actor's movements. The results were very similar to Experiment 2, suggesting that sitting next to each other and sharing the same perspective did not affect the extent to which representing a co-actor's constraint influences an unconstrained actor's movements.

As in the previous experiments, interpersonal synchronization during joint performance was significantly better than would be expected if two actors perform the task independently. Sharing the same perspective did not have an overall effect on participants' coordination performance, as the asynchronies obtained in Experiment 2 and 3 did not differ substantially. The only indication that sharing the same visuospatial perspective supported coordination was the significant effect of Vision in Experiment 3 that was not present in Experiment 2. Observing the other moving in the same direction seems to have provided additional cues facilitating the synchronous landing on the far target.

The first three experiments provide ample evidence that the unconstrained actor represented that her co-actor's movements were constrained by an obstacle. However, it is

unclear whether the unconstrained actor represented 1) the object property constraining the co-actor's action (obstacle height) or 2) specific parameters of the co-actor's movement itself (peak height of movement trajectory).

2.5 Experiment 4

In order to find out whether unconstrained co-actors represent the height of the obstacle or the height of their co-actor's movement we introduced a new factor to the task. In particular, one of the two co-actors was a confederate who performed her movements in such a way that she always moved forward with considerably higher movement amplitude than backward, regardless of obstacle presence (i.e., she was instructed to move forward about 10 cm higher than backward), see Figure 4. If unconstrained actors (naïve participants) represent the amplitude of the confederate's movements, they should show a larger peak height for forward than for backward movements. If unconstrained actors represent the height of the confederate's obstacle, the peak height of their movements should be similar for forward and backward movements.

2.5.1 Method

Participants. Twelve individuals (7 female, $M_{age} = 23.1$ years, $SD = 2.68$ years) participated in the study. All participants were right-handed and had normal or corrected-to-normal vision. Participants performed the experiment together with a confederate (female, 26 years old) who was presented to them as another participant. Participants signed prior informed consent and received monetary compensation. They were debriefed after completing the experiment. One participant reported to have suspected that his partner was a confederate when asked during debriefing – he was excluded from the study and replaced with another naïve participant. The study was performed in accordance with the Declaration of Helsinki.

Apparatus and procedure. Apparatus and procedure were the same as in Experiment 3, except for the fact that the Vision and No Vision blocks in the joint condition were run in a fixed order such that Vision always came first. This was done in order to ensure that participants had visually encountered the confederate's movements before going into the No Vision block so that they were aware of the confederate's particular way of moving even if they could not observe the movements anymore.⁸

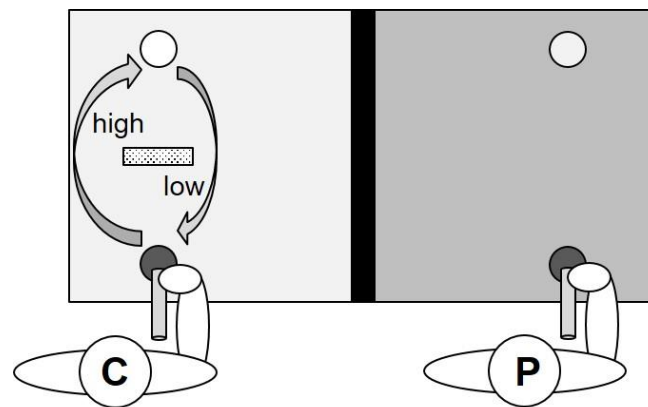


Figure 4. Experimental setup of Experiment 4. A confederate (C) acted together with a naïve participant (P). Unbeknownst to the participant, the confederate was instructed to consistently perform her forward movements higher than her backward movements, both when the obstacle was present and when it was absent. As in previous experiments, the obstacle could be either absent for both actors or present for one.

2.5.2 Results

We analyzed the naïve participants' and the confederate's data separately. We excluded trials where movements were not properly completed (0.2 % and 0.3 % in the individual and joint condition for the participants' data; 0.1 % and 0.2 % in the individual and joint condition for the confederate's data). We included movement direction as an additional factor into the

⁸ Note that order of blocks did not have an effect in the previous three experiments.

analysis of peak height because one of the alternative hypotheses predicted an effect of movement direction.

Peak height: Confederate. Movements in which peak height deviated more than two standard deviations from the confederate's mean in a mini-block were excluded. We removed 4.3 % of forward and of backward movements in the individual condition and 4.5 % of forward and 3.8 % of backward movements in the joint condition. We first carried out a manipulation check for the confederate's peak height data (see Figure 5). A 2 X 2 X 2 ANOVA with Vision, Obstacle, and Movement direction as factors showed a significant main effect of Movement direction, $F(1,11) = 505.77$, $p < .001$, $\eta_p^2 = .979$, indicating that the confederate moved significantly higher during the forward compared to the backward movements (M_{diff} between forward and backward: about 11.6 cm). As instructed, the confederate also moved generally higher when the participant moved over an obstacle (thereby conforming to the behavior participants had displayed in Experiments 1-3), as shown by a significant main effect of Obstacle, $F(1,11) = 106.27$, $p < .001$, $\eta_p^2 = .906$. There were no other significant main effects or interaction effects (all $p > .17$).

Peak height: Participants. Movements in which peak height deviated more than two standard deviations from a participant's mean in a mini-block were excluded. We removed 4.5 % of forward and 3.7 % of backward movements in the individual condition and 4.0 % of forward and 4.1 % of backward movements in the joint condition. To determine whether participants took the confederate's asymmetric movement pattern into account when planning their own actions, we tested whether they also moved significantly higher going forward than backward, as the confederate did.

Results from a 2 X 2 X 2 ANOVA with the factors Vision, Obstacle, and Movement direction showed that unconstrained participants did not move higher going forward compared to backward (see Figure 5). Unexpectedly, they even showed an effect in the opposite direction

and moved higher going backward compared to forward, as indicated by a main effect of Movement direction ($F(1,11) = 7.41, p = .020, \eta_p^2 = .403$). These differences were quite small though (< 1 cm) and had arguably nothing to do with our manipulation⁹. As predicted, the analysis also revealed a main effect of Obstacle, $F(1,11) = 18.53, p = .001, \eta_p^2 = .627$, indicating that unconstrained participants moved higher when the confederate moved over an obstacle. There were no other significant main effects or interaction effects (all $p > .15$).

Mean absolute asynchrony. Trials in which mean absolute asynchronies deviated more than two standard deviations from a pair's mean in a mini-block were excluded (4.6 %). As in the previous three experiments, asynchronies were larger when one of the co-actors moved over an obstacle, as indicated by a significant main effect of Obstacle, $F(1,11) = 5.99, p = .032, \eta_p^2 = .352$ (Vision No Obstacle: $M = 32.7$ ms, Vision Co-actor Obstacle: $M = 39.0$ ms; No Vision No Obstacle: $M = 35.6$ ms; No Vision Co-actor Obstacle: $M = 40.6$ ms). There was no significant main effect of Vision ($F(1,11) = 0.56, p = .470, \eta_p^2 = .049$) and no significant interaction effect, $F(1,11) = 0.17, p = .684, \eta_p^2 = .016$.

We tested whether co-actors were more synchronized during joint performance (averaged across all conditions) compared to a baseline estimate calculated from the individual performances of the two pair members (i.e., a naïve participant paired with a confederate) that was recorded before the joint condition¹⁰. A paired-samples t-test confirmed that asynchronies were significantly smaller when the two pair members interacted in the joint condition than when they acted independently, $t(11) = 4.32, p = .001$, Cohen's $d = 1.25$ ($M_{joint} = 37$ ms, $SD_{joint} = 6$ ms; $M_{individual} = 95$ ms, $SD_{individual} = 46$ ms). Since the presence of the obstacle had significantly affected asynchronies during joint performance, we additionally computed the

⁹ Analyses for Experiments 1-3 showed the same (non-significant) effect of Movement direction also for Experiment 1 ($F(1,23) = 3.35, p = .080, \eta_p^2 = .127$) as well as descriptive trends in the same direction for Experiments 2-3, suggesting that the effect occurred independently of our manipulation in Experiment 4.

¹⁰ Estimates derived from the individual baseline before and after the joint condition did not differ; $t(11) = 0.26, p = .803$, Cohen's $d = 0.07$.

baseline comparison separately for the two Obstacle conditions. Paired-samples *t*-tests (Bonferroni-corrected with $\alpha = .025$) confirmed that pair members were significantly better coordinated during joint performance (No Obstacle vs. the individual baseline without obstacle, $t(11) = 4.22$, $p = .001$, Cohen's $d = 1.22$; Co-actor Obstacle vs. the corresponding individual baseline, $t(11) = 4.26$, $p = .001$, Cohen's $d = 1.23$).

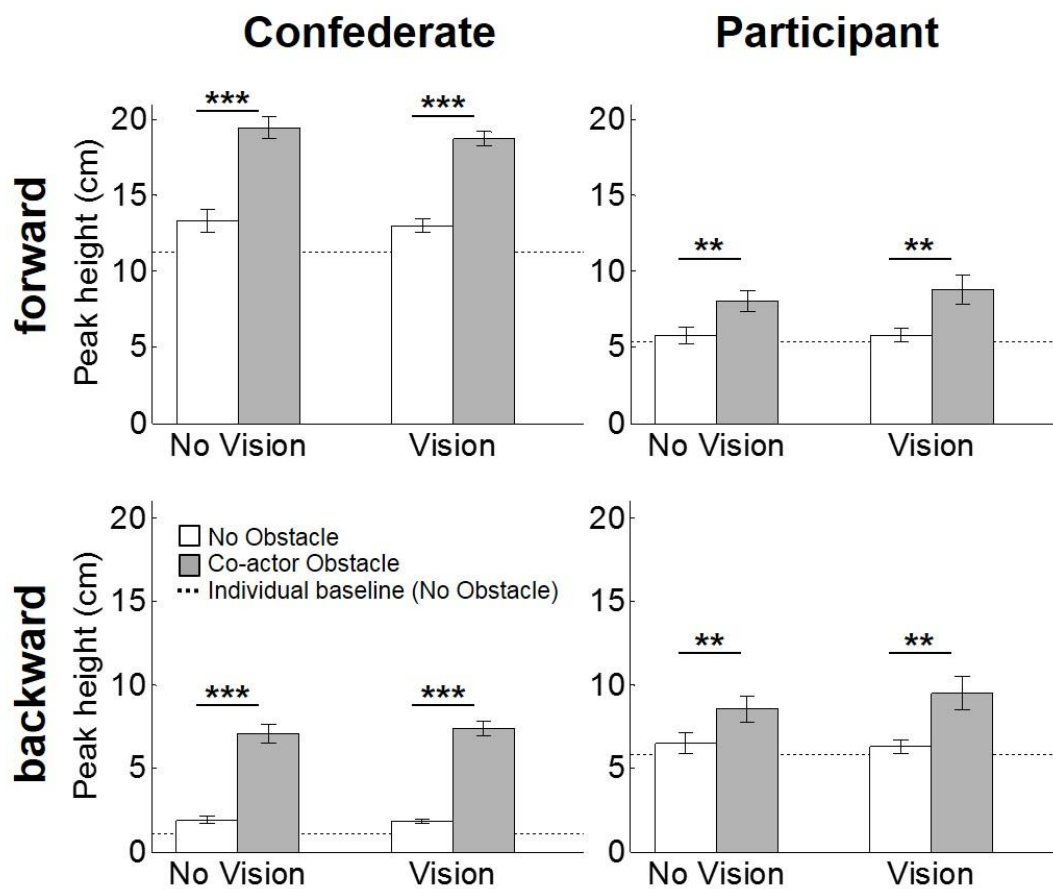


Figure 5. Peak height data from Experiment 4, depicted separately for the confederate's and the participants' performance (left and right panels, respectively) and separately for forward (upper panels) and backward movements (lower panels). As instructed, the confederate moved significantly higher going forward compared to backward. Participants did not show the same pattern, indicating that they did not represent their co-actor's movement itself but the obstacle height that constrained the co-actor's movement. As in Experiments 1-3, participants generally moved higher when their co-actor moved over an obstacle. The dashed horizontal lines represent peak height in the first individual baseline. Error bars reflect Standard Errors.

(** $p < .01$, *** $p < .001$)

2.5.3 Discussion

Experiment 4 asked how unconstrained actors represent a co-actor's task constraint. The results demonstrate that participants represented the object property constraining the confederate's movements (obstacle height) and not the amplitude of the confederate's movement.

As expected, pair members were significantly better coordinated when performing jointly than when performing independently. It is not surprising that the absolute level of asynchronies was lower in comparison to the asynchronies in the previous experiments because the confederate was well-trained in the task and was instructed to try her best to coordinate with the participant. Given the confederate's knowledge and specific performance instructions, the ensuing coordination performance between the naïve participants and the knowledgeable confederate is not comparable to the performance of participants in the previous experiments. Hence, the coordination results from Experiment 4 must be interpreted with caution.

2.6 General Discussion

In the present study, we examined whether actors rely on task co-representation to achieve temporal coordination with a co-actor even if other coordination processes imply less movement effort. Two co-actors performed a temporal movement coordination task in which the unconstrained actor could either represent her co-actor's task constraint at the cost of performing more effortful movements or slow down her own actions only based on feedback about the co-actor's movement tempo. The results of four experiments consistently showed that unconstrained actors represented their co-actor's task constraint such that they increased the amplitude of their own movement when their co-actor moved over an obstacle. These effects were more pronounced when coordination demands were higher (Experiment 1 vs. 2) and did not differ across different visuospatial perspectives (Experiment 2 vs. 3). The results of

Experiment 4 indicate that unconstrained actors represented the object property constraining their co-actor's movements rather than parameters of these movements. Going back to the joint winter walk example from the introduction, our findings suggest that when person A is walking next to person B whose path is obstructed by a series of snow heaps, A co-represents these snow heaps and partially adjusts the amplitude of her own movements to keep the same tempo as B.

Importantly, the increase in movement amplitude in unconstrained actors' movements cannot be explained in terms of purely perceptual mechanisms such as visuomotor interference (Brass et al., 2000; Kilner et al., 2003; Sacheli et al., 2012), dynamic entrainment (Richardson et al., 2007, 2009), automatic imitation (Heyes, 2011; Naber et al., 2016; Wang & Hamilton, 2012), or motor priming (Griffiths & Tipper, 2009) because movement amplitude increased to the same degree irrespective of whether unconstrained actors could observe their co-actor moving over an obstacle or not. The results from Experiment 4 provide a further indication that observing the co-actor's movement did not lead to assimilation. If mimicry of observed movements had played a role, participants should have adopted a similar movement pattern as the confederate, moving higher forward than backward, when they could observe the confederate moving. Moreover, the increase in unconstrained actors' movement height cannot be explained by the actors' own previous experience with the obstacle in the individual condition of the experiment. If such a carry-over effect from the individual to the joint condition had occurred, the increase in unconstrained actors' movement height should have occurred throughout the joint condition, independently of the co-actor's task constraint.

Across Experiments 1 to 3, participants showed successful interpersonal movement coordination as indicated by the lower asynchronies in the joint condition relative to a baseline of asynchronies expected on the basis of the respective co-actors' independent individual performances. Interestingly, the general level of asynchronies in the joint condition was quite similar across experiments even though interpersonal coordination was more challenging in

Experiments 2 and 3 where less external timing information was available. The fact that the asynchronies between co-actors' independent task performances were considerably larger in the two latter experiments compared to Experiment 1 (see Figure 3) also indicates higher coordination demands. This is suggested by the ensuing larger difference between the asynchronies from the individual and the joint condition which indicates that co-actors needed to compensate more in the joint condition to achieve the same level of coordination as in Experiment 1. This points to a larger benefit of representing the constraint of a co-actor when coordination difficulty was high.

It is not surprising that asynchronies were slightly larger when one of the participants had an obstacle while the other did not, compared to synchronizing two movements without obstacles (Experiments 1-3). It is surprising, however, that visibility of the co-actor's movements hardly affected the quality of coordination. Only when participants shared the same perspective (Experiment 3) did action observation improve coordination beyond the level achieved in the No Vision condition, indicating that sharing the same viewpoint may help with using visual information for coordination.

Going beyond the extensively studied effects of automatic task co-representation during parallel, yet independent, actions (cf. van der Wel & Fu, 2015), the aim of the present study was to explore the role of task co-representation in a more interactive setting, i.e., during interpersonal coordination. Our findings demonstrate that when temporal coordination is required, actors rely on co-representation to adjust their own actions to a co-actor's task constraint. Notably, a study by Vesper and colleagues (2013) also indicates that actors represent their co-actor's task constraint (i.e., a longer jumping distance) in order to adjust the temporal and spatial properties of their own movement preparation and execution phase accordingly. The present study differs from the latter one in that it used a different type of task asymmetry (i.e., obstacle height instead of distance constraints) as well as a different type of movement task

(i.e., non-ballistic reaching instead of jumping). Importantly, co-actors in Vesper et al. (2013) did not face any obstacles implying that there were no object properties to be co-represented. The use of non-ballistic arm movements in the present study enabled us to manipulate movement height independently of movement distance and thereby provided us with a way to differentiate between the action-constraining object property and the co-actor's movement parameters.

In light of our interpretation of the present results in terms of co-representation, it seems important to clearly define the concept of co-representation as we use it, thereby also highlighting the underlying commonalities and differences between our own and others' accounts. Co-representation refers to the representation of task-relevant aspects of another person's action. Thus, one's own and the other's actions are represented in a functionally equivalent way such that the action at the other's disposal (including task rules governing this action) is represented in addition to one's own action (see Sebanz et al., 2003). Such representations are based on task-relevant aspects of another person's action but do not necessarily need to involve a specification of that other person. Moreover, representing another's action is different from attributing mental states to another person, i.e., it does not imply representing or tracking another's perceptions or propositional attitudes such as knowledge states, beliefs, or intentions (on "mind reading" or mentalizing, see: Butterfill & Apperly, 2013; Heyes, 2014; Kovács, Téglás, & Endress, 2010; Samson, Apperly, Braithwaite, Andrews, & Bodley Scott, 2010; Southgate, Senju, & Csibra, 2007).

Even though co-representation does not imply explicitly representing another's beliefs or intentions, the process may still be modulated by the intentionality of the other agent such that only intentional or believed intentional actions are co-represented (Atmaca et al., 2011; Tsai et al., 2008). Thus, whereas co-representation should not be confused with explicit mentalizing processes, it nevertheless involves more than bottom-up driven reactions to stimuli

in the environment (Dolk, Hommel, Prinz, & Liepelt, 2013) as it is not based on online perceptual input an actor receives but on the actor's knowledge about a co-actor's task. The fact that co-representation can occur independently of whether visual access to another's action is provided helps for instance to distinguish co-representation of another's task from purely perceptual mechanisms such as visuomotor interference, dynamic entrainment, automatic imitation, or motor priming (see above).

Thus, when situating our account of co-representation on a continuum of the involvement of social cognition, it is located in between accounts that postulate explicit mental state attributions, on the one end, and accounts suggesting that all aspects of the environment (including other agents) are "depersonalized" and perceived as mere stimuli, on the other end.

Regarding the role of co-representation for joint actions where individuals coordinate towards a joint goal, previous work (e.g., Kourtis et al., 2013, 2014; Vesper, van der Wel, et al., 2013) has demonstrated that representing a task partner's action can support real-time action coordination. However, co-representation is not a necessary constituent of joint actions. In the most minimal case, an actor involved in a joint action only needs to represent the joint goal and her own task, and the fact that another agent's contribution is needed to achieve the joint goal (Vesper et al., 2010). Such a representation of a co-actor's contribution can be more or less specified, i.e., the actor may only represent *that* another's contribution is needed, but she may also specify the other's contribution on a more detailed level by representing the other's task (or aspects thereof). Representing the full specification of another's task may often be beneficial for achieving a particular joint action outcome. For instance, when aiming to lift a two-handed basket together with somebody else, it suffices to represent the fact that another agent or force is needed to achieve the goal of lifting the basket (cf. Vesper et al., 2010). However, sometimes it may be beneficial to represent another's contribution more specifically, e.g., when the basket

must not be tilted to avoid contents falling out, it is crucial to represent that the other agent needs to lift the basket at the exact same moment and with the same speed as oneself.

Is it possible that the present case of joint action coordination can be explained without postulating co-representation and that alternative explanations for the observed effects can be found? Based on the observed data pattern, we argue that the concept of co-representation is indeed necessary to explain the present findings. Specifically, we find that unconstrained actors selectively increase their own movement height when their co-actor moves over an obstacle compared to when the co-actor does not move over an obstacle. This is consistent with findings from van der Wel and Fu (2015) who showed a height modulation even when coordination was not a requirement. In van der Wel and Fu's study and in the present case, the adjustment of movement height is observed irrespective of whether unconstrained actors can see their co-actor's movements or not, excluding explanations based on purely perceptual mechanisms. Even in the absence of visual feedback, actors are still informed about their co-actor's task constraints (i.e., about whether the co-actor has to move over an obstacle or not). In this case, the only online feedback actors receive about their co-actor's performance is the sounds that are produced by the co-actor's landing on the target. However, the fact that unconstrained actors receive this auditory feedback cannot explain why they increase their own movement height in response to the co-actor's obstacle constraint. To explain this behavior, one must assume that unconstrained actors represent the fact that their co-actor moves over an obstacle since they selectively increase their own movement height only when the obstacle is present for the co-actor. Importantly, the information about the obstacle is not specified by the auditory feedback and therefore, the feedback alone cannot explain the observed increase in the unconstrained actors' movement height. Thus, postulating that unconstrained actors represented their co-actor's height constraint seems to provide the most parsimonious explanation for the observed effects. This interpretation is consistent with the assumption that unconstrained actors take into

account the task-relevant contextual features (here: the height of the co-actor's obstacle). Unconstrained actors are familiar with the obstacle (as they have experienced it themselves) and can therefore represent this constraint without necessarily needing to consider the mental states of a co-actor.

One may argue that the present findings could also be interpreted as co-representation of a task partner's cognitive effort. Supposedly, moving over the obstacle makes the synchronization task more difficult such that the actor who is required to move over the obstacle does not only need to spend more movement effort but also more cognitive effort in order to perform the task successfully. Recent work (Desender, Beurms, & Van den Bussche, 2016) has shown that interference effects in reaction time tasks are modulated by a co-actor's task difficulty such that actors exerted more cognitive effort themselves when their co-actor exerted more effort. In the context of the present study, representing another's task constraint could be conceived of as an instance of representing another's task difficulty. Hence, the unconstrained actor's modulation of movement height in response to the co-actor's obstacle may be interpreted as an expression of the co-represented cognitive effort. However, whereas Desender et al. (2016) used an interference task where response times reflect cognitive effort, our dependent variable of movement height provides a measure of movement effort that is not necessarily related to cognitive effort.

Considering the effects of varying coordination demands provides further insight into the question of co-represented cognitive effort. Specifically, we predicted that an increase in coordination demands in Experiment 2 compared to Experiment 1 would require co-actors to take each other's actions into account more strongly. This should in turn lead to a stronger increase in the unconstrained actor's movement height. This prediction was confirmed by the results of Experiment 2. However, the obstacle constraint for the co-actor stayed the same

across experiments and hence also the cognitive effort required to move over the obstacle did not change. Thus, it is unlikely that co-represented cognitive effort can fully explain our results.

A further question emerging from the present set of experiments is whether the conclusion that actors represent the object property constraining the co-actor's action rather than the specific parameters of the co-actor's movement can be generalized across different task contexts. One possibility is that co-actors generally represent invariant aspects of a joint task. Because object properties are more stable than movement parameters, this would predict that representing object properties takes precedence over representing movement parameters.

However, co-representing movement parameters may be especially important during continuous movement coordination (e.g., dancing) where co-actors need to synchronize and mutually adjust their movements at all times (e.g., Noy, Dekel, & Alon, 2011). In contrast, when interpersonal coordination is discrete (e.g., when co-actors need to arrive synchronously at particular target locations, as in the present study), it may be sufficient for co-actors to represent the properties constraining each other's movements. A further possibility is that the degree of familiarity with another's action may affect the likelihood that specific movement parameters are represented. If individuals are highly trained in performing a particular action jointly, they may represent each other's movement parameters (possibly in addition to action-relevant object properties). Participants in the present study may not have been sufficiently familiar with their co-actor's movements for effects of movement co-representation to emerge. Future studies may investigate the influence of motor expertise on the representation of movement parameters.

Together, our findings suggest that people have a tendency to represent others' task constraints when faced with the challenges arising from real-time interpersonal coordination.

Chapter 3. Co-representing the Order of Others' Actions

3.1 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 et al., 2003), such as when two dance partners coordinate their steps.

Previous research has demonstrated that the coordination of actions within and between individuals may rely on similar processes (e.g., Richardson, Marsh, & Baron, 2007; Schmidt et al., 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., Richardson, Marsh, Isenhowe, et al., 2007; Schmidt et al., 1990) as well as between the limbs of one individual acting bimanually (Heuer, 1996; 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 (Sebanz et al., 2003; Atmaca et al., 2011), attention allocation processes (Böckler et al., 2012; Kourtis et al., 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 joint movement coordination tasks. When two co-actors need to temporally coordinate movements

of different difficulty, they make similar adjustments in action execution (Vesper, van der Wel, et al., 2013) as one individual performing movements of different difficulty with her two limbs (Kelso et al., 1979; Marteniuk, MacKenzie, & Baba, 1984). Moreover, van der Wel and Fu (2015), as well as our own work (see Chapter 2) 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, & Goodman, 1983). Finally, della Gatta and colleagues (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 a reaching 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 (see Figure 1A).

