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Interpersonal coordination in a functional joint action: Insights from a manual ball-and-beam paradigm

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Affidavit

I, undersigned, Marijn S.J. Hafkamp, hereby declare that the work presented in this manuscript is my own work, carried out under the scientific supervision of Reinoud J. Bootsma and Remy Casanova, in accordance with the principles of honesty, integrity and responsibility inherent to the research mission. The research work and the writing of this manuscript have been carried out in compliance with both the French national charter for Research Integrity and the Aix-Marseille University charter on the fight against plagiarism.

This work has not been submitted previously either in this country or in another country in the same or in a similar version to any other examination body.

Groesbeek, The Netherlands, 20th of December 2024



List of publications and conference contributions

1) List of publications and or patents [1] produced in the context of the thesis:

    1. Hafkamp M.S.J., Casanova R., Bootsma R.J. (2023). Freezing and freeing of degrees of freedom in joint action learning. *Frontiers in Psychology*. 14: 1287148. https://doi.org/10.3389/fpsyg.2023.1287148
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[1] This list includes published articles, articles submitted for publication and articles in preparation, as well as books, book chapters and/or any form of exploitation of the results of work specific to the thesis project discipline.

[2] The term 'conference' is generic. It includes 'conference', 'congress', 'workshop', 'colloquium', 'national and/or international meetings', etc.

6. Hafkamp M.S.J., Casanova R., Bootsma R.J. (2024). Exploring the process of interpersonal coordination using a novel ball-and-beam task (oral presentation). *REPAIRS Closing Conference. Groningen, The Netherlands*.
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Abstract

In this thesis we investigated the interpersonal coordination of movement behavior in the context of a functional, that is, a goal-directed joint action. To do so, we developed a new experimental paradigm in which participants had to control a ball rolling on a long and hand-held beam. By continuously adjusting the inclination angle of the beam, they were to roll the ball reciprocally between two targets, with the goal to hit these targets as often as possible during a trial. This ball-and-beam task could be performed individually, in solo action, as well as dyadically, in joint action. Overt communication was precluded in all settings. In a series of three experiments, we showed that the mode of interpersonal coordination in joint action was qualitatively dependent on the task experience of dyad members in solo action. Results showed that unexperienced dyads adopted a sequential mode of interpersonal coordination, while experienced dyads opted for a more successful, simultaneous mode of coordination. Building upon this finding, we developed a novel methodology to assess the transfer of skill from solo action to joint action. We found that those performance characteristics that were somehow related to ball speed were strongly propagated from the solo to the joint action, while the characteristics related to ball accuracy and beam consistency were only moderately transferred. Also, the dyad members that produced a higher ball speed in solo action were more likely to take the lead in the interaction. From this we concluded that the stability of the interpersonal coordination emerged from the dyads' interaction, while being constrained by the task goal to bring the ball up to speed. More generally, our results demonstrated that an ecological account of joint action needs to address not only the stability, but also the functionality of the interpersonal coordination.

Keywords: Interpersonal coordination, joint action, collaboration, motor control, motor learning, synergies, ecological psychology

Résumé

Nous avons étudié la coordination interpersonnelle des mouvements dans le contexte d'une action conjointe fonctionnelle. Nous avons développé un nouveau paradigme expérimental dans lequel les participants devaient contrôler une balle sur une longue poutre tenue à la main. En ajustant continuellement l'angle d'inclinaison de la poutre, ils devaient faire rouler la balle réciproquement entre deux cibles, dans le but d'atteindre ces cibles aussi souvent que possible au cours d'un essai. Cette tâche pouvait être exécutée individuellement, en solo, ou en dyade, en commun. La communication ouverte était exclue dans tous les contextes. Dans trois expériences, nous avons montré que le mode de coordination interpersonnelle dans l'action conjointe dépendait qualitativement de l'expérience de la tâche des membres du dyade dans l'action solo. Les résultats ont montré que les dyades inexpérimentées adoptaient un mode séquentiel de coordination interpersonnelle, tandis que les dyades expérimentées optaient pour un mode de coordination simultanée plus efficace. Sur la base de ces résultats, nous avons développé une nouvelle méthodologie pour évaluer le transfert de compétences d'une action solo à une action conjointe. Nous avons constaté que les caractéristiques de performance liées à la vitesse de la balle se propageaient fortement de l'action en solo à l'action conjointe, tandis que les caractéristiques liées à la précision de la balle n'étaient que modérément transférées. En outre, les membres de la dyade qui produisaient une vitesse de balle plus élevée en solo étaient plus susceptibles de prendre la tête de l'interaction. Nous en avons conclu que la stabilité de la coordination interpersonnelle provenait de l'interaction des dyades, tout en étant limitée par l'objectif de la tâche. Plus généralement, nos résultats démontrent qu'une approche écologique de l'action conjointe doit prendre en compte non seulement la stabilité, mais aussi la fonctionnalité de la coordination interpersonnelle.

Most clés : Coordination interpersonnelle, action conjointe, collaboration, contrôle moteur, apprentissage moteur, synergies, psychologie écologique

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In the spring of 2021, I received an exciting phone call. I had been admitted to REPAIRS, a European research project that would include 15 PhD students from all over the world. After two years of COVID, this phone call opened the door to a new world. A world of experiments and literature, of colleagues and new friends. But I also felt that it closed the door to a world that I already knew and that I had come to love. I was about to move to Marseille, which meant that I had to say goodbye to my friends and family at home. In the three years that followed, I thoroughly enjoyed working within REPAIRS. The diversity in our consortium, the late night discussions at the Network Training Events (NTEs) and the trips to conferences together: it was a true pleasure. At the same time, I have missed my life in the Netherlands and struggled to find my way in Marseille. Living abroad was not for me, it turned out. And because there are two faces to this story, I also want to thank two groups of people. First, all of those who made the journey of this PhD such a fun ride and who contributed to this thesis, each in their own way. I will do this part in broken English, the language of science. And second, all of those who made me feel so welcome when coming back home, whether it was for a short trip at Christmas or a longer stay during summer. This I will do in Dutch, the language of IKEA, so I've been told in Marseille.

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Introduction

Human behavior is strongly embedded in the environment in which it takes place. In almost everything we do, we have to coordinate our actions with the world that surrounds us. We respond and anticipate, we create and destroy, we lead and we follow, we give and we take. All of these actions constitute certain ways for us to get in contact with our surroundings, either directly or indirectly. Our actions are, in essence, relational practices (Reed, 1982, 1988; Tamboer, 1988). This implies that an understanding of even the most basic forms of human behavior require, first and foremost, an understanding of the world to which they relate (Gibson, 1979). This unavoidably brings us to the question of how we should understand the world around us. What are the core elements of our surroundings, of the environment that we face from day to day? At first glance, our environment seems to be infinitely varied and impossible to classify. We live in a world that consists of buildings, streets, cars, parks and so on and so forth. This world is not only diverse, but also highly dynamic (Van Dijk, 2021, 2021b; Withagen et al., 2024). It changes from instant to instant. A second look, however, reveals a common denominator among these items. In almost every component of our environment, we can recognize the fingerprints of human existence (Costall, 1995; Heft, 2007, 2020). Our buildings have been constructed by humans, our streets are laid by humans, our cars are produced by humans and even our nature parks are often designed or at least adapted by humans. In other words, the world in which we live, to which we respond and anticipate, is thoroughly humanized.

An important cause as well as a consequence of living in a humanized world is that we have become highly dependent on other human beings for our survival. Our modern way of living, with online and offline societies stretching the entire planet, relies on incredibly large collaborations of individuals (Wijnberg, 2023). Throughout the history of humankind (Harari, 2014; Bregman, 2020), we have created global communication networks, financial and health care systems and massive entertainment industries. Perhaps beyond our immediate realization, these systems are continuously dependent on the direct and indirect cooperation of millions of individuals. In this perspective, it is safe to say that human behavior is, above all, a social enterprise. We respond and anticipate *to humans*, we create and destroy *human* artifacts, we lead and follow *other humans*, and we give *to* and we take *from humans*. Of course, we also coordinate our actions with non-living objects and non-human entities, but for evolutionary reasons, our behavior capitalizes to a large extent on our ability to coordinate and collaborate with other individuals. We need each other, more than we may want to admit. In this context, it should come as no surprise that we are remarkably good at such interpersonal coordination. Without much effort, we are able to tune into the actions of others to create a fluent interaction (a 'social eddy', Marsh et al., 2006). Imagine the following situation.

You are walking in a supermarket, looking for a soup to buy for dinner. Suddenly, your eye catches a familiar face: perhaps a good friend from high school that you haven't seen in a while. You turn your head, call out her name and walk in her direction. She notices you too, smiles and comes your way. Within the time course of a few seconds you have

shaken each other's hands and started a lively conversation about the past. Although this joint action seems to be nothing out of the ordinary – it occurs on a daily basis – the shaking of hands requires a remarkably complex coordination of movement behavior. The two of you have to adjust your steps and walking velocities to each other to end up in exactly the right position to shake hands. Moreover, each of you has to stretch out their hand to an undefined location to meet there with the right velocity. Not too fast, for the hands would painfully collide. But also not too slow, for the interaction would become quite awkward. And on top of that, you have to do all of this without verbalizing any of your actions or instructing each other what to do. In fact, you probably act without even thinking about it. Taken together, this deceivingly simple activity of shaking hands requires an intricate process of interpersonal coordination. It constitutes a complex cooperative activity that involves all of your body's limbs, as well as those of your co-actor. And intriguingly, the outcome of the action seems to emerge 'on the fly'. It is not fully determined in advance but it unfolds while you are in interaction with the other person. Yet, the shaking of hands also counts as one of the most universal joint actions that we as humans can perform! With some practice, we are capable of performing much more complex interactions. We can, for instance, dance with a partner, by coordinating our steps not only with the sound of the music but also with the movements of our co-actor. From an artistic perspective, partner dancing can look like the merging of two bodies, a celebration of harmony. But from a scientific viewpoint, the interpersonal coordination involved in this activity belongs to the same category as that of shaking hands. What characterizes the behavior in both examples, is the interpersonal coupling of movement behavior in space and time. Also, in both cases the coordination seems to arise from the interaction, without any overt communication. It is this type of interpersonal coordination, functional and emergent, that we investigate in the current thesis.

Over time, the topic of interpersonal coordination has been studied by many different scientific fields. From social psychology to anthropology and from neuropsychology to human movement sciences: various disciplines have attempted to get a grip on this phenomenon. Given that my scientific background is in the last of these branches, I will approach interpersonal coordination an issue of human movement. That is, my point of departure in this thesis will be Nikolai Bernstein's (in)famous degrees of freedom problem (Bernstein, 1967), a problem that is at the heart of understanding purposeful behavior. Nikolai Bernstein was a Soviet scientist living in the first half of the twentieth century (Bongaardt, 1996, Bongaardt & Meijer, 2000; Meijer & Bruijn, 2007). Although his accomplishments are diverse and his work comprehensive (Bongaardt & Meijer, 2000), his most important contribution to the study of human movement was arguably the identification of its core problem (Turvey 1990). To Bernstein, the complexity of human movement can only be appreciated if one realizes that it involves the mastering of an innumerable number of degrees of freedom (DFs) in our body. These DFs can be defined concretely, in terms of joint angles (Guimarães et al., 2020), but also more abstractly, in terms of action possibilities for the agent (Newell & Vaillancourt, 2001). But regardless of its exact definition, friend and foe agree that the movement apparatus consists of an extraordinarily large number of DFs and that any voluntary action requires these DFs to

be controlled. Without such control, the achievement of a goal would be virtually impossible. Now let us return to the example of shaking hands with a friend. Is it possible to frame this joint action as a problem of mastering the body's degrees of freedom?

The act of stretching out your hand to shake someone else's requires a complex coordination between the anatomical components your arm. You can stretch out your hand by extending your elbow, but also by rotating your shoulder. Moreover, you can extend your wrist or use a combination of movement in all three joints at the same time. The same is true for the subsequent act of shaking hands. You can shake your hand by moving your wrist up and down, but also by freeing your shoulder joint and keeping your wrist still. In other words, the number of ways in which this action can be performed is almost infinite. A different way to say this, is that the arm-shoulder system is composed of many degrees of freedom that need to be mastered for the goal to be achieved. Note here, that the friend in front of you is faced with the exact same problem as you are. She, too, has an almost infinite number of options to stretch out her hand and shake yours. And importantly, the solutions that the two of you choose need to be compatible! Your bodies need to be coordinated not only with respect to themselves or the inanimate environment, but also with respect to each other. For the goal of a joint action to be achieved, a *coupling* of movement behavior should occur. In other words, the bodies involved in the interaction should not only solve an individual degrees of freedom problem, but also a collective one. Yet, once the interaction unfolds, this problem is miraculously solved, probably without either of you being aware of the complexity that your bodies were confronted with just a moment ago.

Throughout the history of human movement sciences, multiple theories have been proposed for how the body would solve the problem of coordination. Arguably, these theories can be divided into two categories (Floegel et al., 2023). The first category of explanations is rooted in the mind-body dualism of René Descartes. These theories claim that the body is under control of a supervenient mind and that mental representations of the world are required to achieve such control. They reflect an approach to behavior that focusses on human cognition, via the study of the human brain. Henceforth, I shall refer to this approach as the cognitive approach, or cognitive psychology in short[3]. The second category of explanations is based on the animal-environment mutualism of Charles Darwin. These theories claim that the coordination of the body is self-organized, without the need for an omniscient mind that pulls the strings. They reflect an approach to behavior that focusses on the cycle of perception and action, via the study of behavioral dynamics. Henceforth, I shall refer to this approach as the ecological-dynamical approach, or ecological psychology in short. Over the years, the cognitive and the ecological approach have evolved alongside each other, occasionally leading to heated debates

[3] The field of cognitive psychology arose in the mid-20th century, primarily in response to behaviorism, and further developed into the neurosciences that are dominant in the behavioral and movement sciences of today. The philosophical roots of this approach, however, date back to the time of René Descartes and (arguably) remained the same even since. As such, I will generally use 'cognitive psychology' or the 'cognitive approach' to denote psychology's mainstream standpoint that the brain and brain processes are in control of human behavior.

(Meijer et al., 1988; Beek & Meijer, 1988; Van Wieringen, 1988; Aune et al., 2008). Due to their fundamental differences, they developed radically different accounts of movement coordination, both in the intra- and interpersonal domain. In the first chapter of this thesis, I will draw these contrasts as sharp as possible. My aim in doing so is twofold. In the first place, I want to provide a proper context for discussing the state-of-the-art research into interpersonal coordination, so as to prepare for the remainder of the thesis. Knowledge of the history of a discipline can provide new perspectives on findings and create a deeper understanding of a particular topic. In the second place, I wish to reveal the meta-theoretical assumptions that underlie the study of human (movement) behavior. In a time when progress in science is often driven by technological advancements rather than by theoretical breakthroughs (Krakauer et al., 2017), I believe that the philosophical groundwork of psychology deserves to be highlighted. From Cartesian dualism to Darwinian mutualism: this is the story of how to approach the coordination of human movement.

1. From Cartesian dualism to Darwinian mutualism: How to approach the coordination of human movement

1.1. Cognitive psychology

A widely accepted premise in modern day psychology is that the control and the coordination of our body is in the hands of our most complex organ: the human brain. Or, as renowned neurobiologist Dick Schwaab puts it succinctly: 'We [humans] *are* our brain' (Swaab, 2014, emphasis added). In his book, Schwaab envisions the brain as a large command center that controls not only the internal states of the body, like our thoughts and emotions, but also the external states, such as the movements of our limbs. The brain is claimed to monitor, to respond, to organize, to store and last but not least: to engage in social interactions. Like any other premise in science, this claim has not remained unchallenged. Over the years, it was met with fierce criticism from philosophers (e.g. Chemero, 2009) as well as neuroscientists (e.g. Krakauer et al., 2017; Gomez-Marin & Ghazanfar, 2019), who all provided arguments for why human behavior cannot be reduced to processes in the brain. Recently, it even led to a counter publication with the playful title 'We are our body' (Houterman, 2019). But despite this resistance, the brain-as-control-center remains one of the most powerful metaphors in psychology. It continues to guide behavioral experiments, including those in the domain of joint action (Azaad et al., 2021; Sebanz & Knoblich, 2021; Van Der Wel et al., 2021). The main reason for this persistence is that the metaphor is rooted in an age-old intellectual tradition of interpreting the body as a passive instrument that needs to be infused with life – or controlled with commands – for it to perform (Dijksterhuis, 1950; Withagen, 2010). One of the prominent figures in this tradition is René Descartes, a French philosopher who advocated a distinction between what we would nowadays call mind and body. To understand the work of Descartes and why it had such an impact on the modern field of psychology, we need to go back to the days of the scientific revolution in Western Europe.

1.1.1. Cartesian dualism

In many aspects, the scientific revolution was a breakthrough in the history of humankind (Withagen, 2010; Harari, 2014; Bregman, 2020). It formed the start of the Enlightenment – the Age of Reason – and it provided a new way of acquiring knowledge about the world. After centuries of dominance by a dogmatic Christian church, the world was no longer (only) known from reading the Bible, but (also) from making systematic observations. Within a few decades, this scientific revolution would turn our understanding of the world upside down. Throughout the Middle Ages, the flow of nature had been understood in terms of God's will. People believed that the Holy spirit had somehow infused the planet with life, causing the events of everyday life to unfold as they

did. This theological world view was derived from the ancient ideas of Aristotle (384 to 322 BC, Athens), who had written about intrinsic forces that would drive objects to their natural place in the universe. Rain, for instance, would fall down because its intended place would be on the ground. As such, Aristotle had asserted that all substances had an intentional propensity to move from one place to another. Although the Church would add the concept of a divine spirit to this view, the idea of intrinsic movement stood firm for centuries (Withagen, 2010). This changed, however, with a series of rigorous experiments. Scientists like Galileo Galilei (1564-1642) and Isaac Newton (1643-1727) demonstrated convincingly that objects did not have an intrinsic force, but that they moved as a function of *external* forces. These external forces were not specific to the object in question, but applicable to any other object in the universe. Thus, an apple does not fall to the ground because it belongs there, but because it is pulled to the ground by the force of gravity. Likewise, the motion of planets is not given in by God's will, but by the same force of gravity that pulls the apple to the ground. Thus, the flow of the universe, from the waves of the sea to the rolling of a ball, could now be captured with the laws of physics. Dijksterhuis refers to this process as the 'mechanization' of our world view (Dijksterhuis, 1950; Withagen, 2010).

Initially, the new mechanistic outlook on the world was only applied to the non-living domain. Research focused on the movement of celestial bodies in the sky and on physical objects on our planet. It took not long, however, before the realization sank in that not only the inanimate world, but also the animate world is ultimately subjected to Newtonian forces. In 'De Motu Animalium' (1680), Italian scientist Giovanni Borelli (1608-1679) was among the first to apply the principles of mechanics to human and animal movement. By computing the external forces that worked on a body during activities like walking and flying, he derived the muscular forces that are exerted during these activities. With these analyses, he laid the groundwork for what would later become the field of biomechanics. By conceptualizing the muscles as levers and pulleys, Borelli openly speculated about the mechanistic character of bodies. These speculations led, for instance, to the powerful insight that muscles do not expand, but contract in order to move the joints. But perhaps more importantly, his work contributed to the rapid mechanization of the animate world (Withagen, 2010). Not long after, engineers would start to build animal robots with life-like functions, which were famously exposed in the Gardens of Versailles. An exquisite example of this was the pooping duck of De Vaucanson (1709 – 1782). Such robots were reflective of the zeitgeist: animal behavior was believed to be an affair of forces and mechanisms, not unlike the ticking of a clock. But what about human behavior? The question rose whether our behavior could also be understood in terms of levers and pulleys, causes and mechanisms.

According to René Descartes (1596 – 1650), this question should be answered negatively (Withagen, 2010). Human life is not mechanistic and generic, but intelligent and unique in its sort. As most important reason for this claim, he argued that humans are the only species that are able to reason. In contrast with cats and dogs, we have the capacity to think rationally and to reflect on our actions. In 'Principia Philosophiae' (1644), he claimed that this rationality is given in by an *immaterial* soul residing in the

pineal gland, just under the brain. He referred to this soul as the 'res cogitans', the thinking substance. To the body, he referred as the 'res extensa', the *material* substance. Thus, he advocated a dualism of body and soul. Although he was not the first to propose a dualism – Plato had already defended a similar idea more than 2000 years before him (Tamboer, 1988) – Descartes' thesis would have a lasting impact on psychology. This is not to say that the philosophy of Descartes was undisputed in the centuries that followed (Reed, 1997; Withagen et al., 2010). In contrast, it would evoke countless debates among scholars. Anatomist Thomas Willis (1625 – 1675), for instance, would argue that not the pineal gland but the brain on top of that is the main determinant of our behavior. Physician Robert Whytt (1714 – 1766), as another example, would use observations from decapitated frogs to conclude that the soul could not possibly reside in the head. It must, so he proposed, be pervaded throughout the entire body (Meijer et al., 1988; Reed, 1997)! Around the same time, Julien de la Mettrie (1709 – 1751) would defend the opposite position. The human body was, to his idea, devoid of any spiritual substances like a soul. It was in essence a mechanistic apparatus. A standpoint that would later be famously defended by materialists such as Thomas Huxley (1825-1895). Nevertheless, when the scientific discipline of psychology emerged around 1890, and the religious concept of the soul was replaced by the contemporary notion of the mind (Reed, 1997), the conclusion was this: Body and mind – the physical and the mental – should be regarded as separate entities. The dualism of Descartes had survived the whirlwind of ideas in the 18th and 19th centuries and would form the foundation of the discipline of psychology.

Crucial to dualism of Descartes is the idea that the body, as opposed to the mind, can be understood in mechanical terms (Withagen, 2010). As a vehicle of the mind, the human body requires internal or external control in order to act purposefully. Tamboer (1988) referred to this as a substantial image of the body, which he contrasted with more relational images. The latter perspective will come to the fore in the section on Ecological Psychology (1.3). Perhaps the best illustration of the body's mechanization is the brain-as-computer metaphor, which arose around the 1960s in the field of psychology (R. A. Schmidt, 1975; Cisek, 1999; Brette, 2022). Recall also the command center analogy that Schwaab used to describe the human brain. On the one hand, these metaphors served as helpful demystifications of a behavioral system that is otherwise hard to fathom. On the other hand, they have created a stereotypical version of the body that has guided the research in psychology. This substantial body image can be summarized in three key assumptions. First of all, human behavior is assumed to be caused by mechanisms that are *intrinsic* to the body (Vaccari, 2003). These mechanisms may be hidden from sight and highly complex, but they can in principle be understood in isolation from the environment. Secondly, the mechanisms of behavior can be broken into constituent parts which retain their function in isolation from each other. Much like a machine that can be dismantled and reassembled, the human body and its behavior can be studied in parts. Essential to this view, is the belief that elements of behavior, or of the body for that matter, do not derive their meaning from the whole that they compose. Each building block should have meaning in and of itself. Thirdly, in a substantial body the mind only as an indirect access to the outside world. While visual, haptic, olfactory and other sensations stimulate

the body's senses, only the mind can compose these sensations into a meaningful whole. This creates an internal representation of the outside world, on the basis of which the mind can be in (indirect) contact the body's environment. Likewise, the mind produces purposeful actions by bringing together the relevant 'units of movement' that are it its disposal in the neural networks of the brain (Reed, 1982, 1988). As such, the coordination of movement becomes an issue of biomechanical control of the body. In this context, it is understandable that cognitive psychology's study of human movement we come to be known as the science of *motor control* (Schmidt & Lee, 2005).

1.1.2. A cognitive approach to motor control

As explained in the introduction of this thesis, the study of human movement is much indebted to the work of Nikolai Bernstein. At the time Bernstein developed his ideas (1920-1950), the coordination of movement was assumed to be based on a concatenation of elicited reflexes (Bongaardt & Meijer, 2000). This reflex chaining hypothesis was originally posed by William James (James, 1890), the father of modern psychology, and further developed by physiologist Charles Sherrington (Sherrington, 1906). It is not difficult to see how this theory was rooted in the mechanistic view of the human body (Withagen & Michaels, 2005). Human movement was thought to be generated in the same way that the pressing of a button would evoke the motion of a robot. But as James readily admitted, reflexes alone do not suffice to explain willful and adaptive behavior. Bernstein went even further to assert that *any* theory of coordination should at least provide an account for how the body masters its many degrees of freedom. Given the substantial image of the body, this implied that the human mind would consistently be confronted with a massive control problem. It would have to activate the muscles of the body like a puppeteer that has to pull the strings of his puppet (Turvey 1990). With the rise of the computer metaphor, this control problem would become synonymous with the algorithmic problems that a computer faces in executing a task (R. A. Schmidt, 1975; Cisek, 1999; Brette, 2022). In other words, the field of cognitive psychology would borrow concepts from information theory to approach the problem of coordination (Beek & Meijer, 1988; Adams, 1987; Warren, 2006; Huys et al., 2014). The most straightforward example of this is the cognitive notion of a motor program, which would be constitutive of the (early) cognitive approach to motor control (Schmidt & Lee, 2005).

A motor program can generally be defined as a stored blueprint for an action, similar to an algorithm in the software of a computer (Schmidt & Lee, 2005). The hardware, in this example, would be biological architecture of the central nervous system. In the earliest accounts of motor programs, such blueprints were proposed to contain a sequence of muscle commands that would be carried out by the body, without any peripheral feedback (Lashley, 1951; Keele & Posner, 1968). Later accounts suggested that the programs were more abstract, in the sense that the provided more global instructions for classes of actions, such as the throwing or kicking of an object (R. A. Schmidt, 1975; Shea & Wulf, 2005; Schmidt & Lee, 2005). In the most recent versions, the blueprints for action are claimed to reside in lower neural networks in the spinal cord (Bizzi et al., 2008; d'Avella & Lacquaniti, 2013). This would leave 'room' for the brain to engage in other

tasks, such as establishing social interactions. But in any of these accounts, the role of the brain would be to select, compile and parametrize a limited set of building blocks for action. Note how this process is characteristic for the functioning of a machine (Withagen, 2010). It breathes Cartesian dualism. This dualism is even more apparent in the internal model approach to motor control (Wolpert, 1997; 2000, 2011). Internal models are looped optimization algorithms that select limb trajectories on the basis of criteria such as minimum energy, minimum jerk or combinations thereof (Todorov & Jordan, 2002, 2004). The assumption underlying these models, is that the algorithms are somehow embedded in the neural hardware of brain. In combination with more abstract 'higher order' concepts like motivation, empathy or emotion, these algorithms would constitute an indispensable building block for the generation of human movement behavior.

1.1.3. From intra- to interpersonal coordination

If one thing stands out from the preceding overview, it is that Cartesian dualism renders human movement to be an issue of biomechanical control. Those who wish to understand the coordination of our actions would need to acquire an insight into the control center that pulls the body's strings. This conclusion has important implications for the coordination of movement *between* individuals – the topic of this thesis. To begin with, we have seen that study of motor control is a purely mechanical affair. This means that all potentially helpful concepts like empathy or trust should be regarded as additional building blocks in a larger architecture that supports interpersonal coordination (Vesper et al., 2010). That is, 'social' concepts are extrinsic to the mechanisms for motor control. At the same time, our behavioral system may have developed specific mechanisms dedicated to social interactions (Sebanz et al. 2006, 2021; Knoblich et al., 2011 Azaad et al., 2021; Vesper et al., 2010, 2017). In any case, however, we are looking for a set of mechanism that are complementary to the algorithms of motor control. A second implication of the Cartesian dualism, is that the mechanisms for interpersonal coordination are to be found inside the architecture of the human brain. They are localizable, at least in principle (Pacherie & Dokic, 2006; Newman-Norlund et al., 2007; Rizzolatti 2004, 2010). After all, the body is an instrument of the mind and the mind resides in the brain. De facto, this implies that the interpersonal coordination of movement can be reduced to an interpersonal coordination *of minds*.

Traditional research into social behavior involved experimental paradigms with participants seated behind a computer, responding to stimuli that popped up on a screen (**Figure 1.1**). Instead of joint angles trajectories and muscle recordings, outcome measures included reaction times (RT) and verbalized responses (e.g. Sebanz et al., 2003, 2005). At first glance, it seems that such research can hardly tell us something about interpersonal coordination. After all, these studies do not involve much movement. A closer look reveals, however, that the conceptual framework developed with this work is essential to understand the cognitive perspective on social coordination. In particular, it is the construct of a shared representation, also known as a co-representation, that is key to this approach (Sebanz et al., 2005; Van Der Wel, 2015). According to cognitive psychology, the only way for humans to anticipate to each other, is to mentally simulate

the task setting from the perspective of the other individual. In other words, interpersonal coordination requires us to 'look through the eyes of our partner'. Under the assumption that we possess dedicated mechanisms to do so and that these mechanisms can be studied in isolation from the algorithms of motor control, one can investigate interpersonal coordination in simple stimulus-response settings. To illustrate, Sebanz and colleagues (2005) found that the RT of participants in a two-choice paradigm was contingent on the task demands of the co-actor next to them, even if those demands were irrelevant to their own performance. This suggested that they took the task of the other individual into account ('co-represent') in the preparation of their own response, leading to a longer RT. Extrapolating this finding to the hypothetical setting of carrying a table together, this co-representation mechanism would be helpful to anticipate on your partner's upcoming movements (Sebanz et al. 2006, 2021; Knoblich et al., 2011; Vesper et al., 2010, 2017).