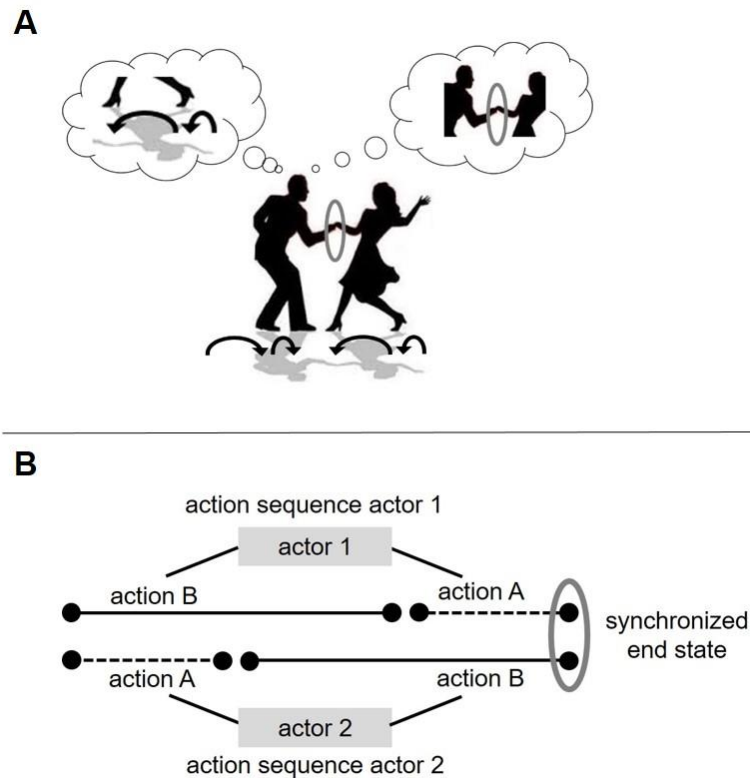


Figure 1. Exemplary (A) and schematic (B) depiction of a joint action situation in which two co-actors perform the same actions in a different order (i.e., B-A vs. A-B), with the joint goal of synchronizing the end state of their action sequences. The thought bubbles in A represent the two possible representations co-actors could hold: They could either represent the actions within each other's sequence or they could merely represent the end state of the whole sequence.

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 Figure 1B). 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).

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 (Figure 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 achieve this synchronization is to make the overall duration of one's own action sequence as invariant, and thus predictable, as possible (Vesper et al., 2011; Vesper et al., 2016). 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, Ivry, Hazeltine, Kennerley, & Cohen, 2003, Diedrichsen, Grafton, Albert,

Hazeltine, & Ivry, 2006; 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 motor parameters for left and right hand need to be concurrently specified during motor programming (Heuer, 1993; Heuer & Klein, 2006; 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; Mechsner & Knoblich, 2004; Mechsner et al., 2001; Kunde & Weigelt, 2005; 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 motor parameters. In contrast to bimanual reaching 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; Wolpert et al., 2003).

At the cognitive level, co-actors might represent each other's actions in terms of action goal states, specifying the perceptual characteristics of movement targets. Thus, when

representing not only their own but also a co-actor's perceptually different movement targets, response selection may get more demanding and actors might have difficulties keeping apart their own and their co-actor's movement targets. This would be in line with the finding that individuals performing a similar task bimanually have difficulties keeping apart which hand needs to move to which target (cf. Diedrichsen et al., 2003). The following six experiments were performed to establish whether co-actors represent the order of each other's actions and if so, at which level interference arises.

3.2 Experiment 1

Experiment 1 tested the hypothesis that co-actors represent the order of actions within each other's action sequence. If this hypothesis is correct, co-actors should show interference when the order of their actions differs, resulting in slower performance than when the order is the same. If co-actors do not represent the actions within each other's action sequence (but merely the end state of the whole sequence), no interference – and thus no performance slowdown – is expected.

3.2.1 Method

Participants. In Experiment 1, fifteen women and five men participated in randomly-matched pairs (6 only-female pairs, 1 only-male pair, $M_{age} = 22.5$ years, $SD_{age} = 3.65$ years, range: 18-32). Members of one pair knew each other beforehand. All participants were right-handed and had normal or corrected-to-normal vision. They signed prior informed consent and received monetary compensation. The study was approved by the Hungarian United Ethical Review Committee for Research in Psychology (EPKEB).

Apparatus. The experimental setup consisted of a table (110 cm long, 55 cm wide) with two parallel columns of four circular cardboard markers (diameter 5 cm) attached to it (Figure

2). The two columns were aligned with the table's short side at a horizontal distance of 40.5 cm. The constant center-to-center distance between markers in a column was 13.3 cm. The first marker in each column indicated the start location and the last marker indicated the final target. The two inner markers in each column served as close and far intermediate targets. Start location and final target were colored blue and intermediate targets were colored orange. The two inner markers in each column served as close and far intermediate targets. Start location and final target were colored blue and intermediate targets were colored orange.

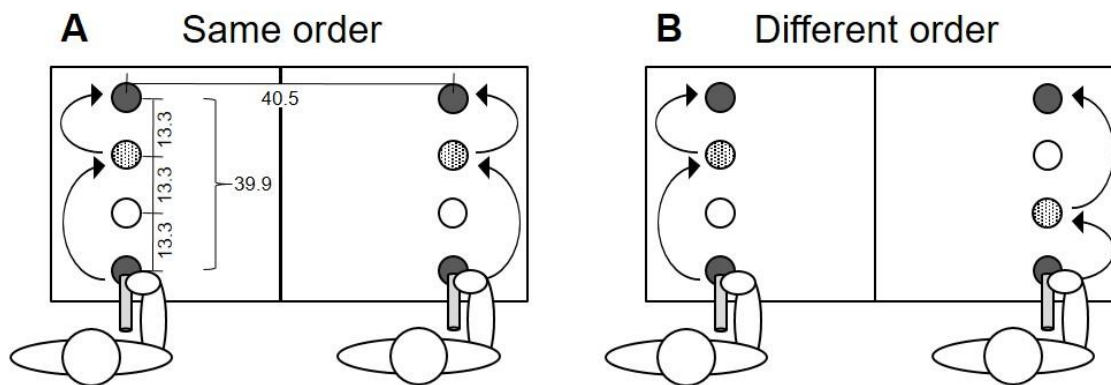


Figure 2. Sketch of experimental setup for Experiments 1-3. Co-actors performed long and short movements either in the same order (A) or in a different order (B). Distances are in cm.

The two participants were seated next to each other at the table's long side (Figure 2) and held a wooden dowel rod (height: 20 cm, diameter: 2.5 cm, weight: 50 g) in their right hand with a power grip. A Polhemus G4 electro-magnetic motion capture system (www.polhemus.com) was used to record participants' movement data at a constant sampling rate of 120 Hz via a motion capture sensor that was attached to the top of each dowel rod. Instructions were displayed on a 24" Asus computer screen (resolution 1920 x 1080 pixels, refresh rate 60 Hz), positioned on a separate table in front of the participants at a distance of 160 cm (see Figure 4). Data recording was controlled by Matlab 2014a.

Procedure and stimuli. The participants were instructed to perform two consecutive aiming movements as fast as possible, moving from the start location to one of the intermediate targets and onwards to the final target while synchronizing their landing times on the final

target. Importantly, the synchronization instruction applied to the final target only. At the beginning of each trial, participants rested their dowels on the start location until they heard a short tone (440 Hz, 100 ms) that served as a go signal. Participants then performed the instructed movement sequence. After having landed on the final target, they moved back to the start location. Then the next trial started. There was a 5s-interval between the start of one trial and the start of the next trial, giving participants sufficient time to complete their movement sequences and to return to the start location for a short rest (for comparable intervals used in a similar task, see Schmitz et al., 2017; van der Wel & Fu, 2015).

There were 12 blocks of twelve trials (144 trials total). Across blocks, it was varied whether participants performed the actions in their respective action sequence in the same order or in a different order, i.e., whether both participants moved to the same intermediate target or not. Accordingly, each block started with an instruction that specified the action sequences to be performed by each participant. The display showed the same layout of markers as seen on the table (Figure 4A, row 1, panels 1-2). The start and final markers had the same color as the markers on the table. One intermediate marker in each column was colored orange and one was colored white. In blocks of the ‘same order’ condition, the same intermediate targets in the two columns were colored orange (Figure 4A, row 1, panel 1). This served to instruct the two participants to either both perform a short movement followed by a long movement (‘short-long’) or a long movement followed by a short movement (‘long-short’), see Figure 3. In blocks of the ‘different order’ condition, different intermediate markers in each column were colored orange (Figure 4A, row 1, panel 2). This instructed the two participants to perform different action sequences so that one participant performed a short movement followed by a long movement whereas the other participant performed a long movement followed by a short movement, see Figure 3. Once participants had indicated that they were ready to start, the

experimenter manually started the block and a start tone marked the beginning of the first trial. The display remained on the computer screen throughout the entire block.

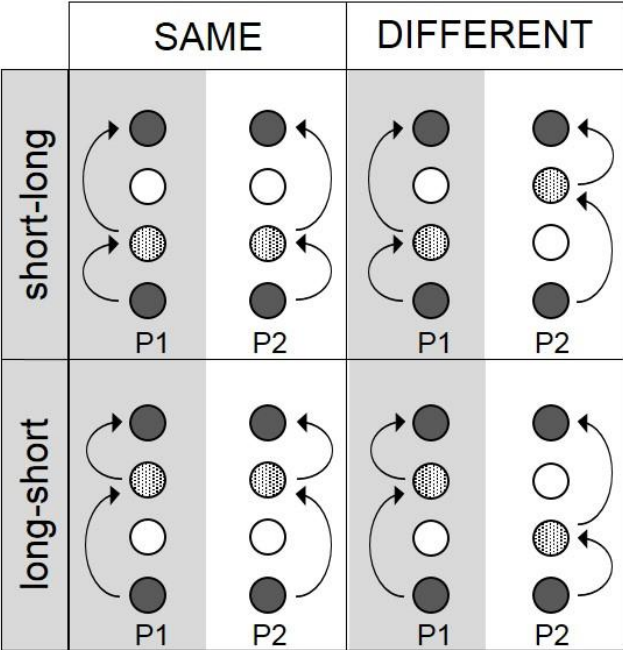


Figure 3. Four types of blocks in Experiments 1-3. Participants performed sequences of two movements of differing distance, in the order ‘short-long’ or ‘long-short’. The two participants in a pair either performed the same sequence or a different sequence.

The twelve blocks were run in 3 sets of 4 blocks. Each set of blocks consisted of two blocks where participants performed their actions in the same order, one block where Participant 1 performed short-long sequences and Participant 2 performed long-short sequences, and one block where Participant 1 performed long-short sequences and Participant 2 performed short-long sequences (see Figure 3). The order of blocks was randomized within each set of 4 blocks, with the constraint that blocks of the ‘same order’ condition alternated with blocks of the ‘different order’ condition.

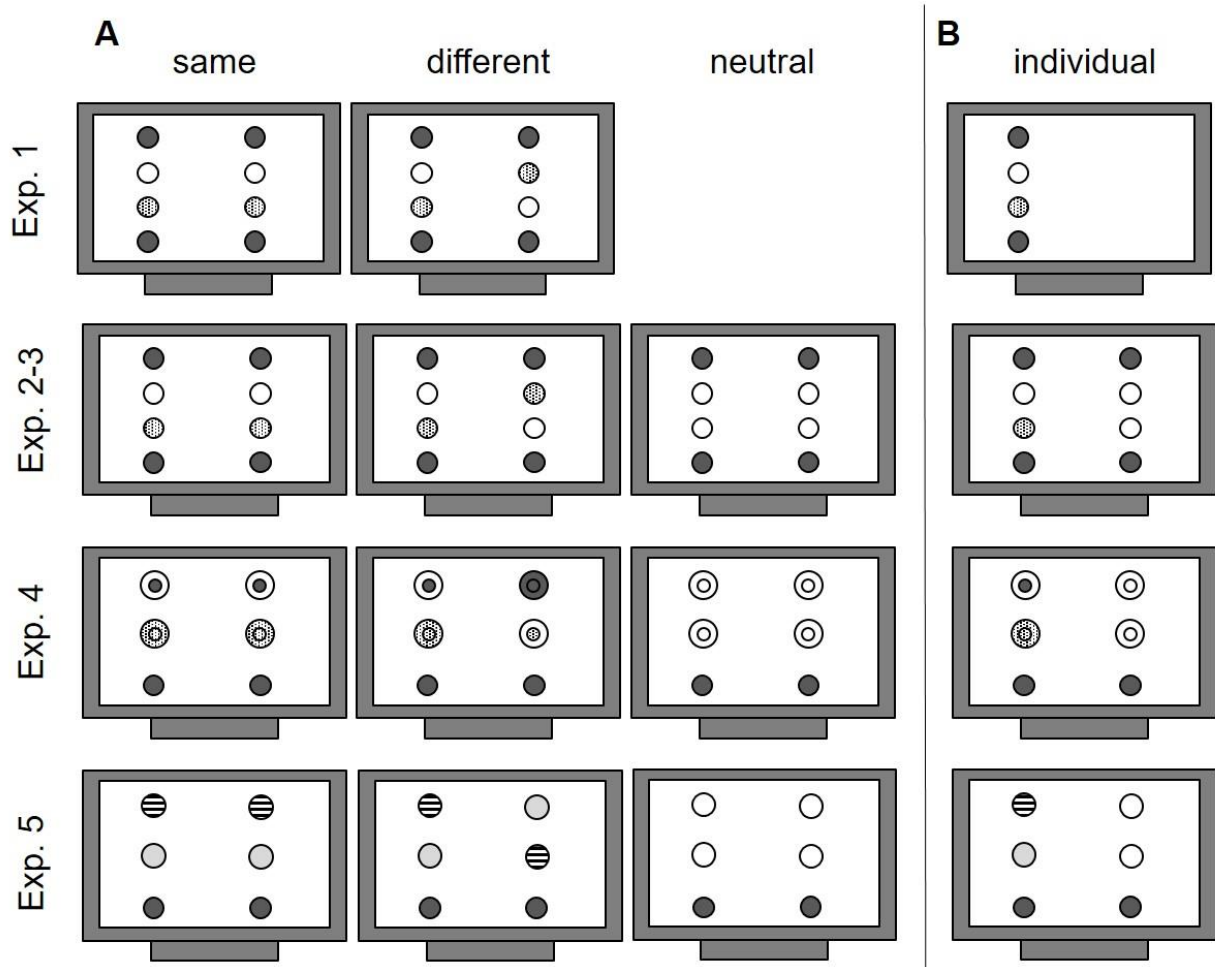


Figure 4. (A) Displays used in Experiments 1-5 to instruct participants to perform action sequences in the ‘same order’ or in a ‘different order’. ‘Neutral’ refers to the uninformative displays that were presented while co-actors performed the task in Experiments 2-5. (B) The fourth column shows the displays used in the individual baseline.

Before performing the joint task, participants completed two blocks of individual trials that served as a baseline. Only one column of markers was displayed either on the left or right side of the computer screen, depending on the participant’s seating location (which remained the same in the joint condition), see Figure 4B (row 1). Participants performed one block of short-long sequences and one block of long-short sequences. While one participant performed the task individually, the other participant waited outside of the testing room, and then they switched.

At the end of the experiment, participants were asked to report (in writing) whether they had used a specific strategy to achieve the task goal of synchronizing with their partner. The experiment lasted about 45-50 minutes in total.

Data preparation and analysis. Before extracting movement times (MTs) from participants' movement data, all movement trajectories were filtered using a 4th-order two-way low-pass Butterworth filter with a cutoff at 20 Hz. Movement onset was defined as the point when movement velocity exceeded 5% of peak velocity for the first time (see, e.g., Zopf, Truong, Finkbeiner, Friedman, & Williams, 2011), with peak velocity defined as the maximal horizontal velocity. Movement offset was defined as the point of minimal movement height *after* the intermediate target had been passed. This spatial criterion was used because initial analyses indicated that it was the most reliable criterion to define movement offset. MT was computed as the time interval between movement onset and offset, thus capturing the time participants needed to move from the start location to the final target. As a measure of coordination performance in each pair, we computed the mean absolute asynchrony between co-actors' landing times on the final target. Matlab 2013b and 2016a was used for data preparation, and statistical analyses were performed in IBM SPSS 22.

3.2.2 Results

Preliminary analyses indicated that the manipulation of the order of actions within co-actors' sequences had no effect on movement preparation times (RTs). Therefore, we analyzed only MTs and asynchronies. MTs for short-long and long-short movement sequences did not differ in the individual baseline ($p = .542$), making it unlikely that any of the effects reported below can be explained by the order of short and long movements in a sequence alone¹¹. We excluded the first and last trial in each block to avoid potential starting and stopping effects (see

¹¹ There were also no MT differences between short-long and long-short sequences in the individual baselines of Experiment 2 ($p = .179$) and Experiment 3 ($p = .080$), respectively.

Smits-Engelsman et al., 2002). Trials in which participants covered less than 75 % of the distance between start location and final target were also excluded from further analysis (0.2 %). Finally, MTs exceeding two standard deviations around the mean were excluded per participant per block (3 %) and asynchronies exceeding two standard deviations around the mean were excluded per pair per block (4.5 %).

MT. Figure 5 displays MTs in the ‘same order’ and in the ‘different order’ condition. Participants’ MTs were longer when the co-actor performed her actions in a different order ($M = 657$ ms, $SD = 166$ ms) compared to when the co-actor performed her actions in the same order ($M = 632$ ms, $SD = 149$ ms). A paired t-test showed that this difference was highly significant, $t(19) = -4.94$, $p < .001$, *Cohen’s d* = -1.11.

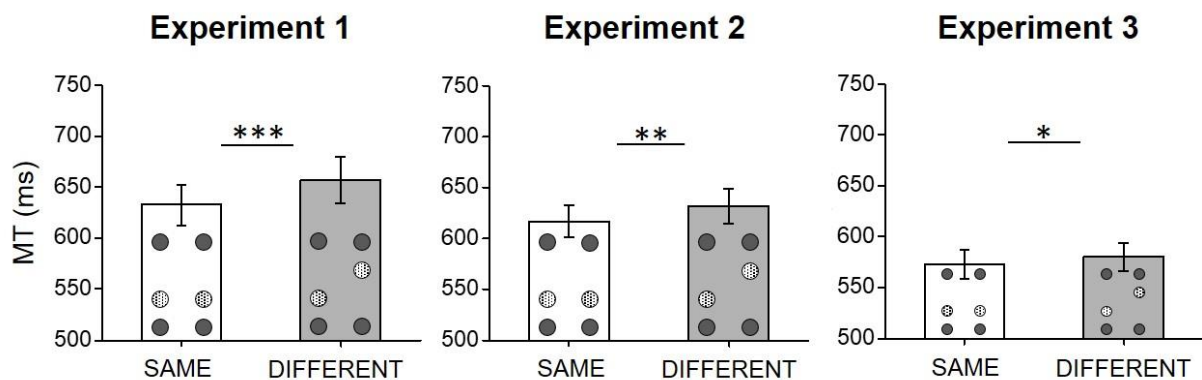


Figure 5. Movement times (i.e., times between movement onset at start location and movement offset at final target) for the ‘same order’ and the ‘different order’ condition for Experiments 1-3. Movement times were significantly longer when a co-actor performed her actions in a different order. Error bars indicate Standard Errors. (* $p < .05$; ** $p < .01$; *** $p < .001$)

Asynchrony. Asynchronies in the ‘same order’ condition ($M = 35$ ms, $SD = 7$ ms) were numerically smaller than asynchronies in the ‘different order’ condition ($M = 42$ ms, $SD = 14$ ms) but the difference was not significant in a paired t-test, $t(9) = -2.08$, $p = .067$, *Cohen’s d* = -0.66.

3.2.3 Discussion

The results of Experiment 1 showed that actors moved more slowly when a co-actor performed her actions in a different order. This finding provides first support for the hypothesis that co-actors represent the order of actions within each other's action sequence and that this interferes with their own performance. However, it is also possible that observing a co-actor perform different movements might have interfered with actors' own motor planning and execution (visuomotor interference; Kilner et al., 2003; Sacheli et al., 2012). Moreover, the perceptual content of the instruction screen might also have affected co-actors' performance because they had continuous visual access to the screen where their own and their co-actor's target configurations were displayed. Thus, the interference in the 'different order' condition might have been caused by the perceptual discrepancy between the two displayed target configurations.

3.3 Experiment 2

Experiment 2 was conducted to ensure that the slowdown in movement times observed in Experiment 1 was due to co-actors' conflicting representations of action sequences rather than due to low-level perceptuomotor processes such as visuomotor interference (e.g., Kilner et al., 2003; Sacheli et al., 2012). To this end, co-actors in Experiment 2 performed the joint task without seeing each other. To exclude the possibility that interference was caused by the different target configurations displayed on the instruction screen, no instructions were displayed during task performance. Rather, the target display was replaced by a neutral display that did not specify the intermediate target positions (Figure 4A, row 2, panel 3). The same neutral display was used in the individual condition to exclude the possibility that displaying a second set of targets might affect performance.

If co-actors' representations of each other's action sequences cause interference, then performing different sequences should again take longer than performing the same sequences. However, if co-actors' performance slowdown in Experiment 1 was due to visual influences, then no slowdown should occur in Experiment 2.

3.3.1 Method

The methods in Experiment 2 were the same as in Experiment 1, with the following exceptions:

Participants. Fourteen women and six men participated in randomly-matched pairs (5 only-female pairs, 1 only-male pair, $M_{age} = 24.1$ years, $SD_{age} = 4.33$ years, range: 19-40).

Apparatus. In the joint condition, a partition (styrofoam material on wooden mount; height: 55 cm, width: 65 cm, depth: 0.5 cm) was placed on the table between participants so that they could no longer see each other. The partition was also present in the individual condition.

Procedure and stimuli. The display that informed participants about the current target configurations was only shown *before* participants started to perform the joint task in each block. Once participants were ready to start, the experimenter started the block and the required sequences for both co-actors were displayed on the screen, with the current intermediate target locations marked in orange (Figure 4A, row 2, panels 1-2). After 3 s, the display turned 'neutral', i.e., the intermediate markers turned white (Figure 4A, row 2, panel 3). About 2 s later, a start tone was played and the first trial began. In the individual condition, participants' own target configuration was shown on one side of the screen and in addition, a neutral target configuration was shown on the other side (Figure 4B, row 2). After 3 s, the display turned neutral and was the same as in the joint condition.

3.3.2 Results

Prior to analysis, we excluded all trials that did not meet a minimal horizontal distance criterion (0.2 %). Values exceeding two standard deviations around the mean were excluded (2.9 % for MT, 3.5 % for asynchrony).

Preliminary manipulation check. The presence of an additional target display in the individual baseline did not affect participants' performance, as a comparison between individuals' MTs from Experiment 1 and 2 was not significant ($p > .7$).

MT. Figure 5 displays MTs in the 'same order' and in the 'different order' condition. As in Experiment 1, participants' MTs were significantly longer when the co-actor performed her actions in a different order ($M = 632$ ms, $SD = 125$ ms) compared to the same order ($M = 617$ ms, $SD = 118$ ms), $t(19) = -3.15$, $p = .005$, *Cohen's d* = -0.70.

To test whether the size of this effect differed between Experiments 1 and 2, we computed a mixed ANOVA with the within-subject factor Co-actor order (same, different) and the between-subject factor Experiment (E1, E2). The analysis showed a significant main effect of Co-actor order, $F(1,38) = 32.86$, $p < .001$, $\eta_p^2 = .464$, but no significant interaction between the factors Co-actor order and Experiment, $F(1,38) = 1.74$, $p = .196$, $\eta_p^2 = .044$. MTs did not differ between experiments, as indicated by a non-significant main effect of Experiment, $F(1,38) = 0.21$, $p = .649$, $\eta_p^2 = .006$.

Asynchrony. Asynchronies in the 'same order' condition ($M = 44$ ms, $SD = 12$ ms) were significantly smaller than in the 'different order' condition ($M = 53$ ms, $SD = 13$ ms), $t(9) = -3.85$, $p = .004$, *Cohen's d* = -1.23, indicating that co-actors were less well coordinated when they performed their actions in a different order. Based on previous literature showing that less variable temporal performance correlates with smaller asynchronies, we conducted a post-hoc t-test comparing the variability (in form of standard deviations) of MTs in the two conditions. The results showed that standard deviations were significantly higher in the 'different order'

condition ($M_{\text{different}} = 38$ ms) compared to the ‘same order’ condition ($M_{\text{same}} = 33$ ms), $t(19) = -3.30$, $p = .004$, *Cohen’s d* = -0.74.

A comparison between asynchronies from Experiment 1 ($M_{\text{AsyncE1}} = 38$ ms) and Experiment 2 ($M_{\text{AsyncE2}} = 48$ ms) showed that co-actors were significantly better coordinated in the first experiment, $t(18) = -2.12$, $p = .048$, *Cohen’s d* = -0.91.

3.3.3 Discussion

Experiment 2 provided evidence that the slowdown in co-actors’ performance was likely due to co-representing the order of each other’s actions within an action sequence. The results showed that co-actors moved more slowly when they performed actions in a different order even when they could not see each other moving. Thus, the slowdown cannot be explained in terms of visuomotor interference. Moreover, the slowdown cannot be attributed to the display on the instruction screen because a neutral display was displayed while the task was performed. The slowdown in movement time observed in Experiments 1 and 2 was of similar size. Thus, it is unlikely that visual access to a co-actor’s movements and/or to the target display contributed to the slowdown in Experiment 1.

In contrast to Experiment 1, co-actors coordinated their actions more successfully when the order of their actions was the same. This finding may reflect a regularity demonstrated in previous research: in the absence of perceptual feedback, less variable temporal performance facilitates coordination (Glover & Dixon, 2017; Vesper et al., 2011; Vesper, Schmitz, Sebanz, & Knoblich, 2013; Vesper et al., 2016). Indeed, a post-hoc analysis showed that the variability of MTs was significantly higher when co-actors performed their actions in a different order, suggesting that the lower variability in the ‘same order’ condition may have facilitated coordination.

Co-actors in Experiment 2 did not coordinate their movements as successfully as in Experiment 1. This indicates that the opportunity to observe each other's movements facilitated coordination in Experiment 1 and that coordination was more difficult when relying solely on prediction and auditory feedback (i.e., the sound the co-actor created when hitting the target; see Chapter 2 for a similar finding).

3.4 Experiment 3

In Experiments 1 and 2, the two co-actors were given the joint instruction to synchronously arrive at the final target location. Experiment 3 investigated whether having such a joint goal is a necessary precondition for co-actors to take each other's action sequences into account. Previous research has indicated that people represent others' actions even when coordination is not required (e.g., Böckler et al., 2012; Eskenazi et al., 2013; Sebanz et al., 2003; van der Wel & Fu, 2015). Thus, performing an action sequence alongside another person might be sufficient to trigger a representation of this person's action sequence. To test this, participants in Experiment 3 performed the same task without being instructed to coordinate. If having a joint goal is not a necessary pre-condition for taking each other's action sequences into account, co-actors should again move more slowly when performing their actions in a different order than when performing their actions in the same order.