In recent years, this research has expanded in two directions. On the one hand, behavioral studies have been conducted to find evidence for co-representations in more embodied task settings (e.g., Schmitz et al., 2017). Participants moved from sitting in front of a computer to interacting with each other in reality. On the other hand, studies have investigated the neural embedding of the co-representations (Gallese, 2003; Newman-Norlund et al., 2007; Rizzolatti 2004, 2010). In particular, the hypothesis has been

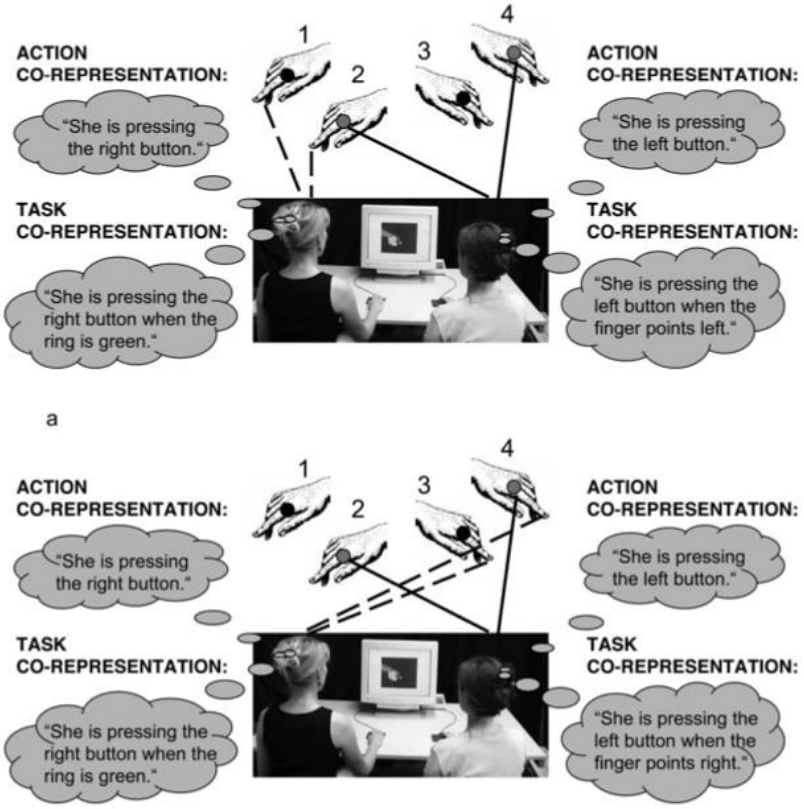


Figure 1.1 : The typical set-up of an experiment to study social behavior from a cognitive perspective. Participants have to respond to stimuli on the screen. The think bubbles represent the hypothetical mental (co-)representations of the action, which would serve to coordinate the behavior between the two participants. From: Sebanz et al. (2005)

explored that the mirror neuron system, famously discovered in the ventral prefrontal cortex of macaque monkeys (Rizzolatti et al., 1996), plays a role in our ability to interact with others. In the next section, I present a brief overview of both strands of research. Moreover, I review empirical studies into other hypothetical mechanisms for interpersonal coordination, like action monitoring (e.g. Loehr et al., 2013), sensorimotor communication (Vesper et al., 2011) and inter-brain synchrony (Réveillé et al., 2024). Rather than aiming to be complete, my goal is to sketch the outlines of the mechanistic framework for social behavior of cognitive psychology.

1.1.4. Contemporary research

Behavioral evidence for co-representations is mostly provided by studies that show how people engaged in a joint action take the task constraints of others into account in their own actions. For instance, Meyer et al. (2013) conducted an experiment in which participants had to pass an cylinder to another participant, who then had to put it on a shelf with a variable height. Critically, the cylinder could be grasped in two different ways and the instruction for participants was to take over the cylinder in the same way their partner had given it to them. Results showed that participants quickly learned to adjust their grip choice to the height of the shelf on which *their partner* had to put the cylinder. In other words, participants anticipated to the task demands of the other individual engaged in the joint action. This suggests that humans have the ability to look through the eyes of a partner to facilitate joint action. Schmitz et al. (2017) showed that people can even take each other's task demands into account when this implies an increased movement effort for themselves. In their experiment, dyads of participants performed back-and-forth reaching movements between two targets, with the aim to synchronize their landing times. As a twist, one of the individuals had the additional task to avoid an obstacle, while the other had a free reaching path. Motion analyses showed that participants with the free reaching path tended to simulate the obstructed path of motion of their partners. This suggested that they took the constraints of the other individual into account in their own planning, providing support for the co-representation hypothesis.

With respect to the neural embedding of the co-representation mechanism, EEG studies indicated that several brain regions are involved (Newman-Norlund et al., 2007; Kourtis et al., 2013, 2019). For instance, multiple frontoparietal cortex regions associated with action selection were equally activated by stimuli cueing a solo action as by stimuli cueing a joint action (Kourtis et al., 2013). This result was later replicated in other settings, such as the familiar joint activity of clinking of glasses with someone at a party (Kourtis et al., 2014). A neural mechanism that is particularly interesting in this context is common coding of perception and action. Also known under the intuitive name of 'mirror neurons' (Gallese, 2003; Rizzolatti 2004, 2010), this involves a class of neurons that spike both when an individual performs an activity and when they observe *another* individual performing that same activity. Such neurons were first discovered in the ventral prefrontal cortex of macaque monkeys (Rizzolatti et al., 1996), but were soon also found in human brains. The exact role of these neurons in our behavior is still under debate. Some claim that the neurons constitute a mechanism for empathy: our ability to

understand and feel for other individuals (Gallese, 2003). Others have criticized the premature generalization of findings from monkey studies to human behavior (Hickok, 2009) and the meta-theoretical assumptions underlying the interpretations of mirror neuron research (Krakauer et al., 2017). In the next section, I will address these concerns in more detail.

Another mechanism which may facilitate interpersonal coordination is our ability to monitor the performances of others (Van Schie et al., 2004). This allows us to detect the deviations in our co-actor's performances, which often constitute events in which we have to intervene or adapt our own actions to succeed in the joint performance. In an EEG study, Loehr et al. (2013) investigated the brain activity of two piano players playing during a duet. The experimenters manipulated the piano keys so that a false tone was occasionally produced during the performance. Recordings showed that the brains of both players were sensitive to the false tones, regardless of who produced the error. In a follow up study, they found that the extent of the brain response was larger when the false tone was involved in a joint harmony rather when it was involved in a solo piece (Loehr et al., 2015). This supported the hypothesis that error detection is a mechanism well suited for interpersonal coordination. Brain areas that are specialized in the monitoring of human (limb) movements are the extra-striate body area (EBA) and the superior temporal sulcus (STS) (Newman-Norlund et al., 2007). Furthermore, there is empirical evidence that we are particularly skilled in paying attention to the same environmental features as our partner in the joint action, a mechanism known as joint attention (Sebanz et al., 2006; Innocenti et al., 2012). In a visual search experiment Brennan et al. (2008) showed that dyads were more efficient in searching on the screen for an object when they shared their gaze (i.e., where they looked on the screen) with someone else. This suggests a facilitating role of joint attention in collective activities.

A helpful facilitator of interpersonal coordination is sensorimotor communication. This is a non-verbal way of communication that is based on making your movements more predictable (Pezzulo et al., 2013, 2019; Vesper et al., 2017). Research into sensorimotor communication often involves dyadic tasks in which one participant has to take the lead, while another has to follow. Usually, the leading participant has more information than the follower and the issue under study is if (and if so, how) this participant communicates that information to their co-actor without talking. For example, Sacheli et al. (2013) instructed dyads to jointly grasp a bottle-shaped object. The leader of the two was given specific instructions as to where to grasp the bottle, whereas the follower was merely instructed to coordinate with the leader. Analyses of both participant's movements revealed that leaders were inclined to exaggerate the aperture of their grip and to decrease the variability of their movement. This suggests that they increased the predictability of their movement behavior so as to facilitate the interpersonal coordination. Vesper & Richardson (2014) studied an dyadic tapping task in which one of the two participants had knowledge of the target locations. Likewise, they found that leaders exaggerated the height of their tapping movement in order to make themselves predictable to followers. But sensorimotor communication can also be bidirectional, as shown by Van Der Wel et al. (2011). In their experiment, participants had to move an

unstable inverted pole back and forth between two targets by each pulling on a cord attached to the base of the pole. Results revealed that dyads produced pulling forces that were strongly overlapping, in particular when the targets were smaller and the accuracy demands higher (**Figure 1.2**). This suggests a haptic form of sensorimotor coordination, much like a mutual force channel to inform each other about your actions. More generally, haptic interactions have been shown to be essential to interpersonal coordination (Ganesh et al., 2014; Takai et al., 2023).

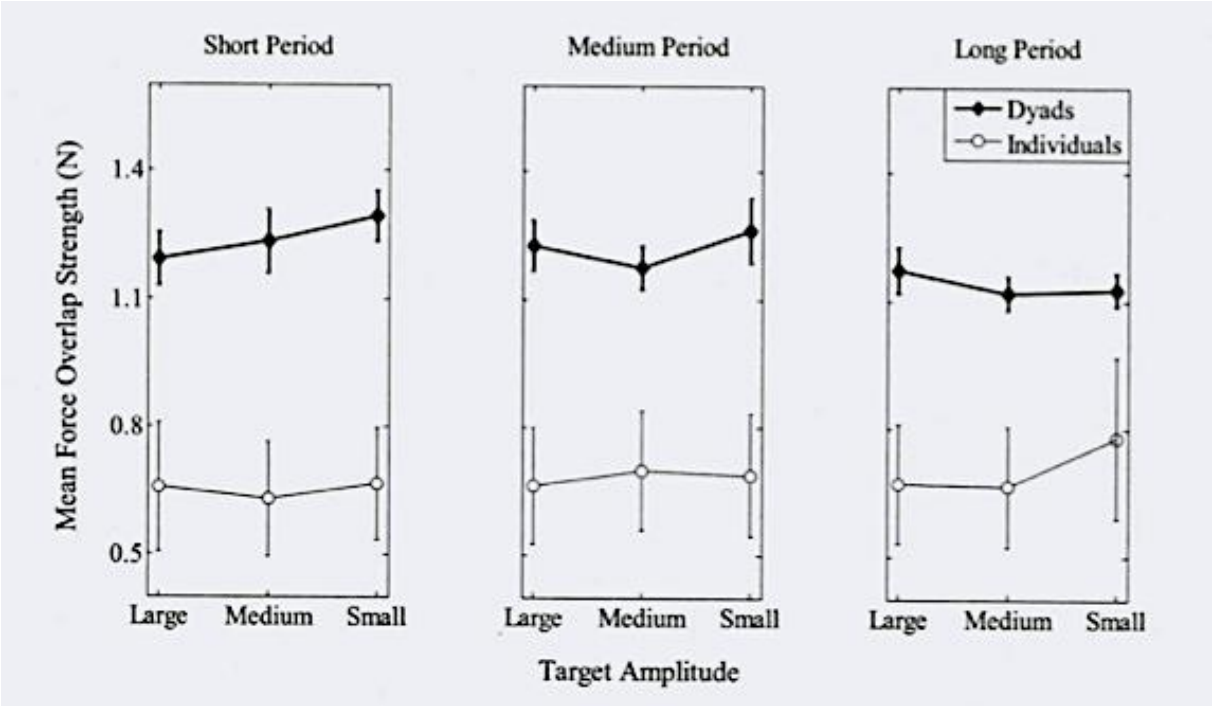


Figure 1.2 : The amount of force overlap (N) in individuals (white) and dyads (black) in the reciprocal movement of a pendulum with a short (left), medium (middle) and long (right) period time. The force overlap was larger in the dyadic conditions, in particular when the targets were smaller. This suggests a haptic form of communication, whereby co-actors covertly inform each other about their movement behavior. From: Van der Wel et al. (2011)

The last phenomenon that I would like to touch upon in this overview is that of Inter Brain Synchrony, IBS in short (Réveillé et al., 2024). IBS refers to the degree of spatiotemporal similarity between two patterns of brain activity during the performance of a joint action (**Figure 1.3**). It can be measured with various techniques, such as electro-encephalography (EEG), functional magnetic resonance imaging (fMRI) or functional near infrared spectroscopy (fNIRS). While these techniques differ in the measured resolution, they are all informative about where and when the brain is active during a performance. This is also called 'hyper scanning' (Hamilton, 2021). Even though hyper scanning studies are more and more conducted, a cohesive theoretical framework with respect to IBS is currently lacking (Réveillé et al., 2024). Some claim that interpersonal synchronization of brain activity is a mechanism for social coordination in itself. For instance, it would be a mechanism for shared intentionality between individuals (Fishburn et al., 2018) or non-

verbal information transmission (Hasson et al., 2012), not unlike to the supra-natural concept of telepathy ('mind reading'). Others argue that IBS is not a mechanism in itself, but that it reflects other mechanisms that facilitate or enable interpersonal coordination (Réveillé et al., 2024). To speculate, it may be a reflection of activity in the beforementioned mirror neuron system for common coding of perception and action. But in any case, IBS constitutes an interesting phenomenon that certainly requires more research before any conclusions with respect to its role in interpersonal coordination can be drawn.

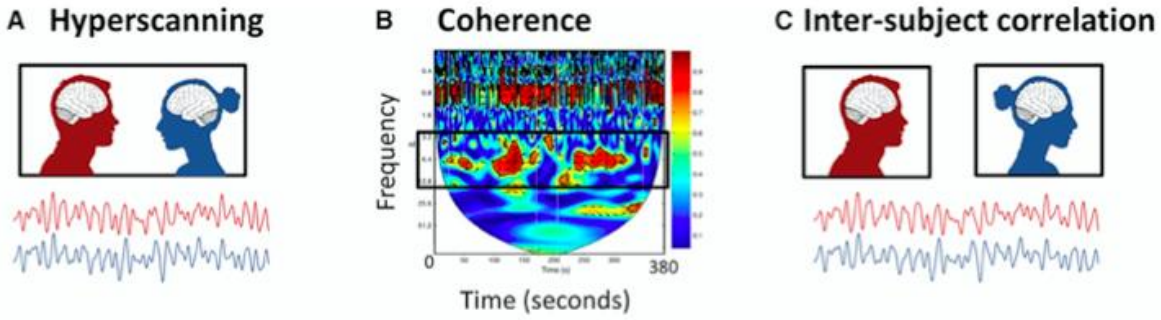


Figure 1.3: A visualization of hyper scanning, the simultaneous measurement of brain activity of two or more individuals via for instance fMRI or EEG. From: Hamilton (2021)

1.1.5. Reflection

Cognitive psychology holds that interpersonal coordination is facilitated by a variety of neural mechanisms. From shared representations to action monitoring and from sensorimotor communication to inter brain synchronization: the list is long and far from exhausted. But how do these mechanisms relate to one another? Usually, they are assumed to be organized in a hierarchical fashion, from higher order to lower order cognition (Sebanz et al. 2006; Vesper et al., 2010, 2017). In this structure, higher cognition refers to more abstract psychological concepts, such as empathy or intention. These concepts are abstract in the sense that they are relatively intangible: they are difficult to measure, to observe and to localize. This is problematic, since the cognitive framework is rooted in a mechanist approach to body and behavior, according to which the behavioral system can in principle be reduced to its constituent parts. Luckily, however, lower order cognition comprises more concrete mechanisms that are easier to map out and record. The mechanisms of action monitoring and sensorimotor communication would belong to this realm, since they are easily measured with EEG or motion capture systems. An interesting outlier in this hierarchical organization is the common coding of perception and action, hypothetically caused by the mirror neuron system (Rizzolatti & Sinigaglia, 2010). One the one hand, mirror neurons are associated with empathy and social understanding, concepts that are usually attributed to the category of higher order cognition. On the other hand, mirror neurons represent a direct and observable neural mapping from perception to action, implying that the mechanism belongs to lower level

cognition. One way to account for this apparent paradox would be to consider mirror neurons as an intriguing exception – a special case – to an otherwise orderly cognitive organization. This is the most common interpretation of the mirror neuron system (Gallese, 2003; Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). An alternative interpretation could be that this anomaly reflects a deeper, meta-theoretical problem in the hierarchical-mechanistic framework for interpersonal coordination (and human behavior more generally). In this thesis, I propose to follow the latter interpretation. In what follows, my aim is to reveal the philosophical deficiencies of a cognitive psychology, so as to pave the way for an alternative (ecological) approach to interpersonal coordination.

To begin with, many concepts in psychology are ascribed to the brain, while they can only sensibly be attributed to the behavioral system as a whole (Krakauer et al., 2017). This mistake is also known as the mereological fallacy or category mistake (Smit & Hacker, 2014) and it is among the most commonly made errors in cognitive psychology. Case in point is the (in)famous claim of Dick Schwaab that "we are our brain" (Swaab, 2014). But this is by no means the only example. Think, for instance, about the concept of empathy being attributed to the mirror neuron system (Rizzolatti & Sinigaglia, 2010). Or consider the monitoring of human movement, which we saw is (at least partially) ascribed to the brain's STS and EBS regions (Newman-Norlund et al., 2007). In each of these examples, the behavior of the human being as a whole is reduced to some pattern of neural activity in the brain. This is fundamentally incorrect, since behavior takes place at the interface of our body with its environment, and not in the theatre of mind underneath our skull. The limbs with which we move and the ground against which we push off are all constitutive of our behavior, even in the most elementary sense of the word. Human behavior is not (only) a cognitive affair, but (also) an embodied and embedded phenomenon (Gomez-Marin & Ghazanfar, 2019). Postulating that we are our brain is to neglect these dimensions of our behavior. This is not to say that any cognitive psychologist would ever deny that we have a body or that our actions are situated in an outside world. However, by claiming that we are equal to our brains' activity, the tacit assumption is that the brain can somehow account for the embodied and embedded dimensions of the body's behavior. It would do so by generating an internal representation of the external world (R. C. Schmidt et al., 2011), including a representation of the body itself (Carruthers, 2008). In facilitating joint action, we have seen that the brain is even claimed to create co-representations of other individuals (Sebanz et al., 2003). Unfortunately, the psychological concept of a representation is philosophically problematic, since it raises a new set of meta-theoretical issues (Turvey et al., 1981).

As Warren (2006) points out elegantly, an internal representation leads to a "somewhat solipsistic view of perception and action" (Warren, 2006, p. 360). As a human agent, you do not observe your surroundings, but you only see, hear, smell and feel a mental representation thereof. Likewise, you do not have the control over your own limbs, but you merely perform cognitive operations on an internal representation of your body. If this were indeed the case, then the question can be raised where this representation comes from, given that the actor (i.e., the mind) has never been in direct epistemological

contact with the outside world (Turvey et al., 1981). How could one ever verify what the representation stands for in the 'real world' if any contact with that world is cut off? A similar issue applies to the concept of a motor program (e.g. Schmidt, 1975). How can such a program explain the coordination of movement behavior if it is unclear where the presupposed spatiotemporal organization in the program comes from in the first place? Of course, one could appeal to innate representations of the world and of one's body, which would allow a human being to navigate through the environment without having acquired any prior experiences. In 'Critique of Pure Reason' (1787), Immanuel Kant already spoke of an inborn framework for space and time that would be necessary to have experiences. Yet, this explanation would beg the question of how individuals are able to learn, adapt and develop if they are deprived form any contact with the world. One way or another, issues of circularity (i.e., explanatory regress, Warren, 2006) haunt the theoretical framework of cognitive psychology.

The position that behavior cannot meaningfully be attributed to brain process alone, does not, of course, make it illegitimate to study the role that neural mechanisms may play in the generation of behavior. However, it renders a direct 'mapping' of brain processes onto behavior very complex and perhaps even principally impossible. Aside from the issues mentioned before, a more practical problem is that the brain exhibits a deep degeneracy (Marom, 2009): the same behavior may result from different neural circuits, while different behaviors may arise from the same circuit (Krakauer et al., 2017). This phenomenon also occurs on a behavioral level, where we refer to it as the multiple realizability of functions (Withagen & Michaels, 2005) or as motor equivalence (in the case of movement generation) (Schoner, 1995). We have seen an example of such motor equivalence in the introduction of this thesis, when I spoke of the infinitely many ways in which an individual can shake hands. This degeneracy implies that brain-behavior mappings are either one-to-many, many-to-one, or even many-to-many. In this perspective, it is no surprise that a cohesive theoretical framework for the mapping behavior onto the brain, or vice versa, is lacking. Neuroscientific research is often driven by advancements in technology rather than by advancements in the understanding of cognition and behavior (Krakauer et al., 2017). This is also reflected in the lack of consensus on the level of brain organization that should be studied. Research into mirror neurons, for example, was initially based on single cell recordings in macaque monkeys (Rizzolatti et al., 1996), but,within decades the focus had shifted to the recording of neural populations and entire brain regions (Rizzolatti & Sinigaglia, 2010). Remarkably, the interpretation of how mirror neurons may relate to behavior – i.e., via empathy or social understanding – has remained the same throughout the years. Add to this that empirical support for the behavioral manifestation of social understanding is still lacking and the problems of cognitive psychology reveal itself.

From the arguments presented here, I conclude that a psychology rooted in Cartesian dualism is untenable. The hierarchical-mechanistic approach to behavior and cognition runs into several philosophical problems and is not in accordance with empirical reality. As intuitive as the computer metaphor may be, I argue that it draws upon an analogy that does not do justice to the nature of our behavioral system. Our body is not a machine, but

a living system. Living systems are self-sustained and they are organized in a functional rather than in a mechanical manner (Reed, 1982, 1988). Living systems exhibit a certain goal-directedness with respect to their environment, something that machines do not have (or at least not in the same way as animals) (Gomez-Marin & Ghazanfar, 2019). In my view, the degeneracy in our brain and behavior is as a reflection of those properties. Thus, I conclude that a deeper understanding of behavior can only be acquired when one starts by investigating the behavior's functional role in the environment rather than by (only) exploring its mechanism in the brain. Functionalism, as opposed to mechanicism, is rooted in the work of Charles Darwin, one of the most famous biologists of all time.

1.2. Ecological psychology

Published more than two centuries after 'Principia Philosophiae' of René Descartes (1644), Charles Darwin's 'On the Origin of Species' (1859) counts as one of the most influential books in the history of science. In this publication, Darwin provided a groundbreaking theory about the evolution of life on earth, including the life of humankind. Having collected evidence from all over the world, he proposed that a simple combination of individual variability and inheritance of traits accounts for the long term adaptation of species to their environment. The rationale is as follows. Most animals produce more offspring than what can survive. From this pool of infants, only those who have a good fit to their environment will live to have the opportunity to procreate. As a result, only those who are best adapted to their natural environment will pass on their traits to the next generation. Under the condition that the environment remains invariant on a short timescale, this implies that the next generation is more likely to be adapted to the environment than their parents. This way, a species evolves as a function of selection pressure exerted by their natural environment. Given that we, as humans, live in that world too, we are no exception to this process. Whereas Descartes had claimed that human life is unique in its sort, Darwin argued that we are a descendant of the apes. It is well known this claim led to strong opposition from religious institutes at the time. Less well known, however, is that Darwin's ideas would also come to have a profound impact on psychology, a field that would emerge in the decades following his work. This impact can be summarized in two key insights, which would provide a fertile ground for an ecological psychology to be built upon.

1.2.1. Darwinian mutualism

The first key insight derived from Darwin's evolution theory is that human behavior has evolved to become adapted to the environment. That is, our behavior is given in by a primal need to establish *functional relationships* with our surroundings that help us to survive (Reed, 1982, 1988). Our actions, movement behavior included, constitute ways for us to relate to our environment, to achieve goals (Tamboer, 1988). According to phenomenological philosopher Merleau-Ponty, we should therefore understand a movement as a bodily being-in-the-world rather than as a reflection of all that occurs in

the mind's palace (Merleau-Ponty, 1945). In contrast with what is assumed in cognitive psychology, the body is not passive, isolated and waiting to be controlled by the brain. It is active, related and exploring the world in which it lives. In doing so, the body is pulled through the environment by what Merleau-Ponty refers to as 'intentional threads' (Houterman, 2019). This dynamic portrayal of body and behavior ties in well with the second fundamental insight from the work of Darwin: Life on earth is self-sustained. Ecosystems constitute a dynamic balance between species and their environments (Godfey-Smith, 2024). Although the process of evolution is open-ended, or perhaps because of that, nature has the capacity to organize itself and to settle into stable situations in the absence of external control. This is only possible because of a mutual dependency of animals, plants and their environment (Oyama, 2000; Van Dijk, 2021a, 2021b; Withagen et al., 2024). The realization that human behavior is situated in self-sustaining ecosystems would turn psychology upside down. Among the first to explore these implications was the philosophical school of American pragmatism and functionalism, pioneered by William James in the late 19th century (Backe, 2001; Green, 2009).

In 'The Principles of Psychology' (1890), William James approached the human mind by situating it in the process of evolution. He proposed to conceive of cognitive concepts, like emotions, as functionalities to accommodate for our survival (Backe, 2001). Inspired by his mentor, John Dewey further developed this by applying the notion of functionality to the actual cycle of perception and action. To do so, he borrowed an example from the opening pages of James' work: that of a child burning her hand on a candle (Green, 2009). In the mechanistic tradition, James had proposed that an event like this was best understood as a concatenation of stimulus-response-reflexes, initiated by the flame that touched the hand and followed by a percept and a series of retraction movements. Dewey, in contrast, argued that the process was more circular than that. According to him, it starts by the 'act' of seeing the flame: "Now if this act of seeing stimulates another act, the reaching, it is because (..) seeing and grasping have been so often bound together to *reinforce* each other, to help each other out, that each may be considered practically a subordinate member of a bigger coordination." (Dewey, 1986, emphasis added). While the seeing is necessary to reach accurately, the reaching also aids the seeing of the flame because the child has to keep her eye on it. In the 'bigger coordination', of which Dewey speaks, both Darwinian insights tacitly come back. First, the behavior is not a mechanistic chain of stimulus and response, but a functional relationship between the girl and the flame. Seeing and reaching are likely to have evolved together, since one cannot be without the other. Second, the reciprocity of perception and action give rise to the self-sustained character of the so-called bigger coordination. As members of that coordination, seeing and reaching coordinate each other. Critically, this can only occur because of the open-ended nature of the activity (Van Dijk, 2021). With his work, John Dewey challenged the traditional assertion that perception and action are logically distinct, which had been assumed ever since Descartes' dualism. Not long after, James J. Gibson would provide the final blow to the Cartesian dualism and instead embrace a *Darwininan mutualism* in psychology.

James J. Gibson was a psychologist with a particular interest in the topic of vision (Withagen et al., 2010; Lobo et al., 2018). As a neo-Darwinian, he started his investigation with the function of our visual system. Why do we possess the capacity to see? In contrast with what was (and is) often assumed, he proposed that our vision is not meant for the generation of pictorial representations of the outside world in our head. He argued that our vision is evolved for us to navigate through our environment. As such, the object of our vision is most likely all that is relevant for us to achieve this function. In line with this reasoning, Gibson's next step was to identify the nature of this object. In other words, what is it that we perceive in order to find our way through the world? He asserted that we do not see our environment in terms of its physical properties, but in terms of how we can *use* it, that is, in ecological terms. To describe these properties, he introduced the notion of an affordance. Affordances, so Gibson defined, are "what [the environment] offers the animal, what it provides or furnishes, either for good or for ill" (Gibson, 1979, p. 1919). Crucially, an affordance is a relational concept, similar to the intentional threads of which Merleau-Ponty spoke. What an object offers the animal is not only dependent on that object, but also on the animal itself. For instance, a chair may afford sitting for an adult, but standing for a young toddler, who is smaller and incapable of sitting down on the chair. With this novel psychological concept, he highlighted the reciprocity of animal/agent and environment, which form an inseparable pair.

Having established the 'why' (navigation) and the 'what' (affordances) of perception, Gibson's next step was to devise a theory of *how* agents are capable of perceiving their environment. Being a radical empiricist like William James, he believed that knowledge of the world can only be acquired via meaningful interaction with the world (Lobo et al., 2018). In contrast with James, however, he interpreted these meaningful interactions as a form of direct epistemological contact between agent and environment. The foundation of this direct relationship is formed by the notion of information. Like an affordance, he defined information at an ecological scale. For Gibson, information resided in the structured patterns of energy which specify an affordance to an individual. In the case of vision, these structured patterns consist of an ambient array of light. One the one hand, this array is dependent on the to-be-specified object(s) on which it reflects. Through reflections, the structure in the array is one-to-one related to the shape and texture of an object. When it reaches the eye (or any other structure capable of detecting structure in light), it constitutes a rich pattern of information that is independent of the sensory equipment. On the other hand, the array is also contingent on the perceiver of the object. In particular, it is specific to the movement of the agent in relation to the object that is perceived. The focus of expansion in a changing ambient array, for instance, is informative of the heading direction of the agent and can thus be used to navigate towards the object so as to manipulate it. Moreover, the faster one moves, the faster the structure in the ambient array changes. This illustrates the usefulness of information for finding our way in our environment, which Gibson proposed to be the primary evolutionary function of vision. Note, also, the (Darwinian) mutuality in this concept of information. Like an affordance, information has a relational dimension, between perceiver and to-be-

perceived object (which therefore constitutes the affordance for that perceiver) (Withagen & Van Der Kamp, 2010).

With his theory of visual perception, Gibson shook the field of psychology to its foundations (Bruineberg et al., 2024; Lobo et al., 2018). In extrapolating his ideas to other modalities like hearing or touch, he posed the hypothesis that our perception of the world is fundamentally direct (Michaels & Carello, 1981). That is, due to the richness of information, no indirect representations in the theatre of the mind are required for us to know our environment. This was is in sharp contrast with existing theories of perception, which unanimously assumed that the stimuli on the retina needed to be enriched with meaning for them to be useful. Meaning, so Gibson asserted, resides in the mutual relationship between the animal and its environment. This mutuality also applied to perception and action, which turned out to be two sides of the same coin (Michaels et al., 2001). As much as we need to perceive (the affordances in) our environment to act purposefully, we also need to act in order to perceive that environment properly. This reciprocity was highlighted by his description of the (changing) ambient optical array and would have far stretching consequences for the study of human movement. Any account of coordinated movements would be incomplete without a principled explanation for how these movements are sustained by (and sustaining of) the information specifying an affordance (Turvey et al., 1981; Bootsma 1998). It also implied that the control of our movements (and likewise, our behavior) was no longer believed to be in the hands of an executive center pulling the strings of our body, but embedded in the agent-environment relationship. In the words of Gibson, our behavior is "regular without being regulated" (Gibson, 1979, p. 215). Hence, there was a need for a psychology at an ecological scale, rather than at the level of cognition.