3.4.1 Method

The methods in Experiment 3 were the same as in Experiment 2, with the following exceptions:

Participants. Fourteen women and six men participated in randomly-matched pairs (4 only-female pairs, $M_{age} = 22.7$ years, $SD_{age} = 3.89$ years, range: 19-38). Members of one pair knew each other beforehand.

Procedure. Participants were instructed to perform their movements as fast as possible. The same instruction was given in the joint condition and in the individual baseline. After the experiment, participants were asked whether they thought they had acted differently in the joint condition compared to the individual baseline. This question served to assess whether participants had tried to synchronize with their partner even though not explicitly instructed to do so.

3.4.2 Results

Prior to analysis, we excluded all trials that failed to meet a minimal horizontal distance criterion (1 %). Values exceeding two standard deviations around the mean were excluded (3 % for MT, 3.6 % for asynchrony).

MT. Figure 5 displays MTs in the ‘same order’ and in the ‘different order’ condition. As in the previous two experiments, participants’ MTs were significantly longer when the co-actor performed her actions in a different order ($M = 580$ ms, $SD = 106$ ms) compared to the same order ($M = 573$ ms, $SD = 103$ ms), $t(19) = -2.34$, $p = .031$, *Cohen’s d* = -0.52.

We compared Experiments 2 and 3 by conducting a mixed ANOVA with the within-subject factor Co-actor order (same, different) and the between-subject factor Experiment (E2, E3). The analysis showed a significant main effect of Co-actor order, $F(1,38) = 15.30$, $p < .001$, $\eta_p^2 = .287$. Although the difference was numerically smaller in Experiment 3 (7 ms) than in Experiment 2 (15 ms), the interaction between the factors Experiment and Co-actor order was not significant, $F(1,38) = 1.93$, $p = .172$, $\eta_p^2 = .048$. MTs in Experiment 3 ($M_{E3} = 577$ ms) were numerically smaller than in Experiment 2 ($M_{E2} = 625$ ms), but the difference was not significant, $F(1,38) = 1.80$, $p = .188$, $\eta_p^2 = .045$.

Asynchrony. Asynchronies in the ‘same order’ condition ($M = 83$ ms, $SD = 36$ ms) did not differ from asynchronies in the ‘different order’ condition ($M = 79$ ms, $SD = 28$ ms), $t(9) =$

-0.92, $p = .382$, *Cohen's d* = 0.29. As co-actors in Experiment 3 were not instructed to synchronize their landing times on the final target, it is expected that asynchronies in Experiment 3 are higher than in the two previous experiments where co-actors aimed to synchronize their landing times. We chose to conduct a comparison between Experiments 2 and 3 because they were identical except for the coordination instruction (whereas Experiment 1 additionally differed in terms of visual access). As expected, co-actors were significantly better coordinated in Experiment 2 ($M_{\text{AsyncE2}} = 48$ ms) compared to Experiment 3 ($M_{\text{AsyncE3}} = 81$ ms), $t(18) = -3.13$, $p = .006$, *Cohen's d* = 1.40.

3.4.3 Discussion

The results of Experiment 3 indicated that having a joint goal was not a necessary precondition for co-actors to represent each other's action sequences. Acting alongside a co-actor was sufficient to trigger co-representation. Whereas this result is in line with earlier research on task co-representation (e.g., Sebanz et al., 2003, 2005), it is less consistent with recent evidence demonstrating that co-actors need to conceive of their actions as joint to take each other's actions into account (della Gatta et al., 2017).

Co-actors in Experiment 3 performed their movements generally faster compared to Experiment 2. Most likely, this decrease in movement times can be attributed to the absence of a coordination constraint. Not being required to coordinate, co-actors shifted – intentionally or unintentionally – towards a form of competitive behavior where they tried to beat each other to the target. Indeed, 12 out of 20 participants reported that they moved faster in the joint condition because they were affected by the sound of their task partner's target hits, which motivated them to reach their own target at least as fast or faster than the other. Five of these participants mentioned explicitly that they experienced the task as an “undeliberate competition”. Thus, interference from a co-represented action sequence seems to even occur under conditions that

are perceived to involve competition. This is in line with evidence for co-representation of a task partner's actions in a competitive context (Ruys & Aarts, 2010).

3.5 Experiment 4

Experiment 4 tested whether interference from co-represented action sequences is specific to differences in movement distance or whether it is a more general phenomenon. If the interference reflects a more general tendency to plan and execute own action sequences while additionally specifying parameters of a co-actor's action sequence, interference should also occur when another's movements differ in other parameters that affect movement difficulty. We tested this by varying target sizes, a parameter that is known to systematically affect movement difficulty (Fitts, 1954).

3.5.1 Method

The methods in Experiment 4 were the same as in Experiment 3, with the following exceptions:

Participants. Thirteen women and seven men participated in randomly-matched pairs (4 only-female pairs, 1 only-male pair, $M_{age} = 21.5$ years, $SD_{age} = 1.72$ years, range: 19-26). Members of one pair knew each other beforehand.

Apparatus. The intermediate target was located exactly half-way between start location and final target, dividing the total distance into two equal distances of ~20 cm, see Figure 6. Whereas the start marker had a diameter of 5 cm as in previous experiments, the intermediate and the final markers differed in size, with diameters of 3.8 cm and 7.6 cm, respectively. By selecting these sizes, we matched movement difficulty in Experiment 1-4 in terms of their index of difficulty ($ID = \log_2(2 \times \text{distance}/\text{width})$) as defined by Fitts' law (1954). In Experiment 4,

big targets (corresponding to short movements in Experiment 1-3) had an ID of 2.4 and small targets (corresponding to long movements in Experiment 1-3) had an ID of 3.4.

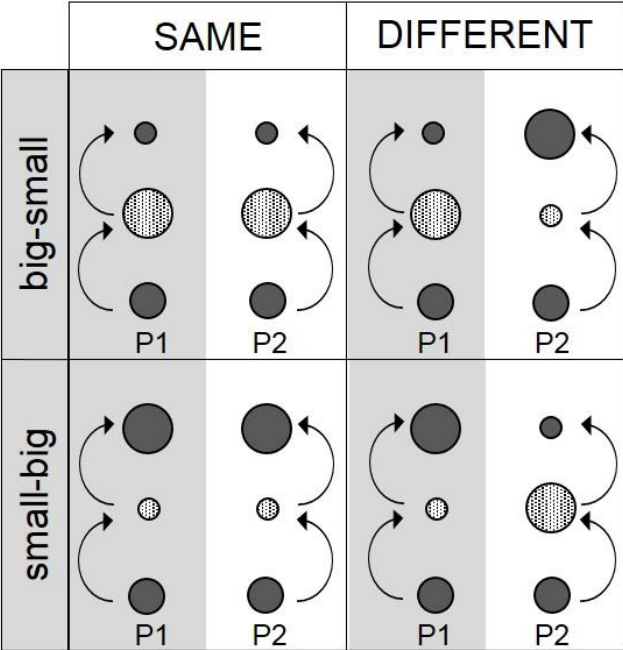


Figure 6. Four types of blocks in Experiment 4. Participants performed sequences of two movements to targets of different sizes, in the order ‘big-small’ or ‘small-big’. The two participants in a pair either performed the same sequence or a different sequence.

Procedure and stimuli. Participants were instructed to synchronize their landing times on the final target and to perform their movements as fast as possible.

Across blocks, it was varied whether the sizes of the intermediate and final target were the same or different for the two participants. Before each block, the experimenter arranged the small and big target markers on the table and the corresponding target configuration was displayed on the instruction screen. The display showed the intermediate and final markers pictured as a small circle within a bigger circle, outlined in black. In blocks of the ‘same order’ condition (Figure 4A, row 3, panel 1), the intermediate markers were colored such that the entire big circles were orange whereas for the final markers only the small inner circles were

orange, or vice versa. This served to instruct the two participants to either both perform a movement to a big target followed by a movement to a small target ('big-small') or a movement to a small target followed by a movement to a big target ('small-big'), see Figure 6. In blocks of the 'different order' condition, the circles in the two columns were colored differently such that for the intermediate marker in one column the entire big circle was orange whereas for the intermediate marker in the other column only the small inner circle was orange, and vice versa for the final markers (Figure 4A, row 3, panel 2). This instructed the two participants to perform different action sequences so that one participant performed a movement to a big target followed by a movement to a small target whereas the other participant performed a movement to a small target followed by a movement to a big target (Figure 6). After 3 s, both intermediate and final target circles on the instruction screen turned white such that only the black outlines of the small circles within the big circles were displayed while co-actors performed the task (Figure 4A, row 3, panel 3).

Before performing the joint task, participants completed two blocks of individual baseline trials. Participants performed one block of big-small sequences and one block of small-big sequences.

3.5.2 Results

Prior to analysis, we checked whether any trials failed to meet a minimal horizontal distance criterion but no trials had to be excluded. Values exceeding two standard deviations around the mean were excluded (3.2 % for MT, 4.1 % for asynchrony).

MT. Figure 7 displays MTs in the 'same order' and in the 'different order' condition. As in the previous experiments, participants' MTs were significantly longer when the co-actor performed her actions in a different order ($M = 683$ ms, $SD = 151$ ms) compared to the same order ($M = 669$ ms, $SD = 151$ ms), $t(19) = -3.72$, $p = .001$, *Cohen's d* = -0.83.

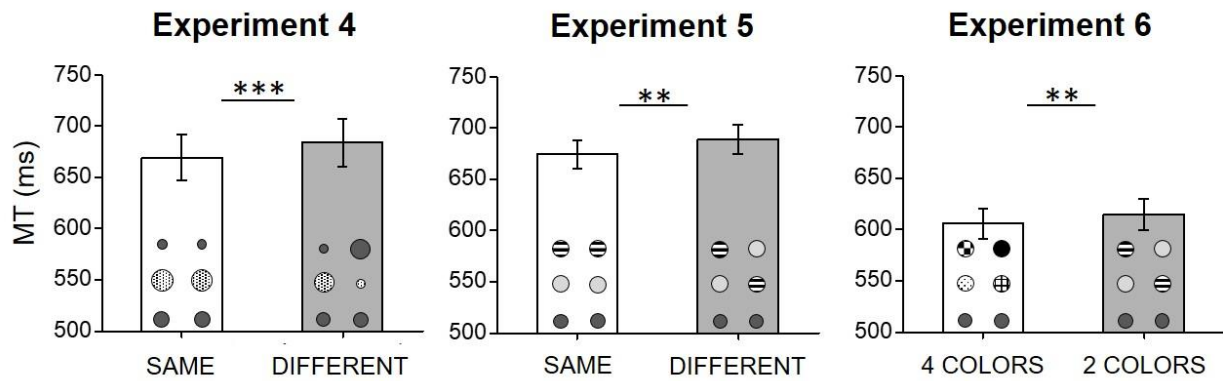


Figure 7. Movement times for Experiments 4-6, displayed separately for the ‘same order’ and the ‘different order’ condition. In all experiments, actors’ movement times were significantly longer when a co-actor performed her actions in a different order. Error bars indicate Standard Errors. (** $p < .01$; *** $p < .001$)

Asynchrony. Asynchronies in the ‘same order’ condition ($M = 40$ ms, $SD = 14$ ms) and the ‘different order’ condition ($M = 41$ ms, $SD = 13$ ms) did not differ significantly, $t(9) = -0.26$, $p = .803$, *Cohen’s d* = -0.08, indicating that co-actors were equally well coordinated regardless of whether the order of their actions differed.

3.5.3 Discussion

Experiment 4 showed that participants moved more slowly when a co-actor performed movements to targets that differed in size from their own targets. This finding generalizes the results from Experiments 1-3 by demonstrating that the previously observed interference is not specific to movement distance but more generally related to movement difficulty. Thus, the results from Experiments 1-4 suggest that the interference occurred at a motor level where concurrent specification of co-actor’s movement parameters led to a slowdown in specifying own movement parameters.

The target size manipulation in Experiment 4 improved the current task design in one important aspect. In Experiments 1-3, the target layout on the table consisted of two

intermediate targets, yet only one of these targets was task-relevant in a given block of trials. Thus, actors had to actively remember and select the target that was currently task-relevant and inhibit a response to the other one, which may have implied an additional cognitive cost. In Experiment 4, however, only one intermediate target was present so that the possibility of such additional costs was excluded.

Participants' explicit reports indicate that most of them were not aware that the target size manipulation affected their behavior. Only a single participant reported that she had moved more slowly when the order of her partner's target sizes differed.

3.6 Experiment 5

Experiment 5 aimed to test whether interference from co-representing another's action sequence can also arise at the cognitive level of goal selection. Research on bimanual control has established that bimanual interference during reaching movements is not exclusively related to the specification of motor parameters but may also emerge due to processes related to selecting and specifying target locations (e.g., see Diedrichsen et al., 2006). It has been shown that it is easier to coordinate two hands when the final goal states of the required movements are the same, e.g., when target locations are specified by the same cues (Diedrichsen et al., 2001, 2006; Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Weigelt et al., 2007), when targets share perceptual characteristics such as color (Diedrichsen et al., 2003), or when the instructed final orientation of two manipulated objects is the same (Kunde & Weigelt, 2005). Bimanual costs related to goal-selection can be substantially larger than those related to motor programming (Diedrichsen et al., 2006), and benefits during goal-selection may even cancel out movement-related costs (Diedrichsen et al., 2003; Weigelt et al., 2007).

Based on these findings from the bimanual domain, we predicted that interference might occur when the action sequences performed by two co-actors imply selecting targets with

different perceptual characteristics. To test this prediction, we removed any differences in motor parameters so that co-actors performed two sequential movements of equal movement difficulty. The difficulty of the goal selection process was manipulated by varying the color of the movement targets in the action sequences of the two co-actors. Co-actors either moved to targets of the same color or to targets of different colors, implying same or different goal states. If interference arises due to the difficulty of selecting between different goal states, a slowdown in performance should occur when co-actors move to targets of different colors.

3.6.1 Method

The methods in Experiment 5 were the same as in Experiment 4, with the following exceptions:

Participants. Fourteen women and six men participated in randomly-matched pairs (5 only-female pairs, 1 only-male pair, $M_{age} = 22.6$ years, $SD_{age} = 2.50$ years, range: 19-29).

Apparatus. Intermediate and final markers both had a diameter of 5.4 cm (see Figure 8). This size was chosen to create an ID of 2.9 for both movements, representing the average of the two IDs (2.4 and 3.4) used in the previous experiments. The intermediate and the final markers were yellow and brown, respectively.

Procedure and stimuli. Across blocks, it was varied whether the colors of the intermediate and final target were the same or different for the two participants. Before each block, the experimenter arranged the yellow and brown target markers on the table and the corresponding target configuration was displayed on the instruction screen.

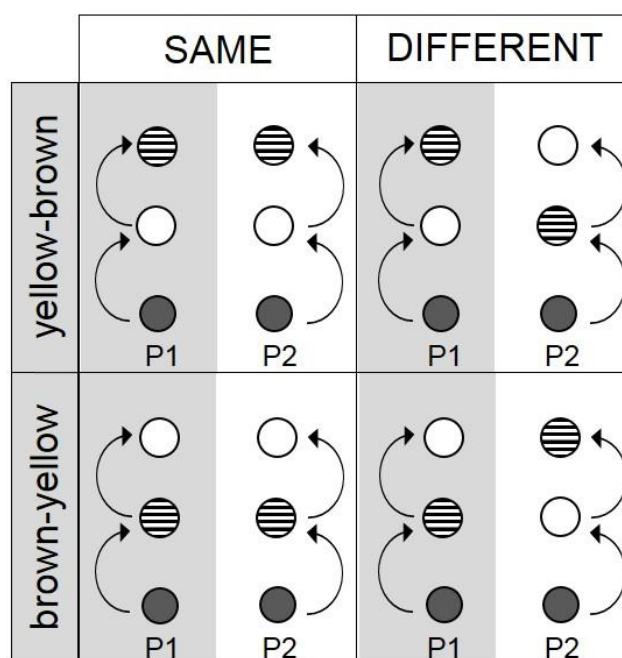


Figure 8. Four types of blocks in Experiment 5. Participants performed sequences of two movements to targets of different colors, in the order ‘yellow-brown’ or ‘brown-yellow’. The two participants in a pair either performed the same sequence or a different sequence.

In blocks of the ‘same order’ condition, the intermediate and final markers in the two columns on the instruction screen were of the same color (Figure 4A, row 4, panel 1). Thus, the two participants both performed a movement to a yellow target followed by a movement to a brown target (‘yellow-brown’) or a movement to a brown target followed by a movement to a yellow target (‘brown-yellow’), see Figure 8. In blocks of the ‘different order’ condition, the intermediate and final markers in the two columns differed in color (Figure 4A, row 4, panel 2). Thus, the two participants performed different action sequences so that one participant performed a movement to a yellow target followed by a movement to a brown target whereas the other participant performed a movement to a brown target followed by a movement to a yellow target (Figure 8).

Before performing the joint task, participants completed two blocks of individual baseline trials. Participants performed one block of yellow-brown sequences and one block of

brown-yellow sequences. At the end of the experiment, participants were asked whether they had noticed any difference in their performance with respect to the order of their own and their partner's target colors.

3.6.2 Results

Prior to analysis, we excluded all trials that failed to meet a minimal horizontal distance criterion (0.2 %). Values exceeding two standard deviations around the mean were excluded (2.3 % for MT, 4.4 % for asynchrony).

MT. Figure 7 displays MTs in the 'same order' and in the 'different order' condition. Participants' MTs were significantly longer when the order of the co-actor's target colors was different ($M = 689$ ms, $SD = 106$ ms) than when it was the same ($M = 674$ ms, $SD = 107$ ms), $t(19) = -4.13$, $p = .001$, *Cohen's d* = -0.92.

Asynchrony. A comparison between asynchronies from the 'same order' and the 'different order' condition revealed no significant differences, $t(9) = -1.34$, $p = .215$, *Cohen's d* = -0.42, indicating that co-actors coordinated their movements equally well regardless of whether the order of target colors was the same ($M = 37$ ms, $SD = 9$ ms) or different ($M = 39$ ms, $SD = 6$ ms).

3.6.3 Discussion

Experiment 5 showed that participants moved more slowly when a co-actor performed movements to targets that differed in color from their own targets. This finding demonstrates that interference from co-representing another's action sequence can also arise at the cognitive level of goal selection. As the action sequences performed by two co-actors did not differ in terms of motor parameters, interference cannot be attributed to difficulties with motor programming but must have emerged due to the difficulty of keeping apart one's own and a co-

actor's action goal states. Similar costs during goal selection have been observed for bimanual performance (Diedrichsen et al., 2003). It is noteworthy that according to the explicit reports, none of the participants in the present experiment was aware that their performance was affected by their partner's target colors.

3.7 Experiment 6

The aim of our final experiment was to disentangle two hypotheses about how co-representing another's action sequence causes interference at the level of goal selection. One possibility is that *unspecific* interference occurs whenever the goal states of two co-actors' individual actions (in an action sequence) differ in their perceptual characteristics. Another possibility is that *specific* interference occurs if task-relevant characteristics overlap between the goal states of two co-actors' individual actions (cf. Diedrichsen et al., 2003, Experiment 3) such as when they produce actions with the same goal states in a different order. Here, interference would arise because a co-represented action sequence specifies the same goal states as one's own action sequence while the order of these states differs.

To test whether interference is specific, we compared a condition where co-actors had two different sets of target colors and moved to targets of different color (no overlap in task-relevant perceptual characteristics) to a condition where co-actors had the same set of target colors and moved to targets of different color (overlap in task-relevant perceptual characteristics, same as the 'different' condition in Experiment 5). If interference is specific, a slowdown in movement times is only expected in the latter but not in the former condition.

3.7.1 Method

The methods in Experiment 6 were the same as in Experiment 5, with the following exceptions:

Participants. Fifteen women and five men participated in randomly-matched pairs (6 only-female pairs, 1 only-male pair, $M_{age} = 21.3$ years, $SD_{age} = 1.73$ years, range: 18-24). Participants were asked whether they could clearly distinguish all target colors and all participants answered this question affirmatively. However, after the experiment one participant reported a strong preference for a specific color combination. This participant and her task partner were replaced by a new pair of participants.

Apparatus. The movement distances and target sizes were identical to Experiment 5, yet the colors of the targets differed. The color of the start marker was grey. The colors of the intermediate and final markers varied between conditions; they could be either yellow, brown, blue, pink, green, or purple (see Figure 9 and below for details).

Procedure and stimuli. The design of Experiment 6 differed from the previous experiments as we did not compare a ‘same order’ to a ‘different order’ condition. Rather, we reran the ‘different order’ condition from Experiment 5 where the order of the two participants’ target colors differed (‘yellow-brown’ vs. ‘brown-yellow’) and compared it to a condition where the two participants’ targets had four entirely different colors. We refer to the former as the ‘2 colors’ condition and to the latter as the ‘4 colors’ condition. Before each block, the experimenter arranged the differently colored markers on the table and the corresponding target configuration was displayed on the instruction screen.

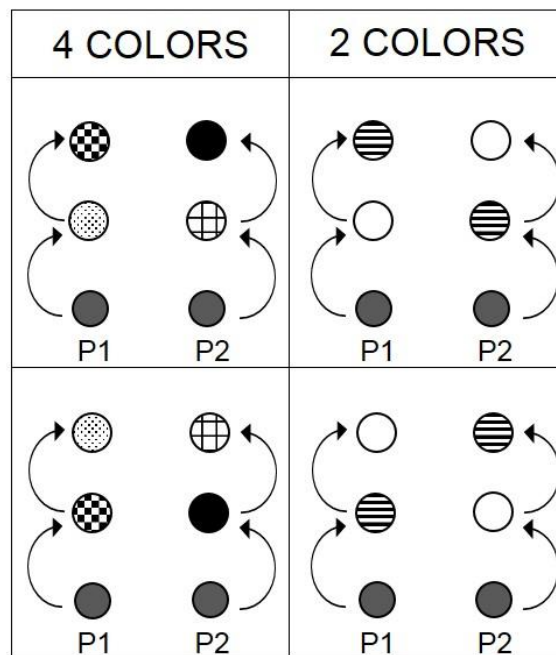


Figure 9. Four types of blocks in Experiment 6. Participants performed sequences of two movements to targets of different colors. In blocks of the ‘4 colors’ condition (left column), the target colors were different for the two participants in a pair such that P1’s colors were pink and blue while P2’s colors were green and purple. In blocks of the ‘2 colors’ condition (right column), the two participants shared the same set of brown and yellow targets but the order in which the colors occurred was different (e.g., P1: brown-yellow, P2: yellow-brown).

In blocks of the ‘4 colors’ condition, Participant 1 performed a movement to a pink target followed by a movement to a blue target whereas Participant 2 performed a movement to a green target followed by a movement to a purple target (P1: pink-blue, P2: green-purple), or Participant 1 performed a movement to a blue target followed by a movement to a pink target while Participant 2 performed a movement to a purple target followed by a movement to a green target (P1: blue-pink, P2: purple-green), see Figure 9. In blocks of the ‘2 colors’ condition, one participant performed a movement to a yellow target followed by a movement to a brown target while the other performed a movement to a brown target followed by a movement to a yellow target (see Figure 9).

Before performing the joint task, participants completed four blocks of individual baseline trials. Participants performed one block of yellow-brown sequences, one block of brown-yellow sequences, one block of pink-blue/green-purple sequences, and one block of blue-pink/purple-green sequences.

3.7.2 Results

Prior to analysis, we excluded all trials that failed to meet a minimal horizontal distance criterion (0.1 %). Values exceeding two standard deviations around the mean were excluded (3.1 % for MT, 3.8 % for asynchrony).

MT. Figure 7 displays MTs in the ‘4 colors’ and in the ‘2 colors’ condition. Participants’ MTs were significantly longer when the co-actor’s movement targets had the same two colors arranged in different order ($M = 614$ ms, $SD = 112$ ms) than when the co-actor’s movement targets had entirely different colors ($M = 605$ ms, $SD = 114$ ms), $t(19) = -3.24$, $p = .004$, *Cohen’s* $d = -0.72$.

We compared the size of the effects in Experiment 5 and 6 by means of a mixed ANOVA with the within-subject factor Co-actor order (same, different) and the between-subject factor Experiment (E5, E6), where the ‘4 colors’ condition was classified as ‘same’ and the ‘2 colors’ condition was classified as ‘different’ for Experiment 6. The analysis showed a significant main effect of Co-actor order, $F(1,38) = 27.54$, $p < .001$, $\eta_p^2 = .420$. The interaction between the factors Co-actor order and Experiment was not significant, $F(1,38) = 1.46$, $p = .235$, $\eta_p^2 = .037$. There was a significant main effect of Experiment, indicating that MTs in Experiment 6 were shorter than in Experiment 5, $F(1,38) = 4.27$, $p = 0.046$, $\eta_p^2 = .101$ ($M_{E5} = 682$ ms; $M_{E6} = 610$ ms).

Asynchrony. A comparison between asynchronies from the ‘2 colors’ and the ‘4 colors’ condition revealed no significant effects, $t(9) = -1.13$, $p = .289$, *Cohen’s* $d = -0.36$, indicating

that co-actors coordinated their movements equally well irrespective of whether they shared the same set of target colors ($M = 44$ ms, $SD = 17$ ms) or not ($M = 46$ ms, $SD = 17$ ms). A comparison between asynchronies from Experiment 5 and 6 showed that co-actors were equally well coordinated in the two experiments, $t(18) = -1.26$, $p = .224$, *Cohen's d* = 0.57 ($M_{\text{AsyncE5}} = 38$ ms; $M_{\text{AsyncE6}} = 45$ ms).

3.7.3 Discussion

The findings of Experiment 6 supported the hypothesis that interference from representing a co-actor's action sequence is specific and occurs only if one's own action sequence and another's action sequence overlap in the perceptual characteristics of action goal states. Movement times were slowed down when co-actors moved to targets that shared the same color set compared to when they moved to targets whose colors were from entirely different color sets.

These results do not fully rule out the theoretical possibility that additional unspecific interference may occur when two co-actors perform action sequences that specify non-overlapping goal states, as in the '4 colors' condition in Experiment 6. However, the comparison of Experiment 5 and 6 provided no indication that the slowdown in movement times in Experiment 6 was smaller than the slowdown in movement times in the same-different comparison of Experiment 5. Thus, it is likely that the interference effect observed in the previous experiments was also caused by specific interference. No interference seems to occur when co-actors perform a sequence of actions with the same goal states ('same condition' in Experiment 5) or with entirely different, non-overlapping goal states ('4 colors' condition in Experiment 6).

3.8 General Discussion

The aim of the present study was to investigate whether co-actors have a tendency to represent each other's action sequences, even if doing so is not necessary for joint task performance. To this end, we designed a novel joint task where two co-actors performed sequences of goal-directed actions. Each sequence consisted of two individual actions that differed in terms of the difficulty of the movements to be performed (Experiments 1-4) or in terms of the perceptual characteristics of the action goal states (Experiments 5-6). Supporting our prediction that co-actors represent each other's action sequences, the results of Experiment 1-5 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.

Importantly, this slowdown cannot be attributed to low-level visuomotor processes (e.g., Kilner et al., 2003; Sacheli et al., 2012) but must be a result of internal representations because it also occurred when co-actors could not observe each other's movements (Experiments 2-6). In line with previous research on co-representation (e.g., Sebanz et al., 2003; van der Wel & Fu, 2015), we found that a joint coordination goal was not a prerequisite for co-actors to represent each other's action sequences as a slowdown was also observed when co-actors did not have the joint goal of synchronizing arrival times at the final location (Experiment 3). In line with findings from research on the coordination of bimanual movements (e.g., Diedrichsen et al., 2006), we found that interference can arise due to differences in the difficulty of the individual movements that two co-actors perform as part of an action sequence (Experiments 1-4) as well as due to differences in the perceptual characteristics of the goal states two co-actors' actions are directed at (Experiments 5-6).

The results of Experiment 6 indicate that interference at the level of goal selection occurs if one's own action sequence and another's action sequence overlap in the perceptual characteristics of goal states. More generally, this suggests that interference due to co-

representing another's action sequence is restricted to situations where co-actors perform the *same* actions in a *different* order and does not occur in situations where co-actors perform entirely different actions.

At present, it remains an open question whether interference in all of our six experiments was caused at the level of representing action goal states. This assumption could explain the differences in movement times observed in Experiments 1-4 because participants may have represented the action sequences as “far target – close target” or “small target – big target” at the level of the individual actions' goal states. Alternatively, interference in Experiments 1-4 may have occurred at the level of specifying motor parameters, as suggested by previous findings on bimanual control (e.g., Heuer, 1993; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998; Spijkers & Heuer, 1995; Spijkers et al., 1997). Manipulating movement difficulty and perceptual characteristics of action goal states within the same experiment may help to answer this question.

It is important to consider potential alternative explanations for the effects observed in the present study. Given that co-actors received visual feedback (Experiment 1) and auditory feedback about each other's actions, they may have unintentionally entrained with one another. Entrainment is a form of emergent coordination based on low-level perception-action links that can be described as a coupling of rhythmic oscillators and is observed in mechanical as well as in biological systems (e.g., Schmidt & Richardson, 2008; Shockley et al., 2003; for a review, see Shockley & Riley, 2015).

Co-actors in the present experiments may have become coupled simply because they could see each other's movements (Experiment 1) or hear each other landing on the targets while performing short or long movements (Experiments 1-3). A temporal coupling would imply that co-actors differentially adjust their movement times to each other such that the actor with the longer distance speeds up her movement and the actor with the shorter distance slows

down her movement, which would have resulted in (uninstructed) synchronous arrival at the intermediate target. As co-actors were instructed to perform their movements as fast as possible, speeding up even further might not have been possible for the actor with the longer distance due to a natural performance limit. Thus, the entrainment hypothesis primarily predicts a slow-down of movement times for the short movements, and potentially a (comparably smaller) speed-up in movement times for the long movements. On the level of the whole action sequence, this would imply an overall increase in movement times, just as observed in the present study. Importantly, according to the entrainment hypothesis, this overall increase should result from an increase in movement times for the short movements.

To determine whether there was any support for the entrainment hypothesis, we examined the origin of the overall increase in movement time. This was done by analyzing the first movement to the intermediate target to see whether actors' movement times increased selectively when they performed a short movement while their co-actor performed a long movement (in Experiments 1-3). We found that the increase in movement times did not vary as a function of the actors' own movement distance. Rather, movement times increased to a similar degree for short and long movements, i.e., actors slowed down whenever a co-actor's movement differed in distance. This suggests that the overall increase in movement times cannot be ascribed to a specific increase in short movements only, as would have been predicted if co-actors had become temporally coupled due to perceptual feedback (cf. Shockley & Riley, 2015).

It is important to note that, in any case, entrainment processes cannot explain the results of Experiments 5 and 6. As co-actors' movement distances in these experiments did not differ, co-actors tended to land on the intermediate target roughly at the same time and hence there were no differential needs to assimilate to one another. Thus, the observed increase in movement times in the last two experiments cannot be attributed to processes of entrainment.

Regarding the effects of representing a co-actor's action order, it is interesting to consider a recent finding by Gambi et al. (2015). Using a joint picture naming task, these authors found that participants took longer to name pictures when they believed that their task partner was also naming pictures (Gambi, Van de Cavey, & Pickering, 2015). Specifically, when participants named two pictures, their naming latencies increased when they believed that their task partner was naming the same pictures in the reverse order. Whereas this result seems to perfectly correspond to the findings of the present study, Gambi and colleagues (2015) found a similar increase in naming latencies when participants believed that their task partner was naming the pictures in the same order. The authors suggest that speakers use their own language production system to represent their task partner's linguistic intention (but not the content of their utterance), such that concurrent language production is slowed down (Gambi et al., 2015). The difference in the results pattern between Gambi and colleagues' study (2015) and the present study indicates that there may be a systematic difference in how task partners represent linguistic sequences and action sequences. Thoroughly investigating such differences in future studies seems worthwhile.

The present findings raise several further questions for future research. One question is whether interference from co-representing another's action sequence occurs exclusively when actions are performed concurrently or whether similar interference occurs when co-actors take turns in performing their actions. A recent study on picture naming (Gambi et al., 2017) found an increase in participants' utterance duration when a co-actor concurrently named a different picture but no effect for consecutive naming. However, Diedrichsen et al. observed interference in a bimanual task in which participants used their left and right hand in alternation (Diedrichsen et al., 2003, Experiment 4) suggesting that interference from co-representing another's action sequence may also occur in tasks where co-actors take turns. A similar prediction could also be

derived from earlier studies on co-representation where participants took turns in performing actions defined by different task rules (Sebanz et al., 2003).

Another interesting question is whether the presence of a co-actor is necessary or whether the belief that another person is acting in another room is sufficient to trigger co-representation of action sequences. Previous research (e.g., Atmaca et al., 2011; Tsai et al., 2008; Vlainic, Liepelt, Colzato, Prinz, & Hommel, 2010) suggests that the mere belief might be sufficient. Follow-ups on the present study could address the question of whether such beliefs have differential effects on the co-representation of action sequences at the level of specifying action goal states and at the level of specifying motor parameters.

Finally, further studies are needed to address the generality of the observed interference from co-representing another's action sequence. Would introducing more extreme differences between co-actors' movement difficulty lead to a proportional increase in interference? Would increasing the number of individual actions in a sequence increase or reduce interference? How do experts at joint action such as dancers and musicians avoid or overcome such interference? Answering these questions could make an important contribution towards advancing our understanding of when and how individuals mind others when jointly performing actions.

Chapter 4. Communicating Hidden Object Properties

4.1 Introduction

Language plays an essential role in our lives because, among other reasons, it has the crucial function of serving as a coordination device (Clark, 1996). When we coordinate our actions with others, verbal communication often facilitates the coordination process, helping us to achieve a joint goal (e.g., Bahrami et al., 2010; Clark & Krych, 2004; Fusaroli et al., 2012; Tylén, Weed, Wallentin, Roepstorff, & Frith, 2010). It has even been argued that it is impossible for people to carry out joint activities without communicating (Clark, 1996). For instance, if two people want to carry a heavy sofa together, they often first talk about who is going to grab which side of the sofa. Of course, communication can also be non-verbal, such as when one person points to one side of the sofa and thereby informs the other where to grab it, and the other nods in agreement.

Such non-verbal gestures as well as spoken language have a primarily communicative function, i.e., they are produced to transmit information to others. However, there are also forms of communication that piggy-back on instrumental actions. By modulating movements that are instrumental for achieving a joint goal, a communicative function can be added on top. For instance, when carrying a sofa together, the person walking forwards may exaggerate a movement to the left when a turn is coming up (see Vesper, Abramova, et al., 2017). Thereby, she not only performs the instrumental action of turning but also the communicative action of informing her partner (who is walking backwards) about the upcoming turn. What makes these types of actions communicative is that actors systematically deviate from the most efficient way of performing the instrumental action, thereby providing additional information that enables observers to predict the actor's goals and intentions (Pezzulo et al., 2013). This, in turn, facilitates interpersonal coordination and the achievement of joint goals.

Thus, “sensorimotor communication” differs from typical verbal or gestural communication in that the channel used for communication is not separated from the instrumental action (Pezzulo et al., 2013). Individuals may resort to sensorimotor communication during online social interactions where the use of language or gesture is not feasible or insufficient (Pezzulo et al., 2013) – because the verbal channel is already occupied, because a joint action requires proceeding at a fast pace that renders verbal communication impossible (Knoblich & Jordan, 2003), or because a message is cumbersome to verbalize but easy to express by a movement modulation.

Until now, experimental studies (Candidi, Curioni, Donnarumma, Sacheli, & Pezzulo, 2015; Sacheli et al., 2013; Vesper & Richardson, 2014) as well as theoretical work (Pezzulo et al., 2013) on sensorimotor communication have almost exclusively focused on joint actions where interaction partners needed to communicate about spatial locations of movement targets (but see Vesper et al., 2016, for an exception). This raises the question of whether sensorimotor communication can more generally help with achieving joint action coordination. As there is no a priori reason to think that the flexibility of sensorimotor communication is limited, it is an open question whether its usage extends beyond the communication of spatial locations.

To address this question, the present study investigated whether sensorimotor communication provides an effective means for communicating non-spatial, hidden object properties that cannot be reliably perceived visually. In particular, our aim was to find out whether and in what way joint action partners succeed in bootstrapping a sensorimotor communication system that enables them to coordinate their actions with respect to a hidden object property, such as when selecting objects that match in weight. If joint action partners succeed, this would provide evidence that the scope of sensorimotor communication extends from conveying information about spatial locations to non-spatial, hidden object properties. The second aim of the present study was to find out whether, when given a choice, joint action

partners are more likely to create sensorimotor communication systems or symbolic communication systems. Testing which communication system people prefer can provide insights into the driving forces behind the emergence of novel communication systems.

4.1.1 Previous research on sensorimotor communication

In most empirical studies on sensorimotor communication, task information in interpersonal coordination tasks was distributed asymmetrically such that one actor had information that the other was lacking. To provide the missing information to their co-actors, informed actors then modulated certain kinematic parameters of their actions, such as movement direction (Pezzulo & Dindo, 2011; Pezzulo et al., 2013), movement amplitude (Sacheli et al., 2013; Vesper & Richardson, 2014), or grip aperture (Candidi et al., 2015; Sacheli et al., 2013), thereby informing their co-actors about an intended goal location. Relatedly, studies with infants have shown that caretakers display similar kinematic modulations (e.g., slow, repetitive, exaggerated movements) to support infants' learning ('motionese'; Brand, Baldwin, & Ashburn, 2002; Koterba & Iverson, 2009; Pitsch, Vollmer, Rohlfing, Fritsch, & Wrede, 2014). Even the mere belief to be interacting with a child instead of an adult influences people's communicative behavior such that they slow down their actions and put more emphasis on crucial communicative elements (Newman-Norlund et al., 2009). In both infants and adults, exaggeration of movement kinematics supports identification and perceptual discrimination of different action alternatives (Pezzulo et al., 2013).

Communication can only be successful if a message is understood by the designated receiver. In particular, the extraordinary human sensitivity to subtle kinematic differences (e.g., Becchio, Sartori, Bulgheroni, & Castiello, 2008; Manera, Becchio, Cavallo, Sartori, & Castiello, 2011; Sartori, Becchio, & Castiello, 2011; Urgesi, Moro, Candidi, & Aglioti, 2006) allows observers to recognize when others' actions deviate from the most efficient trajectory.

To do so, observers rely on their own motor systems to simulate and thereby predict the unfolding of the action and the actor's goal (Aglioti et al., 2008; Casile & Giese, 2006; Cross, Hamilton, & Grafton, 2006; Wilson & Knoblich, 2005; Wolpert et al., 2003). When observing exaggerated actions, the observer's prediction of efficient performance is violated in a way that biases the observer to more easily detect the actor's intended movement goal. Thus, violations from efficiency facilitate the discrimination of the actor's goal while at the same time conveying the actor's communicative intent, thereby simplifying the coordination process (Pezzulo et al., 2013).

Given the previous research, it seems as if the use of sensorimotor communication may be restricted to a narrow domain, i.e., to tasks where co-actors coordinate spatial target locations. One exception is a recent study where joint action partners exaggerated their movement amplitude to facilitate temporal coordination (Vesper et al., 2016). Thus, an important open question is whether sensorimotor communication can go beyond the exchange of spatial and temporal information. Can co-actors use sensorimotor communication to inform each other about properties that they cannot directly perceive? In some joint actions, it may be less relevant to communicate to another person where or when to grasp an object, but it may be more relevant to inform her about a property of the object itself, such as how heavy it is. For example, when one person is handing a moving box over to another person, it is crucial for the latter to know whether the box contains books or pillows, so that she can prepare to lift a heavy or a light weight.

4.1.2 Communicating hidden object properties

The weight of an object is, at least to some extent, a hidden property that cannot be reliably derived from looking at the object – just like other object properties, be it fragility, rigidity or temperature. Even though there are certain cues that help to estimate object weight,

these are not always reliable or can be even misleading. For instance, there are perceptual cues to object weight such as the size of an object (e.g., Buckingham & Goodale, 2010; Gordon, Forssberg, Johansson, & Westling, 1991b) and its material (e.g., Buckingham, Cant, & Goodale, 2009), and there are kinematic cues actors produce while approaching, lifting, or carrying an object (Alaerts, Swinnen, & Wenderoth, 2010; Bingham, 1987; Bosbach, Prinz, & Knoblich, 2005; Grèzes, Frith, & Passingham, 2004 a, b; Hamilton, Joyce, Flanagan, Frith, & Wolpert, 2007; Runeson & Frykholm, 1983; on discrimination of movement kinematics, see also Cavallo, Koul, Ansuini, Capozzi, & Becchio, 2016). However, perceptual cues such as an object's size or material can be misleading (e.g., Buckingham et al., 2009) or uninformative (e.g., for non-transparent objects such as moving boxes). Kinematic cues can be unreliable, or even absent, when objects are light and differ in weight only to a small extent (e.g., Bosbach et al., 2005). Thus, especially when objects do not differ in size or material, when they are relatively light and when their weight differences are small, neither perceptual nor kinematic cues can enable two co-actors to reliably select objects of the same weight.

To investigate the emergence of non-conventional communication about hidden object properties, we therefore chose weight as instance of an object property for which co-actors would need to bootstrap a new communication system. Our question was whether and in what way co-actors would use sensorimotor communication to communicate about weight. Would co-actors rely on systematic modulations of instrumental actions, and if so, which kinematic parameters would they modulate?

Note that communicating about hidden object properties such as weight will necessarily differ from communicating about visually perceivable object properties such as target location. In the previously reported studies, a communicator's subtle deviations from an efficient movement trajectory were directly related to the to-be-communicated property. For instance, in a study where the task-relevant parameter was grasp location, higher movement amplitude

directly implied higher grasp location (e.g., Sacheli et al., 2013). In contrast, hidden properties such as weight do not share this spatial dimension with movement parameters and thus do not directly map onto spatial movement deviations. For instance, reaching for an object with a higher amplitude *does not* in itself imply heavy or light weight. Hence, the present study required creating novel mappings between systematic movement modulations and particular weights without relying on preexisting direct mappings in the motor system. It is an open question whether sensorimotor communication is flexible enough to accommodate these novel mappings.

Provided this flexibility exists, the question emerges whether sensorimotor communication is only one *possible* way of communicating hidden object properties or whether it is also the *preferred* way. Instead of using sensorimotor communication, co-actors might be prone to develop a novel shared symbol system by establishing arbitrary associations between particular symbols and particular instances of a hidden property, akin to natural human language (de Saussure, 1983). Thus, the second aim of the present study was to investigate whether joint action partners generally prefer using sensorimotor communication or symbolic communication for communicating hidden object properties, or whether situational factors affect their preference. To this end, we designed a task allowing for the emergence of either of these two communication systems so that we could test whether the use of sensorimotor communication extends to hidden object properties, and whether the necessity to communicate such object properties favors the emergence of a symbolic, language-like communication system.

4.1.3 Creating non-conventional communication systems

By addressing the emergence of novel communication systems, the present study built on previous work in ‘experimental semiotics’ (Galantucci, 2009; Galantucci, Garrod, & Roberts, 2012) that investigated how communication emerges out of the need to coordinate in

the absence of pre-established communicative conventions. Generally, experimental semiotics explores how novel forms of communication emerge in the laboratory when co-actors cannot rely on conventional forms of communication (de Ruiter et al., 2007; Galantucci, 2005; Garrod, Fay, Lee, Oberlander, & MacLeod, 2007; Healey, Swoboda, Umata, & King, 2007; Misyak, Noguchi, & Chater, 2016; Scott-Phillips et al., 2009). This approach can provide insights into the processes leading to the successful bootstrapping of communication systems (Galantucci et al., 2012). However, instead of analyzing the structure and development of the communication system that would evolve (e.g., Duff et al., 2006; Garrod et al., 2007; Garrod, Fay, Rogers, Walker, & Swoboda, N., 2010; Healey, Swoboda, Umata, & Katagiri, 2002; Healey et al., 2007), our focus in the present study was on investigating which *type* of communication system people would choose to establish.

We designed a coordination task that could be solved only by creating a novel communication system in a situation where participants had nothing but their instrumental movements to communicate. Notably, a few studies in experimental semiotics (de Ruiter et al., 2007; Scott-Phillips et al., 2009) worked with the same constraint, allowing participants to use only their instrumental actions for communication in order to coordinate a meeting point in a virtual environment. However, to our knowledge, the important question of whether and how novel communication systems are established and used to communicate about the hidden properties of objects has not yet been addressed.

In the present study, we explored this question in a series of four experiments. Experiment 1 served to establish that sensorimotor communication extends to hidden properties. Building on this, Experiments 2 and 3 investigated which type of communication system informed participants preferentially choose to establish when given a choice. Experiment 4 asked whether the preference for sensorimotor communication observed in

Experiments 2 and 3 could be reduced by providing symbols that bear an intrinsic relation to the hidden property.

4.2 Experiment 1

In Experiment 1, we asked whether and in what way co-actors would use sensorimotor communication to transmit information about object weight in order to solve a coordination problem. To address this question, we created a task where two co-actors were given the joint goal of establishing a balance on a scale. Each co-actor placed one object on one of the two scale pans. We varied whether only one co-actor (‘asymmetric knowledge’) or both co-actors (‘symmetric knowledge’) received information about the correct object weight beforehand.

In the asymmetric knowledge condition, the informed actor knew the correct object weight and needed to communicate this information to her uninformed co-actor to enable her to choose one out of three objects of different weights to achieve the joint balancing goal. In the symmetric knowledge condition where both co-actors were informed about object weight, no information transmission was required. We predicted that co-actors would not communicate in this condition.

If informed actors engage in sensorimotor communication, they should systematically modulate kinematic parameters of their movements. In contrast to previous studies where co-actors modulated kinematic parameters that directly mapped onto the communicated spatial locations (e.g., Sacheli et al., 2013; Vesper & Richardson, 2014), co-actors in the present study needed to go beyond such direct mappings. Based on the results of a pilot study¹², we predicted that the most likely way to communicate object weight would be to grasp objects of different

¹² In the pilot study (N = 8 pairs), the majority of participants used grasp height (i.e., high vs. low grasps) to disambiguate light vs. heavy weight. The second most preferred communicative signal was the modulation of grasp type (precision vs. power grip), and another strategy was the modulation of movement velocity. Note that the grasp type strategy was only suitable for signaling one of two alternatives (e.g., heavy or light). Thus, this strategy would have been error-prone in our main study because three weights needed to be distinguished.

weights at different heights. Specifically, we predicted that the majority of participants in the present study would choose three clearly distinct grasp heights to refer to the three different object weights. However, the pilot had also indicated that such height-weight mappings are not the only possible way of communicating, as several participants in the pilot had used alternative strategies.

Instead of using sensorimotor communication, co-actors might choose to solely rely on naturally occurring perceptual or kinematic cues to weight to achieve coordination. This is unlikely, however, because there were no visually perceivable differences between the objects used in the present task (same size, same material). Any natural kinematic differences were expected to be minimal because all objects were quite light and differences in weight were small. Nevertheless, to exclude the possibility that co-actors rely on natural kinematic cues, we included an individual non-communicative baseline with a separate participant sample to assess whether any weight-specific kinematic differences occur during individual reach-to-grasp actions.

4.2.1 Method

Participants. We chose a sample size of $N = 12$ (i.e., six pairs) based on the assumption that effect sizes would be quite large because for successful communication participants needed to produce modulations that could be easily identified by their task partner. Only if the communicative signal could be reliably detected despite natural variability (i.e., noise), participants would be able to create an efficient communication system. Accordingly, nine female and three male volunteers participated in randomly-matched pairs in the joint condition (four only-female pairs, one only-male pair, $M_{age} = 22.7$ years, $SD = 2.95$ years, range: 19-29). The two participants in each pair did not know each other prior to the experiment. In the

individual baseline, five female volunteers and one male volunteer participated individually ($M_{age} = 23.7$ years, $SD = 1.80$ years, range: 21-27).

In the joint condition, three participants were left-handed but used their right hand to perform the task. In the individual condition, all participants were right-handed. All participants had normal or corrected-to-normal vision. Participants signed prior informed consent and received monetary compensation. The study was approved by the Hungarian United Ethical Review Committee for Research in Psychology (EPKEB).

Apparatus and stimuli. We used two sets of three tube-like objects (height: 25.7 cm, diameter: 5.2 cm) that were visually indistinguishable. The objects were plain white (Figure 1). They differed in weight such that there was one light (70 g), one medium (170 g), and one heavy object (270 g) in each set.

The experiment was performed using an interactive motion-capture setup (Figure 2). Two participants were standing opposite each other at the two long sides of a table (height: 102 cm, length: 140 cm, width: 45 cm). The table was high enough such that participants could comfortably reach for objects on the table surface. A 24" Asus computer screen (resolution 1920 x 1080 pixels, refresh rate 60 Hz) was located at one short end of the table. The screen was split in half by a cardboard partition (46 cm x 73 cm) such that different displays could be shown to the two participants who could only see one half of the screen, respectively. At each long side of the table, two circular markers (3.2 cm and 6.4 cm diameter) were located on the table surface with a distance of 45 cm between them. The smaller circle served as the 'start position' and the larger circle served as the 'object position'. At the short end of the table opposite to the screen stood a mechanical scale (height: 11.5 cm, length: 26 cm, width: 11.2 cm, distance from object position: ca. 57 cm), see Figure 2.

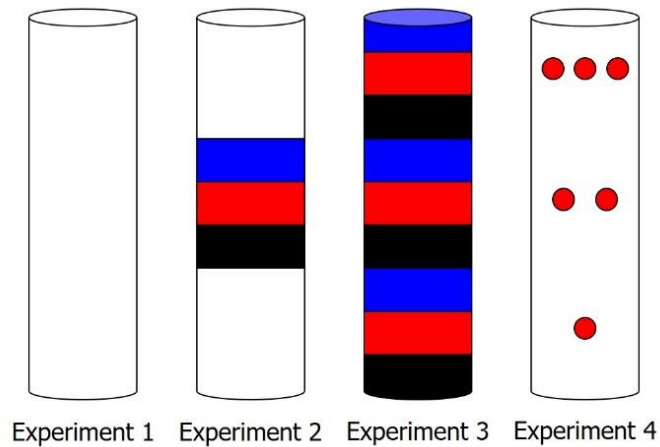


Figure 1. The different object designs that were used in the four experiments. In each experiment, two identical sets of three objects were used, one set for each co-actor. Each object set contained one light, one medium, and one heavy object. The six objects used in each experiment were visually indistinguishable.

On a second lower table (height: 75 cm, length: 35 cm, width: 80 cm) next to the scale, the two sets of objects stood aligned before the start of each trial. These ‘object home positions’ were marked on each of the table’s long sides. The objects were arranged in descending weight, with the heaviest object positioned closest to the participants (distances between the start position and the three object positions: 37/45/53 cm). Next to each object position, there was a marker indicating the object’s weight such that participants could easily identify the objects. This weight information was provided by circles (diameter: 5.5 cm) of three different shades such that the darker the shade, the heavier the object¹³. The same type of information was displayed on the computer screen to inform one or both participants (depending on the condition, see below) about the object weight in the current trial.

¹³ Prior literature suggests that people exhibit intuitive brightness-weight mappings, automatically associating darker shades with heavier objects and brighter shades with lighter objects (Walker, Francis, & Walker, 2010).