In the decades following Gibson's work, this ecological psychology would slowly take shape (Bruineberg et al., 2024; Lobo et al., 2018). For instance, a research program was set up to identify the informational variables which specified our environment to us and which we could hypothetically use for navigation. A prominent example of this is the variable tau, which would specify the time-to-contact of an agent with an object (e.g. Lee, 1976 Bootsma, 1988). For further information about the historical development of ecological psychology, I refer the reader to Lobo et al. (2018), Bruineberg et al. (2024) or other reviews. Here, I will focus on the development of an ecological theory of movement coordination, so as to prepare the step towards interpersonal coordination. A key figure in this development was Michael Turvey, an early proponent of the ecological approach (Turvey et al., 1981). In his attempt to apply Gibson's insights to the study of human movement, Turvey discovered Gibson's work was highly compatible with that of Nikolai Bernstein, the father of human movement sciences. Although the Soviet physiologist had developed his ideas decades before Gibson, they had never been translated to English and thus been obscured from the general public (Bongaardt & Meijer, 2000; Meijer & Bruijn, 2007).

1.2.2. An ecological approach to movement coordination

Bernstein's most significant contribution to the field of movement science was the identification of its core problem: How are the infinitely many DFs in the body mastered to produce a skillful movement? However, through a combination of observations and intuitions, he also provided several routes for answering this question (Meijer & Bruijn, 2007; Bongaardt & Meijer, 2000). Much like Gibson, Bernstein rejected the mechanistic notion of body and behavior while embracing a functional approach to the movement system. In developing this perspective, he proposed a physiology of activity, as opposed to the physiology of reaction that was conventional at the time (Reed, 1982, 1988). According to the physiology of activity, an animal is never passively waiting for a stimulus, but always actively evaluating its actions with respect to a goal in the environment. Since the surroundings of an animal change from instant to instant, a continuous stream of information is required for this evaluation to occur. Gibson's concept of information, in the form of a structured pattern of energy surrounding the animal, aligned well with this physiology (Turvey,1981; Turvey 1990). On the other side of the coin, Bernstein underscored the holistic and dynamic nature of movement behavior itself (Bongaardt & Meijer, 2000). Far from being reflexively, movement behavior exhibits a functional structure that allows us to achieve goals. Inspired by Gestalt psychology and organicism (Bongaardt 1996, chapter 3), he spoke of a 'topology of movement' to describe the observable form – the wholeness – that is manifested in skilled performances.

But how does one master its degrees of freedom to acquire such wholeness in one's movements? What is, so to say, the 'inner' process underlying the 'outer' structure of the coordination? To Bernstein, the crux was in the *organization* of control of the movement system (Turvey 1990; Kelso, 1995). He recognized not only the large computational burden of controlling all of the DFs at the same time, but also the fundamental problem that the same commands can lead to different movements, while different commands can produce the same movement ('the issue of non-univocality', Bongaardt & Meijer, 2000; Meijer & Bruijn, 2007). As a solution, he proposed that motor skill acquisition must involve the organization of DFs into larger modules with an intrinsic functional integrity, which can be controlled independently. The Soviet school of Bernstein (Kelso, 1995) referred to these modules as synergies, a key concept in his work. Crucially, a synergy is not an innate response mechanism (akin to a reflex), but a temporarily assembled structure of coordination specific to the task at hand. The task for the learner is to assign control to the level of these synergies (Profeta & Turvey, 2018). Once formed, such synergies provide a stable, yet flexible organization of the movement system that allows the individual to achieve a goal in many different ways (Latash et al., 2007). Case in point, here, was his famous observational study on expert hammer throwing, in which he showed that the repetitive movements of even the most skilled laborers never repeated themselves, despite being successful in every cycle (Bongaardt & Meijer, 2000; Meijer & Bruijn, 2007). In fact, he defined skill ('dexterity') as the ability to solve motor problems in different ways according to the demands of the situation.

Taking a step back allows us to see that Bernstein conceived of movement coordination not only as an observable form, a structure, but also as a process of integrating DFs in the system's hierarchy (Vereijken et al., 1997; Bongaardt & Meijer, 2000). Intriguingly, he switched regularly between these two perspectives (Bongaardt, 1996, chapter 3). In one paper, he would emphasize the functional integrity of the movement system as whole. In another he would study the (neuromotor) process of coordination underneath this observable form. This duality was also reflected in his passion for both biology – the study of life – and mathematics – the study of abstraction. Yet, in his final years he sighed: "Biologists understand the problem but lack the mathematical skills, and mathematicians have the skills but don't understand the problem" (Bernstein 1968, p. 246, cited from: Bongaardt & Meijer, 2000). In my view, this *duality of structure and process* has remained (tacitly) present ever since Turvey and colleagues unified Gibson's perception and Bernstein's action into one psychology. On the one hand, the field further developed the construct of functional integrity in the 'outer' structure of human movement. While this approach was initially inspired by biological functionalism (Reed, 1982, 1988), it later focused more and more on the functional stability of coordinative structures (e.g., Kelso et al., 1984; Latash et al., 2007). On the other hand, much work has been devoted to study the process of coordination that brings these coordinative structures to life (Kelso, 1995). This development was initially inspired by the mathematics and physics of non-linear dynamics and would later blossom into a dynamical systems approach (Beek et al., 1995), coordination dynamics (Kelso, 2021; 2022) or behavioral dynamics (Warren, 2006). While both offsprings meet in their emphasis on movement stability, I pose that they are rooted in different key principles of neo-Darwinian psychology. The notion of functional integrity in the coordinative structures is embedded in the principle of animal-environment mutuality, whereas the notion of dynamics in coordinative processes is reflective of the self-sustaining character of ecosystems. In what follows, I briefly address the major developments in both lines of thought.

1.2.3. The structure of coordination

In an effort to understand the structure of movement behavior, Edward Reed introduced the concept of an action system (Reed, 1982, 1988). An action system, so he proposed, is a functional system evolved to regulate our encounters with the environment. The principles of Darwinian selectionism have equipped us with a locomotion system, a basic orienting system, an appetitive system and so on, and so forth (Reed, 1982, 1988; Bruineberg et al., 2024). In part, this theory was a continuation of Bernstein's physiology of activity. Where the Soviets spoke of an evaluation of the environment, Reed used the term 'regulation' to denote the dynamic and relational nature of bodily movement (Tamboer, 1988). For another part, the action system was complementary with Gibson's perceptual system (Gibson, 1966). As much as we need a perceptual system to detect the affordances of our environment, so we need an action system to *enact* those affordances (Reed, 1982, 1988). For Reed, affordances played the role of resources in the environment that exerted selection pressure on a species to evolve its action systems (Reed, 1996). Through this interpretation, he not only explicitly put

Gibson's affordance in an evolutionary perspective, but also underscored the functionality that is inherent to our movement behavior. The coordination of movement serves only one purpose: establishing meaningful relationships with the environment that ultimately aid our survival.

In my view, Reed's answer to the 'why' of movement coordination was unprecedented in its conceptual value and clarity. It made Bernstein's intuition of a purposeful wholeness in our movements explicit and thereby reframed the issue of coordination from a mechanical to a functional affair. Reed's conceptualization of the 'what' of coordination, however, remained somewhat superficial. As pointed out by Withagen & Michaels (2005), the ontology of the action system concept was rather scantly addressed. Withagen & Michaels (2005) proposed that action systems should be understood as the animal's (innate or acquired) ability to achieve functional relationships with its environment. On how this ability manifests itself within the action, they remain silent. Reed, (1982, 1988) himself argued that actions are composed of postures (persistencies in an animal-environment relation) and movements (transformations of one posture into another posture). With this claim, he intended to point at the relational character of movement coordination (Turvey, 1990). The units of our actions are not neurobiological (reflexes, programs), but organizational with respect to the environment (Reed, 1988). On what observable form these postures and movements would have or how they were brought about, he did not elaborate.

An example of how a functional ecological approach like Reed's can serve as an entry point to identify structures of coordination was later provided by the research of Vereijken et al., (1992a, 1992b, 1997) on discovery motor learning in a rhythmic ski-simulation paradigm. As a first step to understand the task paradigm, Vereijken et al. (1992b) identified the pertinent characteristics of the agent-environment (here: participant-platform) relationship that participants had to establish to acquire success. In the ski-simulation paradigm, this amounted to a particular timing of the participant's side-to-side movements with respect to the phasing of the platform, required to exploit the passive elastic forces of the apparatus. This functional analysis provided the proper context to identify and understand the structure of the whole body coordination displayed by participants. Upon reinterpretation of their data, Vereijken et al. (1997) realized that participants learned to structure their body's as a swinging pendulum, so as accomplish the required timing with respect to the platform (**Figure 1.4**). First, they configured their body as an inverted pendulum, unstable and static. Then, they transformed into a hanging pendulum, more stable, but inefficient. At last, expert performers structured their body as a buckling pendulum, dynamic and highly efficient. These functional transformations into a new coordinative structure, to accommodate for goal achievement, constitute an excellent example of what Bernstein referred to as "the organization of control of one's movement" (Turvey, 1990).

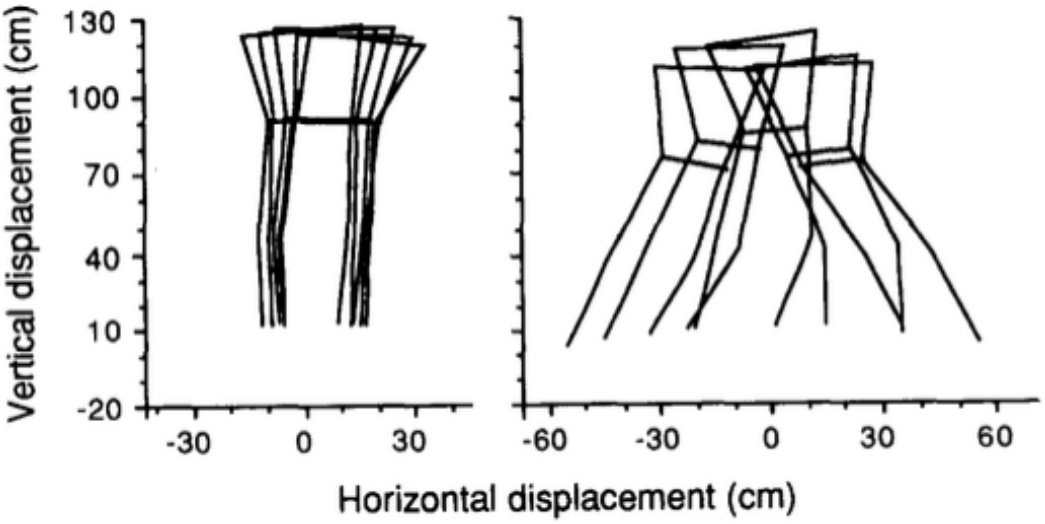


Figure 1.4: Stick figure representation of a novice (left) and an expert performer (right) in the ski-simulation paradigm of Vereijken and colleagues (1992, 1997). While the movements of the novice are structured like an inverted pendulum, the experts' movements have the structure of a (buckling) pendulum. From: Vereijken et al. (1997)

In his 'Outline of a theory of action systems' (1982), Reed also proposed a way in which the functional integrity of an action system can be tested empirically: "Experimenters should vary the animal-environment relationship in a way that is relevant to the hypothesized function of the act (..). If such perturbations cause the agent's behavior to be altered in a systematic manner in accordance with the hypothetical function, then this counts as evidence for the functional specificity of the act." (Reed, 1982, p. 121). Not long after, a series of intriguing experiments into speech production (Kelso et al., 1982; 1984) would employ just this strategy to test the functional specificity of the articulatory system. Kelso et al. (1982) investigated the hypothesis that the articulatory system (qua action system) was organized into a synergy. Recall that Bernstein defined as synergy as a flexible organization of degrees of freedom that acts as a functional whole. Anatomically speaking, the articulatory system consists of several DFs, such as the tongue, the lips and the jaw. If this system was indeed organized as synergy, a sudden perturbation of one of these DFs during the speech would immediately invoke other DFs to compensate for this in order to preserve the *functional integrity* of the whole. In an experiment, they unexpectedly halted the movement of the jaw for a few milliseconds amidst the production of the syllable 'b'. Recording of the movements showed that the lips immediately compensated for the jaw perturbation, while the tongue showed *no* sign of any compensation. However, when the same procedure was conducted during the production of a 'z', the effect reversed: the tongue compensated while the lips did not respond! This revealed that the DFs of the articulatory system were not mechanically, but functionally organized to produce the demanded syllable. Thereby, they provided clear evidence for a synergistic structure of coordination in the action system under study (Kelso et al., 1982; 1984).

In the decades following this work, the focus of the ecological approach would relocate from identifying the structure of coordination (the 'what'), to studying the process of the coordination (the 'how'). During this time, the experimental paradigms also changed. The chosen tasks were almost exclusively rhythmic and devoid of any goal in relation to the environment of the participants. As a result, the concept of functionality –despite its firm embedding in neo-Darwinian thinking– slowly disappeared from the scene. A partial revival occurred when Scholz & Schöner (1999) introduced a new methodology to analyze the structure in movement variability: the Uncontrolled Manifold analysis (UCM) (Schöner, 1995). With this technique, it became possible to identify functional compensations between degrees of freedom, just like those in the articulatory system of Kelso et al. (1982; 1984). The benefit of the UCM was that it was no longer necessary to perturb the action system. The compensations simply revealed themselves in the structure of variability under normal conditions. The UCM analysis partitions the trial-to-trial variability of the system's DFs into two components. The first component captures all DF variability that does *not* affect the value of a chosen outcome parameter. For instance, all the joint angle variability of the arm and shoulder that leaves the location of the tip of the finger invariant (Valk et al., 2019). In more technical terms, this variability is located along a solution manifold onto which all combinations of DFs provide the same outcome of the parameter (i.e., VUCM). The second component, in contrast, captures all DF variability that *does* affect the parameter. In the example of pointing, this would be all the variability of the shoulder, elbow and wrist joints that affect the location of the finger. This DF-variability is located perpendicular to the manifold (i.e., VORT). If the variability along the manifold is larger than that perpendicular to it (VUCM > VORT), one can conclude that the DFs compensate for each other to stabilize the chosen parameter. If, indeed, this stabilization is beneficial to the task performance, it suggests a preservation of functional integrity during the action. This is claimed to be a hallmark of a synergy (Latash et al., 2007; Riley et al., 2011).

With the UCM analysis, it became possible to extract structures of coordination in movement. It is important to realize, however, that the notion of functionality – as intended by Gibson and Reed – is not necessarily intrinsic to this method. Although the UCM may demonstrate whether system components preserve a parameter's stability, additional empirical work is required to determine whether this parameter also preserves the *functionality* of an action. One way to do so, is by changing the environmental circumstances such that the urgency (or 'acuteness', Reed, 1982) of the established relationship increases. If the compensations of the DFs increase and the stability of the outcome parameter improves accordingly, the conclusion can be drawn that this parameter supports the enactment of the affordance. In that case, an argument can be made that the degrees of freedom are organized into a synergy. If not, then the only claim that can be made, is that a particular indicator of performance remains invariant under one set of conditions, while being variable in another. To clarify, the scientific question that distinguishes these two cases, is not the 'what', but the 'why' of movement coordination: why is the action system under study coordinated the way it is? Given the primacy of the animal-environment relation in ecological psychology, I argue that the only

way to identify *meaningful* structures of coordination is to start from this functional question – and to manipulate the action system accordingly. I note, however, that the majority of the studies employing the UCM method have been observational. Whether it is a force production task (e.g. Latash et al., 2002), a pointing paradigm (e.g. Domkin et al., 2005) or an analysis of the golf movement (Morrison et al., 2016). The UCM is predominantly used to study stability of movement coordination rather than its functionality. In section **1.2.7. Reflection** I come back to this issue.

To sum up, the foregoing discussion revealed three fundamental insights about the coordination of purposeful actions. First and foremost, the coordinative structure of our movements is tailored to the demands (that is, the affordances) of the environment. As such, the observable form of movement cannot be understood without taking the environment –in particular the demands of the to-be-achieved task– into account. Secondly, the structure of coordination is not rigid or invariant, but flexible and adaptive. As most clearly illustrated by the work of Kelso et al. (1982; 1984) on speech production, the degrees of freedom of an action system are collectively involved in preserving the functional integrity of that action. An alternative way to comprehend this is that intentional movement possesses an intrinsic stability in the face of (internal or external) perturbations, as evidenced by the mutual compensations of the DFs to sustain goal achievement. And thirdly, both the task specificity and the flexibility/stability of an action are accomplished by grouping the body's DFs into larger modules, called synergies (Latash et al., 2007). Bernstein envisioned these synergies as relatively *autonomous* organizations of DFs, in the sense that they coordinate the system with a minimal recourse to an intelligent executive such as the brain. One way or another, the DFs have the ability to (re-)organize themselves without the interference of some command center that prescribes their actions. Or in the words of Gibson (1979), our actions are regular without being regulated. At the time Bernstein put forward his synergy hypothesis, knowledge of how coordination can arise autonomously was lacking. However, in the decades following his work, the domains of physics (thermodynamics) and mathematics (non-linear dynamics) would provide the concepts and tools necessary to develop Bernstein's intuition of autonomous synergies into a full-fledged theory of self-organization in human movement (Kelso 1995; Withagen, 2010; Lobo et al., 2018; Bruineberg et al., 2024). To understand this development, we need to make a small excursion to the physics: the discipline of matter and energy in space and time.

1.2.4. The process of coordination

From the perspective of physics, the coordinated actions of a living organisms can be understood as expressions of *order* in complex systems (Kelso 1995; 2021; 2022). The term 'order' refers to a stable pattern or structure between the elements (particles, tissues etc.) that make up a system. Whenever order in a system arises, physicists say that the entropy of that system is low. Traditional physics assumes that the entropy in a system always increases over time until at some point a thermodynamic equilibrium with maximum entropy is reached. This is known as the second law of thermodynamics. This law seems to suggest that all systems in nature have the tendency to move away from

ordered states over time. In the context of living organisms, this would imply that structures of coordination in behavior would become increasingly scarce as time passes, until the biological system would reach a state in which no structure in the coordination is left. This implication is hard to reconcile with the empirical observation that most of our behavior as human animals is highly coordinated, structured or patterned. It suggests, in other words, a large conceptual gap between the notion of coordination (order) in physics and the notion of coordination (purposeful behavior) in psychology. In the second part of the twentieth century, however, this gap would be bridged by a generation of scientists that provided a new perspective on how order arises in complex systems (Haken, 1983; Nicolas & Prigogine 1977). One of the most vocal of these was Nobel Prize winner Ilja Prigogine. In this work, Prigogine showed that the second law of thermodynamics can be escaped if a system has the opportunity to exchange energy with its surroundings. By dissipating energy into the environment, a system can create local minima in its entropy and structured patterns between its elements. Importantly, these structures can sustain themselves through the continued dissipation of energy and they can be re-structured whenever the conditions in the system change. Prigogine used the term dissipative structures to characterize such spontaneous patterns. His work showed that open systems can 'live' far from a thermodynamic equilibrium. But perhaps more importantly, he showed that open systems have the capacity to organize themselves, a feature that was music to the ears of early proponents of Gibson's ecological psychology (Turvey 1990; Kelso 1995).

In a fascinating manuscript called 'On the concept of coordinative structures as dissipative structures: theoretical lines of convergence', Kugler and colleagues (1980) started from the observation that human beings are open systems. Like any other organism on the planet, we live by virtue of our exchange of energy and matter with the environment. In this perspective, it seems reasonable to hypothesize that the coordination of our actions abides to the laws of open, complex systems as described by Prigogine. More specifically, it may well be possible that the coordinative structures that characterize our movement behavior constitute examples of the self-sustained, dissipative structures of which Prigogine spoke. In working out this hypothesis, Kugler et al. (1980) speculated that groups of muscles that cooperated in a functional synergy may be analogous to the 'thermodynamic engines' known from the disciplines of non-linear physics. An important inspiration for this theory was the conceptualization of rhythmic movement as that of a self-sustained oscillator. Self-sustained oscillators can maintain their periodic behavior without any external regulation of the timing. For instance, a pendulum clock can sustain regular oscillations via an escape wheel mechanism that dissipates a small amount of energy (stored in a spring or weight) that exactly matches the energy that is lost to friction and resistance. Although an continuous influx of energy into the pendulum system is required to sustain the oscillation, this input is not specific to the timing of the clock and thus not involved in how the (rhythmic) pattern of coordination plays out. It is in this way that Kugler et al. (1980) envisioned the body's capacity to form dissipative structures of coordination.

Inspired by the pendulum metaphor, Kugler and Turvey (1987) initiated a research program that was aimed at uncovering the lawful nature of rhythmic movement. As an experimental paradigm, they developed the task of rhythmic, hand-held pendulum swinging. In a series of rigorous experiments, they discovered some remarkable regularities in the rhythmic behavior. Most prominently, they found that the period time of the oscillation scaled with the length and the mass of the hand-held pendulums. Intriguingly, these results almost perfectly aligned with the period times of a pendulum-spring model with exactly the same length-mass ratio. In other words, the groups of muscles involved in the rhythmic movement acted as a biological spring that oscillated the hand-held pendulum, merely by virtue of the passive elastic and gravitational forces that worked on the system. Akin to a pendulum, such spring-like structures of coordination exhibit an intrinsic stability to which Bernstein had already referred in his work on rhythmic, repetitive movement behavior. However, at the time Bernstein developed his ideas, the concepts to describe such intrinsic stabilities were lacking. Later, this toolbox would be developed by a branch of mathematics called non-linear dynamics, for instance by Andonov and Lyapunov (1972) (Bongaardt & Meijer, 2000). With non-linear dynamics it is possible to model the time evolution of a system with an intrinsic stability, also known a (dissipative) dynamical system. Mathematically, this time evolution constitutes the solution of a differential equation with non-linear terms. Graphically, it can be portrayed as a converging, often circular trajectory in a phase space that is spanned by all the possible states of system and its derivatives. Regardless of its initial conditions, a dissipative system is always pulled towards a set of preferred locations in this space, which is called an attractor. In the case of self-sustained rhythmicity like in the experiments of Kugler and Turvey (1987), this attractor is in the form of a circle, a limit cycle attractor (**Figure 1.5**).

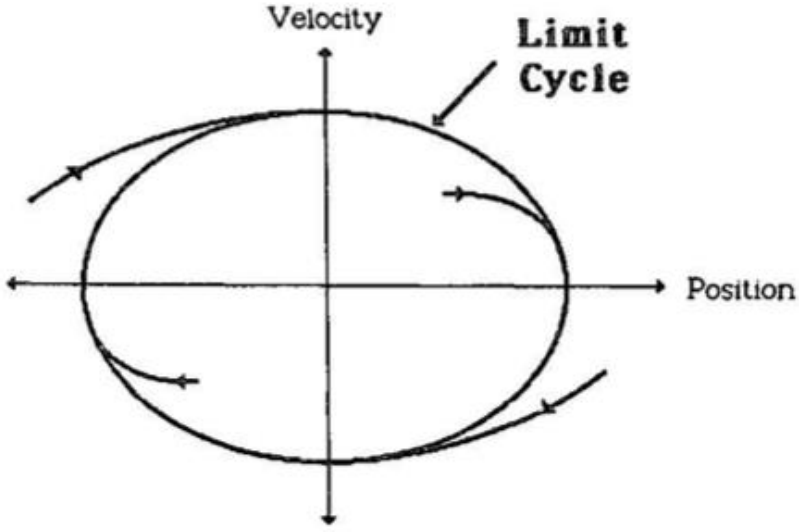


Figure 1.5: Limit cycle attractor in a two-dimensional phase plane. From: Kay (1988)

Even though the work of Kugler and Turvey (1987) suggested that (rhythmic) coordination exhibited a dissipative structure, hard evidence was for this claim was lacking. The possibility that the lawfulness originated from some neuronally wired program could not be excluded. To understand what may count as evidence for self-organization, it may be helpful to consider an example. The example I will use is that of laser light. Laser light has been investigated extensively by German physicist Hermann Haken, who counts as one of the pioneers of self-organization in nature (Haken, 1983). Laser light starts off as a group of particles (the laser atoms) in a cloud of gas (Haken and Wunderlin, 1990). When energy is pumped into this cloud, the electrons of the atoms start to oscillate, one by one. Every particle oscillation induces the emittance of a light wave. With low amounts of energy, the light waves are emitted randomly. But once the energy reaches a critical level, the atoms abruptly synchronize in their oscillations and a collective wave of light is emitted. To the human eye, this wave looks like a sharp beam: laser light is generated. The crux of this spontaneous process of synchronization is in the local and non-linear interactions between the particles. Once the emitted waves hit each other, they start to amplify, leading to larger and larger waves. At the critical point, the amplifications are so large that they enslave other particles into the same rhythm. In a circular process of positive feedback, this enslavement rapidly leads to so many particles oscillating at the same frequency that no laser atom can escape the rhythm: a collective pattern or structure of coordination is born. Haken referred to this collective pattern as an *order parameter*, since it describes the order in the system. In this particular case, he proposed to use the relative phase (in-phase, 0 degrees) as order parameter. Later, we will see that the relative phase is also well applicable to describe order in the movement system, like for instance the spatiotemporal patterning between limbs. Haken conceptualized the energy input as a *control parameter*, since it was a necessary variable to induce the synchronization. It is crucial to understand, however, that the control parameter does not prescribe the order of the system in any way. Like the energy input in a self-sustained pendulum, the control parameter is non-specific to the structure of coordination that emerges.

How can laser light help us to find proof for self-organization in movement? The answer lies in the abrupt, spontaneous character of the atoms' synchronization. This constitutes a qualitative shift in the behavior of the system, in this case from disorder to order. A self-organized system is characterized by transitions like this, either from disorder to order or from one ordered state to another. When 'living' far from a thermodynamic equilibrium, a system is in a continuous search for stable states with low amounts of entropy. And to achieve such states, it must go through what are called 'non-linear phase transitions'. Or, in the language of mathematics: bifurcations from one attractor to another. These phase transition have a set of identifiable properties (Haken and Wunderlin, 1990; Kelso 1995). First, they occur abruptly, as opposed to a gradual (linear) change. Second, they are announced by sudden increases in the variability of the system, known as critical fluctuations. These fluctuations indicate a loss in stability of the 'old' state of the system. And third, the system is slower to respond to perturbations. Like the critical fluctuations, this is an indication that the system's current stability is declining

and that the search for a new stable regime is on its way. If, and only if, these three characteristics can be identified, evidence for self-organization is provided. It was Scott Kelso, movement scientist at Haskin's laboratories, who would find such proof in movement behavior (Kelso, 1995). In his book 'Dynamic patterns: Self-organization of brain and behavior', he lively describes how a non-linear phase transition first revealed itself in the spontaneous act of mimicking of animal locomotion with his fingers: "By alternating the fingers of my hands and synchronizing the middle and index fingers between my hands, I was able to generate a 'gait' that shifted involuntarily to another 'gait' when the overall motion was speeded up. Talk about the spontaneous formation and change of ordered patterns!" (Kelso 1995, p. 46).

Soon after this discovery, Kelso put the transition to the test in a series of experiments (Kelso, 1984). The task for the participants was simple: oscillate both of your index fingers back-and-forth to the sound of a metronome. Pilot testing readily showed that participant could only stably produce two modes of rhythmic coordination. Either their moved their fingers in synchrony (i.e., in phase) or they moved their fingers in an alternating manner (i.e., anti-phase). In other words, the movement system was bistable. However, when the metronome frequency was stepwise increased from 1.25 Hz to 3.50 Hz, the anti-phase mode of coordination became unstable at higher frequencies. In fact, when participants were instructed not to resist any transitions in the coordination when that felt to be more comfortable, they showed an abrupt switch from anti-phase to in-phase upon reaching a critical frequency (**Figure 1.6**). This was similar to the 'finger-gait' shift Kelso had experienced and also showed similarities to the spontaneous synchronization of the particles in laser light. Beyond the threshold, the system was monostable. Only in-phase could stably be produced. Yet, when the frequency was gradually lowered until below the

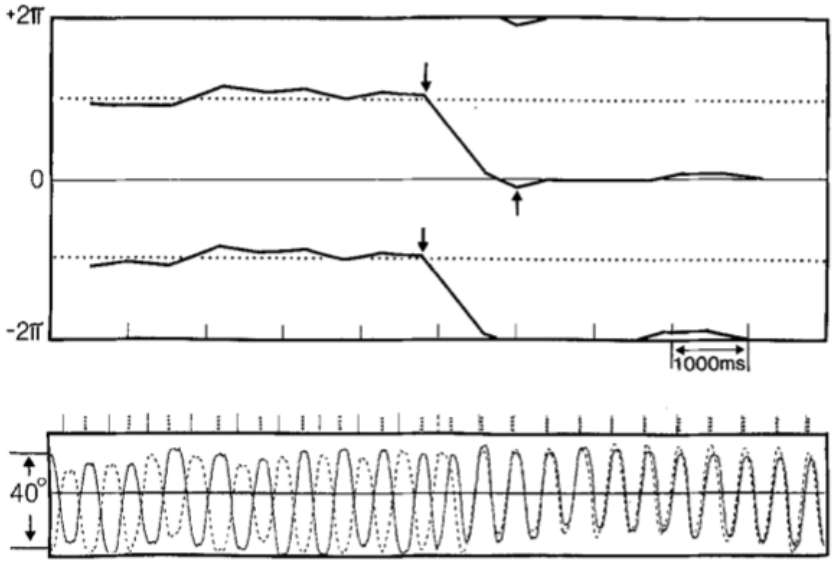


Figure 1.6: The position timeseries of the left (solid line) and right (dashed line) index finger during metronome-dictated, oscillatory movement (lower panel). When the cycling frequency increases, the fingers abruptly switch from moving antagonistically to moving in synchrony. The upper panel displays the phase relationship between the fingers, which transitions from anti-phase to in-phase. From: Haken et al. (1985)

critical threshold, the fingers did not immediately return to the anti-phase pattern. This is also known as hysteresis, a hallmark of non-linearity. Follow-up studies confirmed other hallmarks of non-linear phase transitions, such as loss of stability as evidenced by critical fluctuations (Kelso et al., 1986) and critical slowing down (Scholz et al., 1987). Immediately after the empirical foundations had been laid, Haken et al. (1985) formalized the findings into a formal mathematical model that would come to be known as the HKB model for rhythmic coordination. Within this model, the two fingers were conceptualized as dissipative oscillators that interacted through a non-linear coupling function, from which the pattern of coordination –including the transition– spontaneously emerged. The order parameter was given by the relative phase between the two oscillators and the control parameter was expressed in the frequency of oscillations. In an extended version of Schöner et al. (1986) the critical fluctuations were modelled by adding stochastic noise to the system.