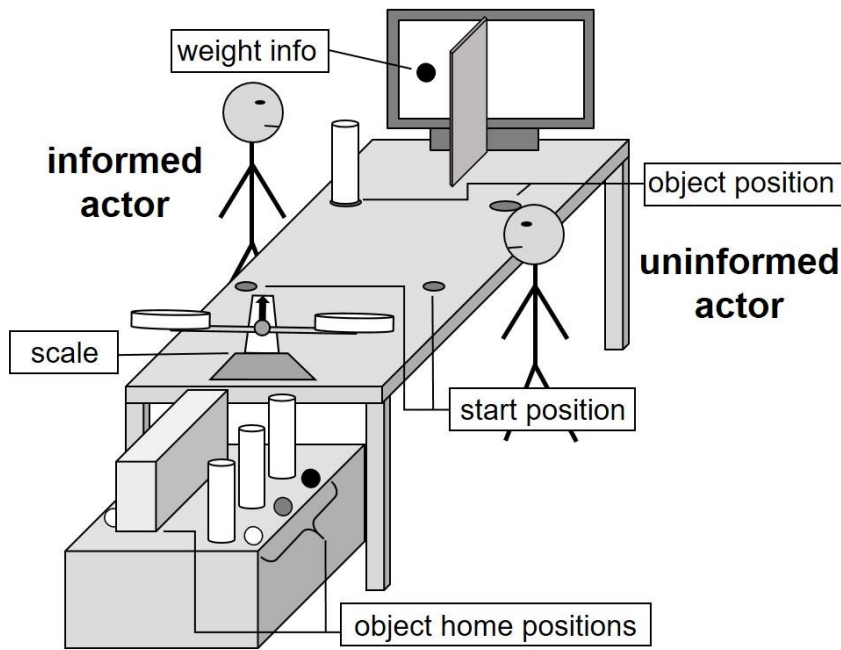


Figure 2. Schematic depiction of the experimental setup, showing a trial from the asymmetric knowledge condition. In this condition, one object was located at the ‘object position’ on the informed participant’s side. This participant knew the weight of the object but her partner did not know the weight. The informed participant performed a reach-to-grasp movement from the start position towards the object and paused with her hand on the object. The uninformed participant’s task was to choose one out of three objects on the home positions that matched the weight of the informed partner’s object. Once the uninformed participant had chosen an object, both participants lifted their objects and synchronously placed them on the scale.

A Polhemus G4 electro-magnetic motion capture system (www.polhemus.com) was used to record participants’ movement data with a constant sampling rate of 120 Hz. Motion capture sensors were attached to the nail of each participant’s right index finger. Experimental procedure and data recording was controlled by a Matlab (2014a) script.

Procedure. Before the start of the experiment, participants were instructed in writing as well as verbally by the experimenter.

Joint condition. The two participants were informed that their task was to place objects on a scale with the joint goal to balance the scale by choosing objects of equal weight.

Participants were informed that there would be three different weights. Each participant placed one object on one of the two scale pans. Participants were instructed to “coordinate and work together” to achieve the joint goal. They were not allowed to talk or gesture. Before the main experiment started, eight practice trials familiarized participants with the procedure.

In the main experiment participants completed two blocks of 36 trials. In half of the trials, information about object weight was provided to both participants (‘symmetric knowledge’) and in the other half of the trials, information was provided to only one of the participants (‘asymmetric knowledge’). In the asymmetric trials, it was varied which of the two participants received information such that participants were informed equally often overall. The order of asymmetric and symmetric trials was randomized. The three different object weights occurred equally often in the two trial types in a randomized order. In total, each weight occurred 12 times in the symmetric and asymmetric knowledge conditions.

Each trial proceeded as follows (see Figure 3): In the beginning of each trial, participants placed their index finger (with the motion sensor attached to it) on the starting position. Then, participants were verbally instructed (through a voice recording) to close their eyes. This was necessary so that participants could not observe the experimenter while she quickly arranged the objects as required for the specific trial. About 3.6 s later, participants were verbally informed who would receive weight information (e.g., “Only Participant 1 receives information.”) and who would start the trial (e.g., “Participant 1 starts.”). About 8 s after onset of the trial information, participants were verbally asked to open their eyes again (“Open!”).

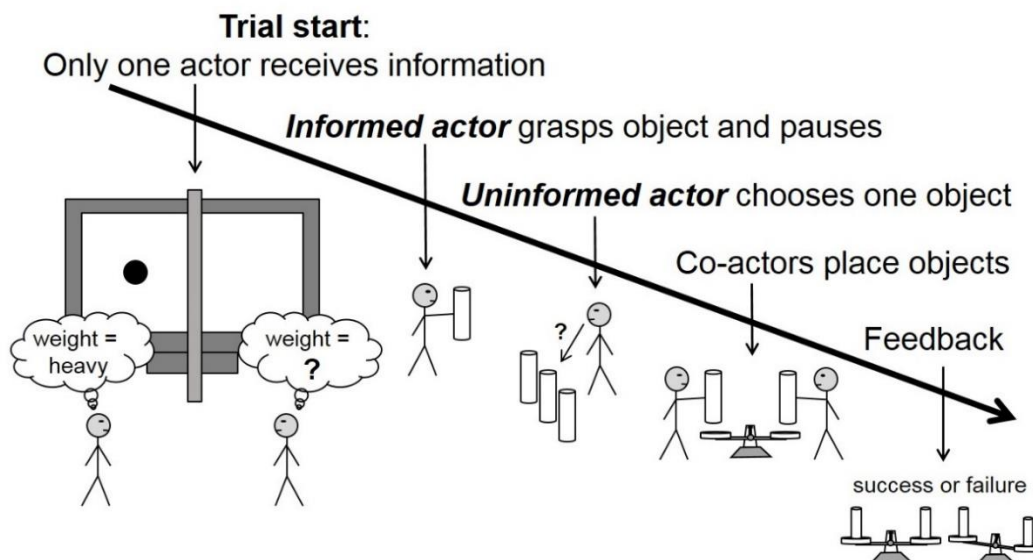


Figure 3. Sequence of events in a trial of the joint asymmetric knowledge condition.

They could now check their side of the computer screen for weight information provided by a light, medium, or dark shaded circle (3.9 cm diameter) indicating a light, medium, or heavy object. In the symmetric knowledge condition this information was displayed on both sides of the screen, in the asymmetric knowledge condition this information was displayed only on the informed participant's side. Participants were given a time window of 3 s to process the information displayed on the screen, then they heard a short tone (440 ms, 100 Hz) that served as the start signal for the participant who initiated the joint action.

In the asymmetric knowledge condition the informed participant performed a reach-to-grasp movement towards the object positioned in front of her and paused with her hand on the object. Once the informed participant had reached the object, a short tone (660 ms, 100 Hz) was triggered to indicate that the uninformed participant could start acting. The uninformed participant's task was to choose one out of three objects of different weights (located on the object home positions) that matched the weight of her partner's object. The second set of objects was covered so that the uninformed participant could not see which object was missing from her partner's object set. After the uninformed participant had chosen one of the objects, both

participants lifted their objects and placed them on the respective side of the scale to receive immediate feedback about their task success. In the symmetric knowledge condition, the participant instructed to initiate the joint action reached for and grasped the object in front of her and a tone was triggered (660 ms, 100 Hz). Then the other participant grasped the object of equal weight positioned in front of her and both participants proceeded to place the objects on the scale that always reached a balance in this condition. At the end of each trial, the experimenter removed the objects from the scale.

After the end of the experiment, participants filled out a questionnaire in which they were asked to explain how they had solved the task (i.e., whether they (and their partner) had followed a specific strategy to inform each other about the object weight).

Individual baseline. Participants were informed that their task was to lift and place objects of three different weights. They were instructed to perform their movements in a natural way. The course of each trial was kept as similar as possible to the joint condition. Participants performed 36 experimental trials (i.e., each weight occurred 12 times). Following the verbal instructions, participants closed their eyes and opened them again (just as in the joint condition, except that there was no further information given in between), then they received the weight information on the screen, heard the starting tone, and reached for and grasped the object located in front of them. After their hand had reached the object, another tone was triggered. Following the tone, participants placed the object on one side of the scale. Before the start of the experiment, participants performed three practice trials to get familiar with the procedure. After the experiment, they were asked whether they had noticed anything about the way they had performed their movements.

Data analysis. Data preparation was conducted in Matlab 2013b. Prior to analysis, all movement data were filtered using a 4th-order two-way low-pass Butterworth filter at a cutoff of 10 Hz. In the joint condition, the analysis of movement data focused on the participant who

performed the first reach-to-grasp movement in a trial. In the individual baseline, all individual movement data from the first reach-to-grasp movement were analyzed.

Statistical analyses were performed using IBM SPSS 22 as well as customized R scripts (2016). Linear mixed models analyses were carried out using ‘lme4’ (Bates, Maechler, Bolker, & Walker, 2014). We used linear mixed effects models to determine whether informed participants modulated their grasp height as a function of object weight. To this end, we first centered all grasping position data for each participant and trial on the mean of the medium weight. We used absolute values because we were interested in systematic differences between grasp heights for different object weights regardless of the specific mapping direction (i.e., higher grasp positions could be mapped to lighter or heavier weights). We then used the medium weight as a reference group and compared it to light weight and to heavy weight. We clustered the data by participant and by pair by modeling random intercepts. We also clustered by weight by including random slopes. In a subset of cases (i.e., 8 out of 16 models), random slopes could not be included because the models failed to converge. We report unstandardized coefficients, which represent the mean differences in grasp height in cm. Significant differences between the grasp heights for medium vs. light weight and for medium vs. heavy weight imply that participants consistently grasped objects of different weights at different heights. Within each experiment, we compared whether the size of the differences in grasp height between heavy and medium weight and between light and medium weight differed as a function of condition (i.e., asymmetric knowledge vs. symmetric knowledge).

In addition, we derived the signed differences in grasp height between adjacent weights to determine whether participants mapped high grasps to light weights and low grasps to heavy weights, or vice versa. We computed one signed difference value per participant by first taking the difference between the mean grasp height values for medium and light objects ($\Delta_{\text{medium-light}}$) and between the mean grasp height values for heavy and medium objects ($\Delta_{\text{heavy-medium}}$), and

then averaging across these two difference values. Positive difference values imply that heavy objects were grasped at higher positions than light objects whereas negative difference values imply the reverse.

Finally, we computed matching accuracy as a measure of joint task performance. Trials in which the two co-actors had achieved a balanced scale by choosing objects of equal weight were classified as ‘matching’ and trials in which the co-actors had chosen objects of different weight were classified as ‘mismatching’. Overall accuracy was calculated as the number of matching trials as a percentage of all trials. This measure was computed only for the asymmetric condition because success was guaranteed in the symmetric condition.

4.2.2 Results

Due to technical recording errors or procedural errors (e.g., participants started a trial too early), 2.3 % of trials in the individual baseline and 6.3 % of trials in the joint condition were excluded from the analysis.

Grasp height. In the joint asymmetric condition, informed participants’ grasp height for the medium weight differed significantly from the grasp height for the light weight ($B = 7.23$, $p < .001$) and from the grasp height for the heavy weight ($B = 7.83$, $p < .001$), see left panel in Figure 4a. There was also a significant difference between the grasp heights for the medium weight and the light weight ($B = 5.55$, $p < .001$) and between the grasp heights for the medium weight and the heavy weight ($B = 6.99$, $p < .001$) in the symmetric condition (see right panel in Figure 4a). This shows that informed actors modulated their grasp height as a function of weight regardless of whether their co-actor was informed about object weight.

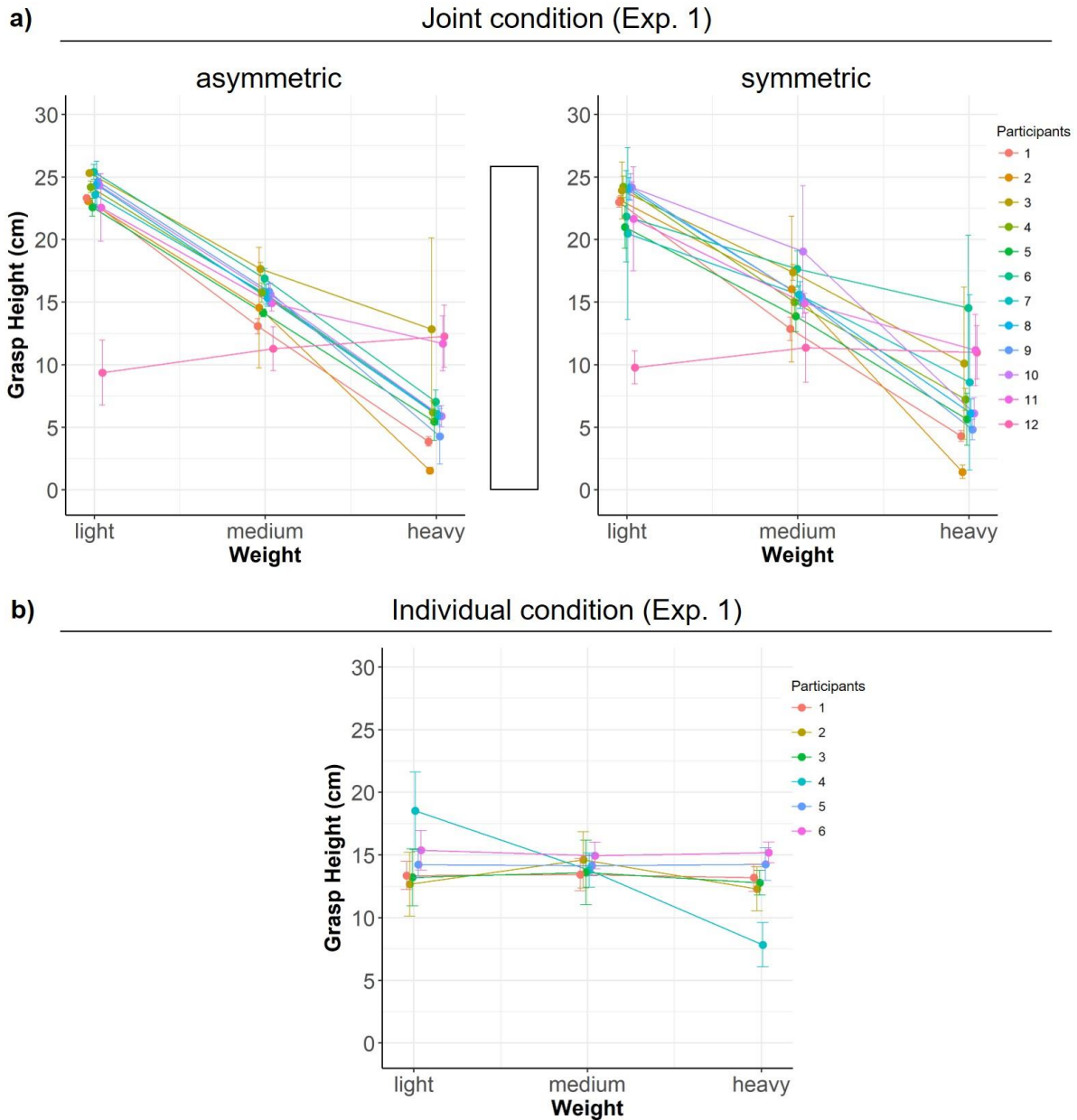


Figure 4. Mean grasp height a) in the joint condition and b) in the individual baseline of Experiment 1 is shown as a function of object weight and participant. In the joint condition, all participants but one consistently grasped light objects at the top, medium objects around the middle, and heavy objects at the bottom. Participants modulated their grasp height as a function of weight regardless of whether their co-actor possessed weight information (symmetric knowledge) or not (asymmetric knowledge). In the individual baseline, participants grasped objects around the same height irrespective of their weight. The object centrally depicted in a) serves as a reference with respect to where participants' grasp positions were located on the object. Error bars show standard deviations.

There was a significant difference between the size of the grasp height differences in the asymmetric and the symmetric condition for the comparison between medium and light weight ($B = 1.60, p = .003$), indicating that the height difference was larger in the asymmetric condition. However, there was no difference between the conditions for the comparison between medium and heavy weight ($B = 0.66, p = .228$).

Participants grasped light objects at the top and heavy objects at the bottom, as suggested by the negative value of the signed difference in grasp height ($M_{asymmetric} = -7.91$; $M_{symmetric} = -7.10$). Figure 4a illustrates that in the joint condition, all participants but one mapped high grasps to light weights.

In the individual baseline, participants grasped all objects at the same height irrespective of their weight (see Figure 4b). Participants' grasp height for the medium weight neither differed significantly from the grasp height for the light weight ($B = 0.92, p = .169$) nor from the grasp height for the heavy weight ($B = 0.81, p = .323$).

Matching accuracy. In the joint asymmetric condition, co-actors achieved an overall accuracy of 91.8 % (Figure 5). This value differed significantly from 33% chance performance ($t(5) = 22.85, p < .001$, Cohen's $d = 9.34$), demonstrating that informed actors successfully communicated information about the object weight to their uninformed co-actors such that these were able to choose an object of equal weight, thereby achieving the joint goal of balancing the scale.

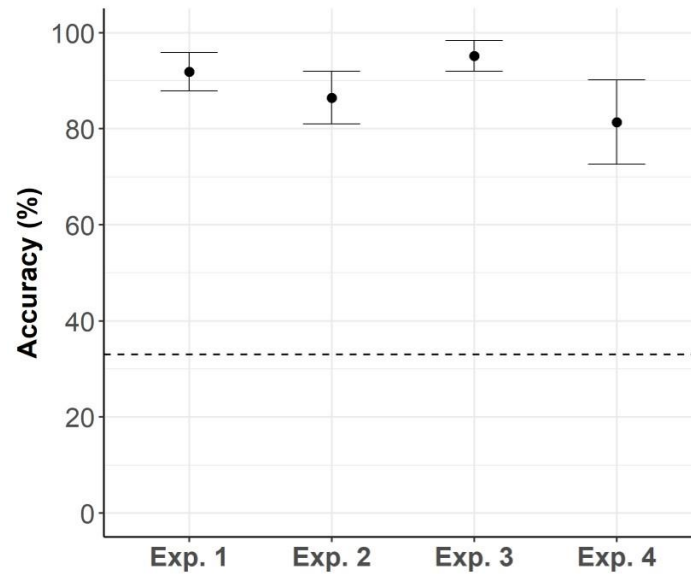


Figure 5. Accuracy in the joint asymmetric condition for Experiments 1-4 as percentage of trials in which co-actors chose objects of equal weight. In all experiments, accuracy was high and significantly above chance performance (33%, dashed horizontal line), with no accuracy differences between any of the experiments. Error bars show Standard Errors.

Verbal reports. Eleven out of twelve participants in the joint condition explicitly reported to have used height-weight mappings. Only one participant reported a different strategy, namely modulating the velocity of her reach-to-grasp movement (by moving faster for light and slower for heavy objects), see participant 12 in Figure 4a. This participant's co-actor reported to have first used her own (height-weight) mapping and to have later adjusted to her partner's velocity modulations.

4.2.3 Discussion

Experiment 1 showed that informed actors transmitted information about object weight to their uninformed co-actors by systematically modulating their instrumental movements, mapping different grasp heights to different weights. This indicates that the scope of sensorimotor communication extends beyond spatial locations to hidden object properties such

as weight. The behavioral findings are in line with participants' verbal reports: All participants but one reported to have used height-weight mappings.

Contrary to our prediction that actors will engage in communication only if the communicated piece of information is relevant for their co-actor (Sperber & Wilson, 1995; Wilson & Sperber, 2004), participants in Experiment 1 consistently transmitted information about the object weight, irrespective of whether their co-actor was informed or not. There may be several reasons for why informed participants engaged in communicative modulations even when their partner was informed as well. First, the persistent use of communication may not have served an informative function but instead may have supported the overall functionality of the emerging communication system. It is likely that once co-actors had managed to establish a communication system, using this system consistently served to confirm its functionality and to acknowledge the joint use of the system to the co-actor, thereby demonstrating the actor's commitment to the joint action (see Michael, Sebanz, & Knoblich, 2015, 2016).

This type of behavior may bear resemblance to “back-channeling” in conversation where listeners use “hmhm”-sounds, nods, or eye contact to signal their understanding to the speaker (Clark & Schaefer, 1989; Schegloff, 1968), thereby making the meaning of the speaker's utterance part of the common ground between interlocutors (Clark, 1996; Clark & Brennan, 1991). Besides serving this coordinative function, back-channeling is also used to show one's attentive and positive attitude towards a speaker and to indicate interest and respect for the speaker's opinion (e.g., Pasupathi, Carstensen, Levenson, & Gottman, 1999). In the present experiment, maintaining the communicative modulations despite their informative redundancy may have served a similar function as back-channeling, with the difference that it was used as an active (rather than responsive) means by the communicator to demonstrate her positive and supportive attitude towards the interaction.

The redundant use of communication may have been especially critical in the very beginning of the interaction when co-actors first needed to invent and establish a communication system. By using communicative modulations when there was mutual knowledge about the weight of a given object, co-actors could rely on this common ground to make manifest the intended meaning of a specific modulation. This way, co-actors could reassure each other that they were on the same page, thereby building up new common ground and establishing a functional communication system.

A further reason for co-actors' redundant use of communication may be that trials in which both co-actors were informed randomly alternated with trials in which one of the co-actors was lacking information. Once co-actors had established a functional communication system, it may have been less costly for them to consistently adhere to the established system instead of spending extra effort to switch back-and-forth between a communicative and a non-communicative mode.

Experiment 1 provided initial evidence that sensorimotor communication can be used to communicate hidden object properties such as weight. In Experiment 2, we proceeded to address our second question of whether sensorimotor communication is only one *possible* way of communicating hidden object properties or whether it may also be the *preferred* way when symbolic means of communication are potentially available.

4.3 Experiment 2

The aim of Experiment 2 was to test which type of novel communication system two co-actors preferentially establish when faced with a coordination challenge that requires transmitting information about hidden object properties. Would they rely on sensorimotor communication, mapping particular movement deviations to particular instances of the hidden

property, or would they rely on symbolic communication, establishing arbitrary mappings between particular symbols and particular instances of the hidden property?

To provide participants with an opportunity for bootstrapping a symbolic communication system, we attached patches of three different colors on each object's surface. The three different colors had no intrinsic relation with the different object weights but provided an opportunity for communicating weight in a symbolic manner by mapping specific colors to specific object weights. We predicted that actors would display this mapping by systematically grasping the object at the location of the respective color patches. However, if sensorimotor communication is preferred over symbolic forms of communication, participants should communicate object weight by systematically grasping objects of different weights at different heights, as observed in Experiment 1.

4.3.1 Method

The method used in Experiment 2 was the same as in Experiment 1, with the following exceptions:

Participants. In the joint condition, seven female and five male volunteers participated in randomly-matched pairs (two only-female pairs, one only-male pair, $M_{age} = 22.9$ years, $SD = 2.69$ years, range: 19-30). In the individual baseline, three female and three male volunteers participated individually ($M_{age} = 23.0$ years, $SD = 1.29$ years, range: 21-25). All participants were right-handed.

Apparatus and stimuli. The objects were white, with three colored stripes (width: ~3 cm) taped horizontally around each object's midsection (i.e., from 8 up to 17 cm), see Figure 1. The three stripes were colored in blue, red, and black, respectively (from top to bottom).

Data analysis. To assess whether participants created stable mappings between colors and object weights, we analyzed whether participants grasped the objects at the different color

patches. As we could not exclude the possibility that participants would use not only the three colors of the patches but also the white spaces of each object, we included a white category into our analysis. For each weight, we computed a rank order of colors depending on the frequency with which a participant touched the four different colors for each object weight. We then applied a sampling-without-replacement procedure mapping the most frequently touched colors to object weights, making sure that each color is only selected once (see Appendix for an exemplification).

This procedure gave us one value (in %) per weight per participant, indicating how often each participant had used the selected color in those trials in which the given weight had occurred. If a perfectly consistent color-weight mapping was applied for all weights in all trials, the three ‘color usage percentages’ should all be significantly above chance level. If no consistent color-weight mapping was applied, these values should not differ from chance. For all three weights, the ‘color usage percentages’ were tested against the chance level of 25 % using one-sample t-tests. A significant difference in all tests implies that participants consistently grasped objects of different weights at different color patches.

4.3.2 Results

Due to technical recording errors or procedural errors, 2.8 % of trials in the individual baseline and 4.2 % of trials in the joint condition were excluded from the analysis.

Grasp height. In the joint asymmetric condition, informed participants’ grasp height for the medium weight differed significantly from the grasp height for the light weight ($B = 4.02$, $p = .034$) and from the grasp height for the heavy weight ($B = 3.84$, $p = .032$), see left panel in Figure 6a. There was also a significant difference between the grasp heights for the medium weight and the light weight ($B = 3.53$, $p < .001$) and between the grasp heights for the medium weight and the heavy weight ($B = 3.67$, $p < .001$) in the symmetric condition (see right panel in

Figure 6a). There was no significant difference between the size of the grasp height differences in the asymmetric and the symmetric condition (medium vs. light: $B = 0.58$, $p = .288$; medium vs. heavy: $B = 0.25$, $p = .648$). As in Experiment 1, these results indicate that informed actors modulated their grasp height as a function of weight, regardless of whether their co-actor possessed weight information or not. Also in line with Experiment 1, light objects were predominantly grasped at the top and heavy objects at the bottom, as suggested by the negative value of the signed difference in grasp height ($M_{asymmetric} = -1.65$; $M_{symmetric} = -1.76$).

Figure 6a illustrates the inter-individual differences between participants in the joint condition. Half of the pairs (i.e., three out of six) mapped specific grasp heights to specific weights. Two of these pairs (participant numbers 1-4) mapped high grasps to light weights, whereas one pair (participant numbers 11-12) used the reverse mapping. The other three pairs did not show any weight-specific differences in grasp height (see section *Verbal reports* below). Interestingly, participant 11 modulated her grasp height only in the asymmetric condition when her partner was uninformed about object weight but not in the symmetric condition when her partner was informed. All other participants who used grasp height differences to communicate weight did so irrespectively of whether their partner was informed or not.

As in Experiment 1, participants' grasp height in the individual baseline did not differ for different weights (see Figure 6c). Grasp height for the medium weight neither differed significantly from the grasp height for the light weight ($B = 0.15$, $p = .243$) nor from the grasp height for the heavy weight ($B = 0.20$, $p = .312$).