The HKB model would constitute a new paradigm for the ecological approach to human movement coordination (Schöner & Kelso, 1988; Kelso, 2021). An important reason for this, was the abstract nature of the model. The two non-linearly coupled oscillators would not only account for the rhythmic coordination of two fingers, but also of various other limbs with respect to each other. It introduced a new vocabulary to domain of human movement sciences, with an emphasis on stability and non-linearity. Rather than searching for neural structures that would support movement behavior, the goal became to map observable patterns of coordination onto compact differential equations that could describe and predict the time evolution of a system's order parameter. By some, this is called the dynamical systems approach (Beek et al., 1995), by others coordination dynamics (Schöner et al., 1992), behavioral dynamics (Warren, 2006) or ecological dynamics (Leach et al., 2021). The modus operandi is, nevertheless, the same in all approaches. Because of its focus on mathematical formulas, dynamical approaches have often been accused of being purely descriptive (Beek et al., 1995). However, as I hope to have shown here, the approach is in fact grounded in a solid theoretical-physical framework, which is known as Synergetics (Haken, 1983). Before making the step towards interpersonal coordination, I would like to remind the reader how the ecological approach to both the structure and the process of movement coordination are firmly rooted in Darwin's principles of evolution. Earlier, I showed how the functional approach to the structure of movement is embedded in the rationale of animal-environment mutuality. Here, I highlighted the self-sustained or self-organized character of human movement, which exhibits regions of stability the same way an ecosystem settles into an equilibrium. With this structure-process duality in mind, we are going to make the step from intra- to interpersonal coordination. How can this two-sided theoretical framework help us to understand the coordination of movement between two individuals?

1.2.5. From intra- to interpersonal coordination

In the first part of this chapter, I showed how Descartes' dualism formed the fertile soil for a cognitive doctrine of motor control. In this context, the study of interpersonal coordination became a search for (neural) mechanisms of joint action (Sebanz et al. 2006,

2021; Knoblich et al., 2011 Azaad et al., 2021; Vesper et al., 2010, 2017). In opposition to this, the second part of this chapter revealed that Darwin's mutualism paved the way for an ecological doctrine of functionality and self-organization. One of the first to apply this approach to *interpersonal* coordination was social psychologist Darren Newtson (Newtson et al., 1987). In a time when the HKB-model got a firm foothold in the discipline of movement science, Newtson et al. (1987) articulated the following intuition: "If action consists of coupled oscillator units [i.e., dissipative structures], interaction *between* persons may consist of the coupling of such units *across* two persons. That is, since these are open systems, two persons may configure to the same set of environmental constraints and coordinate their behavior in the same manner as they coordinate any other multiple-configuration behavior." (Newtson et al., 1987, p. 219, emphasis added). In the vocabulary of Bernstein, Newtson hinted at the presence of interpersonal synergies (Riley et al., 2011): coordinative structures that span more than one individual so as to generate and sustain successful joint actions. After all, the open character of organic systems does not seem to preclude the possibility of self-organization across multiple human agents. Moreover, from a functional perspective it is equally possible that multiple agents sustain a collective relationship with their shared environment. This is to say that in joint action, individuals cooperate to achieve a common goal with respect to their surroundings, which seems to require a common structure of coordination.

Not long after Newtson had put forward his interpersonal synergies hypothesis, Schmidt et al., (1990) would support it with compelling empirical evidence. Amidst a series of follow-up studies on HKB (for review, see Kelso, 2021), Schmidt and colleagues, (1990) decided to test the predictions of HKB in an interpersonal context. In an experiment, they asked pairs of seated and visually coupled participants to oscillate their lower legs at a metronome-dictated frequency. Participants were instructed to move their legs in either a symmetrical (in phase) or alternate (anti-phase) mode of coordination with respect to each other. Similar to the what had been found by Kelso et al. (1984), both phase modes could be performed stably at low frequencies of oscillation (**Figure 1.7**). However, when the frequency of oscillation was stepwise increased from 0.6 Hz to 2.0 Hz, the anti-phase mode of coordination abruptly destabilized. In a follow-up experiment, dyads were instructed not to resist any potential behavioral transitions, upon which a spontaneous shift to in-phase occurred at a critical frequency. Further supported by the findings of critical fluctuations and hysteresis, Schmidt et al., (1990) concluded that they had witnessed a non-linear phase transition. This result had two implications. First of all, it confirmed the abstract nature of the HKB model. The same principles of (rhythmic) coordination seemed to apply to systems with very different material components. Second, Schmidt et al., (1990) showed that interpersonal coordination is not based on cognition, but on lawful information. After all, the experimental setting precluded any explanation for the phase transition in terms of neural structures, since the two individuals were each equipped with a different central nervous system. With Schmidt et al., (1990)'s work, a tentative theory of interpersonal synergies was established, which would be worked out in more detail the decades that followed (Marsh et al., 2006; Schmidt & Richardson, 2008; Riley et al., 2011; Fusaroli et al., 2014; Araújo & Davids, 2016).

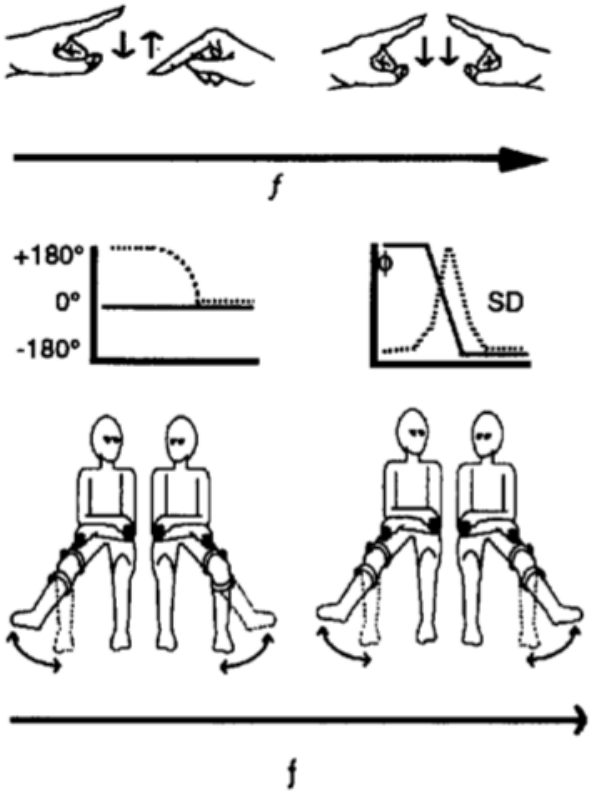


Figure 1.7: Graphical representations of the experimental paradigms of Kelso et al. (1984) (upper panel) and Schmidt et al. (1990) (lower panel). In both studies, a spontaneous transition from anti-phase to in-phase was observed, accompanied with a sudden increase in the variability of the relative phase (middle panel). This suggests a non-equilibrium phase transition in intra- as well as interpersonal coordination of rhythmic movement. From: Turvey (1990)

1.2.6. Contemporary research

Beginning with the seminal study of Schmidt et al., (1990), an ecological research tradition developed in which interpersonal coordination was conceptualized in terms of a coupled-oscillator model (Schmidt and Richardson, 2008; Coey et al., 2012; Lagarde, 2013). Sometimes this research strongly adhered to the HKB-model or to extended versions thereof (e.g., Schmidt and Turvey, 1994; Schmidt and O'Brien, 1997). Other times experiments or models were more loosely inspired by HKB (e.g. Harrison and Richardson, 2009; Richardson et al., 2015). But in any case, the process of interpersonal coordination became synonymous with the entrainment of two dissipative oscillators (De Poel, 2016). To clarify, the coupled oscillators are generally seen as the conceptual placeholders of human agents, in an admittedly narrow definition of interactive behavior (Lagarde, 2013; Huys et al., 2018). Nevertheless, the coupled-oscillator model turned out to be a powerful tool to understand various (process) aspects of interpersonal coordination (Schmidt & Richardson, 2008). To begin with, the model accounts for the widely reported phenomenon of spontaneous movement synchronization between individuals. In a dyadic pendulum swinging experiment, Schmidt and O'Brien (1997) showed that no explicit

instructions with respect to the interpersonal coordination were required for participants to fall into synchrony with each other. Although the phase relationship between the two pendulums (each held by a different participant) were more variable than what had been shown in the original work of Schmidt et al., (1990), cross spectral analyses of the movements showed that the relative phase between the visually coupled participants was predominantly in the regions of 0 degrees (in-phase) or 180 degrees (anti-phase). Likewise, Oullier et al. (2008) showed that spontaneous phase synchronization (in-phase) emerged as soon as two individuals could see each other move, even in the absence of any metronome sound to which the periodic movement was made. The finding of spontaneous phase locking was further found in for instance side-by-side chair rocking (Richardson et al., 2007), side-by-side treadmill walking (Van Ulzen et al., 2008), and even in elite level athletic track running (Varlet & Richardson, 2015). When adopting a broad perspective on these findings, one could argue that spontaneous synchronization is a hallmark of self-organization in biological systems (Strogatz, 2003; Kelso, 2021). From groups of fireflies in the rain forest (Winfree, 1967) to pools of pacemaker cells in the heart (Michaels et al., 1987), many coordinated activities in nature occur by virtue of collective synchronization. Looking at the narrower case of phase locking in movement behavior, one can also argue that it merely constitutes one of many different forms of interpersonal coordination. In joint actions, it very often occurs that individuals deviate from synchrony, which is not necessarily detrimental to the joint performance (Abney et al., 2015; Wallot et al., 2016). As an example, one of the two individuals may take the lead in the interaction, while the other follows (Hofmans et al., 2019; Takai et al., 2023). Can the coupled-oscillator model account also for such forms of interpersonal coordination?

With coupled oscillators as a point of departure, there are two ways in which deviations from synchrony can be studied (Lagarde, 2013; De Poel, 2016). The first of these is to adapt the oscillators (i.e., the model agents) so that the two are not identical anymore. If these adaptations lead to systematic changes in the spatiotemporal relationship between the oscillators, this may explain asynchronies in real-world interpersonal coordination. This rationale was first applied by Schmidt and Turvey (1994) in a study into side-by-side anti-phase pendulum swinging. In this experiment, the length of the pendulums was adapted to induce between-participant differences in the eigenfrequencies of the (wrist-pendulum) oscillators. Results revealed two things. First of all, the variability in the relative phase between the two participants increased when the difference in the oscillator's intrinsic frequencies was larger. This suggested that the stability of rhythmic interpersonal coordination was contingent on the similarity between two individuals. Secondly, Schmidt and Turvey (1994) showed that the participant holding the shorter pendulum with the higher eigenfrequency tended to take a small but significant lead in the interaction. In fact, they showed that the difference in between-participant relative phase was proportional to the difference in intrinsic frequencies, a finding that was predicted by the (extended) HKB model (Haken et al., 1985; Schöner et al., 1986) and replicated by Amazeen et al. (1995). This provided a first and important indication that a 'social construct' such as leadership in interpersonal coordination may be lawfully related to dynamical properties of the two individuals in the interaction. In a follow-up

experiment, Schmidt et al. (1994) showed that the variability in the relative phase was not only affected by the difference in eigenfrequencies, but also by their social competence. To be more specific, results showed that the interpersonal coordination in anti-phase pendulum swinging was less stable when the two individuals had a similar level of social competence (i.e., both highly competent). More recently, studies showed that the stability of intentional phase-locked pendulum swinging was lower in individuals with schizophrenia (Varlet et al., 2012) and social anxiety disorder (Varlet et al., 2014). Such findings show that the coupled-oscillator paradigm can be linked to social constructs.

A second way in which deviations from synchrony can be investigated is by a manipulation of the coupling between the oscillators. In the original experiment of Schmidt et al., (1990), the dyads were coupled visually. More recent work confirmed that other forms of coupling can also lead to HKB-like coordination. For instance, in an intriguing experiment involving blinded participants walking behind each other, Harrison and Richardson (2009) showed that a purely mechanical coupling of a foam appendage induced spontaneous phase locking in the locomotion patterning between participants. Furthermore, in a famous study into collective clapping of audiences, Néda et al. (2000) showed that interpersonal synchronization can also occur on the basis of auditory coupling. Despite the diversity in the modalities investigated, most of these studies adhered to HKB's assumption of a symmetry (Haken et al., 1985). This is known as isotropic coupling and it was proposed with the goal to retain simplicity in the model. But, as remarked by De Poel (2016), such isotropic couplings are unlikely to occur in the real world. A much more probable scenario is anisotropic coupling, an symmetry in the interaction. Meerhoff and De Poel (2014) conducted an experiment in which dyads of basketball players were instructed to perform a synchronous side-to-side stepping task. At a given signal, they were instructed to switch from in-phase to anti-phase. While in one condition the participants were facing each other, in another condition one of the participants was facing the wall. Results revealed that the coupling asymmetry in the latter condition also induced asymmetry in the switching behavior. That is, the participant with more visual information was more likely to adapt to his partner and tended to follow rather than lead in the interaction. A similar finding was reported by Reynolds and Osler (2014). In a study of interpersonal sway synchrony during stance, they demonstrated that asymmetry in the visual information induced the 'sighted' participant to lag behind the 'blinded' participant. Both Meerhoff and De Poel (2014) and Reynolds and Osler (2014) found behavioral asymmetry in symmetrical conditions, suggests that anisotropy may be the rule rather than the exception (De Poel, 2016).

The literature reviewed so far shows that the coupled-oscillator model provides several routes to understand interpersonal coordination. In the last two decades, these routes have been further explored with increasing attention for the functional context of the interaction. An example of this is provided by the dissertation work of Cuijpers (2019), who studied the joint activity of crew rowing. From the perspective of coordination dynamics, crew rowing can be considered as the functional cooperation of a set of mechanically and informationally coupled oscillators (De Poel et al., 2016). In a series of

studies, Cuijpers and colleagues (2019) showed that the HKB model is well-suited to understand interpersonal coordination in a sports context like this. It provides clear predictions with respect to the stability of rowing in both in-phase and anti-phase. At the same time, Cuijpers (2019) showed that not all model predictions of HKB held in the context of rowing. For instance, when the frequency of the strokes increased, the variability of the relative phase between the crew rowers *decreased*, indicating a higher coordinative stability at higher oscillation frequencies (Cuijpers et al., 2017). In contrast, HKB predicts an *increase* in the variability at high oscillation frequencies. Additionally, Cuijpers et al. (2015) found that anti-phase rowing was not necessarily lower in stability than in-phase rowing, which was also in apparent contrast with the HKB. A similar discrepancy between theory and practice was found by Huys et al. (2018). In an experiment with dyadic rope turning, they found that the variability of the relative phase between the participants' periodic hand movements decreased when the turning rate increased. Again, this was in contradiction with what may be expected from the HKB model of rhythmic coordination.

The examples of Cuijpers (2019) and Huys et al. (2018) illustrate the value of a coupled oscillator model for framing interpersonal coordination. Simultaneously, they demonstrate the unique constraints of each task context. There are multiple ways to deal with this idiosyncrasy. One way is to extend the model, like the inclusion of stochastic noise (Schöner et al., 1986) or the breaking of symmetry in the coupling (Treffner et al., 1995). A different way is to open up to new dynamical models that better fit the demands of a task (Lagarde, 2013). The architecture of these model may differ drastically from the standard that was set by Haken et al., (1985). An example of such modelling is provided by Richardson et al. (2015). In an experiment, pairs of participants had to perform repetitive and diagonally crossing aiming movements between two targets on a large computer screen. While doing so, they only saw their own cursor and the moving cursor of their co-actor and they were not allowed to talk. The results showed two things. To begin with, all dyads quickly established a stable mode of interpersonal coordination, even though a significant deviation from an in-phase or anti-phase mode was required to be successful (**Figure 1.8**). This highlights the adaptivity of cooperating individuals: the asymmetry demanded by the task constraints emerged spontaneously. In second place, the results showed a spontaneous leader-follower dynamics in almost all dyads, suggesting an intrinsic functionality to role divisions. In tradition with coordination dynamics, Richardson et al. (2015) modelled the moving points as self-sustained oscillators. With the model, they showed that both the elliptical shape of the trajectories and the phase lag between the participant most likely arose from an asymmetry in the coupling between the participants. Notably, the non-linear coupling function that they proposed not only consisted of attractor parameters but also of repellor parameters. As expected, this marked a significant difference with the classic coupled-oscillator model of Haken and colleagues (see De Poel, 2016 for a broader discussion of antagonistic coupling).

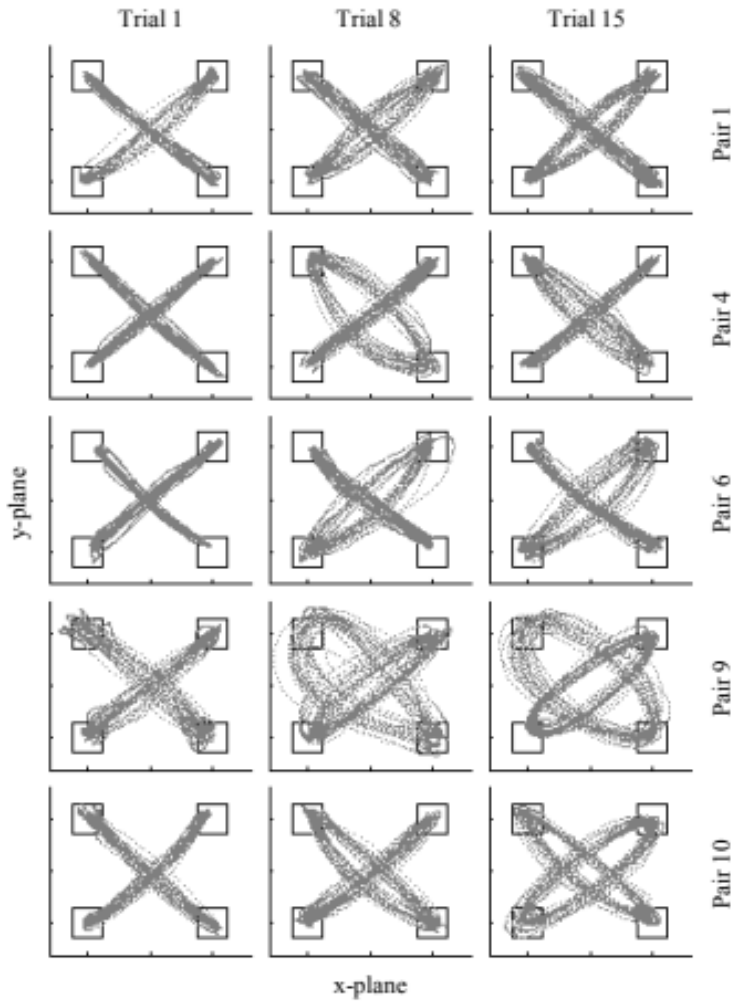


Figure 1.8: The cursor trajectories of 5 exemplary dyads in trial 1, 8 and 15 of the session. Participants had to move the cursor reciprocally and diagonally between the targets. Asymmetry in the dyad's interaction emerged spontaneously, with elliptical trajectories instead of straight trajectories in the target to target motion. From: Richardson et al. (2015)

The attentive reader may have noticed that all research discussed so far concerned continuous joint actions. Within the ecological-dynamical approach, there is a deep conceptual link between self-organization as a theory of coordination and coupled oscillators as a way to model such coordination (Beek et al., 1995; Kelso, 2021; 2021). Given this link, the field has predominantly focused on rhythmic experimental paradigms that allowed for dynamical modelling of joint action (Schmidt and Richardson, 2008; Coey et al., 2012; Lagarde, 2013). Since dynamical models of discrete (joint) actions are much harder to conceive of, the focus on rhythmicity has for long been at the expense of an account for non-periodic joint actions (but see Saltzman & Kelso, 1987; Borooghani et al., 2024). This changed with the introduction of the Uncontrolled Manifold analysis, an innovative technique to reveal coordinative structure in the trial-to-trial variability of discrete (joint) performances (Scholz & Schöner, 1999). By partitioning the variability across trials into components along (VUCM) and orthogonal to (VORT) a solution

manifold, one can assess the extent to which the DFs in an action system stabilize a self-chosen performance variable (Latash et al., 2007). In a joint action system, these DFs can be conceptualized as (components of) the separate individuals that interact, while the performance variable can be assessed at the level of a common goal (Riley et al., 2011). As such, the UCM analysis can reveal to what extent two collaborating agents compensate for each other's movements to stabilize a parameter related to a common goal. In other words, the UCM constitutes a methodology to identify an interpersonal structure of coordination in the context of discrete joint actions.

In an attempt to unite coordination dynamics with the language of UCM, Black et al. (2007) re-analyzed the 'traditional' interlimb in-phase/anti-phase regimes with the UCM analysis. In interpersonal pendulum swinging, they found that members of a dyad compensated for each other's movements to stabilize the relative phase as performance variable. More specifically, the relative phase stabilization was weaker in anti-phase and weaker with larger deviations from the oscillator's eigenfrequencies. Thus, UCM was well suited to uncover interpersonal structures of coordination. The first to make the step to discrete joint actions was Romero et al. (2015). They instructed pairs of seated participants to perform a manual pointer-to-target task in which one participant handled a pointer while the other handled the target. A trial-to-trial UCM analysis showed that the joint angles (DFs) of both dyad members covaried systematically to stabilize the pointer-target meeting point. Moreover, the compensations across the members of a dyad were stronger than within individuals, suggesting a more stable inter- than intra-personal structure of coordination. Montull et al. (2020) investigated interpersonal coordination in a cooperative slackline balancing task in which dyads were holding each other so as not to fall. With the UCM, they showed that dyads covaried their movements to stabilize a dyad's center of mass. A last category of joint actions to which the UCM has been applied, is the domain of team sports (Passos et al., 2016). For instance, Passos et al. (2018) studied compensatory behaviors between ball carriers and support players in two-versus-one rugby play. They found that the two cooperating players covaried their running velocities so as to stabilize the inter-player angle in the situation. As a disclaimer, covariation was only demonstrated in 19 out of the 55 trials. Comparable results were found in doubles badminton play (Passos et al., 2020, 2022). In approximately 40% of the trials, they found that players covaried their velocities to stabilize the inter-player distance on the field (Passos et al., 2020).

1.2.7. Reflection

All in all, this review has revealed two ecological strategies to deal with interpersonal coordination. On the one hand, there is what may be called the 'coupled oscillator approach' (Schmidt and Richardson, 2008). This approach conceptualizes interacting individuals as pairs of coupled and self-sustained oscillators. Among the strengths of this strategy are its lawful accounts for spontaneous synchronization, leader-follower dynamics and role division within continuous joint action. On the other hand, there is what may be called 'UCM approach' (Passos et al., 2022). In this approach, cooperating individuals are conceptualized as two (collections of) degrees of freedom that must

covary in their movement behavior to stabilize some outcome parameter of the joint action. Conceptually, the structure of coordination revealed with the UCM has been linked to that of a synergy. In fact, many even claim that the UCM is a necessary methodological tool to find evidence for synergies, both intra- (Latash et al., 2007) and interpersonally (Riley et al., 2011; Fusaroli et al., 2014; Araújo & Davids, 2016). Strong points of this strategy are its unique account for discrete joint action and its applicability to real-world interactive settings.

On the surface, the two approaches seem to constitute an analytical distinction between continuous and discrete joint action. This categorization, however, only partially applies. With the UCM, it is possible to investigate both periodic and non-periodic (joint) actions. And although, as far as I know, it has never been done in the interpersonal domain, dynamical models can in principle also account for discrete joint actions, via the inclusion of point attractors (Saltzman & Kelso, 1987). So what distinguishes these strategies, apart from their respective applications? I propose that the *structure-process duality*, reflected already in the work of Nikolai Bernstein, forms a more relevant dimension along which the difference between the two approaches can be understood. The coupled oscillator approach, on the one hand, addresses the *process* of interpersonal coordination. With its embedding in coordination dynamics, this approach starts from the assumption of self-organization and devises dynamical models of the interpersonal coordination that capture this process. The UCM approach, on the other hand, is a way to describe the interpersonal *structure* of coordination. It demonstrates how, from trial to trial or from cycle to cycle, the individual's movements are patterned in such a way that the members of a team collectively stabilize a pertinent parameter. Since the form of movement varies between tasks, a unified methodology to describe coordinative structures is highly valuable. But as much as the UCM can tell us about the 'what' of movement, it cannot inform us about the 'how' of it. That is, the underlying process governing the observable structure of coordination remains unknown. This is supported by the fact that the UCM has also been embraced by many researchers outside the ecological-dynamical domain (e.g., Monaco et al., 2018; Hasanbarani & Latash, 2020; Shafizadegan et al., 2022).

In the ecological framework, the conceptual bridge between the two strategies is provided by the notion of stability. Whereas the coupled oscillator approach explains *how* stable interpersonal coordination comes about, the UCM approach is a way to show *what* is being stabilized. Within dynamical systems theory, the concept of stability is crucial. It is modelled with attractors in phase space and it allows for a characterization of human movement as spontaneously emerging and dissolving structures. In the broader context of ecological psychology, however, stability is only one part of a two-sided story. In this chapter, I showed that ecological psychology started from two main neo-Darwinian principles. First, the insight that life on earth is self-sustained. From the ecosystems that span the planet to the behavior of the animals that inhabit them: life is an open-ended act of balance and re-organization. The notion of stability fits well with this principle. In second place, the evolution theory showed that animal and environment form an inseparable pair. Due to this mutual dependency, behavior is to be understood in the

context in which it takes place. In particular, movement behavior provides a way for human beings to relate to a meaningful environment, which Gibson conceptualized in terms of affordances. A concept that fits this principle much better than stability, is that of *functionality*. Unfortunately, the functional character of interpersonal coordination –in Gibson's or Reed's sense of the word– has only scarcely been addressed. What needs to be addressed is the question of *why* a particular aspect of a joint performance needs to be stabilized. What is the added value of coordinating your movement behavior with others?

To avoid any confusion, I do not deny that the UCM allows the researcher to relate dyadic movement behavior to a common goal among the members of a team. One could argue that this constitutes a functional relationship between the agents and their environment. My claim is, however, that this relationship is indirect and not necessarily functional in the way it was intended by Gibson, Reed and followers. It is given by a self-chosen variable which is assumed to be related the goal of the performance. In some cases, this choice may be justified. For instance, in a dyadic pointer-to-target task (Romero et al., 2015) the goal of the task is straightforward and the UCM analysis constitutes a logical first step to unravel the interpersonal structure of coordination. But in most cases, like in a badminton doubles play (Passos et al., 2020, 2022), it is less clear which functional relationship team members aim to establish with their environment. Rather than choosing a (set of) parameters that may or may not be related to the performance goal and analyze to what extent they are stabilized, I suggest a different approach. An approach that is more in line with ecological psychology's emphasis on animal-environment mutuality and that addresses functionality before stability. More concretely, I propose to start the inquiry from the concept of a *social affordance* (Marsh et al., 2006; 2009). A social affordance is that what a cooperation (or: coordination) with another human being offers the individual, sometimes for ill but mostly for good. It provides an answer to the question why individuals commence to coordinate with each other in the first place: an answer that is often necessary to proceed to the questions of what is being coordinated (i.e., the structure) and how this coordination is established (i.e., the process).

Reasons for an individual to engage in a joint action can be diverse. The collaboration with others opens up new possibilities for action that were previously unreachable. A good example of this is the carrying of furniture. While an individual can only carry a small and lightweight chair, a group of individuals can carry much heavier furniture, like a large dinner table. In this perspective, a team functions as a collective effectivity – a tool – to enact new affordances (Marsh et al., 2006; 2009; Baron, 2007). These new affordances are what I referred to as social affordances. They provide the functional context in which the process of interpersonal coordination takes place. The goal of a joint action, and thus the resultant interpersonal structure of coordination, is intrinsically related to that. But surprisingly, research into social affordances is rather scant. In literature, there is only one experimental study that investigated to what extent human agents are actually capable of perceiving a social affordance. In line with the given example, Richardson et al. (2007) investigated if people can perceive the point at which they have to switch from carrying something individually to carrying it with someone else. In series of experiments, they instructed participants to carry a set of planks with an ascending order of length. At

some point, the planks were too large to carry individually. While in one condition the opportunity was offered to use an assistive tool, in another condition they had the choice to get assistance from another participant. Results showed that participants switched from unassisted carrying to tool-assisted carrying at the same body-plank ratio as they switched from individual carrying to joint carrying. This suggests that the engagement in a joint action occurs on the basis of perceptual information about the inadequacy of acting individually. This is a different way to frame a social affordance (Baron, 2007)

The realization that interpersonal coordination offers new and more fruitful ways to engage with the environment is crucial to contextualize not only the structure, but also the process of interpersonal coordination. An example of this is provided by the work of Nalepka et al., (2017), which we may ascribe to the category of dynamical modelling. Nalepka and colleagues (2017) instructed dyads of participants to collect herds of randomly dispersing sheep in the circle of a virtual game field. To fulfill this shepherding task, each participant was provided with a cursor that could be used to drive the virtual sheep into their circle. Initially, all dyads adopted a so-called search-and-recover strategy, in which both participants collected sheep on their own side of the play field. After some practice, a subset of the dyads discovered a new and more effective strategy: coupled-oscillatory containment. In this successful strategy, the members of a dyad instantiated a synchronous rhythm of motion (anti-phase or in-phase) around the sheep. Both task solutions were modelled using the toolbox of non-linear dynamics, but these models did not provide a satisfactory explanation for why such structures of coordination had emerged. What I propose, here, is that an answer to this question can only be acquired when one starts with the social affordance that is to be perceived and enacted. In the context of this task, search-and-recover can be understood as *individualized* behavior. Both participants only take care of the sheep on their own side of the field without taking the movements of their partner into account. As such, they act in accordance with an individual goal. Conversely, the coupled oscillations can be regarded as joint behavior. Both participants coordinate their movements with each other so as to achieve a *common* goal. Thus, what is needed for a dyad to switch from search-and-recover to coupled-oscillations is for them to perceive the inadequacy of acting individually (Baron, 2007). In other words, they have to perceive the social affordance offered by the lay-out of the task. This interpretation was confirmed by the finding that poorly performing dyads were more likely to make the switch to the 'joint' strategy. For them, the social affordance was better visible through the inadequacy of their initial solution.

What I wish to emphasize with this plea for functionality is that interpersonal coordination in daily life is usually not a 'given'. It is the result of a qualitative shift from acting as individuals to acting as a team, initiated by the perception of an social affordance. In the words of Baron, (2007), it "reflects a symmetry-breaking process whereby organisms shift from individual to collective action, [it] involves a phase transition or in Lewinian terms, an 'unfreezing' process or qualitative change." (Baron, 2007, p. 186). Although this phase transition is at the heart of what interpersonal coordination entails, it has for long been obscured from scientific inquiry. The reason for this neglect is clear, yet pervasive: almost all research within the ecological (but also the cognitive) approach

to joint action has employed simple task paradigms in which the form of interpersonal coordination was either imposed or implicit from the demands of the task. From rhythmic pendulum swinging to pointer-to-target aiming: the question whether cooperation would aid the performance, and in *what* form, never occurred. To reiterate, the focus has been on the *how* (i.e., the process) and the *what* (i.e., the structure) of interpersonal coordination, while the why of it was neglected. Now that ecological psychology is in a self-declared stage where it attempts to come to terms with more real-world joint action setting (Lagarde, 2013; Richardson et al., 2015; Huys et al., 2018; Passos et al., 2022), I argue that the functional dimension of interpersonal coordination can no longer be ignored. The why-question serves as a necessary stepping stone to subsequently investigate the structure and process underlying the joint activity.

This leaves us with one final question. How can the functional dimension of interpersonal coordination be investigated? In my view, the best way to do so is to conduct *de novo* learning experiments with challenging perceptuomotor tasks. Examples of what I mean by 'challenging' are the ski-simulation paradigm of Vereijken et al. (1992, 1997) and the shepherding paradigm of Nalepka et al. (2017). In task settings like this, the relationship that participants have to establish with their environment is usually not clear from the start. It needs to be discovered over practice. Within this process of discovery, the functional dimension of interpersonal coordination reveals itself. That is, some dyads will enact the social affordance and make the step from acting individually to acting as a team, while others will be stuck in their solo solution. Some dyads will wait for each other and act one by one, while others will act as one. Once these two groups have been distinguished, it becomes possible to describe the interpersonal structure of coordination and to investigate how this structure came about (i.e., the process). So far, the process of interpersonal coordination has been mostly been investigated via dynamical models that capture the stable attractor states of a team. However, new tools may be required to capture the transition from acting individually to acting as a team. Questions that need be answered are, for instance: What does each individual bring to the interaction? And what do they leave behind, in the process of forming a collective? Is a joint performance qualitatively different from a solo performance? Or is each individual's contribution reflected in the sum of its parts? For these questions to be addressed properly, it should be possible for participants to perform the task both individually *and* dyadically. This way, solo performances can be related to joint performances. Yet, it is crucial that joint performances have the potential to be much more successful than solo performances. If not, a social affordance is absent and the pull for participants to make the transition from acting individually to acting as a team is absent.

In an effort to design a task that met all the above requirements, we introduced in this thesis the manual ball-and-beam task. A novel joint action paradigm to study the interpersonal coordination of movement behavior.

1.3. This thesis

1.3.1. The ball-and-beam paradigm

The manual ball-and-beam task is a perceptuomotor task in which participant have to control a ball rolling on a long and hand-held beam. By continuously adjusting the inclination angle of the beam, participants' goal is to roll the ball fast and accurately between two targets indicated on the beam. In particular, their goal is to hit these targets as often as possible in the timespan of a two-minute trial, by reversing the direction of the ball motion within the target zones. While this goal is easy to understand, the task itself is quite challenging. It requires participants to learn a particular form of indirect control in which the relationship between their own movements and those of the to-be-controlled ball are unknown. As such, it constitutes a promising example of a discovery/de novo learning paradigm. The ball-and-beam task can be performed individually (in a solo action setting) as well as dyadically (in a joint action setting). In the solo action setting, one end of the beam is attached to a static hinge, while the other can be manipulated by the participant. In the joint action setting, both handles are manipulated by another participant.

1.3.2. Outline of thesis

This thesis is organized into 6 chapters. **Chapter 1** served as way to introduce the theoretical framework of the thesis. I provided arguments for my commitment to the ecological research program and proposed to adopt a decidedly functional approach within this program. **Chapter 2** to **5** include reports of experiments conducted with the ball-and-beam paradigm. While **Chapters 2, 3** and **4** are based on articles that have already either been published (Chapters 2 and 3) in or submitted (Chapter 4) to scientific journals, **Chapter 5** contains a preliminary report of our final experiment with this paradigm. **Chapter 6** provides a general discussion of the results found in this thesis, as well as an outlook on the future perspectives of research into the interpersonal coordination of movement.

In **Chapter 2**, we introduced the ball-and-beam paradigm via a first experiment into joint action learning. In this experiment, we had two groups of participants perform the task. One group first performed the task individually (in solo action) and then dyadically (in joint action), while another group first performed the task dyadically and then individually. We found two different modes of interpersonal coordination across both groups. Whereas the first group adopted a complementary mode of coordination with a large number of target hits, the latter group moved more sequentially with a lower number of hits. From this observation, we concluded that solo action practice may serve as a necessary precondition to make the shift from acting individually (i.e., sequentially) to acting as a team (i.e., complementary).

Based on the results of the first experiment, we decided to further explore the transfer of skill from the solo action to joint action, in a two-step experiment. In **Chapter 3** we had participants perform two consecutive solo action sessions of task. We found that

individual learning curves were characterized by an increase in the ball's speed and accuracy, but also by an increase in the beam's range and consistency of the motion. Moreover, we found different strategies of timing of the beam across cycles of motion. We concluded that individual skill acquisition was characterized by a gradual refinement of the beam dynamics, and that multiple timing strategies may lead to success on the task.

In **Chapter 4** the participants of Chapter 3 were paired into dyads to investigate how the individual characteristics of their performances were transferred from the solo to the joint action setting. We found that those characteristics that were (indirectly) related to the ball's speed were strongly transferred from solo to joint action, while those (indirectly) related the ball's accuracy were only weakly to moderately propagated. Moreover, we found that dyad members that acquired more target hits in solo action were more likely to take the lead in joint action. We concluded that the stability and symmetry of the interpersonal coordination emerged from the interaction, while being constrained by the task's goal to hit the targets.

In **Chapter 5**, we explored whether the stability and symmetry of the interpersonal coordination could be improved by training participants in a constrained solo action setting before pairing them into dyads for joint action. Although the constraining the beam's range of motion led a more efficient timing strategy in solo action, the transfer of this adaptation to joint action was weak. Consequently, the stability and symmetry were not significantly affected by the constrained practice.

Lastly, **Chapter 6** serves as general discussion of the results of this thesis. I reflect on the findings in light of the ecological-dynamical framework, discuss the strengths and weaknesses of the ball-and-beam paradigm and I touch upon some of the more practical implications of our work. In conclude this thesis by providing an outlook on the future of research into interpersonal coordination.

2. Freezing and freeing of degrees of freedom in joint action learning

2.1. Abstract

In daily life, we often encounter situations in which we have to coordinate our actions with others to achieve a common goal. These actions are also defined as joint actions. In this study we investigated how a multi-agent system learns to acquire control in a novel joint action task. To this end, we designed a task in which agents had to coordinate their actions so as to control a ball rolling on a long, hand-held beam. Participants' task was to roll the ball as fast and accurately as possible back-and-forth between two indicated targets on the beam, by manually adjusting the inclination angle of the beam. In the joint action version of this task, two participants each hold a different beam extremity. In a solo action version, the participant holds one extremity while the other is attached to a static support. The experiment consisted of two practice sessions that each comprised 15 two-min trials. One group of 12 participants first performed a solo action session of the task and then a joint action session (Group S/J), while another group of 12 participants started with a joint action session, followed by a solo action session (Group J/S). While performance increased over practice in all sessions, we found that in the joint action task dyads without prior solo task experience (Group J/S) adopted a sequential pattern of interpersonal coordination by freezing their motion whenever the other agent moved. In contrast, dyads that had received prior practice in the solo task setting (Group S/J) demonstrated less freezing and more complementary motion during the joint action performance. Lastly, we found that initial practice as a dyad in the joint action task did not result in a significant improvement of a subsequent solo action performance. We concluded that multi-agent motor learning in a novel joint action task is characterized by the initial freezing of task-relevant degrees of freedom, while individual training in a constrained setting can stimulate the freeing of these DFs during subsequent joint action performance.

2.2. Introduction

Humans are social animals. In many of our daily activities we coordinate our actions not only with the physical events or objects that surround us, but also with the actions and intentions of others. Whether we perform a well-practiced dance choreography with a partner or spontaneously help a friend to carry a heavy box, interpersonal coordination is omnipresent and often essential for task success. Tasks in which the coordination between agents is required to achieve a common goal are also known as joint actions (Sebanz et al., 2006; Butterfill, 2012). During a joint action, collaborating individuals are interdependent. For example, when two agents carry a box together, the functionality of

each individual's actions –such as lifting, lowering or rotating the box– is dependent on the actions of the partner. This dependency couples the individual movement systems and creates a functional multi-agent system (Marsh et al., 2006, 2009; Riley et al., 2011). Within this system, agents not only share the goal of carrying a box, but they also share the control over the box. Generally, the acquiring of control in a task involves a process of motor learning, in which an individual progresses over practice from task novice toward task expert (Bernstein, 1967). The current study aimed at characterizing motor learning in a joint action task, in which two agents are in the process of acquiring collective control in their task environment. To do this, we designed a challenging joint action task in which agents had to learn to coordinate their actions so as to control a ball rolling on a hand-held beam.

Interpersonal coordination can be approached as a systemic phenomenon that emerges from the interactions between agents and their environment (Marsh et al., 2009; Riley et al., 2011; Schmidt et al., 2011). For instance, when people are rocking chairs side-by-side, they are spontaneously attracted to a state of synchronous rocking (Richardson et al., 2007). This state of interpersonal coordination is not planned or orchestrated, but it emerges from the visual coupling between the agents and it is constrained by the properties of the system, such as the natural periods of the chairs (cf. Richardson et al., 2007). Such spontaneous coordination of action between agents can in fact emerge from different modes of coupling, whether they are mechanical (e.g., Harrison and Richardson, 2009) or informational (see Néda et al., 2000; for an example of auditory coupling and Van der Wel et al., 2011; for an example of haptic coupling). This phenomenon shows how lawfulness in interpersonal coordination is to be found at the level of the emergent behavior of the multi-agent system, rather than at the level of the processing of information of the individual agents (Marsh et al., 2009). In the following, we refer to this perspective as the systems approach to interpersonal coordination.

In the example of chair rocking (Richardson et al., 2007) interpersonal coordination emerges unintentionally and without a purpose. We defined a joint action task, however, as a task in which interpersonal coordination is required to achieve a common goal. To accommodate for this functional dimension of interpersonal coordination, Riley et al. (2011) proposed the Interpersonal Synergies Theory (IST). IST provides a systems account of coordination between agents who are involved in a joint action. The central concept in this framework is that of a synergy. A synergy is a functional grouping of degrees of freedom (DFs) of a system that temporarily acts as a coordinated unit (Bernstein, 1967; Turvey, 2007; Kelso, 2009, 2022). The core claim of IST is that during joint action these synergies not only emerge within individual movement systems, but also between two or more movement systems, underlying successful interpersonal coordination. For example, interpersonal synergies between the body segments of two individuals are assumed to underly coordination in the act of carrying a box together, as exemplified earlier.

Arguably, to date the most direct empirical support for the IST account of joint action comes from the bimanual pointer-and- target aiming paradigm, in which two agents together have to bring a pointer and a target to coincide (Mottet et al., 2001; Romero et

al., 2015). Mottet et al. (2001) demonstrated that the end-point variance of the relative motion between the pointer and the target was smaller than the sum of the end-point variances of these two effectors. This difference increased when accuracy demands of the task were higher, suggesting a functional interpersonal coupling – or synergy– between the pointer and the target operated by the two individuals. Using the same task paradigm, Romero et al. (2015) showed that not only the end-effectors, but also the joint angles of both individuals compensated for each other to stabilize the relative pointer-to-target motion. Moreover, in a static version of this interpersonal aiming task Ramenzoni et al. (2012) showed that considering the body segments of both individuals as the DFs of one multi-agent system resulted in a larger dimensional compression than considering the body segments as the DFs of two independent movement systems. This implies a stronger functional coupling of DFs between individuals than within individuals, adding to the evidence for the emergence of interpersonal synergies during joint action.

Manual pointing, however, is a relatively simple task for which practice is not required to be sufficiently coordinated. To illustrate, in the study of Romero et al. (2015) successful pointing of collaborating dyads was achieved in all trials and practice merely led to a small decrease in movement time. In contrast, Rigoli et al. (2015) investigated a joint action task in which task control was considerably more difficult to achieve. In their experiment, two agents jointly controlled a virtual ball rolling on a virtual labyrinth platform, by each manipulating a different joystick to tilt the platform. Rigoli et al. (2015) analyzed the performances on the first two trials and found that collaborating dyads spontaneously and mutually adapted to different joystick- to-platform mappings. By limiting their analysis to the first trials, they highlighted the spontaneous and adaptive character of the interpersonal coordination, confirming the findings of Mottet et al. (2001) and Romero et al. (2015) in the pointer-and-target paradigm. Yet, due to the mediating role of gravity and other passive forces in the system, jointly controlling a rolling ball on a tilted labyrinth is much more challenging than bringing a pointer and a target together.

Research in the domain of individual motor learning has demonstrated that patterns of coordination can change significantly and qualitatively over practice when a task is sufficiently challenging (e.g., Vereijken et al., 1997). This raises the question whether multi-agent systems also display qualitative changes in interpersonal coordination over learning. Findings of qualitative shifts in interpersonal coordination in a multi-agent shepherding task (Nalepka et al., 2017) suggest that this might indeed be the case. Therefore, the goal of this study was to characterize a multi-agent motor learning process. To this end, we designed the continuous manually-controlled ball-and-beam task, a new joint action version of the (small-scale) manual ball on beam positioning task explored by Huang et al. (2006).

Our manual ball-and-beam task is a novel and challenging perceptuomotor task in which motion of a ball on a long hand-held beam is controlled by adjusting the inclination of the beam. The goal of the task is to roll the ball as fast and accurately as possible back- and forth between two targets on the beam. Thus, our task design contains elements of both Fitts' classical reciprocal aiming task (Fitts, 1954; Mottet and Bootsma, 1999: Mottet et al., 2001) and gravity-mediated tasks such as virtual labyrinth ball rolling (Rigoli et al.,

2015), inverted-pendulum aiming (Van der Wel et al., 2011) and pole balancing (Foo et al., 2000; Jacobs et al., 2012). The difficulty of the task lies in the non-linear relationship between the motions of the beam and the ball, with the latter governed by the gravitational and other passive forces in the system. The manual ball-and-beam task can be performed alone (i.e., solo action task setting, **Figure 2.1A**) as well as together (i.e., joint action task setting, **Figure 2.1B**). In the solo action task setting, one end of the beam is statically supported while the other extremity can be manipulated by the agent. In the joint action task setting, on the other hand, the inclination of the beam can be adjusted independently by each of the two agents. In other words, in the joint action version, the ball-and-beam system as a whole has two systemic, that is, task- level specific, DFs. The question we address in this contribution is how these two DFs –and hence the two collaborating agents– are coordinated when they learn to control the ball together. In this contribution we therefore focus on the task related changes observed over practice in the solo and joint action settings.

According to Bernstein's (1967) theory of individual motor learning, the first stage of motor skill learning is characterized by the freezing of redundant DFs in the movement system, which he defined as the biomechanical joints of the body. By decreasing the motion around one or more joints, a novice freezes DFs to acquire initial control in a challenging task (Vereijken et al., 1992). Over learning, these DFs are progressively

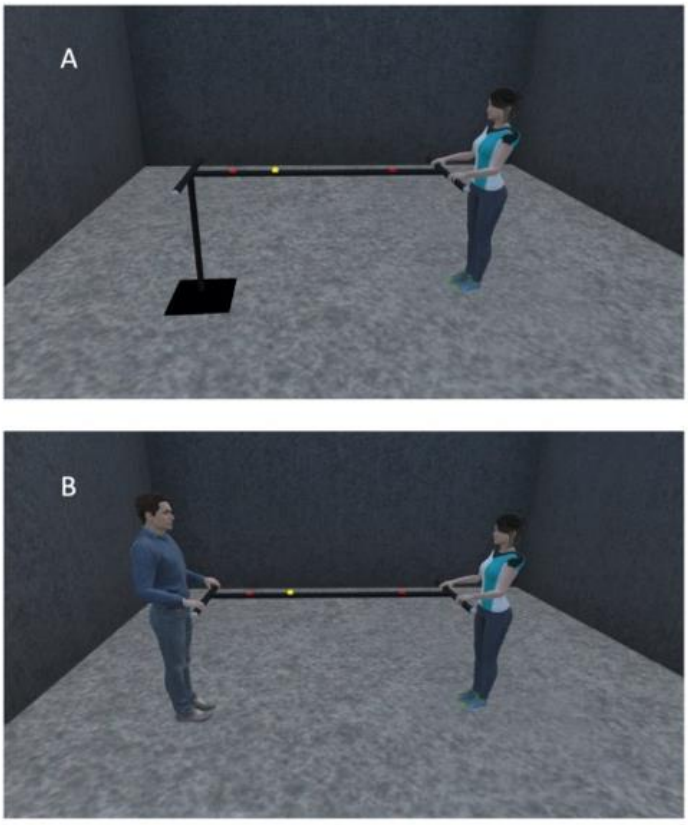


Figure 2.1 : Schematic illustration of the ball-and-beam task configuration used in the solo action task setting (A) and in the joint action task setting (B).

released, which ultimately allows performance-beneficial exploitation of the passive forces in the system without losing control. Due to the exploitation of such passive forces, the expenditure of active forces by the agent decreases, creating a more efficient task execution (e.g., Sevrez et al., 2012). In general, this theory of motor learning is well supported in the literature (see Guimarães et al., 2020). Freezing of joint angles during the first stage of learning has been found in for instance dart throwing (McDonald et al., 1989; Didier et al., 2013), ski- simulation movements (Vereijken et al., 1992; Hong and Newell, 2006) and football kicking (Anderson and Sidaway, 1994; Hodges et al., 2005). Newell and Vaillancourt (2001), on the other hand, proposed to interpret Bernstein's recruitment of DFs as a more abstract adaptation in the dimensionality of the attractor dynamic in the movement system rather than as an increase in recruitment of biomechanical joint angles per se. Underlying this proposal was the idea that DFs of a system are only relevant for learning when they are considered in relation to the demands of the specific task at hand (see also Gray, 2020). Our choice to focus on the coordination of the two systemic DFs of the ball-and-beam system, that is the two agents' contributions to beam motion, rather than on the coordination of the joint angles of each individual, is in line with this idea.

In this general context, we expected that the first stage of a multi-agent motor learning process would be characterized by the freezing of systemic DFs in the ball-and-beam system. More concretely, our first hypothesis was that the motion of one or both of the two individuals in a dyad would initially be minimized to create a more controllable system. Secondly, we hypothesized that individual agents' prior task experience in a constrained task setting would stimulate a multi-agent system to free-up its DFs by releasing the constraints. To test this second hypothesis, we designed an experiment in which participants not only performed the ball-and-beam task as a dyad in the joint action task setting, but also as an individual in the solo action task setting where there is only one systemic DF available. We expected that dyads with prior individual experience in such a constrained (1 DF) solo action setting would more readily display freeing-up of DFs in the (2 DF) joint action setting than dyads without any such individual task experience. We therefore asked one group of participants to first participate individually in a solo action task session before participating in a joint action task session (Group S/J). A second group of participants performed the joint action task session without prior practice on the solo action task. In order to evaluate whether joint action task experience was, in turn, beneficial to solo action task performance, the second group of participants (Group J/S) subsequently participated in a solo action task session.

2.3. Materials and method

2.3.1. Participants

A group of 24 students and junior staff members from Aix Marseille University (9 women, 15 men, with an average age of M ± SD: 24.1 ± 3.7 years) participated voluntarily in this study. All participants were free from known motor impairments and reported

normal or corrected-to-normal vision. Before the start of the first experimental session the participants were informed about the aim and procedure of the experiment. All participants provided written informed consent before participating in the study. The study was approved by the French National Ethics Committee for Research in Sports and Movement Sciences (CERSTAPS) and conducted according to University regulations and the Declaration of Helsinki.

2.3.2. Task and procedure

The task equipment consisted of a standard golf ball (4.3 cm diameter, 46 g weight) that could roll over a 2-m long, 3 by 3 cm V-shaped iron beam, with tubular (length 54 cm, diameter 3 cm) handles perpendicularly attached to its extremities. Participants' task was to roll the ball as fast and accurately as possible back- and-forth between two 15-cm wide targets clearly visible on the beam. Participants were instructed that they would receive one point for every time that the ball reversed direction within a target's boundaries and that their goal was to achieve as many points as possible within a 2-min trial. With both target centers located 60 cm from the beam's midpoint, the center-to-center inter- target distance was 120 cm. Bimanually holding one handle allowed a participant to lift or lower the beam's extremity and thereby change its inclination angle. In the solo action task setting, one of the two handles was attached to a pivot on a static pole, whose height was adjusted to the participant's hip height. In the joint action task setting each handle was hand-held by a different participant. In order to compensate for more than 10 cm height differences between participants, the smaller participant stood on a wide and stable wooden platform that allowed 2-cm stepwise height adjustments.

The experiment consisted of two sessions of practice on the ball-and-beam task completed on two different days, with 1 or 2 days between the sessions. The 24 participants were randomly divided into two groups of 12 participants. One group first performed a solo action session and then a joint action session (group S/J). The other group first performed a joint action session and then a solo action session (group J/S). Participants within each group were randomly paired into dyads for the joint action sessions. Each session began with a short warm-up trial of ~1 min, during which participants were given the chance to familiarize themselves with the ball-and-beam task. This was followed by 15 two-min practice trials, divided in blocks of three trials. Blocks were separated by 2–3 min breaks. During the trials, participants were not allowed to talk or communicate otherwise. Talking was allowed during the breaks but could not concern the task.

At the start of each trial, the ball was placed in the middle of the beam. Verbal signals from the experimenter signaled the beginning ("Go") and the end ("Stop") of a trial. After each trial, participants received verbal feedback on their score, based on experimenter observation. Participants were regularly encouraged to try to improve their score on each new trial, in order to reach the highest score possible within a session. In both the solo and the joint action task practice session participants competed indirectly with the other players via a leaderboard that expressed the high scores of the other participants. Moreover, small (delicacy) prizes were awarded to those with the highest scores. All of

this was intended to motivate participants to perform optimally on each new trial. Participants were asked to refrain from communicating with others about task strategies or any other aspects of the ball-and-beam task.

2.3.3. Data acquisition and analysis

All sessions took place in a darkened room. To capture the motion of the ball and the beam, a reflective marker was attached to each handle and the ball was chosen to be bright yellow. Participants wore dark clothes and black gloves to ensure sufficient contrast with the ball and the markers. All trials were filmed with a tripod-mounted GoPro9 camera that was positioned at a 1-m height and a 2-m perpendicular distance from the midpoint of the beam. This allowed ensuring that all relevant ball and beam motion occurred well within the field of view. The camera was set in linear lens mode so as to obtain minimal image deformation. In the joint action task setting, participants were asked to take place on fixed locations 2.5 m apart, holding the beam in between them. All trials were recorded with a (recalculated) sample frequency of 59.94 Hz and a resolution of 2.7K. Due to technical issues, six trials were excluded from analyses, leaving a total of 534 trials for analysis. No session had more than one missing trial.

Video recordings of all trials were imported into Kinovea (https://www.kinovea.org/), which was used to track the two- dimensional (X, Y) motion of the ball and the two reflective markers on the beam extremities. X and Y position time series were then analyzed using MATLAB. All data were first filtered using a fourth-order low-pass Butterworth filter (cut-off frequency of 3 Hz) and trimmed to the 120-sec trial duration. The ball trajectory was subsequently transformed from motion in a two-dimensional space to one-dimensional motion along the beam, represented by the motion along the virtual line between the two markers, with the inter-marker distance used for calibration. The ball motion and the motion of the two markers on the beam extremities formed the basis of all further analyses. We analyzed the data on three distinct levels of the multi-agent system: (1) the level of task performance, (2) the level of beam inclination and (3) the level of interpersonal coordination.

The level of task performance comprised an analysis of the ball motion. Using a peak finding algorithm, we split the ball position timeseries into separate cycles and counted the number of ball reversals within the target zones to calculate the scores per trial. Average ball speed over a trial was calculated by multiplying the ball cycle frequency with twice the average amplitude of the ball cycles. Thirdly, ball accuracy was expressed in terms of the effective target width reached in a trial. This variable was calculated by multiplying the standard deviation of the ball position peaks around the two targets by 1.96 (Welford, 1968). Lower effective target width therefore indicated higher ball accuracy on a trial.

The second level of the analysis concerned the beam inclination angle. This variable represents the “end-effector” of the ball-beam system, that is, the variable that is manipulated so as to control the ball rolling on the beam. Note that in the joint action version of the task, beam inclination is influenced by the motion of both individuals and thus a result of their underlying coordination. The beam inclination angle was calculated

at each time step by taking the inverse tangent (atan) of the X-Y positions of the two beam extremity markers. From these beam inclination angle time-series we derived an average beam inclination amplitude per trial by multiplying the average absolute inclination angle with $\pi/2$.

Lastly, the third level of the analysis comprised an analysis of the interpersonal coordination. For this, we used the vertical motion of the two beam extremities. We calculated the proportions of the trial times that both participants moved in the same direction (referred to as the supplementarity ratio), in the opposite direction (referred to as the complementarity ratio) or that at least one of the two individuals moved slower than a threshold value of 0.05 m/s (referred to as the freezing ratio). To investigate whether or not the observed freezing was equally divided over the two individuals in a dyad, we calculated individual freezing ratios as well, defined as the proportion of the time that vertical beam velocity of each individual was lower than 0.05 m/s.

2.3.4. Statistical analysis

For the purpose of statistical analysis, we set the data for the missing trials (6 out of 540) to the average value of the 14 remaining trials of that participant (4) or dyad (2) in the corresponding session.

While the participants performing the joint action session as dyads also performed the solo action individually, for the present purposes we did not seek to relate dyads' performance on the joint action task to the corresponding individuals' performance on the solo action task. This led us to adopt a design for the statistical analyses with two groups of twelve participants for the solo action task and two groups of six dyads for the joint action task. A 2 x 2 x 15 mixed-design ANOVA, with the between-participant factors Task (solo action, joint action) and Group (S/J, J/S) and the within-participant factor Practice (15 trials), was used to analyze Task, Group, and Practice effects on dependent variables performance score, average ball speed, effective target width and average beam inclination amplitude, calculated for each trial. For the joint action task setting, interpersonal coordination indicators complementarity ratio, supplementarity ratio and freezing ratio were analyzed using a 2 x 15 mixed-design ANOVA, with the between-participant factor Group (J/S, S/J) and the within-participant factor Practice (15 trials).

For all analyses the significance level was set to $\alpha = 0.05$. Greenhouse-Geisser corrections were applied when violations of the sphericity assumption were detected. Post-hoc tests were performed using Tukey HSD. Where appropriate means and standard deviations are reported as M ± SD.

2.4. Results

2.4.1. Task performance

Performance score. The 2 x 2 x 15 mixed design ANOVA on performance score revealed significant main effects of Practice ($F(7.53, 240.98) = 16.62$, $p < 0.001$, $\eta^2_p = 0.34$) and Task ($F(1, 32) = 6.44$, $p = 0.016$, $\eta^2_p = 0.17$), as well as a significant Task x Group interaction ($F(1, 32) = 4.75$, $p = 0.037$, $\eta^2_p = 0.13$). All other effects were not significant. As can be seen from **Figure 2.2**, the main effect of Practice indicated that both groups improved their scores over trials on both tasks. Post hoc analysis of the Task x Group interaction revealed that the joint action score of Group S/J (44.1 ± 7.6 points) was significantly higher than the solo scores of Group J/S (34.8 ± 6.6 points, $p = 0.047$) and Group S/J (32.8 ± 7.0 points, $p = 0.011$), but not significantly higher than the joint action score of Group J/S (35.7 ± 5.8 points, $p = 0.160$). No other differences were significant.