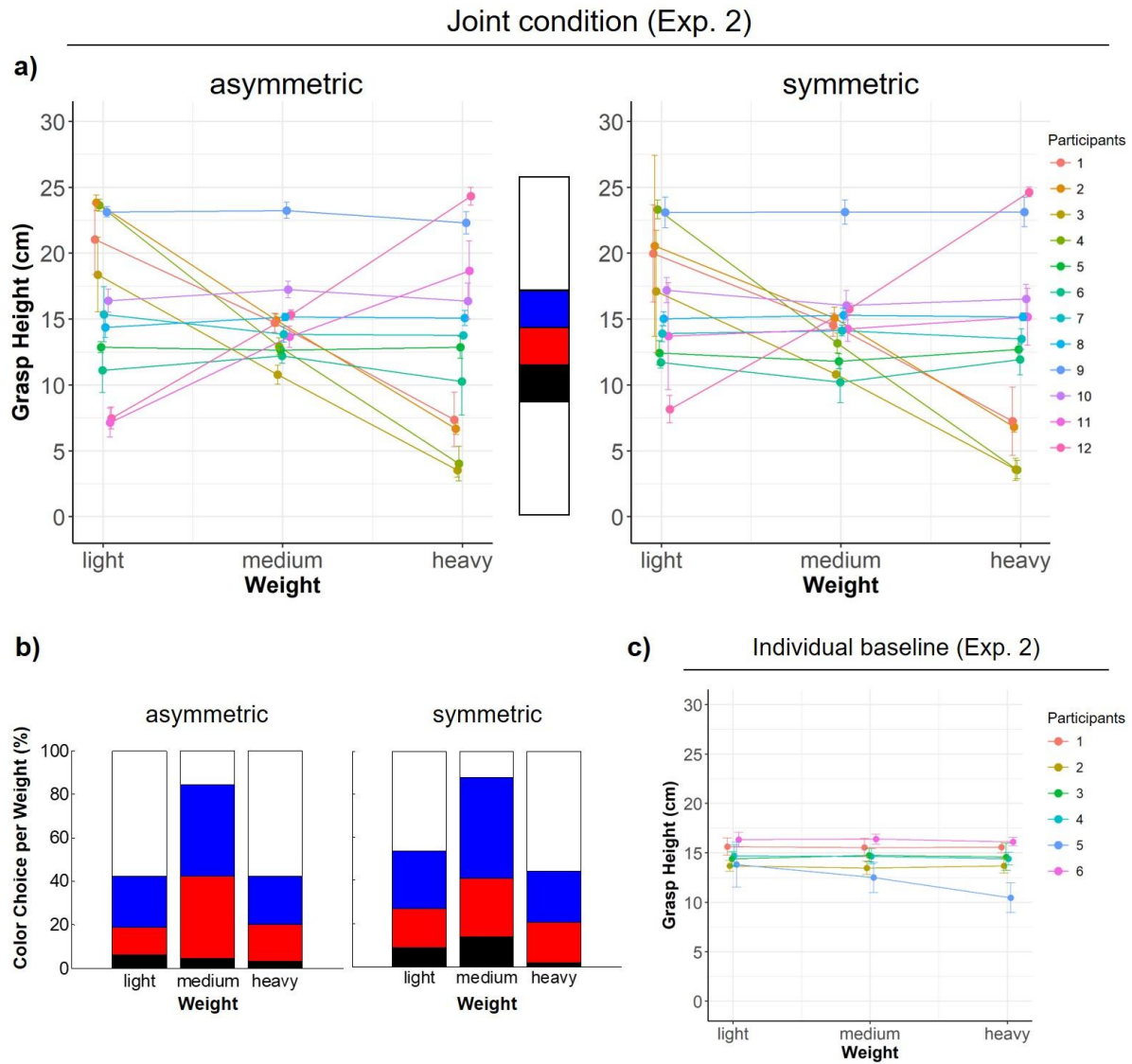


Figure 6. Mean grasp height a) in the joint condition and c) in the individual baseline of Experiment 2 is shown as a function of object weight and participant. In the joint condition, six out of twelve participants systematically modulated the height of their grasp as a function of object weight. Grasp height was not modulated in the individual baseline. The object centrally depicted in a) demonstrates where the three colored stripes were located relative to participants' grasp positions. Error bars show standard deviations. Panel b) shows mean color choice (in % of trials) per weight and condition across participants.

Color choice. For all weights, the 'color usage percentages' were tested against the chance level of 25 % using one-sample t-tests to determine whether participants had

consistently grasped objects of different weights at different color patches (in which case the three ‘color usage percentages’ should all be significantly above chance level). The analysis showed that informed actors in the joint condition did not establish a consistent mapping between the colors and the three object weights (see Figure 6b for descriptive results). In the asymmetric condition, only one out of the three one-sample t-tests for the three weights reached significance, given the Bonferroni-corrected significance level of $p = .008$ accounting for multiple comparisons (light: $t(11) = 1.48$, $p = .166$, Cohen’s $d = 0.43$; medium: $t(11) = 5.77$, $p < .001$, Cohen’s $d = 1.67$; heavy: $t(11) = 1.60$, $p = .137$, Cohen’s $d = 0.46$). The same was true for the symmetric condition (light: $t(11) = 1.27$, $p = .230$, Cohen’s $d = 0.37$; medium: $t(11) = 4.70$, $p = .001$, Cohen’s $d = 1.36$; heavy: $t(11) = 2.03$, $p = .067$, Cohen’s $d = 0.59$). These results imply that only when grasping the medium weight, participants used a particular color with a frequency above chance.

Matching accuracy. Co-actors were successful in reaching the joint goal, as shown by an accuracy of 86.5 % (Figure 5). This value differed significantly from chance performance (33%), $t(5) = 15.71$, $p < .001$, Cohen’s $d = 6.41$.

Verbal reports. Half of the participants (i.e., three out of six pairs) in the joint condition explicitly reported to have used a height-weight mapping to communicate the object weight to their partner (see participant numbers 1-4 and 11-12 in Figure 6a). Two of these pairs mapped high grasps to light objects and low grasps to heavy objects; one pair used the reverse mapping. Two pairs reported to have modulated the velocity of their reach-to-grasp movements to communicate object weight (by moving faster for light and slower for heavy objects), see participants 7-10. One pair modulated the height of the reach-to-grasp trajectory but not the endpoint of the trajectory (i.e., the grasp height at the object), see participants 5-6.

4.3.3 Discussion

Experiment 2 provided first evidence that actors preferred to transmit information about object weight to their co-actors by modulating their instrumental actions rather than by establishing a mapping between particular colors and particular weights. The majority of participants systematically mapped particular grasp heights to particular weights, whereas a minority of participants used alternative strategies such as modulating their movement velocity or the amplitude of their reach-to-grasp movement. Thus, participants seem to have preferred sensorimotor communication, where they communicatively modulated the instrumental action of grasping the object, over symbolic communication that would have involved a systematic grasping of the weight-unrelated color stripes on the objects. The results from the color analysis showed that participants used a particular color with a frequency above chance only when grasping the medium weight. However, using a particular color for just one weight is not sufficient to discriminate between three different weights and thus does not establish an effective communication system. For communication to be efficient and reliable, three consistent color-weight mappings would be required.

These behavioral findings are supported by participants' verbal reports as using height-weight mappings was the most frequently reported strategy.

4.4 Experiment 3

Based on the findings from Experiment 2, one cannot yet conclude that people *generally* prefer to communicate object weight by relying on sensorimotor communication instead of developing a symbolic communication system based on color-weight mappings. In fact, the observed preference may be due to aspects of the task design. Participants may have chosen not to rely on color-weight mappings because the color stripes had been taped adjacently around the objects' midsections, thus requiring quite close attention from observers to discriminate the

color a particular grasp was aimed at. In contrast, using the large-scale grasp height differences may have provided a less ambiguous and more obvious way of communicating.

To determine whether this was the reason that prevented participants from establishing color-weight mappings, we changed the object design in Experiment 3. We attached a multitude of colored stripes (i.e., 3 x 3 different colors) such that the whole object was covered from bottom to top, thereby allowing for a more distinct and large-scale grasping at specific color regions (see Figure 1). In this way, we kept the color design used in Experiment 2 but avoided the potential problem of the stripes' close adjacency.

A further reason for the new design in Experiment 3 was that the new color configuration even allowed for a redundant use of color *and* grasp height, as participants may, for instance, grasp light objects at a 'high red' position and heavy objects at a 'low black' position. If participants disregarded the colors in Experiment 2 because of the proximity of different color patches, then participants in Experiment 3 would be expected to be more likely to (also) use color-weight mappings. If participants have a general preference for sensorimotor communication, then they should again use grasp height and disregard the opportunity to establish color-weight mappings.

4.4.1 Method

The method used in Experiment 3 was the same as in previous experiments, with the following exceptions:

Participants. In the joint condition, six female and six male volunteers participated in randomly-matched pairs (two only-female pairs, two only-male pairs, $M_{age} = 21$ years, $SD = 1.41$ years, range: 18-23). One participant was left-handed but used his right hand to perform the task. In the individual baseline, four female and two male volunteers participated individually ($M_{age} = 23.2$ years, $SD = 1.34$ years, range: 22-25).

Apparatus and stimuli. Nine colored stripes were taped horizontally around each object (stripe width: ~2.9 cm), see Figure 1. Colors alternated in the same way as in Experiment 2, i.e., the stripes were colored in blue, red, and black (from top to bottom), with this alternation repeating three times.

Data analysis. For the color analysis, the ‘color usage percentages’ were tested against the chance level of 33 % (instead of 25 % as in Experiment 2) because there were only three color choices available in Experiment 3.

4.4.2 Results

Due to technical recording errors or procedural errors, 6.9 % of trials in the individual baseline and 6 % of trials in the joint condition were excluded from the analysis.

Grasp height. In the joint asymmetric condition, informed participants’ grasp height for the medium weight differed significantly from the grasp height for the light weight ($B = 7.88$, $p < .001$) and from the grasp height for the heavy weight ($B = 8.51$, $p < .001$), see left panel in Figure 7a. There was also a significant difference between the grasp heights for the medium weight and the light weight ($B = 7.33$, $p < .001$) and between the grasp heights for the medium weight and the heavy weight ($B = 8.00$, $p < .001$) in the symmetric condition (see right panel in Figure 7a). There was no significant difference between the size of the grasp height differences in the asymmetric and the symmetric condition (medium vs. light: $B = 0.52$, $p = .208$; medium vs. heavy: $B = 0.48$, $p = .251$).

Participants on average grasped light objects at the top and heavy objects at the bottom, as suggested by the negative value of the signed difference in grasp height ($M_{asymmetric} = -3.95$; $M_{symmetric} = -3.29$). Figure 7a illustrates that all of the participants in the joint condition mapped specific grasp heights to specific object weights. The majority of four out of six pairs mapped high grasps to light objects; only two pairs used the reverse mapping.

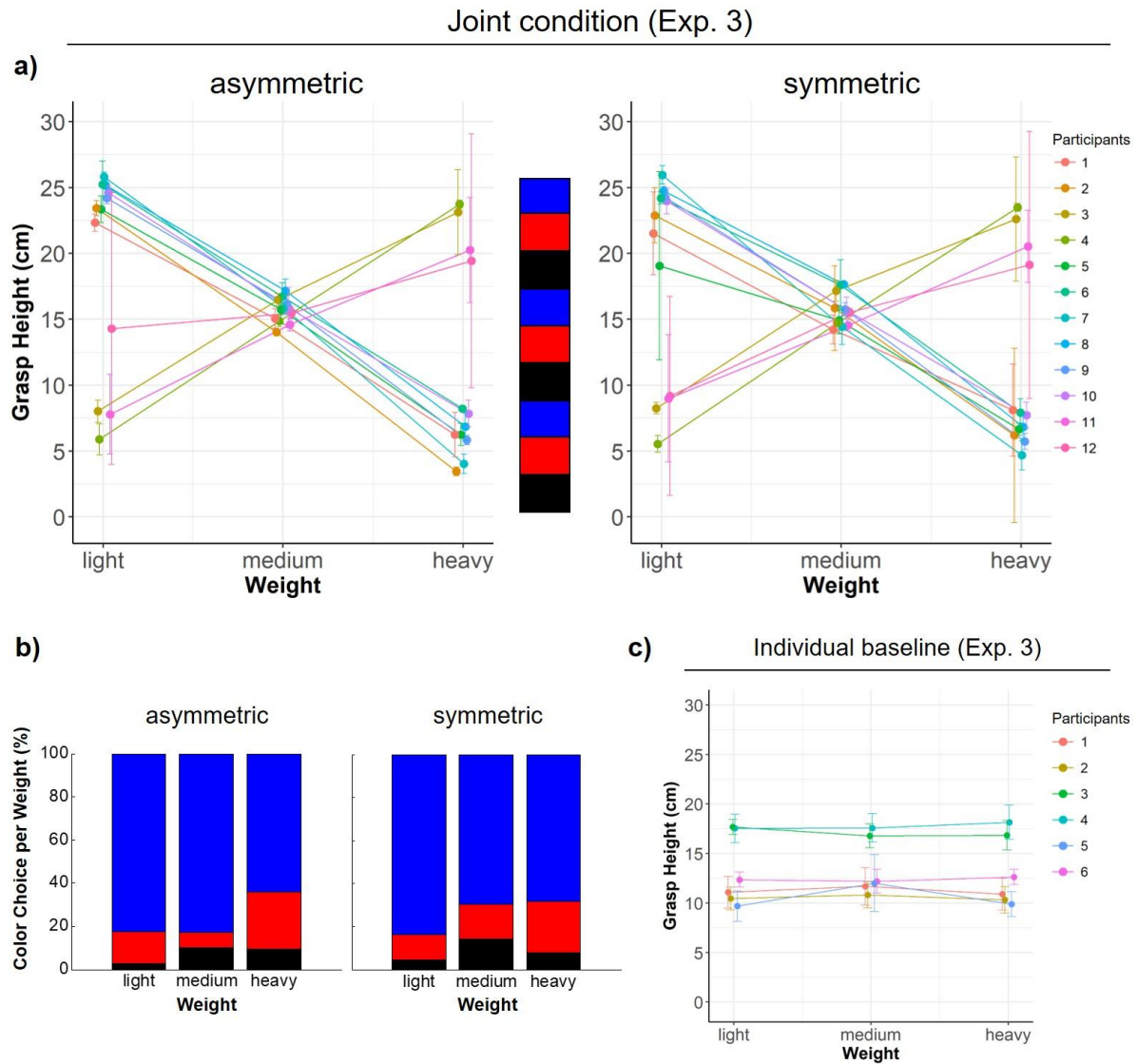


Figure 7. Mean grasp height a) in the joint condition and c) in the individual baseline of Experiment 3 is shown as a function of object weight and participant. In the joint condition, all participants grasped the objects at different heights as a function of their weight. Grasp height was not modulated in the individual baseline. The object centrally depicted in a) demonstrates where the color stripes were located relative to participants' grasp positions. Error bars show standard deviations. Panel b) shows the mean color choice (in % of trials) per weight and condition across participants.

In the individual baseline, participants grasped objects at the same height irrespective of their weight (see Figure 7c). Participants' grasp height for the medium weight neither

differed significantly from the grasp height for the light weight ($B = -0.13$, $p = .369$) nor from the grasp height for the heavy weight ($B = 0.01$, $p = .948$).

Color choice. The analysis of color choice showed no consistent mappings between colors and object weights, neither in the asymmetric nor in the symmetric condition (see Figure 7c for descriptive results). In both conditions, none of the three one-sample t-tests for the three weights reached significance, given the Bonferroni-corrected significance level of $p = .008$ accounting for multiple comparisons (asymmetric: light: $t(11) = 1.56$, $p = .148$, Cohen's $d = 0.49$; medium: $t(11) = 2.05$, $p = .065$, Cohen's $d = 0.59$; heavy: $t(11) = 0.28$, $p = .788$, Cohen's $d = 0.08$; symmetric: light: $t(11) = 1.16$, $p = .272$, Cohen's $d = 0.33$; medium: $t(11) = 0.68$, $p = .508$, Cohen's $d = 0.20$; heavy: $t(11) = 2.69$, $p = .021$, Cohen's $d = 0.78$).

Matching accuracy. Co-actors were successful in reaching the joint goal, as shown by an accuracy of 95.2 % which differed significantly from 33% chance performance, $t(5) = 29.77$, $p < .001$, Cohen's $d = 12.16$ (Figure 5).

Verbal reports. All of the participants in the joint condition explicitly reported to have used a height-weight mapping to communicate the object weight to their partner. Four pairs mapped high grasps to light objects and low grasps to heavy objects; only two pairs used the reverse mapping.

4.4.3 Discussion

Experiment 3 corroborated the findings from Experiment 2, showing that co-actors systematically modulated their grasp height to communicate object weight. As in Experiment 2, sensorimotor communication was preferred over symbolic color-weight mappings. Thus, it is unlikely that participants' disregard of color had been caused by the specific color arrangement in Experiment 2. These behavioral findings are in line with participants' verbal

reports as all participants in the joint condition reported to have used a height-weight mapping to communicate the object weight to their partner.

Notably, the reason why participants in Experiment 3 predominantly grasped the objects at positions colored in blue (see Figure 7b) is that the blue color stripes coincided with convenient positions for low, medium, and high grasps (see Figure 7a). Thus, participants who used a height-weight mapping coincidentally touched the blue color stripes. This does not indicate a color-coding, however, as they touched the blue color irrespective of object weight.

4.5 Experiment 4

Experiments 1 to 3 consistently showed that co-actors choose to communicate the hidden object property weight by systematically modulating their instrumental movements, even when given the choice of creating a communication system based on color-weight mappings. Based on this finding, we asked whether the reason co-actors preferred sensorimotor communication was that color does not bear any intrinsic relation to weight. Any color-weight mappings would have been arbitrary and would have required participants to establish a mapping by trial and error, relying on feedback about whether or not the intended meaning and the interpretation of a symbol were correctly matched. It is therefore possible that if the relation between weight and the available symbols is non-arbitrary, the preference for sensorimotor communication may be reduced.

To test this prediction, in Experiment 4, we used magnitude-related symbols that bear a natural association with weight (small magnitude – light weight, large magnitude – heavy weight). Previous research has shown that there is a general magnitude system in the human brain that processes size-related information from different cognitive and sensorimotor domains (Walsh, 2003). Moreover, it has been proposed that the ability for numerical processing is based on the ability to perceive size (Henik, Glikzman, Kallai, & Leibovich, 2017). Relatedly, an

expectation for larger objects to have larger weights has been indirectly demonstrated by the size-weight illusion (Charpentier, 1891; Ernst, 2009; Flanagan & Beltzner, 2000) which shows that the smaller of two equally-weighted objects is perceived as heavier.

Based on these previous findings, one can expect that people should easily map numerical symbols to weights since large numbers are naturally associated with larger sizes, and in turn with heavier weights. In Experiment 4, we made use of this pre-established magnitude-related association between numerosity and weight in order to test whether co-actors' preference for sensorimotor communication (as observed in the previous experiments) can be shifted to a preference for symbolic communication when the available symbols bear an intrinsic relation to the hidden object property.

To that end, we attached numerosity cues (i.e., 1-3 small dots) on the objects in a way that allowed us to distinguish between the previously used modulations of grasp height and modulations that targeted the numerosity cues. As the majority of participants in Experiments 1-3 had grasped heavy objects at the bottom and light objects at the top, we attached the dots in the reverse order such that three dots (that should be associated with 'heavy') were attached at the top and one dot (associated with 'light') was attached at the bottom of the objects (see Figure 1). If participants in Experiment 4 created mappings between the numerosity cues and the object weights, they would grasp heavy objects at the top and light objects at the bottom. Conversely, if participants disregarded the numerosity cues and continued to use the same grasp height modulations as in the previous experiments, they would grasp heavy objects at the bottom and light objects at the top.

4.5.1 Method

The method used in Experiment 4 was the same as in the previous experiments, with the following exceptions:

Participants. Ten female and two male volunteers participated in randomly-matched pairs (four only-female pairs, $M_{age} = 22.8$ years, $SD = 2.51$ years, range: 19-26). Two pair members had met before (both were students at the same university).

Apparatus and stimuli. The objects used in Experiment 4 were white as in Experiment 1 (Figure 1). Red dots (diameter: 1 cm) were attached to each object in the following way: One dot was located at a height of 5 cm, two dots were located at a height of 13.5 cm, and three dots were located at a height of 22 cm. The same arrangement of dots was attached on the two opposite sides of each object such that they could be seen from all angles.

Procedure. Experiment 4 consisted only of a joint condition. An individual baseline was not deemed necessary because the individual baselines of the three previous experiments had all yielded very consistent data, suggesting that people do not grasp objects in a weight-specific manner when acting individually.

Data analysis. In contrast to the previous three experiments, we used the signed instead of the absolute differences in grasp height as our main parameter in Experiment 4 because we now tested a directional hypothesis. We predicted that participants would grasp heavy objects at the top and light objects at the bottom and not vice versa as in the previous experiments. Positive difference values imply that heavy objects are grasped at higher positions than light objects whereas negative difference values imply the reverse.

We applied the same sampling without replacement procedure as used to analyze participants' choice of color in Experiments 2 and 3, except that we now computed the choice of numerosity cue. To this end, we divided the object into three sections, such that a grasp location in a particular section counted as choice of the particular numerosity cue located within this section. Specifically, the object was divided at the heights of 9.75 cm and of 18.25 cm, such that there were 3.75 cm between these division lines and the adjacent numerosity cue, as the dots were attached at 5, 13.5, and 22 cm, respectively, and had a diameter of 1 cm.

As our prediction in Experiment 4 depended on the observation that participants in the previous experiments mostly used a height-weight mapping in which heavy was coded as a low grasp and light as a high grasp, we tested whether in Experiment 4, participants would be significantly less likely to use this mapping direction. Such a finding would indicate that they made use of the numerosity cues instead of the height-weight mapping. Thus, to test whether participants in Experiment 4 used the same or the reverse mapping, we compared the frequencies of participants' preferred mapping direction (i.e., whether they preferred to map a high grasp location to a light or a heavy weight) between Experiment 4 and Experiment 1. The only difference between the objects used in these two experiments were the numerosity cues attached to the objects' surfaces in Experiment 4. Only participants who used height-weight mappings were included in this analysis because the data from participants who used a different system was lacking the relevant direction values. Fisher's exact test was used to determine whether there was a significant difference between participants from Experiment 4 and Experiment 1 in the mapping direction they preferred.

4.5.2 Results

Due to technical recording errors or procedural errors, 7.9 % of trials were excluded from the analysis.

Grasp height. Consistent with previous findings, informed participants adjusted their grasp height to the weight of the grasped object. In contrast to previous findings, most participants grasped heavy objects at higher positions than light objects, as indicated by the positive difference values ($M_{asymmetric} = 3.13$; $M_{symmetric} = 2.29$), see Figure 8a. Participants' grasp height for the medium weight differed significantly from the grasp height for the light weight ($B = -3.33$, $p < .001$) and from the grasp height for the heavy weight ($B = 2.91$, $p = .003$) in the asymmetric condition (see left panel in Figure 8a). There was also a significant difference

between the grasp heights for the medium weight and the light weight ($B = -2.65, p = .008$) and between the grasp heights for the medium weight and the heavy weight ($B = 2.08, p = .039$) in the symmetric condition (see right panel in Figure 8a).

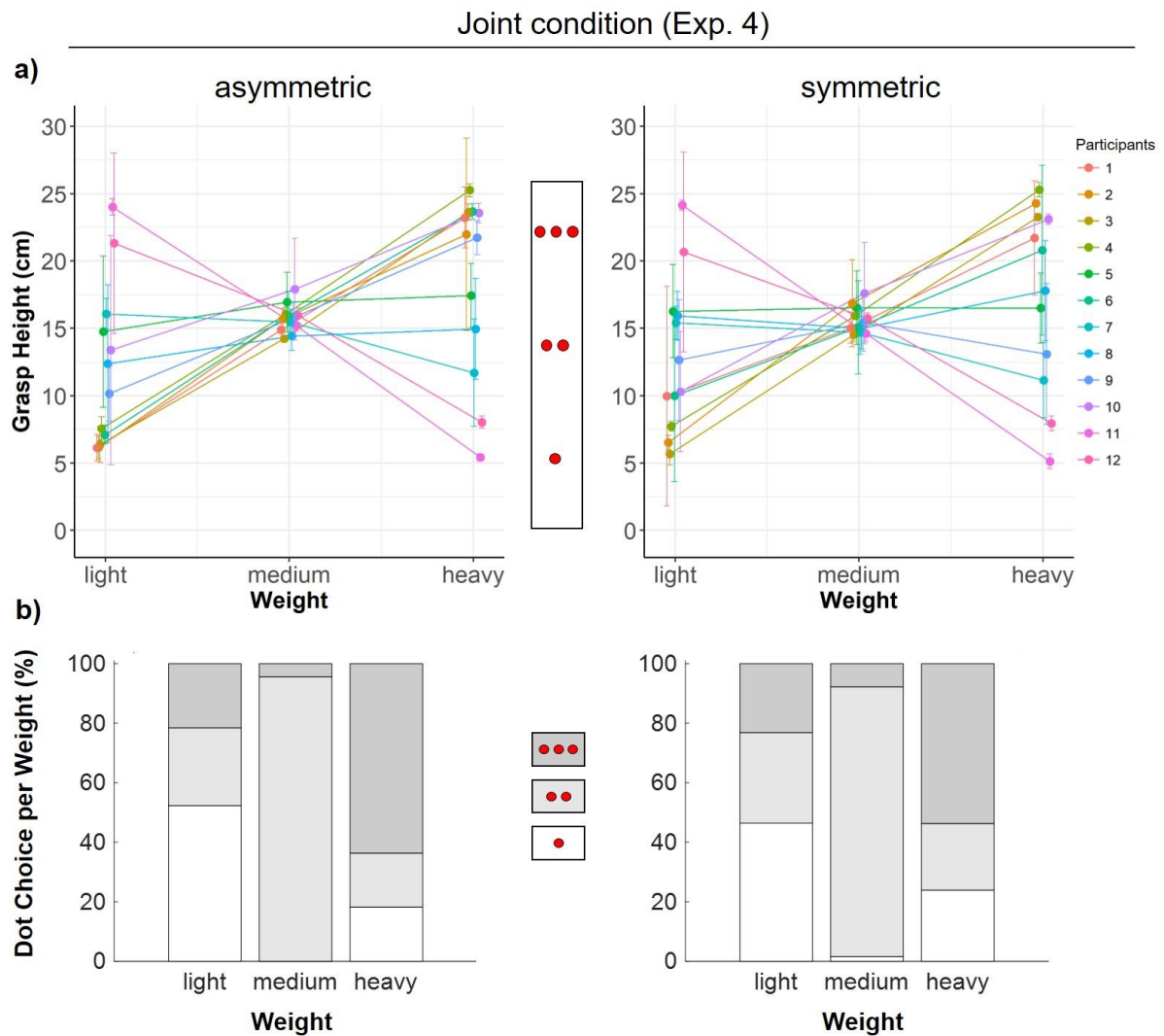


Figure 8. Mean grasp height in Experiment 4 is shown as a function of object weight and participant. Seven out of twelve participants chose grasp positions indicating a numerosity-weight mapping: they grasped light objects at the bottom where one dot was attached, medium objects around the middle (two dots), and heavy objects at the top (three dots). The object centrally depicted in a) demonstrates where the numerosity cues were located relative to participants' grasp positions. Error bars show standard deviations. Panel b) shows the mean choice of dots (in % of trials) per weight and condition across participants. Dark grey represents three dots, medium grey represents two dots, and white represents one dot.