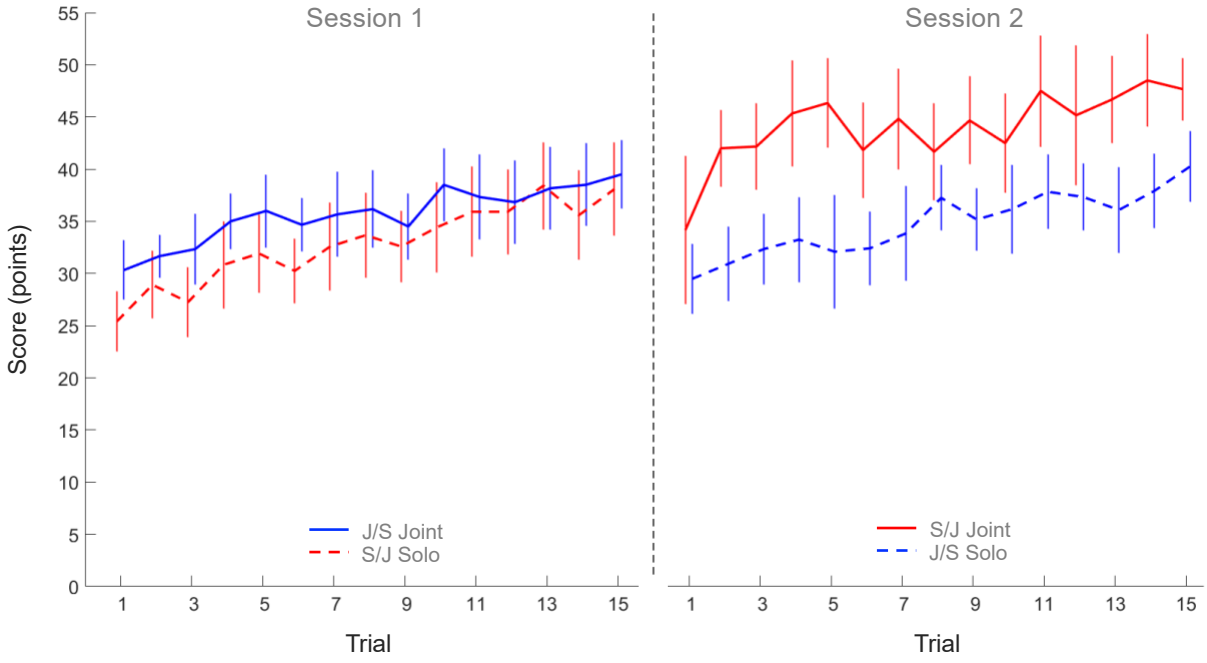


Figure 2.2. : Mean performance scores (points) over practice trials per group and per task. Solid lines indicate joint action task performances, while dashed lines represent solo action task performances. Group S/J (red) first performed the solo action task (Session 1) and then the joint action task (Session 2), whereas Group J/S (blue) first performed the joint action task (Session 1) and then the solo action task (Session 2). Error bars represent between-participant standard deviations.

Ball speed. The 2 x 2 x 15 mixed design ANOVA on average ball speed revealed significant main effects of Practice($F(4.42, 141.53)=8.61$, $p < 0.001$, $\eta^2_p = 0.21$), Task ($F(1, 32) = 20.6$, $p < 0.001$, $\eta^2_p = 0.39$) and Group ($F(1, 32) = 10.5$, $p = 0.003$, $\eta^2_p = 0.25$), as well as a significant Task x Group interaction ($F(1, 32) = 15.5$, $p < 0.001$, $\eta^2_p = 0.33$). All other effects were not significant. As can be seen from **Figure 2.3**, the main effect of Practice

indicated that both groups increased their ball speed over trials on both tasks. Post hoc analysis of the Task x Group interaction revealed that Group S/J displayed a significantly (p < 0.001) higher ball speed on the joint action task (0.68 ± 0.11 m/s) than Group J/S (0.48 ± 0.08 m/s). Group S/J's ball speed on the joint action task was moreover significantly higher than the ball speed on the solo action task of Group S/J (0.44 ± 0.08 m/s, p < 0.001) and Group J/S (0.46 ± 0.06 m/s, p < 0.001). No other differences were significant.

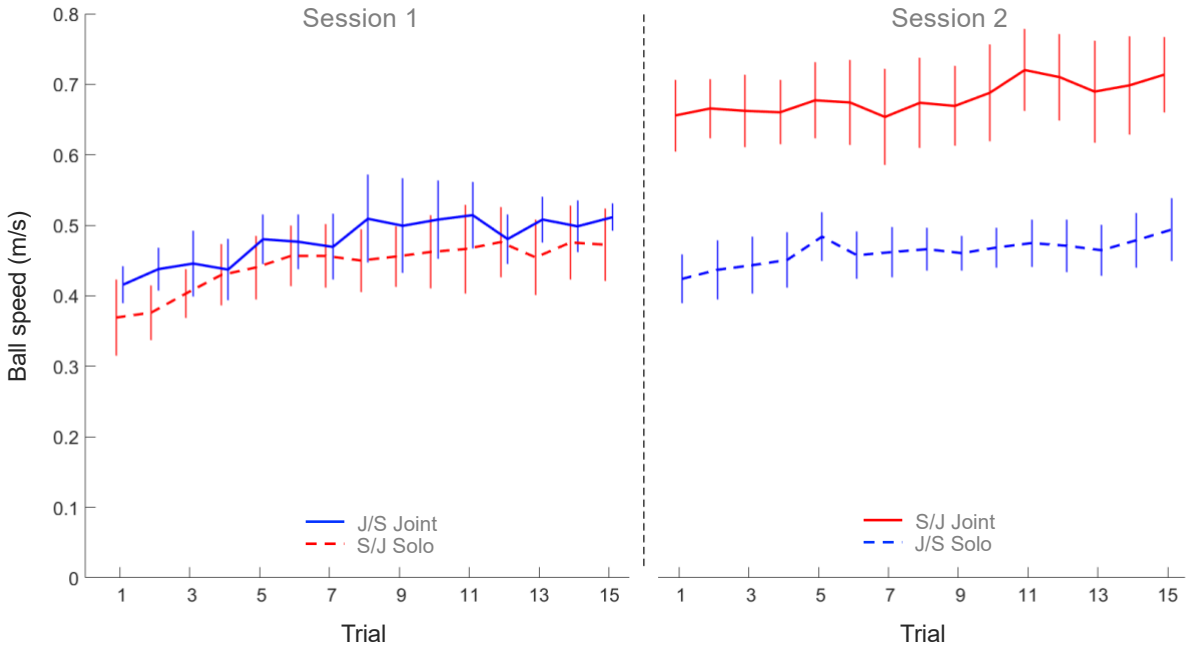


Figure 2.3 : Mean ball speed (m/s) over practice trials per group and per task. Solid lines indicate joint action task performances, while dashed lines represent solo action task performances. Group S/J (red) first performed the solo action task (Session 1) and then the joint action task (Session 2), whereas Group J/S (blue) first performed the joint action task (Session 1) and then the solo action task (Session 2). Error bars represent between-participant standard deviations.

Ball accuracy. The 2 x 2 x 15 mixed design ANOVA on effective target width revealed significant main effects of Practice (F(7.10, 227.16) = 3.36, p < 0.001, η^2_p = 0.10) and Task (F(1, 32) = 7.57, p < 0.010, η^2_p = 0.19). All other effects were not significant. As can be seen from **Figure 2.4**, the main effect of Practice indicated that both groups decreased their effective target width (i.e., increased their ball accuracy) over trials on both tasks. The main effect of Task, on the other hand, indicated that the effective target width of participants in both groups was lower on the solo action task (15.6 ± 3.4 cm) than on the joint action task (19.5 ± 4.9 cm), indicating a general higher ball accuracy on the solo action task.

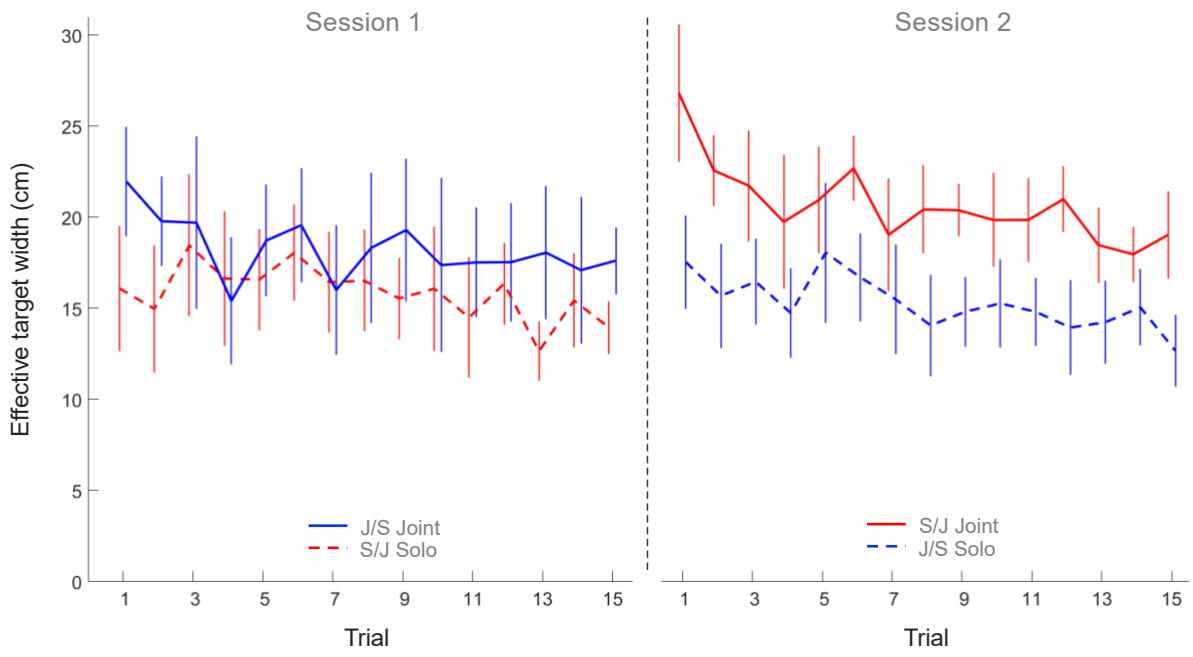


Figure 2.4 : Mean effective target width (cm) over practice trials per group and per task. Solid lines indicate joint action task performances, while dashed lines represent solo action task performances. Group S/J (red) first performed the solo action task (Session 1) and then the joint action task (Session 2), whereas Group J/S (blue) first performed the joint action task (Session 1) and then the solo action task (Session 2). Error bars represent between-participant standard deviations.

2.4.2. Beam inclination amplitude

The 2 x 2 x 15 mixed design ANOVA on average beam inclination amplitude revealed significant main effects of Practice ($F(3.87, 123.91) = 9.54$, $p < 0.001$, $\eta^2_p = 0.23$), Task ($F(1, 32) = 24.3$, $p < 0.001$, $\eta^2_p = 0.43$) and Group ($F(1, 32) = 15.0$, $p < 0.001$, $\eta^2_p = 0.32$), as well as a significant Task x Group interaction ($F(1, 32) = 17.0$, $p < 0.001$, $\eta^2_p = 0.35$). All other effects were not significant. As can be seen in **Figure 2.5**, the main effect of Practice indicated that both groups increased the beam amplitude over trials on both tasks. Post hoc analysis of the Task x Group interaction revealed that Group S/J had a significantly ($p < 0.001$) larger beam amplitude on the joint action task (20.8 ± 6.4 degrees) than Group J/S (10.6 ± 3.0 degrees). Group S/J's beam amplitude on the joint action task was moreover significantly larger than the solo action amplitudes of Group S/J (9.3 ± 3.1 degrees, $p < 0.001$) and Group J/S (9.6 ± 2.2 degrees, $p < 0.001$). No other differences were significant.

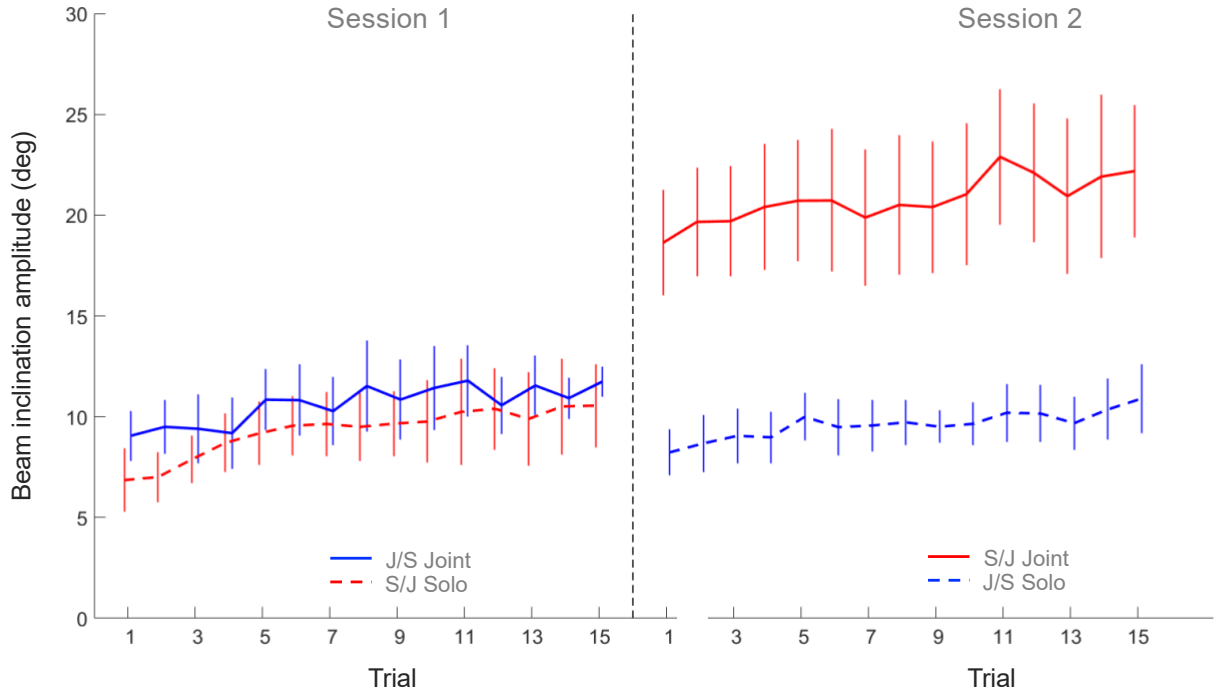


Figure 2.5 : Mean beam angle amplitude (degrees) over practice trials per group and per task. Solid lines indicate joint action task performances, while dashed lines represent solo action task performances. Group S/J (red) first performed the solo action task (Session 1) and then the joint action task (Session 2), whereas Group J/S (blue) first performed the joint action task (Session 1) and then the solo action task (Session 2). Error bars represent between-participant standard deviations.

2.4.3. Interpersonal coordination

To capture the underlying interpersonal coordination, we analyzed the relative directions of vertical motion of both individuals, calculating how frequent (in proportion to total trial time) the two agents were moving in the same direction (supplementarity ratio), in the opposite direction (complementarity ratio) or, for at least one of the agents, not moving at all (freezing ratio). The 2 x 15 mixed design ANOVAs with Group(S/J, J/S) as between-participant factor and Practice (15 trials) as within-participant factor revealed significant main effects of Practice for all three ratios: As can be seen from **Figure 2.6**, the freezing ratio ($F(14, 140) = 2.93$, $p < 0.001$, $\eta^2_p = 0.23$) and the supplementarity ratio ($F(14, 140) = 1.83$, $p < 0.039$, $\eta^2_p = 0.16$) both decreased over practice, while the complementarity ratio increased over practice ($F(14, 140) = 3.10$, $p < 0.001$, $\eta^2_p = 0.24$). Moreover, the ANOVAs revealed significant main effects of Group for both the freezing ratio ($F(1, 10) = 13.6$, $p < 0.004$, $\eta^2_p = 0.58$) and complementarity ratio ($F(1, 10) = 15.5$, $p < 0.003$, $\eta^2_p = 0.61$). Freezing ratio was significantly lower in group S/J (26.7 ± 10.3 %) than in group J/S (49.6 ± 11.1 %), while the complementarity ratio, on the other hand, was higher in group S/J (60.7 ± 13.2%) than in group J/S (37.3 ± 6.4%). Supplementarity ratio was not significantly different between groups (S/J 12.5 ± 7.0%, J/S 13.2 ± 5.3%, $p > 0.05$). All other effects were not significant.

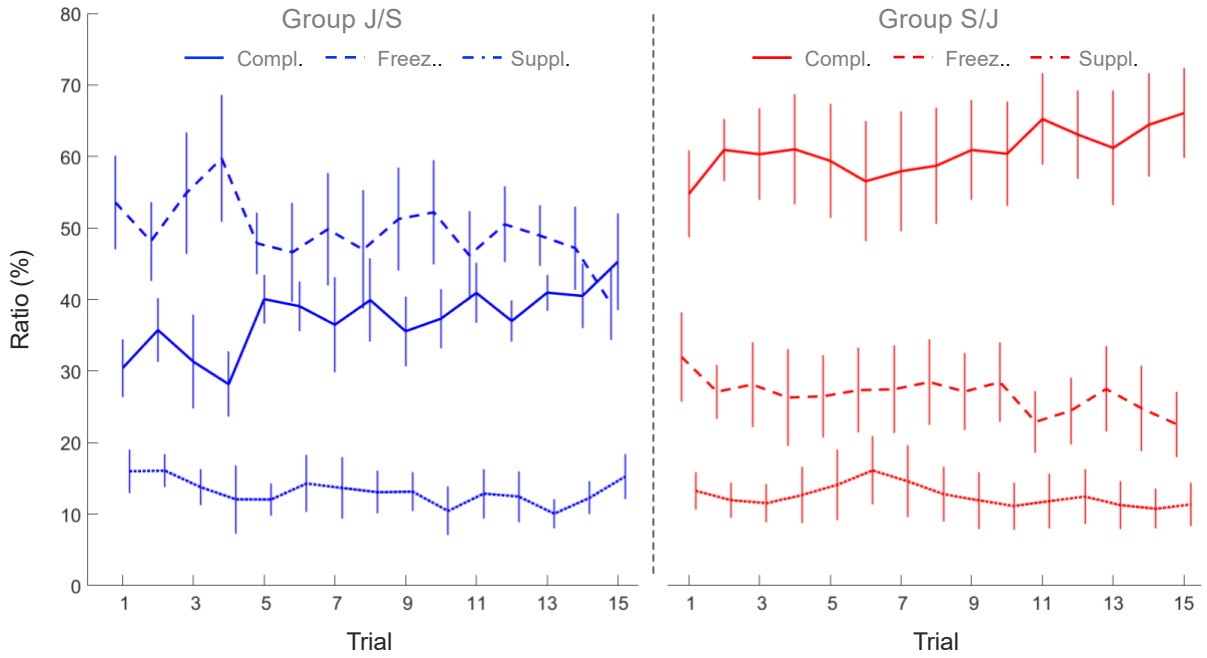


Figure 2.6 : Mean freezing ratio (dashed lines), complementarity ratio (continuous lines) and supplementarity ratio (dotted lines) of the joint action task performances of group J/S (blue) and group S/J (red). Error bars represent between-participant standard deviations.

Individual freezing. The freezing ratio as described above specifies how often at least one of the two individuals in a dyad froze their motion. But it does not indicate to what extent the freezing behavior of both agents overlap during the joint action. To assess this, we analyzed the individual freezing ratios of both agents (i.e., the relative amount of time that an agent's handle had a velocity below the threshold of 0.05 m/s) and compared it to the freezing ratio of the dyad as a whole. When part of the individual freezing is overlapping, the dyadic freezing ratio must be lower than the sum of the individual ratios within a dyad. As shown in **Table 2.1**, the freezing ratio of all dyads was indeed lower than the sum of the individual ratios, implying some degree of overlap in freezing. The amount of overlap, however, was low in both groups (13.5% in group S/J and 14.3% in group J/S). Corroborated by visual inspection of the handle-motion time series, this finding indicates that the freezing of dyads was sequential rather than simultaneous. The sequentiality of the freezing behavior does not necessarily mean that the freezing was also equally distributed over the two agents. As a last step, we compared the two individual freezing ratios to assess the freezing distribution within dyads. As can be seen in the last column of **Table 2.1**, the difference between the two individual freezing ratios was again generally low. In group S/J, the difference was below 6% in all but one dyad (16.1%), while in group J/S – that demonstrated considerably higher dyadic freezing ratios– the differences were all below 22%. This suggests that freezing was more or less equally distributed within dyads, confirming the observed sequentially alternating character of the freezing behavior.

Table 2.1: Average freezing ratio (in percentage of total trial time) per dyad (D) and per agent within a dyad (A) during joint action task performance for group S/J and group J/S.

Group	Dyad	D (%)	A1 (%)	A2 (%)	A1 + A2 (%)	D/(A1 + A2)	|A1 − A2| (%)
S/J	1	38.5	18.0	23.0	41.0	0.94	5.0
	2	13.1	9.9	5.5	15.4	0.85	4.4
	3	17.3	9.3	11.4	20.7	0.84	2.1
	4	36.2	20.3	25.6	45.9	0.79	5.3
	5	31.4	26.0	9.9	35.9	0.88	16.1
	6	23.9	12.5	14.5	27.0	0.89	2.0
J/S	7	42.7	31.6	13.5	45.1	0.95	18.1
	8	64.7	48.7	33.7	82.4	0.79	15.0
	9	33.8	15.0	24.6	39.6	0.85	9.6
	10	53.0	26.7	32.6	59.3	0.89	5.9
	11	45.7	36.7	15.4	52.1	0.88	21.3
	12	57.5	29.9	43.9	73.8	0.78	20.0

2.5. Discussion

The goal of this study was to characterize the process of multi- agent motor learning. How do two individuals learn to coordinate their actions to acquire control in a novel joint action task? To investigate this, we designed the continuous manual ball-and-beam task in which agents had to control a ball rolling on a beam by manually adjusting the inclination of that beam. We asked participants to perform the task alone, in a solo action task setting, as well as in dyads, in a joint action task setting. For present purposes, we did not seek to relate dyads' performance on the joint action task to the corresponding individuals' performance on the solo action task, but focused on the development of performances over practice in both task settings. We found that participants significantly improved their performance over practice in both task settings, as evidenced by gradual increases in the scores over trials. Underlying this improvement in performance was a strong increase in ball speed and a moderate decrease in effective target width. The higher ball speeds were largely caused by increasing beam amplitudes over practice. We note that the observed increases in ball speed together with observed decreases in effective target width, indicating increases in accuracy, suggested an improvement in control over the ball and thereby provided a first indication of successful motor learning in both the solo and joint action task settings. From this perspective, the particularly high ball speeds attained by the S/J group on the joint action task are worth noticing. But how did participants, in particular the dyads in the joint action task setting, establish this improvement in performance over practice?

Based on Bernstein's (1967) theory of individual motor learning, we hypothesized that the first stage of multi-agent motor learning would be characterized by the freezing of systemic, task- relevant DFs to simplify control of the ball-and-beam system. Motion analyses of collaborating dyads in the joint action task confirmed this first hypothesis. In the early trials of dyads without any prior task experience (i.e., group J/S), more than half

of the trial time (53% on average over first five trials; **Fig 2.6**) consisted of the freezing of motion of at least one of the two individuals within a dyad. More specifically, dyads in the J/S group generally displayed a sequential, turn-taking pattern of interpersonal coordination to control the ball. Although these dyads increased the amount of beam movement over practice, the freezing ratio of all dyads in the J/S group remained relatively high throughout the joint action session (46% on average over last 5 trials). On a systemic level, the sequential motion of the two individuals implied that one of the two DFs of the ball-and- beam system was temporarily frozen during each half cycle of the ball. This suggests that the first stage of multi-agent motor learning may be considered functionally equivalent to the first phase of individual motor learning, as described by Bernstein (and corroborated empirically, e.g., Vereijken et al., 1992; Anderson and Sidaway, 1994; Hodges et al., 2005). By freezing task-relevant degrees of freedom, a system is constrained so as to be more controllable, regardless of whether this is a single- or a multi-agent system. As witnessed by the increase in performance score over practice, group J/S indeed progressed in terms of control in the joint action task.

Secondly, we hypothesized that freeing-up of systemic DFs could be stimulated by providing individuals with prior task experience in a constrained solo action task setting. To this end, we asked participants from the S/J group to practice a solo action task before practicing the joint action task and compared their performance to the J/S group that did not have any solo action experience before practicing the joint action task. As expected, we found that the (S/J) group with solo action task experience displayed a considerably lower amount of freezing of DFs (27% on average) during joint action than the (J/S) group without such experience (50% on average). Moreover, motion analyses demonstrated that S/J dyads moved the beam handles simultaneously and in opposite (i.e., complementary) directions for more than 60% of the time, compared to 37% for the J/S dyads. Such complementarity between agents in beam handle motions highlights the collaborative interpersonal coordination developed by dyads of the S/J group, with both individuals within a dyad (i.e., both available systemic DFs) cumulatively amplifying beam inclination adaptations. On a systemic level, compared to the J/S group, the much larger degree of complementarity between the motions of the individuals within the dyads allowed the S/J group to produce larger beam inclination amplitudes, associated with higher ball speeds that allowed to improve the scores. Over joint action practice, the S/J group's complementarity ratio increased (from 59% on the first five trials to 64% on the last five trials), while the freezing ratio simultaneously decreased (from 28% on the first five trials to 24% on the last five trials). While the J/S group showed a similar pattern of change (increase in complementarity ratio from 33% on the first five trials to 41% on the last five trials; decrease in freezing ratio from 53% on the first five trials to 46% on the last five trials), the dyadic coordination patterns remained qualitatively different between the two groups. Taken together, these results indicate that prior training on the constrained solo action task leads to subsequent freeing of systemic DFs during joint action, enabling the multi-agent system to create larger beam inclination amplitudes, exploit the passive forces in the system and improve the performance.

A question that comes up naturally when interpreting these results is whether a continuation of the joint action practice by the (J/S) group without any prior task experience would eventually lead to the same type of interpersonal coordination as demonstrated by the (S/J) group with prior solo action experience. On the one hand, the above-described increase in the complementarity ratio and decrease in the freezing ratio over joint action practice suggests that the interpersonal coordination would have continued to evolve with prolonged practice on the joint action task. This suggests that the performance scores that result from this coordination would also have continued to increase over practice. On the other hand, we recall that motor learning is not necessarily a gradual process. On the contrary, learning often progresses in a discontinuous, stage-like fashion (e.g., Vereijken et al., 1997). It is therefore not unlikely that some of the dyads would have continued to move sequentially for a long time before, if ever, making the transition to a more efficient form of complementary interpersonal coordination. In fact, this is exactly what Nalepka et al. (2017) found in their study of interpersonal coordination in a dyadic shepherding task. Over practice, some dyads soon switched from a suboptimal discrete strategy ("search and recover") to a more efficient continuous solution ("coupled oscillatory containment"), while others continued the search and recover strategy throughout the entire duration of the experiment. Our results suggest a similar distinction between a discrete solution (i.e., sequential motion) and a continuous solution (simultaneous motion). Accordingly, we expect that following prolonged practice some dyads might have made the switch from sequential to simultaneous motion, while others might have continued in the suboptimal solution.

Finally, we evaluated whether joint action practice would lead to better performances in a subsequent solo action session of our ball-and-beam task. To test this, we asked the (J/S) group that started with a joint action task practice session to also engage in a solo action task practice session after that. We found that the solo action performance of this group was not significantly better than that of the (S/J) group that performed the solo action session without any prior task experience. We suggest that the key to understanding this finding might lie in the nature of what is learned during practice on this ball-and-beam task. To acquire control over the ball, one needs to learn how to relate the motion of the beam inclination to the motion of the rolling ball. In other words, the agent needs to learn how to handle a complex and non- linear relationship between the ball and the beam, mediated by gravitational and other passive forces in the system. In the solo action task setting, the agent-induced motion of the beam extremity is fully equivalent to changes in the beam inclination. This implies that an agent learns to couple motion of the beam extremity directly to the motion of the ball. In the joint action task setting, however, two agents independently change the beam inclination. For this reason, the agent not only needs to learn to couple the motion of its own beam extremity to the motion of the ball, but also to the other agent's motion. As discussed above, our results indicated that the multi-agent system approaches this highly challenging task by initially freezing one of its DFs in such a way that only one agent at a time changes the beam inclination. However, such freezing was not only not flawless (in the sense that it only implied handle motion of <0.05 m/s), but was also only partial (60% of the time on

average) and not necessarily always occurring at the exact same handle position. From the perspective of an individual, compared to the solo action task setting, such variations create additional noise that could be detrimental to learning the ball and beam relationship.

An alternative explanation for the absence of a transfer effect from joint action learning to solo action learning could be the sequential form of interpersonal coordination observed during the preceding joint action performances in this group. Agents generally froze their motion when the ball rolled in the direction of their partner and, in turn, started moving when the ball rolled back in their direction. By taking turns in controlling the ball instead of moving concurrently, individual agents only learned to control the ball during one half of the ball's full cycle. Yet, in the subsequent solo action setting agents were forced to control the ball throughout the full cycle instead of only during one half cycle. Speculatively, we suggest that the difference between sequential control in the joint action task and continuous control in the solo action task could be the principal reason for the apparent absence of a transfer effect in this ball-and-beam task. More generally, Karlinsky and Hodges (2018) also found that taking alternating turns in practicing a balancing task and observing someone else practicing that task did not improve the effectiveness of the motor learning process. This suggests that watching the other agent controlling the ball in between the agent's own actions was not beneficial to the motor learning process.

We conclude that motor learning of a challenging, novel joint action task is characterized by the initial freezing of task-relevant degrees of freedom so as to constrain the multi-agent system. Moreover, training in a constrained solo action setting stimulates freeing of DFs during a subsequent joint action performance, leading to significant improvements in joint action performance. Joint action training by itself, however, does not necessarily lead to better solo action performances in the same task. Overall, our results suggest that the distinguishable stages of multi-agent motor learning are functionally equivalent to those of individual motor learning, providing support for a systems approach to interpersonal coordination. As a final point, we note that the ball-and-beam system has been extensively studied by control engineers as a simple laboratory model for nonlinear systems, focusing on the inherent instability of the ball's position on the beam. Feedback-based control schemes using a motor to drive changes in beam inclination angle are therefore typically developed for stabilizing the ball at a designated position (or series of positions) on the beam (e.g., Hauser et al., 1992; Rahmat et al., 2010; Bolívar-Vincenty and Beauchamp-Báez, 2014). Similar work has addressed its 2D extension to the ball- on-plate system (e.g., Fan et al., 2004; Debono and Bugeja, 2015). In the domain of human motor control, however, the manual control of such systems has so far received little to no attention (but see Huang et al., 2006; for an exception). We suggest that the ball rolling task paradigm prefatorily explored in this contribution can offer a window into the processes underlying perceptuomotor control and learning. Indeed, the availability of system models for exploring the lawful relationship between ball and beam motion allows addressing the ball motion driven adaptations in beam motion characteristics in both single-agent and multi-agent settings.