As in previous experiments, there was no significant difference between the size of the grasp height differences in the asymmetric and the symmetric condition (medium vs. light: $B = 0.73$, $p = .194$; medium vs. heavy: $B = 0.69$, $p = .220$), indicating that participants consistently used communicative signals independent of their co-actor's knowledge state.

Numerosity choice. The analysis of numerosity choice showed that participants used consistent mappings between different numerosity cues and object weights (see Figure 8b for descriptive results). In both the asymmetric and the symmetric condition, the three one-sample t-tests for the three weights reached significance, given the Bonferroni-corrected significance level of $p = .008$ accounting for multiple comparisons (asymmetric: light: $t(11) = 4.56$, $p = .001$, Cohen's $d = 1.30$; medium: $t(11) = 6.21$, $p < .001$, Cohen's $d = 1.80$; heavy: $t(11) = 5.09$, $p < .001$, Cohen's $d = 1.45$; symmetric: light: $t(11) = 3.93$, $p = .002$, Cohen's $d = 1.15$; medium: $t(11) = 5.87$, $p < .001$, Cohen's $d = 1.69$; heavy: $t(11) = 3.94$, $p = .002$, Cohen's $d = 1.14$). These results imply that participants consistently placed their grasps onto one specific numerosity section for one specific weight with a frequency above chance level.

Direction of height-weight mapping. In Experiment 4, only 2 out of 9 participants preferred to map high grasp locations onto light weights, whereas in Experiment 1, 11 out of 11 participants preferred this mapping direction. This difference was statistically significant ($p < .001$, Fisher's exact test). This result suggests that participants in Experiment 4 preferred the reverse mapping direction than participants in Experiment 1. Whereas in Experiment 1, participants mapped the height of their grasps to the weights of the grasped objects, in Experiment 4 it was not the grasp height that was mapped to weight but the numerosity cues attached at a certain height. Participants grasped light objects at the bottom where one dot was attached, medium objects around the middle (two dots), and heavy objects at the top (three dots), see Figure 8a.

Matching accuracy. Co-actors in Experiment 4 achieved an accuracy of 81.4 % (Figure 5). This value differed significantly from 33% chance performance, $t(5) = 9.21$, $p < .001$, Cohen's $d = 3.76$.

Verbal reports. Out of the seven participants who showed the predicted height-weight mapping (i.e., participants 1-4, 6, 9-10; see Figure 8a), five participants explicitly reported that they mapped the number of dots to the object weight (i.e., 1 dots = light, 2 dots = medium, 3 dots = heavy) by grasping the object at the position where the respective number of dots was attached. They used this mapping strategically to communicate the object weight to their partner. The two other participants reported that they mapped object height to object weight, without mentioning the dots explicitly. Participant 9 only modulated her grasp height in the asymmetric condition but not in the symmetric condition. Participant 5 also reported to have used a height-weight mapping, yet she developed this strategy only very late in the experiment such that her mean grasp height values do not reflect any differences (see Figure 8a). The two pairs who did not apply the predicted mapping (see participants 11&12 and 7&8 in Figure 8a) reported to have used a height-weight mapping (i.e., the same as observed in previous experiments) and to have modulated movement velocity to indicate object weight, respectively.

4.5.3 Discussion

The results of Experiment 4 provided tentative evidence for our hypothesis that co-actors choose to establish a symbolic communication system by mapping specific symbols to specific object weights if these mappings are not completely arbitrary but rely on natural associations. In particular, there are intrinsic relations between magnitude concepts such as numerosity, size, and weight (e.g., Charpentier, 1891; Henik et al., 2017) that participants in the current experiment exploited to establish a reliable and consistent communication system. For most of the participants, this numerosity-based symbol system overruled the preference for

a height-weight mapping that we had observed in the previous experiments. Participants' verbal reports support these behavioral results as using the dots in a way that associated 3 dots with heavy, 2 dots with medium and 1 dot with light was the most frequently reported communication strategy.

Future research may investigate whether the numerosity-based communication system in the present task was driven by perceptual common ground or by conceptual common ground (see Clark, 1996). This could be done by testing whether co-actors would also rely on the numerosity cues if their objects had different cue configurations, e.g., such that the dots on one actor's object set were attached in the order 3-2-1 from top to bottom whereas the dots on the co-actor's object set were attached in the order 1-3-2. If the usage of the numerosity system was predominantly driven by perceptual common ground, then co-actors might not rely on numerosity if the numerosity configurations differ perceptually. However, if the usage of the numerosity system was driven by conceptual common ground, then co-actors should again rely on this system, mapping different magnitudes to different weights.

4.6 General Discussion

The aim of the present study was to investigate how co-actors involved in a joint action communicate hidden object properties without relying on pre-established communicative conventions in language or gesture. We hypothesized that they would either use sensorimotor communication by systematically modulating their instrumental movements or that they would communicate in a symbolic manner. Given that most previous research on sensorimotor communication focused on the communication of spatial location, our study addressed the important question of whether the scope of sensorimotor communication can be extended to accommodate the need to create mappings with hidden object properties, and if so, whether this way of communicating is preferred over using symbolic forms of communication. To

investigate whether people generally prefer one or the other of these two types of communication systems, or whether situational factors affect their preference, we designed a task that would allow for the emergence of either of the two systems.

The task for two co-actors was to establish a balance on a scale by selecting two objects of equal weight. One actor possessed weight information whereas her uninformed co-actor needed to choose one out of three visually indistinguishable objects that differed in weight, trying to match the weight of her partner's object. The results from Experiments 1-3 consistently showed that informed actors transmitted weight information to their uninformed co-actors by systematically modulating their instrumental actions, grasping objects of different weights at different heights. Whereas participants in Experiments 2-3 preferred sensorimotor communication even if they had the opportunity to create arbitrary mappings between specific colors and specific weights, Experiment 4 showed that introducing symbols that bear an intrinsic relation to weight resulted in a preference switch. The majority of participants now preferred a non-arbitrary mapping between numerosity cues and object weights over the previously used grasp height modulations. Across all four experiments, participants managed to create functional communication systems, as indicated by high accuracy values.

Contrary to our predictions that co-actors would only communicate if it was crucial to achieve the joint goal of balancing the scale, participants engaged in communication even if their co-actor did not need the transmitted information. Rather than serving an informative purpose, this persistent use of communication may have served to maintain the overall functionality of the emerging communication system. Co-actors consistently adhered to the common ground they had established (see Clark & Brennan, 1991), thereby acknowledging and confirming their commitment to the joint action (see Michael et al., 2015). Moreover, we observed during data collection that when both co-actors were informed about object weight, the co-actor who acted second often grasped her object at the same height as the co-actor who

acted first. Since this copying did not have any informative function, we suggest that participants in the role of the addressee might have adhered to the use of the communicative signals in order to acknowledge that they understand the meaning of these signals and to confirm that the shared usage of these signals is part of the co-actors' common ground (see Clark & Brennan, 1991, on "grounding" in communication).

The present findings go beyond the typically investigated cases of sensorimotor communication where communicative deviations directly map onto the to-be-communicated spatial properties (e.g., a higher movement amplitude implies a higher grasp location) and provide first evidence that sensorimotor communication can accommodate mappings between movement modulations and non-spatial properties which must be created *de novo*. Furthermore, whereas typical cases of sensorimotor communication need not necessarily involve conscious processes (Pezzulo et al., 2013), creating the mappings in the present task required a more strategic, most likely conscious, intention to communicate.

An important question arising from the present findings is whether using differences in grasp height is a communicative strategy specific to weight or whether the same strategy could also be applied to other hidden object properties such as fragility or rigidity. A small survey we conducted post-hoc with a new participant sample ($N = 24$) suggested that this strategy might be weight-specific: When asked where they would spontaneously grasp objects of different weights, the majority of participants replied that they would grasp light objects at the top (18 out of 24) and heavy objects at the bottom (19 out of 24). When asked about where they would grasp objects of different rigidity (soft vs. hard) or fragility (breakable vs. unbreakable), no similar consistent pattern of responses emerged.

Thus, people's explicit associations seem consistent with the sensorimotor signals used by participants in the present study who most often communicated 'light' by grasping objects at the top and 'heavy' by grasping objects at the bottom. Together, these findings suggest that

grasp height as a signal for weight was not chosen at random (or due to a lack of alternative options) but because people have clear associations between object weight and grasp height. However, the fact that people have these clear associations points to an interesting discrepancy: Whereas people consistently matched light to high grasp positions and heavy to low grasp positions when asked explicitly, these associations were not reflected in people's individual grasping behavior, as demonstrated by the individual baseline data obtained in the present study.

What is the reason for this mismatch between people's explicit statements and their motor behavior? It is possible that grasp height differences in the individual baselines were absent because the weights of the three objects used in the present study did not differ much. Grasp height differences in behavior might only emerge for sufficiently large differences in weight. To address this possibility, we collected additional data for two objects that strongly differed in weight (70 g vs. 1510 g). We asked a new group of individual participants ($N = 6$) to repeatedly grasp these objects in a randomized order. No weight-specific differences in participants' grasp height were found (see data supplement in Appendix).

However, even though there was no evidence for weight-specific grasping differences in the data obtained in the present task, it is still possible that people's explicit associations are based on certain weight-specific action affordances. For instance, grasping heavy objects around the bottom might improve motor control, affording a more stable grasp and preventing the object from tilting. Such affordance-based grasping preferences might be object- or task-specific such that they emerge only in familiar task contexts, e.g., when people interact with everyday objects such as water bottles or moving boxes.

The question where people's associations in the present study came from points to another, broader question: What can serve as a basis for bootstrapping novel communication systems in the absence of pre-established communicative conventions? In the case of

sensorimotor communication, it is possible that action affordances may serve as a basis for creating communicative mappings, as pointed out above. An alternative possibility is that people could rely on naturally occurring regularities in their physical and cultural environment for creating these mappings. Previous research has demonstrated that people exhibit consistent associations between stimuli features from different sensory modalities, e.g., they consistently associate high-pitched sounds with small, bright, and sharp-edged objects (e.g., Hubbard, 1996; Marks, 1987, 1989; see also Deroy & Spence, 2016). These ‘crossmodal correspondences’ (for a comprehensive review, see Spence, 2011) can be based on natural statistical regularities, e.g., between the size of an object and its resonance frequency (e.g., Coward & Stevens, 2004; Bee, Perrill, & Owen, 2000), but also on structural associations, e.g., between magnitude-related stimuli features such as size and loudness (e.g., Smith & Sera, 1992; Walsh, 2003), or on semantically mediated associations, e.g., between auditory pitch and visual elevation (e.g., Martino & Marks, 1999; also see Walker & Walker, 2012). Interestingly, the latter association between higher pitches and higher positions in space has been shown to exist even in pre-linguistic infants, indicating that language does not establish the mappings between space and pitch but only builds on preexisting mappings (Dolscheid, Hunnius, Casasanto, & Majid, 2014; Walker, Bremner, et al., 2010).

Relatedly, work on ‘mental metaphors’ (Casasanto, 2009) suggests that even abstract ideas often have a basis in how people experience their physical and cultural environment (see Lakoff & Johnson, 1980). Supporting this view, studies have demonstrated that people’s perceptuomotor experience affects their mental representations, for instance such that right-handers associate rightward space with *good* and leftward space with *bad* because they can act more fluently with their dominant hand in the right side of space (Casasanto, 2009; see also Casasanto & Dijkstra, 2010).

Based on the research outlined above, one may hypothesize that naturally occurring associations may serve as ‘natural conventions’ (Deroy & Spence, forthcoming, 2018) when creating novel communication systems, such that co-actors would build on crossmodal correspondences or mental metaphors to create communicative mappings. In line with this idea, it has been suggested that mappings between naturally associated dimensions are more easily identified than mappings between unrelated dimensions (Coward & Stevens, 2004).

Building on the present findings, it would be interesting to explore how people create novel communication systems to transmit information about other hidden object properties such as fragility or rigidity, and what serves as the basis for these systems. In particular, future research may look at properties that are not quantity-based (e.g., using liquid, solid, or particulate contents), as it is possible that communicating these properties generally differs from communicating quantity-based properties such as weight. We used weight in the present study to provide evidence in one domain that sensorimotor communication can be used to communicate hidden object properties. More research is needed to show whether our findings can be generalized to other hidden object properties.

Why did participants in the present study modulate the end state of their action rather than the movement phase, as observed in previous studies (e.g., Sacheli et al., 2013; Vesper et al., 2016)? The preference for grasp height as a communicative signal may be explained by its static (instead of dynamic) nature which allows observers more time to recognize the signal compared to modulations in movement velocity or maximal movement amplitude (e.g., Vesper & Richardson, 2014) which are dynamic in nature and fade quickly. It is also possible that people preferred modulations of the action end state over modulations of the dynamic instrumental movement because these were more clearly recognizable as a communicative signal (see Vesper, Schmitz, et al., 2017). Note, however, that in the present study, differences in participants’ grasp height were highly correlated with differences in the peak height of

participants' reach-to-grasp trajectories. Thus, observers could have already picked up on the communicative signal during the approach phase and then confirmed their first impression by observing their partner's final grasp position. Based on participants' verbal reports, it can be safely assumed that it was the final grasp height that participants aimed to make distinctive for communication, yet while doing so they naturally also modulated their reach-to-grasp trajectories.

Moreover, using differences in grasp height as a communicative signal evokes the prediction that the larger the differences displayed by informed actors, the better uninformed co-actors should be able to recognize the signal. This should be evident in the form of a high correlation between the size of the average difference in grasp height and co-actors' matching accuracy. However, we could not empirically confirm this prediction because the correlations computed from the present data were uninformative due to the very small variability in accuracy between pairs ($M_{\text{Exp1-4}} = 89\%$, $SD_{\text{Exp1-4}} = 14\%$).

It is an open question whether the grasp-based communication system participants established in the present study is generalizable beyond the dyadic interaction in which it was created. This question relates to previous work showing that people adjust to their conversational partners' linguistic preferences by aligning on grammatical structure, task-relevant vocabulary, and referring expressions (e.g., Brennan & Clark, 1996; Brown-Schmidt, 2009; Fusaroli et al., 2012; Garrod & Pickering, 2004; Mills, 2011). Moreover, people adapt their own communicative behavior (i.e., speech and gesture) to their conversational partners' knowledge and beliefs ('audience design'; e.g., Clark, 1996; Clark & Murphy, 1982; Holler & Stevens, 2007; Horton & Keysar, 1996; Newman-Norlund et al., 2009; Özyürek, 2002). A recent study of ours (Vesper, Schmitz, et al., 2017) examined partner-specificity in sensorimotor communication, showing that a sensorimotor communication system created by participants in an interactive task was stable and generalizable to an offline setting rather than

tailored to a specific interaction partner. This provides a hint that the communication system established in the present task might be generalizable as well.

Previous work on partner-specificity in conversation is consistent with the finding that almost all task partners in the present study aligned on the same communicative strategy. In principle, it is possible for co-actors to use different communicative signals, as long as they understand the meaning of each other's signals. However, there were only two (out of 24) pairs where task partners did not use a common strategy. Using a common set of communicative signals may have facilitated coordination, as suggested by previous research on conversation showing that task partners who used the same (task-relevant) language achieved higher levels of coordination (Fusaroli et al., 2012).

Furthermore, it is interesting that most co-actors established a functional communication system very rapidly, needing only a few trials to develop and align on a certain set of signals (for similar findings, see Vesper, Schmitz, et al., 2017). Notably, symmetric trials where co-actors could rely on common ground (Clark, 1996) might have played a critical role in this process: By using communicative signals when there was mutual knowledge about the weight of a given object, co-actors could make manifest the intended meaning of a specific modulation and thereby reassure each other that they were on the same page. This way, they could rapidly build up new common ground and establish a functional communication system.

Regarding our initial question of which type of communication system co-actors preferentially establish to communicate hidden object properties, the present findings suggest that their preference depends on situational factors. Specifically, co-actors showed a consistent preference for sensorimotor communication when the alternative option was to create arbitrary mappings between specific colors and specific object weights. Yet when the mappings were not arbitrary but based on an intrinsic relation between sign and referent, co-actors' preference switched to the use of these mappings. In the present study, we relied on the intrinsic magnitude-

based relation between weight and numerosity by using 1-3 dots as numerosity cues. However, the magnitude dimension could be represented in many other ways, from using numerals (e.g., ‘1’, ‘2’, ‘3’) to gradients of color (e.g., a gradient from white over grey to black, see Walker, Francis, et al., 2010). It is likely that the present findings would generalize to other instantiations of magnitude.

Whether mapping specific colors or numerosity cues to specific weights can be described as a more *symbolic* form of communication compared to the grasp height system can be regarded as a question of definition. Arguably, both types of communication systems can be seen as symbolic in the basic sense that certain elements stand for, or signify, certain other elements. Going beyond this very broad definition, symbols are often contrasted with icons (e.g., Allwood, 2002): Whereas the relation between icons and their referents is homomorph, i.e., related by similarity, the relation between symbols and their referents is arbitrary, e.g., it can be determined by convention (also see the distinction between icons, indices, and symbols introduced by Peirce, e.g. Peirce, 1982).

Given this distinction between symbols and icons, the mapping between specific numerosity cues and specific weights can be regarded as iconic, as it relies on a shared quality between sign and referent (i.e., numerosity and weight share the magnitude dimension). Research in experimental semiotics suggests that icons can evolve into symbols through an interactive grounding process between producer and receiver of the signs (Garrod et al., 2007). In the beginning of a communicative interaction the informational content of an iconic sign is grounded in the sign’s physical appearance but after repeated interactive usage, the icon evolves into a symbol (i.e., an often simpler and more abstract representation) with its informational content being grounded in the users’ shared history (Galantucci, 2009; Garrod et al., 2007).

In contrast to the iconic numerosity signs, the colors used in the present study do not bear any similarity relation to weight. Thus, the mapping between specific colors and specific

weights can be regarded as arbitrary, in this respect resembling typical symbolic word-meaning mappings in human language. Finally, the relation between specific grasp heights and specific weights is not one of similarity, yet it is not completely arbitrary as it is based on people's prior associations which are possibly grounded in weight-specific action affordances (see discussion above).

Thus, the three different signs (i.e., numerosity, color, grasp height) connect to their referent (weight) in different ways (see Peirce, 1998). Whereas there is a preexisting (magnitude-related) connection between numerosity and weight, there is no prior connection between color and weight. This qualifies the former as iconic and the latter as symbolic relation. The connection between grasp height and weight might be classified somewhere in between, as it is not based on similarity yet it is also not arbitrary but based on preexisting associations. The present study has shown that co-actors prefer the latter type of mappings over arbitrary (color-weight) mappings but not over iconic (numerosity-weight) mappings. Together, these findings not only extend previous research on sensorimotor communication but they also provide novel insights into how communication emerges out of the need to coordinate.

Chapter 5. General Discussion

The aim of the present thesis was to further explore the processes underlying interpersonal coordination in human adults. In particular, the present work targeted real-time, non-verbal interactions between two individuals who coordinate their actions at discrete points in time in a shared physical space. I presented three empirical studies designed to investigate to what extent individuals integrate others' task constraints into their own actions when acting together. Whereas the first two studies examined whether individuals represent and adapt to others' task constraints when trying to achieve temporal coordination, the third study asked whether and how co-actors establish novel communication systems if solving a coordination problem requires an active transfer of information. In the following, final chapter of this thesis, I will summarize the findings of these studies and discuss theoretical implications and possible applications, as well as directions for future research.

5.1 Co-actors represent each other's task constraints

In **Chapter 2**, I asked whether actors represent and adapt to a co-actor's environmental constraint to achieve temporal coordination *even if* other coordination processes imply less movement effort. To examine this question, I employed a temporal movement coordination task where two co-actors faced asymmetric constraints. The unconstrained actor could either represent her co-actor's environmental constraint at the cost of performing more effortful movements or slow down her own actions only based on feedback about the co-actor's movement tempo. A series of four experiments showed that unconstrained actors represented their co-actor's constraint (i.e., an obstacle in their way) such that they moved *as if* an obstacle was obstructing their own way as well. The results furthermore indicated that unconstrained actors represented the object property constraining their co-actor's movements (i.e., the height

of an obstacle) rather than parameters of these movements. Together, the findings presented in Chapter 2 showed that representing another person's spatial constraint affects kinematic parameters of one's own movement – even if the constraint does not apply to one's own task.

By demonstrating that people adjust their own movement parameters to a co-actor's environmental constraint, the present study relates to and extends previous work suggesting that people encode others' environments into their own motor programs. Specifically, it has been shown that observing another person avoid an obstacle influences actors' own concurrent (Roberts et al., 2017; van der Wel & Fu, 2015) and subsequent (Griffiths & Tipper, 2009) movement trajectories. The obstacle in a co-actor's movement path primed actors' own action planning such that they performed a higher movement themselves. The present study extends this work on 'obstacle priming' by showing that people encode others' environmental constraints into their own motor programs even if they cannot directly observe these constraints (also see van der Wel & Fu, 2015). This shows that obstacle priming can be triggered not only by visuomotor processes such as entrainment (van der Wel & Fu, 2015), motor contagion (Griffith & Tipper, 2009; Roberts et al., 2017), or imitation (Forbes & Hamilton, 2017), but also by internal representations. Moreover, the present study is – to my knowledge – the first to examine obstacle priming in an interpersonal coordination task. My findings indicate that the tendency to take others' task constraints into account and to thereby compromise one's own movement efficiency prevails over alternative coordination strategies that would require less movement effort.

Future studies may investigate in how much detail others' task constraints are co-represented. This could be done by systematically modulating the height of an obstacle or by modulating the direction of the required avoidance movement (e.g., *over* or *around* an obstacle). Initial evidence comes from a recent study on action observation by Forbes and Hamilton

(2017), suggesting that the specific properties of an obstacle (e.g., its exact height) do not differentially affect how the constraint is encoded in an observer's motor program.

Further findings from the study by Forbes and Hamilton (2017) relate to and conflict with findings from my own study, raising interesting questions for future research. In their study, the authors asked participants to observe a model perform a series of high or 'super high' target-directed pointing movements in the presence or absence of obstacles between the targets. Afterwards, participants pointed to the same targets as the model. It was found that the peak height of participants' movements was higher after observing the model move over obstacles compared to when there were no obstacles in the model's movement path, providing further evidence for the obstacle priming effect. Interestingly, participants moved higher after having observed the model perform 'super high' trajectories compared to high trajectories. As the height of the model's high trajectory was sufficient to clear the obstacles and the 'super high' trajectory was rated as irrational (by a group of independent observers), this finding suggests that participants also encoded others' irrational actions, thereby compromising their own movement efficiency even more (Forbes & Hamilton, 2017).

Notably, this finding is not fully consistent with the results from Experiment 4 of my own study, which showed that participants increased their movement height to the same degree irrespective of whether their co-actor was performing an efficient movement or moving in an extra high, inefficient trajectory. These conflicting findings might be explained by several factors. First of all, Forbes and Hamilton asked participants to imitate the model's actions (i.e., to move to the same targets as the model), which might have resulted in increased attention to the model's movements, and possibly even in the explicit aim of faithfully copying the model's movements. In contrast, participants in my study were not instructed to imitate each other but to focus on synchronizing their movement endpoints with those of their co-actor. To this end,

they represented whether or not their co-actor moved over an obstacle, yet they might not have paid much attention to the specifics of the co-actor's movement trajectory.

Alternatively, it is possible that when engaged in joint actions, people are able to resist encoding others' irrational actions in order not to jeopardize the joint goal. Whereas the tendency to encode and imitate others' irrational behaviors seems pervasive in the case of action observation (e.g., Forbes & Hamilton, 2017; Forbes, Pan, & Hamilton, 2016; Griffiths & Tipper, 2009; Hardwick & Edwards, 2011; Wild, Poliakoff, Jerrison, & Gowen, 2010), it might be reduced during joint action coordination. Specifically, the presence of a joint goal might act as a top-down factor on people's imitative behavior, just as other top-down factors have been shown to affect imitation, e.g., factors such as the saliency of goals (Wild et al., 2010) or social cues (Wang & Hamilton, 2012). In other words, when aiming to attain a joint goal, taking into account a co-actor's task-relevant constraints might have top priority because it directly serves the joint goal. Imitating a co-actor's precise kinematic parameters, however, might not be necessary to achieve the joint goal. Thus, instead of allocating precious cognitive resources to imitation, those resources might be rather focused on the attainment of the joint goal.¹⁴

Even though the tendency to imitate others' irrational behaviors seems futile and costly at first glance, it plays an important role in an early phase of human ontogeny, namely by facilitating children's social learning. It has been shown that children tend to copy causally irrelevant features of an action (Lyons, Young, & Keil, 2007; McGuigan, Makinson, & Whiten, 2011; Nielsen, 2006; Whiten et al., 2016), despite being able to identify the rationality of goal-directed actions in general (Gergely & Csibra, 2003; Scott & Baillargeon, 2013) and in the specific context (e.g., Marsh, Pearson, Ropar, & Hamilton, 2013). Why do children imitate

¹⁴ The latter idea relates to an account postulating that imitation is guided by goals (Bekkering, Wohlschläger, & Gattis, 2000) such that observed actions are organized in a hierarchy of goals and the goals at the top of the hierarchy (e.g., to reach for an object) are more readily imitated than those further down the hierarchy (e.g., to reach with the right hand). Similarly, in the context of joint action coordination, the joint goal would be at the top of the hierarchy.

irrational actions? It has been suggested that exaggerated, seemingly irrational movements often function as ostensive pedagogical cues, teaching young children which actions to imitate and thereby supporting social learning (Gergely & Csibra, 2009). For instance, caregivers often over-articulate vowels in infant-directed speech ('motherese') and exaggerate crucial features within an action sequence ('motionese'; Brand et al., 2002; Koterba & Iverson, 2009; Pitsch et al., 2014) to allow for better identification and perceptual discrimination of the action.

Based on this pedagogical account, it would be an interesting avenue for future research to conduct Experiment 4 from my study with young children, exploring whether they imitate a co-actor's inefficient movements or whether the coordination goal overrides this tendency. This would be informative regarding the scope of 'overimitation' and its role in joint action coordination.

The finding that participants in the present study were not affected by a co-actor's inefficient movements might also be ascribed to the level at which participants represented their co-actor's actions. In particular, it seems that participants represented the object property constraining a co-actor's movements (i.e., the height of an obstacle) rather than the precise parameters of these movements. It has been suggested that actions can be represented at multiple levels (Jeannerod, 1994; Pacherie, 2008), i.e., either at higher, more global levels or at lower levels where action parameters are fully specified in functional and/or kinematic terms. As there is no indication that participants in the present study specified their co-actor's movement kinematics, it seems that they represented their co-actor's action at a higher level (i.e., at a 'macroscopic level'; Jeannerod, 1994), specifying only the movement constraint.

In Chapter 2, I already raised the question of whether the conclusion that people represent the property constraining a co-actor's movements rather than specific parameters of these movements can be generalized across different task contexts. It is possible that representing invariant aspects (e.g., stable object properties rather than variable movement

parameters) of a joint task is generally a good heuristic. In addition to this heuristic, it might be beneficial to represent a co-actor's movement parameters during continuous movement coordination (e.g., dancing) whereas it might be sufficient for co-actors to represent each other's movement constraints when coordinating discrete events such as the synchronous arrival at specific locations. Moreover, it is likely that the degree of familiarity with a particular action partly determines whether movement parameters are taken into account, as the ability to simulate others' movements also depends on an actor's own motor expertise (e.g., Calvo-Merino et al., 2005). Future research could further investigate the influence of motor expertise on the co-representation of movement parameters.

A related question is whether the ability to represent a co-actor's constraint depends on one's own experience with the given constraint. This could be examined in the context of the present study by having one actor who always moves over an obstacle and one actor who has no experience with the obstacle at all. If own motor experience is necessary (or at least helpful) for representing a co-actor's constraint, then no (or at least a smaller) increase in the unconstrained actor's movement amplitude is expected.

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

In **Chapter 3**, I extended previous research on the co-representation of individual actions to action *sequences*, asking whether co-actors represent the order of actions within each other's action sequence even if doing so is not necessary for joint task performance. To address this question, I used a joint movement task where two co-actors concurrently performed action sequences composed of two actions. It was 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, a series of six experiments demonstrated 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, the study indicated that interference can arise due to differences in movement parameters and due to differences in the perceptual characteristics of movement goals. Together, the findings presented in Chapter 3 provided evidence that people represent the order in which a co-actor performs the actions within an action sequence.

Whereas previous research has shown that people represent others' task rules (Atmaca et al., 2011; Böckler et al., 2012; Sebanz et al., 2003), task-relevant kinematic parameters (Vesper, van der Wel, et al., 2013), and task constraints (van der Wel & Fu, 2015; Schmitz et al., 2017), the present study constitutes an important extension by demonstrating that people represent not only the elements of another's task, but also their temporal structure. This finding is entirely novel as it taps into the representation of ordered action sequences rather than looking at individual actions. Moreover, the finding further supports the assumption that people represent aspects of others' tasks even if this is not necessary and might interfere with their own performance. In the present study, co-actors' joint goal of reaching a synchronized end state did not require them to represent the order of each other's actions because synchronization could be based on the overall duration of the sequence which is not affected by the order of actions within the sequence. Hence, the finding that co-actors represented the order of each other's actions confirms that people possess a distinct tendency to represent others' tasks in more detail than required for task performance.

One important finding from the present study was that co-actors experienced interference not merely because their actions were different but because their actions were different but at the same time overlapping. The overlap consisted in the fact that the two co-actors' action goal states (e.g., the perceptual characteristics of the movement targets) were the same. However, co-actors reached these goal states in a different order. The fact that co-actors experienced interference only when performing the same actions in a different order, yet not

when performing entirely different actions, shows that it was the overlap between co-actors' actions that caused the interference, presumably because the overlap increased the relevance of the co-actor's actions. Moreover, this result implies that co-actors represented the temporal structure of each other's actions, as it was the temporal order of the action goal states that led to interference.

Another interesting finding of the present study (see Experiments 1-4) was that people seem to represent the difficulty of others' actions. Difficulty here was defined as the time required to move to a target, quantified based on Fitts' law as a function of the ratio between the distance to the target and the size of the target (Fitts, 1954). Participants experienced interference (as evidenced by a slowdown in movement times) when a co-actor performed movements that differed in difficulty. For instance, movement times were slowed down when a participant performed an easy movement followed by a more difficult movement while her co-actor performed a more difficult movement followed by an easy movement. This slowdown suggests that participants represented the difficulty of each other's actions.

Previous studies have demonstrated the generality of Fitts' law, showing that it holds not only for motor execution (e.g., Fitts & Peterson, 1964; Fitts & Radford, 1966; Langolf, Chaffin, & Foulke, 1976) but also for motor imagery (Decety & Jeannerod, 1995). Moreover, people's behavior reflects an implicit knowledge of Fitts' law: they plan their own actions in accordance with the law (Augustyn & Rosenbaum, 2005) and judge others' observed actions as possible or impossible (Grosjean, Shiffrar, & Knoblich, 2007). In addition, a recent study of our own has shown that people engaged in a joint action detect when a co-actor's movement time deviates from Fitts' law, even when they cannot observe the co-actor moving (Vesper, Schmitz, et al., 2017). Thus, whereas previous studies have demonstrated that people are sensitive to movement regularities as captured by Fitts' law when performing and planning their own actions as well as when perceiving and judging others' actions, findings from the present

study suggest that people also co-represent the (Fitts'-derived) difficulty of a co-actor's action, solely based on knowledge of the co-actor's task (and possibly on their own motor experience).

Consistent with the idea that people represent the difficulty of others' actions, a recent study by Ray et al. (2017) demonstrated that actors plan and execute their own actions in a way that accommodates the difficulty of a co-actor's action. In the study by Ray and colleagues (Ray, de Grosbois, & Welsh, 2017), two co-actors performed a sequential joint action such that one actor first placed an object at an intermediate position and the second actor moved it from there to its final position. Results showed that actors performing the first part of the joint action placed the object at an intermediate position that facilitated the co-actor's subsequent movement. To this end, the first actor took into account the index of difficulty (as captured by Fitts' law) of their co-actor's prospective movement. Interestingly, this facilitatory behavior was modulated by actors' own experience with the co-actor's task. In line with accounts postulating that action and perception rely on a common representational format (e.g., Hommel et al., 2001; Prinz, 1997), this finding suggests that people are better at representing the difficulty of others' actions when they are familiar with the actions themselves (cf. Keller, Knoblich, & Repp, 2007; Knoblich & Flach, 2001).

With respect to my own study, it would be interesting to test whether and in what way motor experience might affect participants' co-representation abilities. In the present version of the study, all participants had prior motor experience as they had performed the task individually before the joint task part. By removing this individual practice phase, one could test whether own motor experience modulates participants' ability to represent a co-actor's task difficulty, as demonstrated by Ray et al. (2017). As participants would naturally gain motor experience during the course of the experiment, one could measure their 'learning curve' by looking at when they start showing an effect of co-representing their co-actor's constraint and at how the size of this effect develops over time. If participants already started co-representing

their co-actor's constraint at the very beginning of the joint task phase, this would suggest that own prior motor experience is not a prerequisite for co-representation.

A major difference between my own study and the study by Ray et al. (2017) pertains to the temporal relation between co-actors' actions. Whereas in my own study, co-actors performed their actions concurrently, co-actors in Ray et al. performed their actions sequentially, with one actor performing the first part of the joint action and the other performing the second part. Both studies provide evidence that actors represent the difficulty of a co-actor's action. However, when performing asymmetric actions concurrently, as in my study, co-representing a co-actor's movement difficulty led to interference with actors' own performance. Conversely, when performing actions sequentially as in Ray et al., co-representing a co-actor's movement difficulty allowed actors to plan and adapt their own action to effectively facilitate their co-actor's action.

The latter finding by Ray et al. extends work on the sequential performance of joint actions which has shown that individuals engage in higher-order planning on a joint level. Specifically, individuals integrate a co-actor's subsequent action into their own action plan in order to facilitate the comfort of the co-actor's action beginning or end state (Dötsch & Schubö, 2015; Gonzalez, Studenka, Glazebrook, & Lyons, 2011; Herboert, Koning, van Uem, & Meulenbroek, 2012; Meyer, van der Wel, & Hunnius, 2013; Ray & Welsh, 2011; see also Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). For instance, participants passed a jug such that the handle was available to be grasped by a co-actor (Ray & Welsh, 2011) and they modulated their grasp position on an object to avoid uncomfortable end postures for a co-actor (Meyer et al., 2013). These findings on the so-called joint 'beginning/end-state comfort effect' also relate to my own findings on co-representation, as will be discussed below.

Finally, one may note that the findings from the present study can be applied to a number of everyday life situations. For instance, consider members of a choir who sing a round, i.e.,

they sing the same voice but begin and end at different times, such as in the famous French nursery rhyme ‘Frère Jacques’. Interference might occur because singers perform the *same* actions in a *different* order, precisely as participants in the present study. Based on the results from the study, one should predict that no (or less) interference will occur if people sing different, independent voices at the same time. Besides in singing, similar interference might occur in activities such as ballroom dance or in other games or sports activities that involve sequences of actions. Moreover, the finding might also be applicable to work environments. For instance, consider factory workers working at an assembly line, putting together specific products piece by piece. Potentially, observing others put together the same pieces in a different order might slow down workers’ performance. It would be interesting to investigate how joint action experts such as professional musicians or dancers, as well as longtime factory workers, learn to avoid or overcome such interference.

5.3 Integrating Chapters 2 & 3: Action co-representation

Taken together, the studies presented in Chapters 2 and 3 extend previous work on co-representation in a number of ways. First of all, both studies depart from the stimulus-response paradigms typically used to study automatic task co-representation (e.g., Sebanz et al., 2003). Evidence from the latter type of studies suggests that participants represent each other’s tasks, i.e., they represent the “specific relationship between particular stimulus conditions and particular actions” (Sebanz et al., 2005, p. 1235). In my studies, however, no such stimulus-response mappings were to be represented, as co-actors did not perform pre-specified responses to particular stimuli but they freely performed goal-directed actions. Here, co-actors represented each other’s actions, or rather, they represented “features of an action a particular person is performing” (Sebanz et al., 2005, p. 1235), including factors constraining these actions. Whereas an extensive amount of research has been devoted to *task* co-representation in the

original sense (for a review, see Dolk et al., 2014), less is known so far about *action* co-representation (but see Vesper, van der Wel, et al., 2013; Kourtis et al., 2013, 2014).

By employing real-time movement coordination tasks, the present studies contributed to our knowledge about the role of action co-representation in coordination, showing that co-actors represent aspects of the environment (Chapter 2) and of the task structure (Chapter 3) that constrain each other's actions and affect each other's movement parameters. The results further suggest that co-actors not only represent aspects that directly affect performance (e.g., movement difficulty) but they also represent aspects irrelevant to performance (e.g., the color of movement targets).

Previous work on the so-called joint 'beginning/end-state comfort effect' described above relates to the findings from Chapters 2 and 3 in that these also suggest that people represent the constraints and the respective difficulty of a co-actor's action. In particular, my studies demonstrated that people take into account how certain task constraints, e.g., obstacles obstructing the movement path (Chapter 2) or relations between target distance and size (Chapter 3), affect the difficulty of a co-actor's action. Similarly, work on the 'beginning/end-state comfort effect' shows that people take into account how task constraints, e.g., certain object affordances, affect the difficulty of a co-actor's action. Whereas in my own studies, individuals cannot influence (but merely adapt to) the difficulty of a co-actor's actions, individuals in the 'beginning/end-state comfort' studies can actively adjust their own action to facilitate that of their co-actor.

Broadly speaking, the present findings are consistent with the idea that people have a strong tendency to represent others' tasks and actions, even if not necessary for task performance. This tendency might have developed because the ability to co-represent plays an important role in monitoring and predicting others' contributions to a joint action and to detect opportunities for joint action when other agents are around. Thus, people's strong susceptibility

to co-representing others' tasks and actions may be attributed to the fact that during the course of human evolution, coordinating and cooperating with others was a highly beneficial, and thus adaptive, behavior. Accordingly, the human cognitive system might have been shaped to meet the demands of joint action (Sebanz et al., 2005). So nowadays, even if coordination is not required in a given moment, people tend to form representations of others' goals and intentions so that they are constantly prepared to predict others and to engage in joint action should the situation arise (Sebanz et al., 2005). This account is in line with findings showing that automatic co-representation can be modulated by social factors such as friendliness, cooperativeness and ingroup/outgroup status, i.e., relevant factors with regard to whether someone qualifies as potential collaborator.

Finally, the present research on co-representation in humans could be applied to work on human-robot interaction (HRI). When designing robotic systems, knowledge about how humans represent other agents' tasks and actions should be considered to facilitate the interaction between human and robotic agents. It is especially important to take into account factors that could potentially interfere with people's behavior in order to eliminate these factors from the outset. For instance, one should consider that the order in which a robotic agent performs its actions may interfere with the performance of co-acting human agents. When designing HRI setups, potential interference could be avoided by taking this fact into account. Thus, when having a robot work next to a human in a factory environment, it should be avoided that the order of the robot's actions interferes with the order of actions the human is supposed to perform. Similarly, one should be aware of the fact that a robot's environmental constraints might affect a co-acting human's performance, even if the constraints only apply to the robot's task.

5.4 Co-actors communicate hidden object properties

In **Chapter 4**, I addressed the interface between coordination and communication, looking at how communication emerges out of the need to coordinate in a situation where knowledge is distributed asymmetrically between co-actors. Building on previous research showing that co-actors systematically modulate kinematic parameters of their instrumental movements to communicate spatial target locations, I asked whether sensorimotor communication also provides an effective means for communicating non-spatial, hidden object properties. Additionally, I aimed to find out whether people prefer sensorimotor communication or symbolic forms of communication, and which factors determine their preference. More generally, the study presented in Chapter 4 extended previous work on experimental semiotics (Galantucci, 2005) by investigating whether and how people spontaneously create novel communication systems out of the need to coordinate their actions with others.

To this end, I created a task where two participants needed to select objects of the same weight while only one participant knew the correct weight in advance. A series of three experiments showed that actors who knew the weight of an object transmitted this weight information to their uninformed co-actors by systematically modulating their instrumental actions, grasping objects of particular weights at particular heights. This preference for sensorimotor communication was reduced in a fourth experiment where co-actors could communicate with weight-related symbols.

Together, the findings presented in Chapter 4 add to previous research on sensorimotor communication in several ways. First of all, the study demonstrates that the scope of sensorimotor communication extends from conveying information about *openly perceivable* spatial locations to the *hidden* properties of objects. Secondly, it shows that systematic movement deviations can be used not only to communicate *discrete, binary* properties such as up and down (Sacheli et al., 2013) or left and right (Pezzulo & Dindo, 2011), but also to

communicate *continuous* properties such as weight. Notably, theoretical work by Pezzulo et al. (2013) has already demonstrated that the scope of sensorimotor communication goes beyond binary properties. However, most empirical studies so far have focused on binary choice tasks (for exceptions, see Vesper & Richardson, 2014; Vesper, Schmitz, et al., 2017). Moreover, whereas previous studies have shown that *dynamic* movement trajectories can be modulated for communicative purposes, the present study shows that also the *static* end state of movement trajectories can serve to convey information (for converging evidence, see Vesper, Schmitz, et al., 2017).

Regarding the latter aspect, it is possible that whether people employ dynamic or static communicative signals depends on the type of coordination required. For instance, if timing is critical such as when co-actors aim to synchronize the end points of their movements, the informed actor might prefer to display distinctive kinematic features early during the movement phase to convey critical information (e.g., the movement target) to her uninformed co-actor, thereby facilitating successful synchronization. This has been shown in a study by Vesper and Richardson (2014) where informed participants increased the velocity of their target-directed movements such that maximum height was reached particularly early. This in turn helped uninformed observers to predict the actor's movement target and to arrive at the same target synchronously. In line with this finding, Pezzulo et al.'s (2013) theoretical account suggests that modifying the timing of a movement helps observers to disambiguate between action alternatives as they receive crucial information early on.

However, if coordination is sequential such that one actor needs to complete her action before her co-actor starts acting (as in the present study), then the first actor might prefer to modulate the static end state of her movement trajectory rather than the dynamic movement phase. When an actor modulates the end state of her action, a co-actor will have sufficient time to perceive and comprehend the communicative signal before planning her own subsequent

action accordingly. This was observed in a recent study of ours (Vesper, Schmitz, et al., 2017) where informed participants who acted first in a sequential joint action modulated the duration of their action end state. By perceiving these temporal modulations, uninformed co-actors could identify the first actor's movement target and move to the same target subsequently.

Thus, the advantage of using a dynamic communicative signal is that it allows to convey information early on in an interaction. In contrast, when using a static communicative signal, information can only be conveyed at a later point in time (i.e., after the movement phase). The disadvantage of using a dynamic signal is that it can be easily missed by an observer because it fades quickly. In contrast, a static signal is of a more permanent nature and thus less likely to be missed.

Naturally, before deciding *how* to communicate (e.g., which type of communicative signal to use), one needs to have an intention to communicate at all. When does an intention to communicate about hidden object properties arise in everyday life situations? More specifically, why would it be relevant to inform someone about the weight of a certain object? This is a justified question, as it might seem that in many situations, people can infer 'hidden' object properties such as weight based on an object's visual appearance (e.g., its size or material). Through experience, people have learned to make quite accurate predictions about weight based on an object's visual surface properties and they implicitly engage in such predictions every time they are about to lift a novel object (e.g., Buckingham et al., 2009; Cole, 2008; Flanagan & Beltzner, 2000; Gordon et al., 1991a, b; Gordon, Westling, Cole, & Johansson, 1993). Based on these learned "appearance-weight associations", people plan their actions and create anticipatory control strategies (Flanagan, King, Wolpert, & Johansson, 2001; Hermsdörfer, Li, Randerath, Goldenberg, & Eidenmüller, 2011; Johansson & Westling, 1988).

However, people may form false predictions if the visual appearance of an object is deceptive (e.g., a heavy object whose surface material or size suggests lightness) or

uninformative (e.g., a nontransparent box). In these cases, object weight cannot be correctly inferred because prior appearance-weight associations are inaccurate or unhelpful. It is in these cases that the communication of hidden properties proves useful. For instance, when person A hands over a nontransparent box, e.g., a suitcase, to person B, B would benefit from receiving information about the weight of the suitcase in advance. This way, B could form accurate expectations and adjust her lifting force accordingly, thereby facilitating a smoothly coordinated handover.

Notably, person B could also form predictions about object weight solely by observing person A lifting the suitcase (e.g., Bingham, 1987; Grèzes et al., 2004a, b; Hamilton et al., 2007; Meulenbroek, Bosga, Hulstijn, & Miedl, 2007; Runeson & Frykholm 1983). Nevertheless, if person A additionally modulated her movements in a communicative way, the weight cues would become more salient and more easily detectable for B. Moreover, whereas people naturally display distinct kinematic features when lifting objects of different weights, this is not the case for other hidden properties such as fragility, rigidity, or temperature. Hence, future studies may investigate whether and how sensorimotor communication may be used to transmit information about these latter properties. Additionally, it would be interesting to study communicative behavior in cases where people's prior appearance-weight associations are mistaken due to deceptive object appearances.

5.5 Integrating Chapters 2-4: Acting on common ground

As already pointed out in the introduction to this thesis, there is not one way of achieving interpersonal coordination, but there are many. What is common to all is that co-actors rely on some form of shared information, or common ground. In addition to sharing information about the joint goal – a minimal requirement for any joint action (Vesper et al., 2010) –, co-actors may share more detailed information about each other's tasks and actions. Specifically,

additional information is shared when co-actors have access to mutually available task knowledge, when they can observe each other acting, or when they can communicate with one another. Whereas accessing mutually available task knowledge and observing each other's actions are what I called 'passive' ways of sharing information between co-actors, communication constitutes an 'active' way of sharing information.

In the present work, both of these ways of information sharing have been observed. When perceptual access was restricted but mutual task knowledge was available, co-actors relied on shared representations of each other's tasks and constraints, and adapted their own actions with these representations in mind (Chapters 2-3). Conversely, when perceptual access was available but task knowledge was distributed asymmetrically between co-actors, the informed actor adjusted her actions in a communicative way to actively transmit task-relevant information to her co-actor who, in turn, used this information to plan her own actions (Chapter 4). By actively transmitting (and receiving) information, co-actors made this information part of their common ground and eliminated the knowledge asymmetry that impeded coordination.

Whereas the joint actions examined in this work differ with respect to whether information is shared in an active or a passive way, co-actors in all cases shared a representation of the joint goal and of the general task structure, and they had mutual knowledge about the actions required by both co-actors, as well as about the factors constraining these actions. Without this basic level of common ground, coordination would not have been feasible, or at best highly challenging.

In the joint actions examined in Chapters 2-3, co-actors initially received task information that enabled them to represent the task and the joint goal, as well as each other's actions and constraints. Purely based on this knowledge (and without being able to observe each other acting), co-actors *maintained* this representation during joint performance, keeping in mind each other's actions (and constraints) in addition to their own. In the joint action examined

in Chapter 4, co-actors not only *maintained* a basic level of common ground (i.e., a shared representation of the task, the joint goal, and each other's actions and constraints), but they actively *established and accumulated* new common ground. During the course of developing a novel communication system, co-actors established the meaning of a set of communicative signals. Whereas this meaning might have been based on co-actors' (independent) prior assumptions (see General Discussion of Chapter 4), it was only through the joint usage that co-actors made this meaning part of their common ground. Through this process of grounding (Clark & Brennan, 1991), co-actors made it mutually manifest that each of them understood the meaning and accepted the usage of a given set of signals.

To sum up, representing others' task constraints may be seen as a form of (passively) *maintaining* common ground whereas communicating task-relevant information may be seen as a form of (actively) *accumulating* new common ground. Importantly, the basic level of common ground that is maintained via co-representation is also the underlying building block for communicative processes that serve to add new common ground on top. Whereas maintaining a representation of others' constraints facilitates coordination by allowing individuals to predict and adapt to others' actions, extending this set of shared representations via communication helps to bridge the gap that naturally exists between individuals' minds, creating mutual access to otherwise private information.

5.6 Conclusion

What are the processes underlying our ability to perform *joint actions*? The present work targeted this question by investigating to what extent individuals integrate others' constraints into their own actions when acting together. In sum, the results of this work show that individuals possess a distinct tendency to take others' constraints into account, sometimes even in more detail than required for performing the joint task. Specifically, individuals represent

others' environmental constraints, others' task-specific constraints in the form of the temporal structure of their actions, and the knowledge others do (or do not) possess – and they integrate these constraints into their own actions even if this compromises individual efficiency. If overcoming another's constraint requires an active transfer of information, individuals flexibly create novel communication systems to transmit this information, thereby facilitating coordination. Taken together, the work presented in this thesis contributes to a better understanding of the processes underlying joint action and it provides further evidence of the human predisposition to act with others in mind.

Appendix

Chapter 4. Sampling-without-replacement procedure used to analyze color-weight mappings.

A

color \ weight	light	medium	heavy
blue	80 % (1)	30 % (2)	0 % (3)
red	20 % (2)	70 % (1)	25 % (2)
black	0 % (3)	0 % (3)	75 % (1)

B

color \ weight	light	medium	heavy
blue	80 % (1)	70 % (1)	65 % (1)
red	20 % (2)	30 % (2)	25 % (2)
black	0 % (3)	0 % (3)	10 % (3)

Figure 1. Exemplary data is shown to illustrate the basic principle of the sampling-without-replacement procedure. For each weight, colors are ranked in order of their usage frequency, with the most used color ranked first. **A:** Blue has the highest overall usage percentage among the first-ranked colors, so it is selected first (for light). Black has the next larger percentage and is thus selected second (for heavy). Finally, red is selected (for medium). **B:** Here, blue also has the highest overall usage percentage among the first-ranked colors, so it is selected first (for light). However, blue is also ranked first for the other two weights, so the largest usage percentage among the second-ranked colors is selected instead (red for medium). Finally, for the heavy weight, the second-ranked color is also red, so the third-ranked color black is selected instead. This gave us one value (in %) per weight per participant, indicating how often each participant had used the selected color in those trials in which the given weight had occurred.

Chapter 4. Supplement data from the individual control experiment.

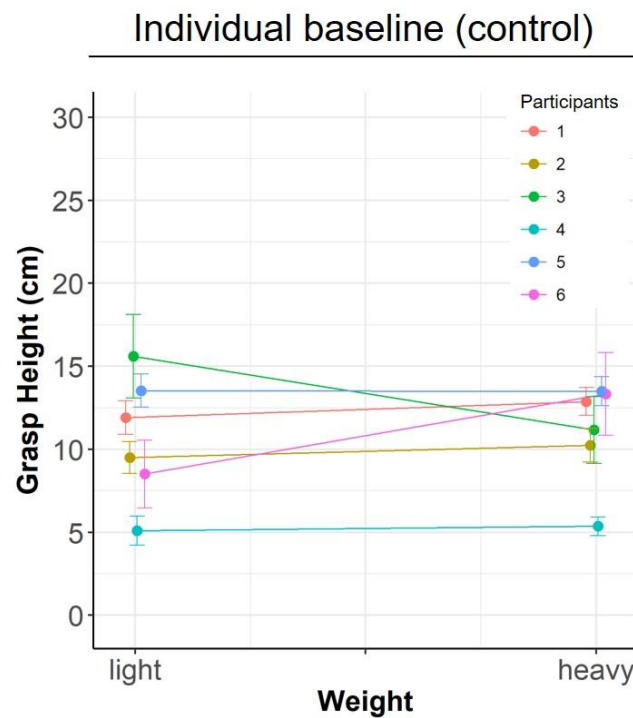


Figure 2. Grasp height is shown as a function of object weight and participant. This data comes from an additional control experiment we conducted to test whether grasp height differences in the individual baselines of our study were absent because the weights of the three objects we used only differed to a small extent (i.e., by 100 g). In the control experiment, a new group of individual participants ($N = 6$) repeatedly grasped two objects that strongly differed in weight (70 g vs. 1510 g) in a randomized order. As illustrated above, participants' grasp height did not differ as a function of weight ($B = 0.38, p = .739$).

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