3. Perceptuomotor skill acquisition in a solo manual ball-and-beam task with varying accuracy requirements

3.1. Abstract

In the manual ball-and-beam task, participants have to control a ball that is rolling continuously on a long and hand-held beam. Since the task can be performed individually, in a solo action setting, as well as collaboratively, in a (dyadic) joint action setting, it allows us to investigate how joint performances arise from individual performances, which we investigate in a series of interrelated studies. Here we focused on individual skill acquisition on the ball-and-beam task in the solo action setting, with the goal to characterize the behavioral dynamics that arise from learning to couple (ball motion) perception and (beam motion) action. By moving a beam extremity up and down to manipulate the beam's inclination angle, the task's objective was to roll the ball as fast as and accurately as possible between two indicated targets on the beam. Based on research into reciprocal aiming tasks, we hypothesized that the emergent dynamics of the beam's inclination angle would be constrained by the size of the targets, such that large targets would evoke a continuous beam movement strategy, while small targets would lead to a discrete beam movement strategy. 16 participants individually practiced the task in two separate six-block sessions. Each block consisted of one trial per target-size condition (small, medium and large). Overall, the number of target hits increased over trials, due to a larger range of motion of the beam's inclination angle, a stronger correlation between the ball and beam motion and a smaller variability of the beam motion. Contrary to our expectations, target size did not appreciably affect the shape of the beam movement patterns. Instead, we found stable inter-individual differences in the movement strategies adopted that were uncorrelated with the number of target hits on a trial. We concluded that multiple movement strategies may lead to success on the task, while individual skill acquisition was characterized by the refinement of behavioral dynamics that emerged in an early stage of learning. We speculate that such differences in individual strategies on the task may affect the interpersonal coordination that arises in joint-action performances on the task.

3.2. Introduction

In the manual ball-and-beam task introduced by Hafkamp et al. (2023), participants have to control the motion of a ball that is rolling on a long, hand-held beam. To do so, they have to adjust the inclination of that beam continuously, so as to use the force of gravity to their advantage. The goal of this novel perceptuomotor task is to roll the ball as

fast and accurately as possible between two indicated targets on the beam, with the instruction to hit (i.e., reverse direction of ball motion within) these targets as often as possible within a pre-defined timespan (e.g., 2min). While its goal is easy to understand for participants, the task itself is quite challenging. It implies an indirect control of the ball's motion via manipulation of the beam's inclination. What makes it particularly interesting is that the task can be performed alone (i.e., in a solo action setting) and in collaboration with someone else (i.e., in a dyadic joint action setting). In the solo action setting, one end of the beam is statically supported while the other extremity is manipulated by the agent. In the joint action setting, the two extremities are manipulated by different agents, meaning that a stable mode of interpersonal coordination is required to control the rolling ball on the beam.

A first study on this task (Hafkamp et al., 2023) demonstrated that the emergence of interpersonal coordination was dependent on the (solo) task experience of the two individuals involved. When both players were unexperienced with respect to the task, they typically moved the beam in a sequential, alternating fashion, each player freezing their motion while the other moved. In contrast, when both players had received individual practice prior to the joint action session, they moved the beam concurrently and in opposite directions. This effect suggests that the mode of interpersonal coordination that arises in a joint action setting, is somehow dependent on the performances of individuals in solo action setting. Apparently, experienced ball-and-beam players bring something to the interaction that unexperienced players do not. There is, in other words, a transfer of skill that affects the outcome of the joint action performance. In a series of studies, we set out to investigate the nature of this transfer, with the goal to understand how a coordinated team can arise from a collection of individuals (Baron, 2007). As a first step, the current contribution aims to identify the pertinent characteristics of individual performances in the solo ball-and-beam setting. How does a player learn to control the ball on this task? And is this learning process the same for all individuals, or do qualitative differences in their performances emerge over practice? In a follow-up contribution, we will explore which aspects of these individual performances are transferred to a joint action setting and which aspects are left behind in the interaction.

In our previous study (Hafkamp et al., 2023) we observed that individual practice in the solo ball-and-beam setting resulted in a significant increase in the number of target hits per trial. In part, this increase was due to a higher average speed of the ball, caused by an increasing range of motion of the beam's inclination angle. This, however, was not the only factor that contributed to the improvement in performance over trials. We also found that, notwithstanding the increase in ball speed, the consistency of the ball motion around the targets improved over practice. Together, these findings indicated that task practice improved a participant's ability to control the ball motion. In other words, it suggested that participants had learned how to coordinate the motion of the beam with the motion of the ball on that beam. To achieve such 'ball-beam coordination', a player needs to learn how to couple its action of lifting and lowering the beam with its perception of the ball rolling between the two targets. As such, the challenge for the player lies in

relating the beam's motion to the pertinent information that specifies the motion of the ball (see for instance Jacobs et al., 2012, for perception-action coupling in pole balancing). This continuous and reciprocal perception-action coupling (Bootsma and van Wieringen, 1990; Bootsma, 1998) ultimately gives rise to an observable dynamics of the ball-beam system, which, following Warren (2006), we refer to as its behavioral dynamics. The primary goal of the current study was to characterize this behavioral dynamics. Which patterns of ball and beam motion arise from the perception-action coupling in this ball-and-beam task? And does the same behavioral dynamics emerge for all individuals or does practice lead to noticeable differences between players?

To understand which behavioral dynamics might arise, it is helpful to take a closer look at dynamical properties of the ball-and- beam task as a physical system (Bolívar-Vincenty and Beauchamp- Báez, 2014; Debono and Bugeja, 2015). For starters, the ball is set into motion by the driving (tangential) component of the force of gravity, with the instantaneous translational acceleration of the ball thus being determined by the inclination angle of the beam. Deceleration of the ball is caused by that same (tangential component of the) force of gravity –now working in opposite directing– but also depends on the contributions of non-linear resistive forces that decelerate the ball at the same time. Thus, by moving the beam extremity up and down, agents accelerate and decelerate the ball via a complex, non-linear and gravity-mediated relationship to the ball. The behavioral question is how a player learns to deal with this particular form of indirect control, in which the relation between one's own movements and those of the to-be-controlled object is yet to be discovered.

Theoretically, the physical properties of the system allow for different strategies of moving the beam, almost all of which would result in continuous rolling of the ball between the targets. One possibility, for instance, is to move the beam in a continuous and harmonic manner, which would be reflected in a constant phase progression of the beam inclination throughout a cycle. Another option would be to accelerate and decelerate the ball in a more discrete fashion, by slowing down or even temporarily stopping the motion of the beam at specific phases in its cycle or by adding corrective sub-movements to each cycle of motion. Due to the ball's translational and rotational inertia, such local stops or deviations from harmonicity in beam motion would not (immediately) prevent the ball from continuing to roll. In other words, the system's physical properties seem to provide room for strategic variability on the part of the agent, that is, multiple task solutions are hypothetically possible. For this reason, we expected that the behavioral dynamics that would arise in the performance of the task would be as much revealing about the underlying perception-action coupling, as about of the physical characteristics of the system.

In spite of the novelty of the continuous ball-and-beam paradigm (but see Huang et al., 2006 for a study on a discrete version), the more general task of reciprocally moving an object between two targets has been studied extensively in the domain of perceptuomotor control (e.g., Mottet and Bootsma, 1999; Billon et al., 2000; Mottet et al., 2001; Bootsma et al., 2004; Bongers et al., 2009; Huys et al., 2010; Valk et al., 2019). Usually, the object in question is an end-effector, such as the tip of the finger or a hand-held stylus, and the

instruction is to move that end-effector as fast and accurately as possible between two targets. Research into such tasks has revealed that the behavioral dynamics of these end-effectors are strongly constrained by the precision requirements of the task (Mottet and Bootsma, 1999; Mottet et al., 2001; Bootsma et al., 2004; Bongers et al., 2009). When the targets are large, implying low demands on the accuracy of the movement, agents move their end-effector in a smooth and continuous manner between the targets. However, when the target size is decreased, agents adopt a more discrete strategy by slowing down their motion in the vicinity of the target zones, ultimately even coming to full stops. Although there is some debate about whether this change in dynamics reflects a transition between two fundamentally different strategies (Huys et al., 2010), or a more gradual adaptation of parameters within the same dynamical structure (Mottet and Bootsma, 1999; Bongers et al., 2009), it is clear that the change is accompanied by a lengthening of the deceleration time. This leads to a longer movement time from target to target, which accounts for the well-known and highly robust speed- accuracy trade-off in the control of our movements (Fitts, 1954; Fitts and Peterson, 1964).

In applying these principles to our ball-and-beam task, we distinguished between the dynamics of the ball and the dynamics of the beam. Due to the inertial properties of the ball, we expected the ball to roll continuously back-and-forth at all times, regardless of the size of the targets or the amount of expertise of the participants. In contrast, we hypothesized that the dynamics of the beam would change as a function of the task's accuracy constraints. More specifically, we expected that the strategy of the lifting and lowering the beam extremity would become more discrete (as opposed to continuous) when the size of the targets was decreased. Thus, we hypothesized that the behavioral dynamics in this task –reflected in the motion of the beam in relation to the position of the ball– would depend on the task's accuracy demands, similar to what has been reported in reciprocal aiming paradigms. To test this hypothesis, we studied individual participants practicing the (solo) ball-and-beam task under three different target size conditions: small targets, medium targets and large targets. With respect to the effect of practice, we speculated that the beam's behavioral dynamics would become more consistent and more continuous over trials, especially in the largest target-size condition, reflecting the process of learning to control the ball on the beam.

3.3. Materials and method

3.3.1. Participants

A group of 16 students and junior staff members from Aix Marseille University (7 women, 9 men, with an average age of M ± SD: 23.3 ± 2.9 years) participated voluntarily in this study. None of them had any experience on the task. All participants were free from known motor impairments and reported normal or corrected-to-normal vision. Before the start of the first experimental session the participants were informed about the aim and procedure of the experiment. All participants provided written informed consent before participating in the study. The study was approved by the French National Ethics

Committee for Research in Sports and Movement Sciences (CERSTAPS) and conducted according to University regulations and the Declaration of Helsinki.

3.3.2. Task and procedure

The task equipment consisted of a standard golf ball (diameter 4.3 cm, weight 46 g) that could roll over a 2-m long, 3 by 3 cm V-shaped iron beam, with tubular (length 54 cm, diameter 3 cm) handles perpendicularly attached to its extremities. Participants' task was to roll the ball as fast and accurately as possible back-and-forth between two targets clearly visible on the beam. Participants received one point for every time that the ball reversed its direction of motion within a target's boundaries, with the objective of achieving as many points as possible within every 2-min trial. With both target centers located 50cm from the beam's midpoint, the center-to-center inter-target distance was 100 cm in all trials. The size of both targets varied from trial to trial and was either 6, 12 or 24 cm. In the following, we will refer to these targets as small, medium and large targets. Bimanually holding one handle allowed a participant to lift or lower the beam's extremity and thereby change its inclination angle so as to accelerate or decelerate the ball. The second of the two handles was attached to a hinge on a static pole, the height of which was adjusted to the participant's hip height.

Participants performed two sessions of individual practice in the solo action setting of the ball-and-beam task that were to be completed on two different days, with one or two days between the sessions. A session began with a short warm-up trial of approximately 1 min, during which participants were given the chance to familiarize themselves with the task. The familiarization was followed by six blocks of practice per session. Each of these six blocks consisted of three trials: one trial with small targets, one with medium targets and one with large targets. The three conditions within a block were presented in a pseudo-randomized order over blocks, such that all possible orders of conditions were presented once during a session. After every two blocks of trials, participants were given a short break of 2–3min. Given the two sessions of practice, each participant performed a total of 12 blocks of practice, corresponding to 36 individual trials. We note that in a follow-up study, these 16 participants were paired into 8 dyads who then practiced of the ball- and-beam task in a joint action setting. Results of this latter study will be reported separately.

At the start of each 2-min trial, the ball was placed in the middle of the beam. Verbal signals from the experimenter signaled the beginning ('Go') and the end ('Stop') of a trial. After each trial, participants received verbal feedback on their score, based on experimenter observation. Participants were regularly encouraged to try to improve their score on each new trial, in order to reach the highest score possible in each target size condition. Participants competed indirectly with the other players via a leaderboard that expressed the high scores of the other participants on each target size condition. Moreover, small (delicacy) prizes were awarded to those with the highest scores. All of this was in function of motivating the participants to perform optimally on each new trial.

3.3.3. Data acquisition and analysis

All sessions took place in a darkened room. To capture the motion of the beam, small reflective markers were attached to each handle through a thin, rigid and 10-cm long aluminum rod. In order to capture the motion of the ball, we chose to use a bright yellow color for the ball. Participants wore dark clothes and black gloves to ensure sufficient contrast with the ball and the two beam markers on the beam. All trials were filmed with a GoPro9 camera that was positioned at a 2-m perpendicular distance from the midpoint of the beam. The camera, set in linear lens mode so as to obtain minimal image deformation, was placed on a tripod at a 1-m height. All trials were recorded with a (recalculated) sample frequency of 29.97Hz and a resolution of 2.7 K.

Video recordings of all trials were imported into Kinovea,1 which was used to track the two-dimensional (X, Y) motion of the ball and the two reflective markers on the beam. X and Y position time series were then analyzed using MATLAB. All data were first filtered using a fourth-order low pass Butterworth filter (cut off frequency of 3 Hz) and trimmed to the 120-s trial duration. The ball's trajectory was subsequently transformed from motion in a two-dimensional space to one-dimensional motion along the beam's longitudinal axis. To do this, we calculated the ball's motion along the virtual vector between the two beam markers, with the inter-marker distance used for calibration. From the trajectories of the two markers on the beam we derived a single inclination angle at each time step by taking the inverse tangent (atan) of the X and Y coordinates of both markers. The one-dimensional time series of the ball motion, on the one hand, and the beam's inclination angle, on the other hand, formed the basis of all further analyses in this contribution. In discussing these analyses as well as the results that follow from them, we progressively move from (1) the motion of the ball, via (2) the coordination of the ball with the beam, to (3) the motion of the beam. All analyses were conducted on all individual trials, including all different target size conditions.

To characterize the movements of the ball on the beam, we used a peak finding algorithm to split the ball position time series into separate half cycles. We used these half cycles to count the number of target hits per trial, which we defined as a ball motion reversal within the (recalculated) target zones of each task condition. By dividing the number of target hits by the total number of half cycles on a trial, we acquired a measure of relative accuracy in the performance. We refer to this measure as the accuracy ratio on a trial. To come to a measure of absolute consistency of the ball's motion around the targets, we also computed the effective target size on each trial. This variable was calculated by multiplying the standard deviation of the ball position peaks around the two targets by 1.96 (Welford, 1968; see also Huys et al., 2010). Lower effective target size therefore indicated a higher average ball consistency on a trial. Lastly, we derived an average of the ball speed on each trial by multiplying the ball's average half cycle frequency by the average peak-to-peak amplitude of the ball's half cycles.

To assess the ball-beam coordination, we first performed a cross- correlation analysis between the time series of ball position and the beam's inclination angle in each individual trial. From these cross- correlations, we derived the maximum Pearson correlation

coefficient and its time-lag (in s). We divided this time-lag by the average half cycle time to come to a relative time-lag (in %) on every trial. Subsequently, we conducted a qualitative analysis on the dynamical patterns of the ball and beam motions in each trial. In this analysis, we interpreted the phase portraits of the ball (i.e., ball velocity as a function of ball position) and of the ball-beam coordination (i.e., beam angular velocity as a function of ball position). Based on inspection of these portraits, we decided to quantify three distinguishable aspects of the underlying beam movements: the range of motion, the variability and the shape of the beam motion pattern.

The range of motion (ROM) of the beam on a trial was calculated by determining the average angular distance between the beam at maximum and minimum inclination. As such, it constituted the average peak-to-peak amplitude of the cyclical beam movement. The variability of the beam's inclination angle on each trial was assessed with the coefficient of variation (CV). To this end, we first divided the inclination angle time series into separate cycles on the basis of the ball position peaks. We chose to use the ball's cycles because these were more consistent in comparison to the beam's cycles. We then time-normalized all cycles to 100 timepoints and calculated the standard deviation over all cycles at each of the timepoints. We averaged all 100 standard deviations to come to one standard deviation per trial, which we divided by the average peak-to-peak amplitude on that trial to come to the CV. Thirdly, we quantified the average shape of the beam movement by taking the ratio (shape ratio, SR) between the average absolute inclination angle and half of the average peak-to-peak amplitude of the beam motion. The SR was inspired by the shape of the histograms of the beam inclination angle on each trial.

As a final analysis, we assessed the relationship between the three beam motion variables on the one hand and three ball-level indicators of performance (target hits, ball speed and accuracy ratio) on the other hand. To do so, we computed the Pearson correlation coefficients over participants between each of these variables for all three target size conditions separately.

3.3.4. Statistical analysis

A 3 × 12 repeated measures ANOVA, with the factors Condition (3 target size conditions) and Practice (12 practice blocks), was used to analyze the following dependent variables: target hits, ball speed, accuracy ratio, ball effective target size, (relative) ball-beam time-lag, maximum ball-beam correlation coefficient, beam ROM, beam CV and beam SR. Pearson correlation coefficients were standardized using a Fisher-Z transformation before performing the analysis of variance. For all analyses the significance level was set to $\alpha = 0.05$. Greenhouse– Geisser corrections were applied when violations of the sphericity assumption were detected. For reasons of readability, all ANOVA results were summarized in a single table. Post-hoc tests were performed using Tukey HSD. Where appropriate means and standard deviations are reported as M ± SD.

3.4. Results

3.4.1. Ball motion

Target hits and ball cycles. As can be seen in **Figure 3.1**, participants enhanced their performance from block 1 to 12, as indicated by a significant increase in the number of target hits over practice (F (4.43, 66.42)=68.72, $p < 0.001$, $\eta^2_p = 0.82$). This increase in hits was different per target size condition, such that larger targets gave rise to a stronger increases in the number of hits (F (22, 330) = 2.40, $p < 0.001$, $\eta^2_p = 0.14$; also see **Figure 3.2A**). More generally, larger targets allowed for more hits on a trial (F(2, 30) = 309.00, $p < 0.001$, $\eta^2_p = 0.95$). Furthermore, **Figure 3.1** shows that the increase in target hits was accompanied by an increasing number of total ball half cycles. This reflected a significant increase in the average ball speed (F(3.20, 47.99) = 19.81, $p < 0.001$, $\eta^2_p = 0.57$) over trials, which took place in all three target size conditions (also see **Figure 3.2B**). As expected, this ball speed varied in accordance with the target size, such that a larger target induced a higher average ball speed (F(1.13, 16.98) = 60.28, $p < 0.001$, $\eta^2_p = 0.80$). Full results of all Condition (3) x Practice blocks (12) ANOVAS are provided in **Table 3.1**.

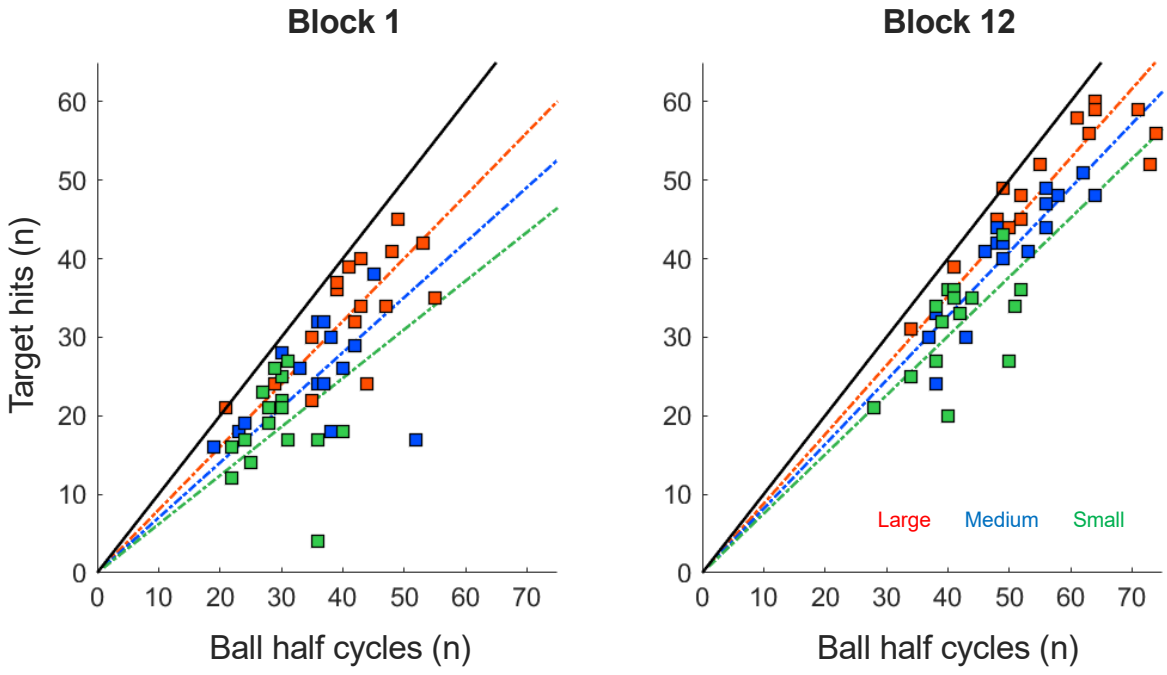


Figure 3.1: Target hits (n) as a function of ball half cycles (n) under each of the three target size conditions (small: green; medium: blue and large: red) in the trials of block 1 and 12. From block 1 to 12, the number of target hits and ball half cycles both increased significantly in all task conditions, indicating an improvement in performance. The increasing slopes in the linear regression lines from block 1 to 12 also indicate an increased accuracy of the performance in all three target size conditions.

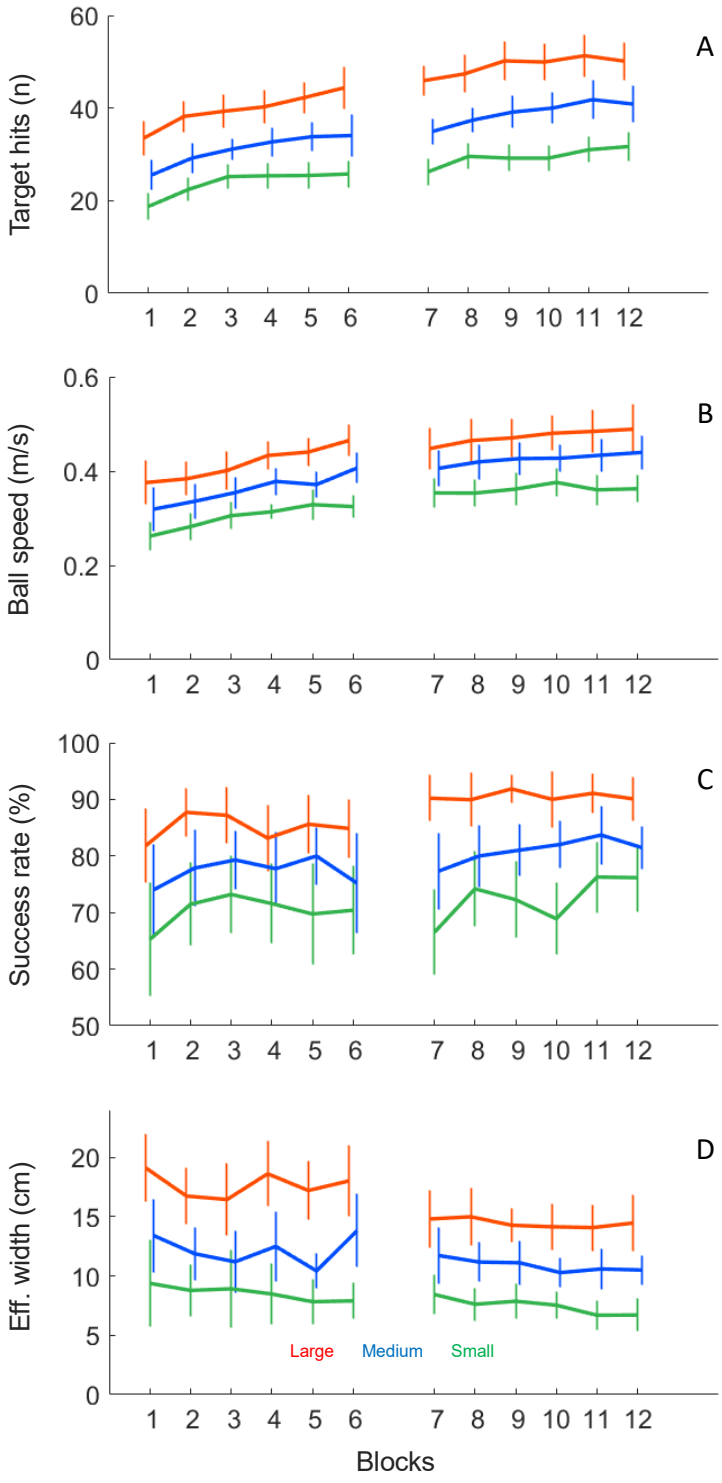


Figure 3.2: Ball motion variables as a function of practice blocks under each of the three target size conditions (small: green; medium: blue and large: red). (A) The number of target hits (n) increased over practice in all conditions and was higher in larger target size conditions. (B) The average ball speed (m/s) increased over practice in all conditions and was higher in larger target size conditions. (C) The average successrate (%), indicating the ball motion accuracy, increased over trials and was higher in larger target sizes. (D) The average effective target size (cm), indicating ball motion consistency, decreased over trials and was lower **in** smaller target sizes.

Ball accuracy and consistency. Figure **3.1** also provides an insight into the accuracy of the performance, since the slope of the linear regression line through the cloud of data points is directly related to the accuracy ratio on the task (45° slope indicating 100% accuracy). In general, the slope increased slightly from block 1 to 12 ($F(4.14, 62.16) = 2.75$, $p < 0.034$, $\eta^2_p = 0.16$), indicating that over practice participants achieved more hits per total number of ball cycles. This increase in success rate (also see **Figure 3.2C**) was not significantly different between conditions ($F(22, 330) = 1.00$, $p = 0.459$, $\eta^2_p = 0.06$), but the success or accuracy ratio was higher when the targets were larger ($F(1.41, 21.17) = 44.11$, $p < 0.001$, $\eta^2_p = 0.75$). These findings were supported by analysis of the consistency of the ball's reversal locations around the targets: Effective target size (see **Figure 3.2D**) also decreased slightly but significantly over practice ($F(3.23, 48.47) = 2.75$, $p = 0.049$, $\eta^2_p = 0.16$) and was also higher for larger target sizes ($F(1.40, 20.96) = 98.87$, $p < 0.001$, $\eta^2_p = 0.87$). In contrast to the success rate, we observed a significant difference in the rate of change per condition, where the effective target size decreased more for larger targets ($F(22, 330) = 1.61$, $p = 0.042$, $\eta^2_p = 0.10$).

3.4.2. Ball-beam coordination

Cross-correlation analysis. To quantify the ball-beam coordination, we conducted a cross- correlation analysis of the relation between ball position and beam inclination angle. As shown in **Figure 3.3A**, maximum correlation was found at small positive time-lags, which indicated that the cyclic motion of the beam lagged behind that of the rolling ball for the majority of the cycle. This was the case in all trials. The Condition (3) x Practice (12) repeated measures ANOVA (**Table 3.1**) demonstrated that the absolute size of the time-lag shortened over practice ($F(2.58, 28.67) = 10.29$, $p < 0.001$, $\eta^2_p = 0.41$), was shorter in large target size conditions ($F(1.25, 0.44) = 65.79$, $p < 0.001$, $\eta^2_p = 0.81$) and decreased more strongly with larger target sizes ($F(22, 330)=1.61$, $p = 0.043$, $\eta^2_p = 0.10$). Most of these differences became smaller, but nevertheless persisted, when we corrected the time-lag for the half cycle duration resulting in a relative time-lag (**Figure 3.3B**). The relative time-lag also decreased significantly over practice ($F(2.83, 42.38) = 6.75$, $p < 0.001$, $\eta^2_p = 0.31$) and was also shorter for larger target sizes ($F(1.18;17.69) = 59.531$, $p < 0.001$, $\eta^2_p = 0.80$), but the decreasing trend over practice was not significantly different between conditions ($F(22, 330) = 0.87$, $p = 0.639$, $\eta^2_p = 0.06$). The maximum correlation coefficient between ball position and beam inclination angle increased significantly over practice, most prominently in the first blocks (**Figure 3.3C** $F(4.77, 71.49) = 38.48$, $p < 0.001$, $\eta^2_p = 0.72$). Moreover, the correlation between the time series was significantly higher when targets were larger ($F(1.39, 20.82) = 68.65$, $p < 0.001$, $\eta^2_p = 0.82$), but the rate of change over practice was not significantly different between target size conditions ($F(22, 330) = 0.47$, $p = 0.981$, $\eta^2_p = 0.03$). Interestingly, the correlation coefficients leveled off after a few practice blocks, before increasing again in the first block of the second session (block 7, **Figure 3.3C**). In all subsequent blocks, however, the correlation coefficient remained stable, suggesting that a full covariation of ball position and beam inclination was not possible, desirable or both. To investigate the reason for this, we continued with a qualitative analysis of the patterns of the ball and beam system.

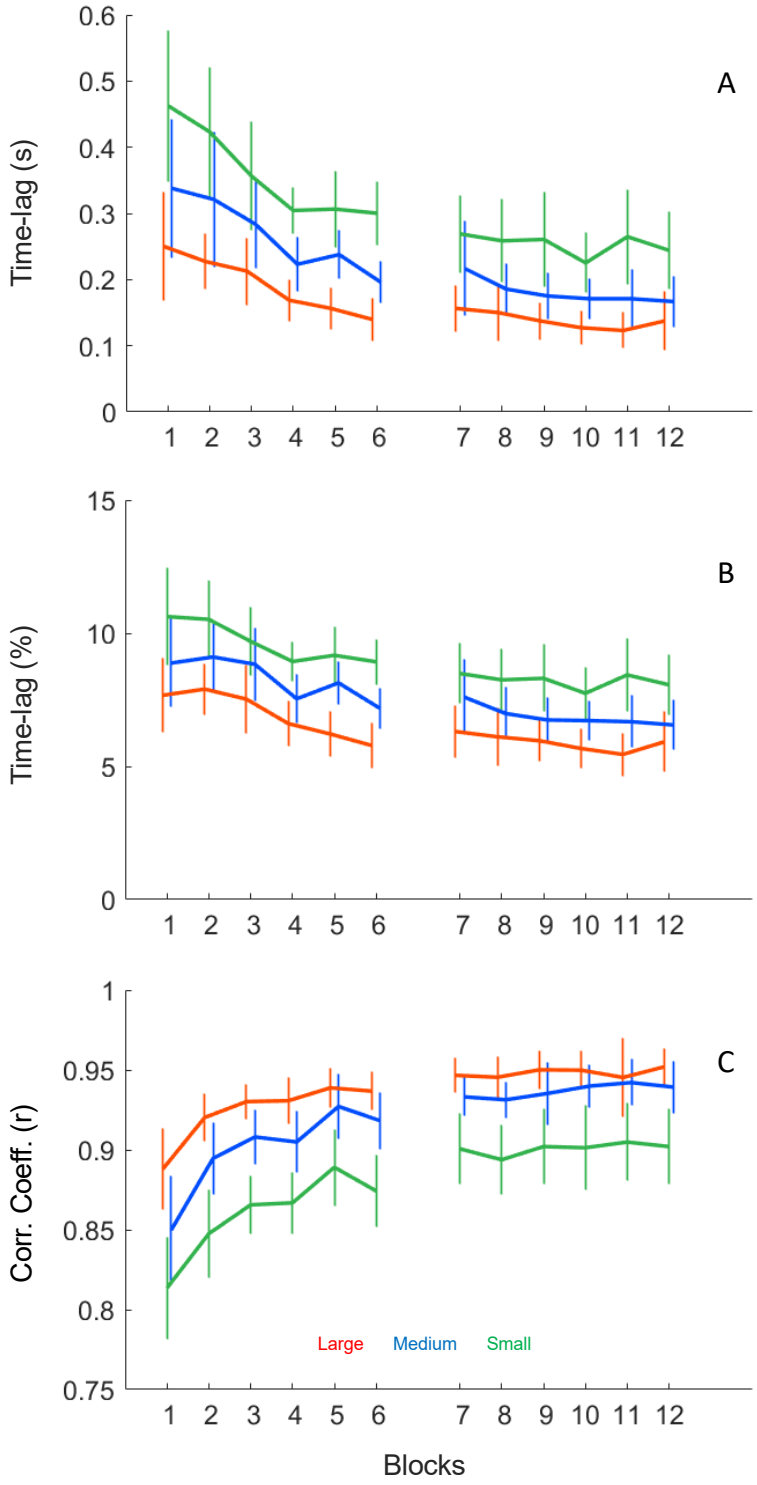


Figure 3.3: Ball position – beam inclination angle cross-correlation results as a function of practice blocks under each of the three target size conditions (small: green; medium: blue and large: red). (A) The time- lag (s) between ball position and beam inclination decreased over practice and was shorter for larger targets. (B) The relative time-lag (%) between ball position and beam inclination decreased over practice and was shorter for larger targets. (C) The average maximum correlation coefficient increased over blocks, most prominently in the first blocks. The correlation coefficient was higher in larger target size conditions as compared to the smaller target sizes.

Table 3.1: Results of Condition (3 sizes) x Practice (12 blocks) repeated measures ANOVAs on ten dependent variables: Four related to the ball motion (Target hits, Ball speed, Accuracy ratio and Effective target size), three related to the ball-beam cross correlation analysis (Time-lag, Relative time-lag and Maximum correlation coefficient) and three related to the beam motion (Beam range of motion ROM, Beam variability CV and Beam shape ratio SR).

	Effect	*F*	(df)	*p*	η_p^2
Target hits	Condition	309.00	(2, 30)	< 0.001	0.95
	Practice	68.72	(4.43, 66.42)	< 0.001	0.82
	Condition * Practice	2.40	(22, 330)	< 0.001	0.14
Ball speed	Condition	60.28	(1.13, 16.98)	< 0.001	0.80
	Practice	19.81	(3.20, 47.99)	< 0.001	0.57
	Condition * Practice	1.24	(22, 330)	0.215	0.08
Accuracy Ratio	Condition	44.11	(1.41, 21.17)	< 0.001	0.75
	Practice	2.75	(4.14, 62.16)	0.034	0.16
	Condition * Practice	1.00	(22, 330)	0.459	0.06
Effective size	Condition	98.87	(1.40, 20.96)	< 0.001	0.87
	Practice	2.75	(3.23, 48.47)	0.049	0.16
	Condition * Practice	1.61	(22, 330)	0.042	0.10
Time lag	Condition	65.79	(1.25, 0.44)	< 0.001	0.81
	Practice	10.29	(2.58, 28.67)	< 0.001	0.41
	Condition * Practice	1.61	(22, 330)	0.043	0.10
Relative time-lag	Condition	59.53	(1.18, 17.69)	< 0.001	0.80
	Practice	6.75	(2.83, 42.38)	< 0.001	0.31
	Condition * Practice	0.87	(22, 330)	0.639	0.06
Max. corr. Coef.	Condition	68.65	(1.39, 20.82)	< 0.001	0.82
	Practice	38.48	(4.77, 71.49)	< 0.001	0.72
	Condition * Practice	0.47	(22, 330)	0.981	0.03
Beam ROM	Condition	28.79	(1.08, 16.24)	< 0.001	0.66
	Practice	14.94	(2.79, 41.82)	< 0.001	0.50
	Condition * Practice	2.49	(22, 330)	< 0.001	0.14
Beam CV	Condition	43.15	(1.38, 20.62)	< 0.001	0.74
	Practice	22.26	(4.91,73.71)	< 0.001	0.60
	Condition * Practice	0.97	(22, 330)	0.509	0.06
Beam SR	Condition	52.09	(1.08, 16.25)	< 0.001	0.78
	Practice	2.20	(4.44, 66.64)	0.072	0.13
	Condition * Practice	0.53	(22, 330)	0.961	0.02

Qualitative analysis. To characterize the behavioral dynamics of the ball-and-beam system, we first addressed the dynamics of the ball on the beam. As illustrated in **Figure 3.4** (left panels) by the phase portraits of ball motion for two characteristic participants P2 and P10 in practice blocks 1 and 12, the ball rolled continuously and in a close-to-harmonic manner in all trials and under each of the three target size conditions (see **3.6. Supplementary material** for all participants). In the second place, we looked at the dynamics of the beam in relation to the ball. We found that the beam's inclination angle oscillated in a manner that was characteristic for a participant. In order bring this out most clearly, we plotted the beam inclination velocity as a function of the ball position, thereby capturing the behavioral dynamics of this task in one graph. In the right panels of **Figure 3.4** these ball-beam plots are shown for the same two characteristic participants (P2 and P10) in practice blocks 1 and 12 under all three target size conditions (See **3.6. Supplementary material** for all participants). Two different beam-motion strategies arise from visual inspection of these graphs. The first strategy, adopted by the majority of the participants including P2 (**Figure 3.4**, upper right panel), was to maintain the beam at (close to) maximum inclination angle to set the ball into motion, before making one continuous movement to the opposite inclination peak in order to decelerate the ball and stop its motion within the target zone; it was then maintained there to set the ball in motion for the next half cycle. We refer to this strategy as the extreme-stop strategy. A second strategy, used by a minority of the participants including P10 (**Figure 3.4**, lower right panel), was to move the beam in two phases towards the opposite inclination, by stopping or slowing down the movement when the ball was about halfway between the targets. We call this strategy the middle-stop strategy. Although both strategies have in common that they are discrete as opposed to continuous, the locus at which participants stopped or slowed down their motion was different. This becomes even clearer when considering the histograms of the beam's inclination angle, which captures the distribution of the inclination angle within a trial (**Figure 3.5**). Extreme stoppers exemplified by P2 (**Figure 3.5**, left) spend most time at maximum or minimum inclination angles (U-shaped histograms), while middle stoppers exemplified by P10 (**Figure 3.5**, right; see **3.6. Supplementary material** for all participants) spend more time at inclination angle zero (bell-shaped histograms). Based on these results, we decided to use the shape ratio (SR), defined as the ratio between the average absolute inclination angle and half of the average peak-to-peak amplitude, to quantify the different strategies.

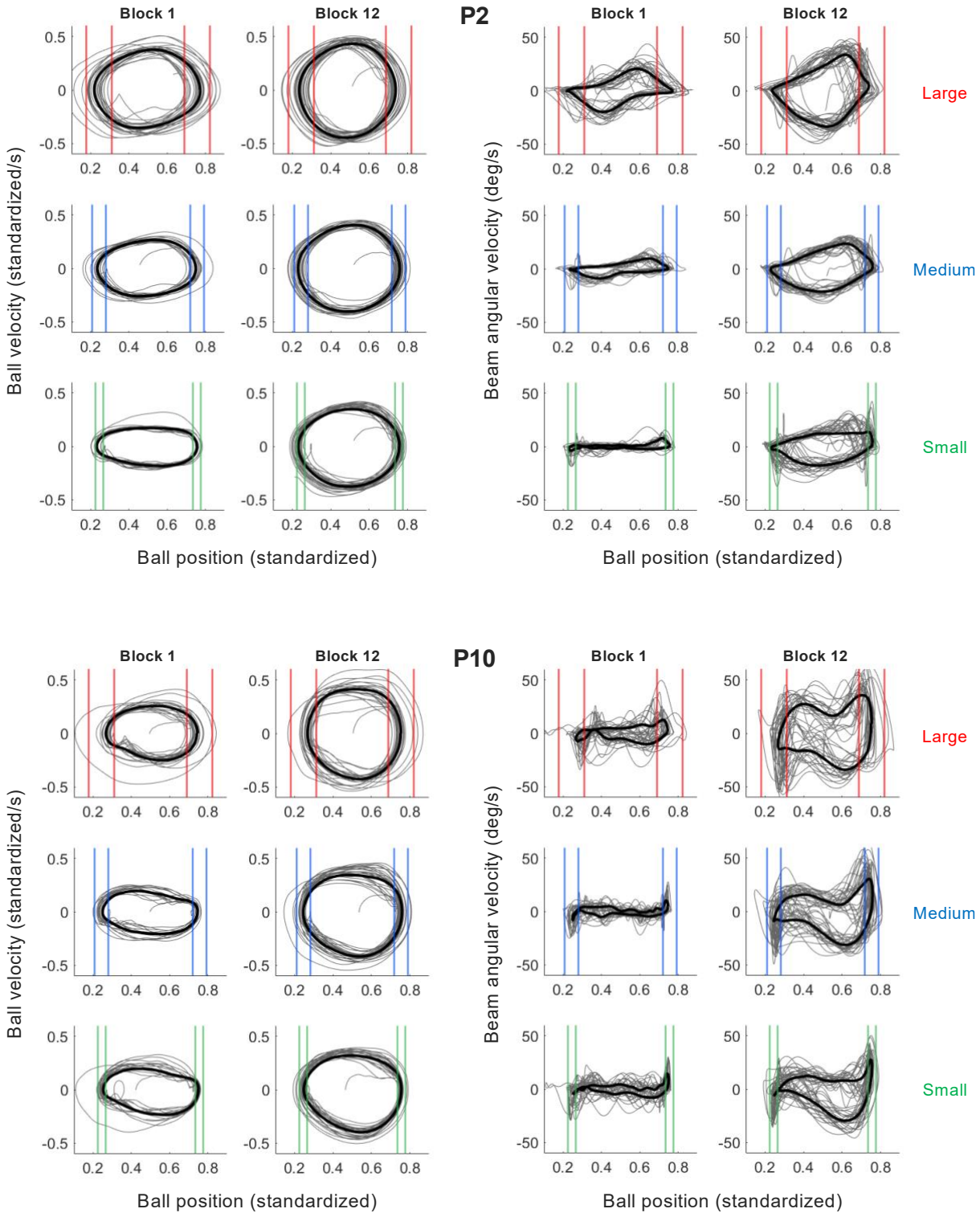


Figure 3.4 : Plots of the ball velocity as a function of the ball position (left) and the beam angular velocity as a function of the ball position (right) for two illustrative participants (P2 upper panels, P10 lower panels). Shown are the trials from block 1 and block 12 for all three target size conditions (small: green; medium: blue and large: red). The thin gray lines in each panel represent the behavior observed over all cycles and the thicker black lines the cycle-averaged behavior. Two different movement strategies are discernable, which are relatively stable between target size conditions. Ball position is standardized to beam length (200 cm).

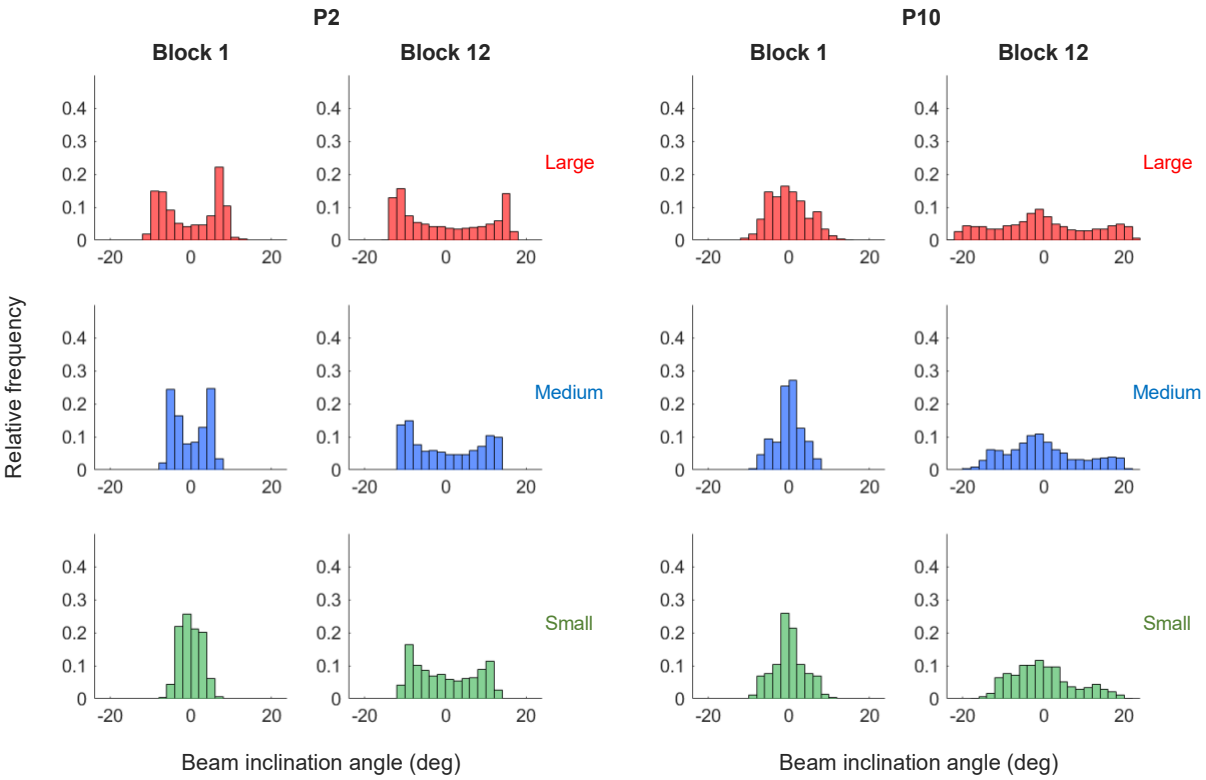


Figure 3.5 : Beam inclination histograms of the two illustrative participants in (P2, left and P10, right) for blocks 1 and 12 under the three target size conditions (small: green; medium: blue and large: red). While some participants spend much time at high inclination angles, others did the reverse.

3.4.3. Beam motion

Based on the above interpretation of the ball-beam phase planes, we had quantified three characteristic aspects of the beam motion, which we compared between conditions and over trials (**Table 3.1**). The beam's range of motion (ROM) increased significantly over practice (**Figure 3.6A**, $F(2.79, 41.82) = 14.94$, $p < 0.001$, $\eta^2_p = 0.50$). The ROM was larger when the target sizes were larger ($F(1.08, 16.24) = 28.79$, $p < 0.001$, $\eta^2_p = 0.66$) and it increased at a stronger rate in these conditions ($F(22, 330) = 2.49$, $p < 0.001$, $\eta^2_p = 0.14$). Secondly, the beam's coefficient of variation (CV) declined significantly over trials (**Figure 3.6B**, $F(4.91, 73.71) = 22.26$, $p < 0.001$, $\eta^2_p = 0.60$), a finding that was visible in all target size conditions. Moreover, the CV was significantly different between conditions, such that the relative variability was higher when the target sizes were smaller ($F(1.38, 20.62) = 43.15$, $p < 0.001$, $\eta^2_p = 0.74$). Thirdly, the shape ratio (SR) showed an increasing, but non-significant trend (**Figure 3.6C**, $F(4.44, 66.64) = 2.20$, $p = 0.072$, $\eta^2_p = 0.13$). SR progressed slightly over the first few trials after which it stabilized for the rest of the two practice sessions ($F(4.44, 66.64) = 2.20$, $p = 0.072$, $\eta^2_p = 0.13$). However, a comparison of the task conditions revealed that the SR was different depending on the target size ($F(1.08, 16.25) = 52.09$, $p < 0.001$, $\eta^2_p = 0.78$). This is to say that the SR was larger with larger target sizes.

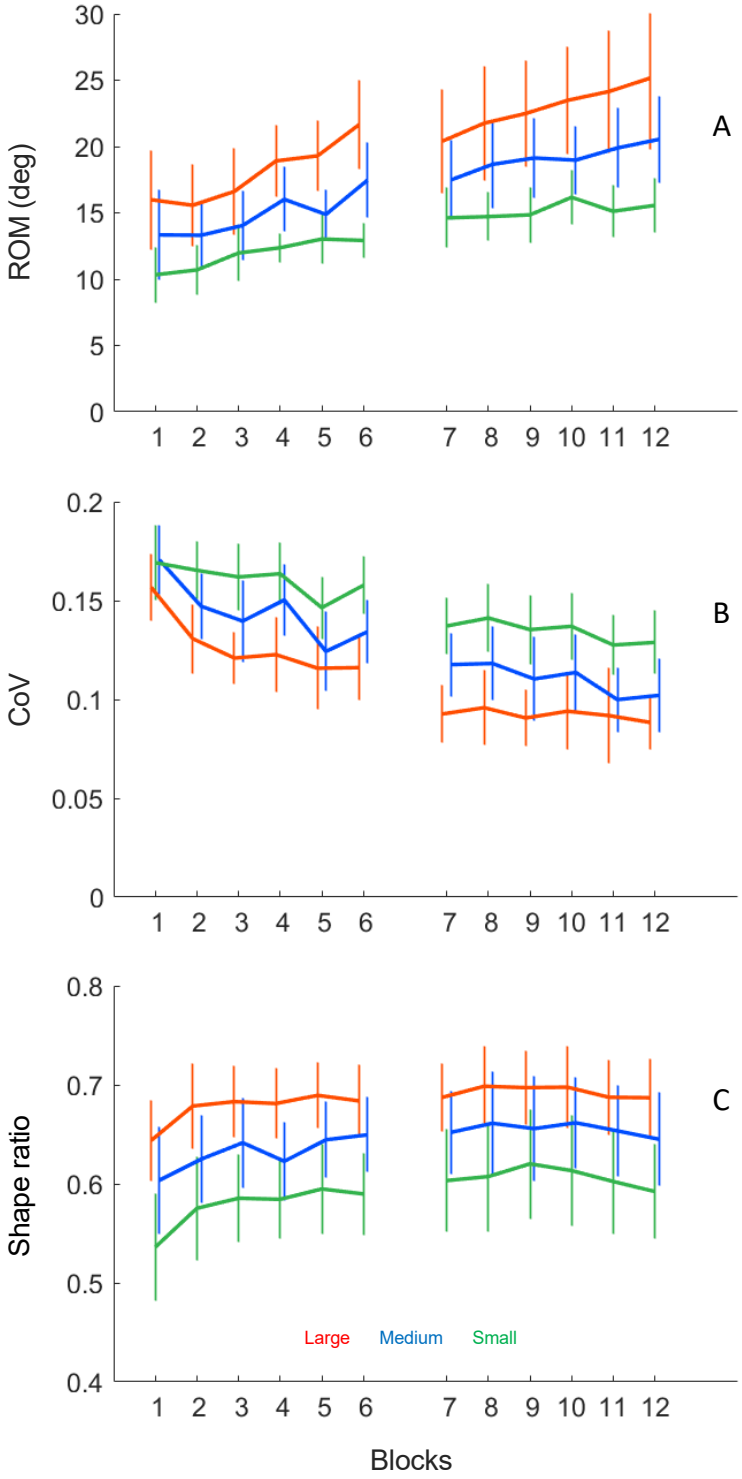


Figure 3.6: Beam motion variables as a function of practice blocks under each of the three target size conditions (small: green, medium: blue and large: red). (A) The average beam range of motion (ROM), defined as the average peak-to-peak amplitude in degrees, increases over practice in all conditions. (B) The average beam coefficient of variability (CV), defined as the average standard deviation divided by the range of motion, decreases over practice in all conditions. (C) The average beam shape ratio (SR), defined as the average absolute inclination angle divided by half the range of motion, is nearly invariant over practice, while different between task conditions.

3.4.4. Relationship ball and beam performance

To assess how the three beam motion variables related to the ball-level performance on this task, we computed Pearson correlation coefficients between each of the three beam motion variables and all three ball-related indicators of performance (target hits, ball speed and accuracy ratio). As shown in **Table 3.2**, the beam's ROM correlated moderately high with the number of target hits in all conditions, indicating that a higher movement amplitude usually resulted in a larger number of target hits and was thus associated with task success. The ROM was also strongly correlated with the ball speed in all task conditions, while correlations of the ROM with the accuracy ratio of the ball were low and non-significant, indicating that the range of motion had impacted the ball's speed but not its accuracy. The beam's coefficient of variation, on the other hand, was negatively correlated with the number of target hits when targets were large in size, but uncorrelated in the smallest target size condition. This suggested that good performances were generally associated with low amounts of beam motion variability in the larger target size conditions, but not in the smallest target size conditions. The correlations of the beam's CV with the ball speed and accuracy ratio were low and non-significant in all task conditions. Lastly, the SR of the beam's movement was uncorrelated with the number of target hits in all three target size conditions, suggesting that task performance was independent from the shape of the beam movement. The SR only had a significant and moderately negative correlation with the ball's accuracy ratio in the small target size condition. This indicated that an extreme-stop strategy was associated with lower a ratio of points over cycles in the small target size conditions, but not in the other two task conditions.

Table 3.2: Pearson correlation coefficients between the three beam motion variables (beam ROM, beam CV and beam SR) and each of the three indicators of task performance target hits, ball speed and accuracy ratio (or success rate) in each of the three target size conditions (small, medium, large).

	Target Size					
	Small		Medium		Large	
	r (14)	*p*	r (14)	*p*	r (14)	*p*
Target hits						
Beam ROM	+0.72	0.002	+0.62	0.011	+0.63	0.009
Beam CV	−0.55	0.026	−0.46	0.076	−0.09	0.752
Beam SR	−0.20	0.466	−0.11	0.695	−0.22	0.408
Ball speed						
Beam ROM	+0.97	< 0.001	+0.94	< 0.001	+0.84	< 0.001
Beam CV	−0.32	0.231	−0.30	0.265	−0.35	0.183
Beam SR	−0.41	0.115	−0.09	0.732	−0.40	0.128
Accuracy ratio						
Beam ROM	−0.25	0.355	−0.20	0.461	+0.15	0.581
Beam CV	−0.27	0.302	−0.11	0.664	+0.22	0.409
Beam SR	+0.16	0.551	−0.14	0.609	−0.59	0.002

3.5. Discussion

In this study we investigated individual skill acquisition in the solo setting of the manual ball-and-beam paradigm, a challenging task that requires a continuous perceptuomotor coordination to control a ball rolling on a hand-held beam. In particular, we were interested in the behavioral dynamics (Warren, 2006) that would arise from learning a perception-action coupling in this task. Based on research on reciprocal aiming tasks with similar instructions—i.e., moving an end-effector as fast and accurately as possible between two targets– we hypothesized that the emergent behavioral dynamics would be dependent on the accuracy constraints of the task. More specifically, we expected that small targets would invoke a discrete strategy of moving the beam, while large targets would lead to a more continuous movement strategy. To test this hypothesis, we had participants practice the task in two individual training sessions with three different target size conditions.

To start with, practice on the task resulted in an overall improvement of the performance (**Fig 3.2**), most clearly demonstrated by the increase in the number of target hits per trial. This finding was in accordance with our earlier study using this task (Hafkamp et al., 2023) and provided an indication that participants acquired (the fundamentals of) the skill to control the motion of the ball on the beam. Also in line with Hafkamp et al. (2023), we found that the increase in the number of target hits was accompanied by a strong (35%) increase in the average ball speed from block 1 to 12 and a smaller (12%) increase in the ball's accuracy or success rate (hits/cycles). In combination, these results demonstrated that participants learned to control the ball's motion at increasingly high speeds, suggesting that they indeed acquired an improved and task-specific coupling of perception and action.

New in this contribution was the introduction of three different target sizes, which were used to investigate the influence of task-level accuracy demands on the performance. As predicted by the speed- accuracy trade off in perceptuomotor control (Fitts, 1954; Fitts and Peterson, 1964; Plamondon and Alimi, 1997), we found that larger target sizes resulted in higher ball speeds (**Fig 3.2B**) and lower ball motion consistencies around the targets zones (**Fig 3.2D**). In other words, the lower the demand on accuracy, the higher the speed of the rolling ball. Our goal in this contribution, however, was to look beyond the outcome measures of ball speed and accuracy and to study the underlying behavioral dynamics that gave rise to these movement properties. To do so, we did not limit our analysis to the dynamics of the ball alone, but combined it with a dynamical analysis of the concurrent and underlying movements of the beam, since the two are relatedly through a gravity-mediated coupling. In accordance with our expectations, the inertial properties of the ball resulted in a continuous ball motion in almost all blocks of practice. Only in the smallest target size conditions did the ball occasionally (though very rarely) come to a full stop, breaking the otherwise rhythmic motion of the ball between the two targets. Thus, whereas the speed-accuracy trade-off in manual reciprocal aiming tasks usually arises from significant qualitative changes in the dynamics of the end-effector (Mottet and Bootsma, 1999; Mottet et al., 2001; Bongers et al., 2009; Huys et al.,

2010), the changes in the dynamics of a ball rolling on a beam are more subtle and appear to be of a quantitative rather than of a qualitative nature (**Fig 3.4**, left panels). This is to say that ball showed a similar limit-cycle dynamics in all target size conditions. On the one hand, this might indicate that no qualitative behavioral changes occurred in response to the accuracy demands on the task. On the other hand, the physical properties of the system might have concealed any behavioral changes, meaning that differences in the beam's motion patterns were not visible in the ball's motion on the beam. To further investigate this, we interpreted the dynamics of the beam's inclination angle in relation to the ball.

The cross-correlation analysis of the ball position with the beam's inclination angle (**Fig. 3.3**) revealed that a maximum correlation between the time series was found at small positive time-lags, indicating that the motion of the beam lagged slightly behind that of the rolling ball, for at least the largest part of the average movement cycle on a trial. Over the course of a trial, participants thus systematically adapted their beam motion to the (perceived) ball motion. In contrast to the ball motion, however, the pattern of movement of the beam's inclination angle was not harmonic or continuous, but mostly discrete (**Fig 3.4**, right panels). Following the literature on reciprocal aiming (Mottet and Bootsma, 1999; Mottet et al., 2001; Bootsma et al., 2004; Bongers et al., 2009; Huys et al., 2010), we had hypothesized that large accuracy demands would give rise to a discrete movement strategy of the beam, while low demands on accuracy would lead to a more continuous movement of the beam. In the present study we did not find such a qualitative contrast between target size conditions in the nature of the end-effector (here beam) dynamics. All participants adopted a discrete pattern of beam motion in all task conditions, independent of the demands on accuracy. Thus, continuous sinusoidal movements of the beam were never adopted as a fruitful task solution by the participants, even when target sizes were large. This suggests that the type of indirect control characterizing the ball-and-beam task may be fundamentally different from the direct control of the end-effector in manual reciprocal aiming and therefore must be interpreted in a different way. Further indication for this was provided by the remarkable finding of stable inter-individual differences in the beam dynamics deployed. This was in contrast with the behavioral dynamics as found in traditional paradigms of reciprocal aiming, which are generally comparable between individuals (Mottet and Bootsma, 1999; Mottet et al., 2001; Bongers et al., 2009; Huys et al., 2010). The individual differences could not be defined on a continuum from discrete to continuous strategies, but were instead defined by the locus of stopping or slowing down within the beam's cycle of motion (see **Fig 3.5**).

The first strategy that we found was referred to as an extreme-stop strategy. In this scenario, adopted by the majority of the participants, the beam motion was paused at the minimum/maximum inclination angle to set the ball into motion. After this pause, participants produced one, continuous movement to the other extreme (i.e., from minimum to maximum inclination or vice versa) to decelerate the ball and stop it in the next target zone; participants then maintained the beam at this extreme position so as to repeat the process for accelerating the ball in the other direction. In a second scenario,

participants did not produce one, continuous movement between extremes, but divided each half cycle into two phases. In the first phase, (almost) immediately after onset of the ball motion, the beam was brought to inclination angle zero, while in the second phase the beam moved from zero to the opposite extreme angle to decelerate the ball and stop it in the next target zone. These two phases were thus separated by a short stopping or slowing down of the beam movement, leading us to refer to this beam-motion pattern as a middle-stop strategy. Both strategies shared a discrete rather than continuous character, which contributed to the small delay of the beam inclination relative to the ball position that was found in the cross-correlation analysis. Nevertheless, the locus of stopping or slowing down differed between the two strategies, which had significant implications for the control process underlying the performance. To understand the significance of this difference, we need to consider the gravitational effect of stopping at these two different loci in the beam's cycle.

At the extreme points of inclination, the driving (tangential) component of the gravitational force acting on the ball is at its peak. This implies that the ball accelerates/decelerates maximally over the period that the beam motion is stopped at these loci. Any small difference in the beam's inclination angle at this point therefore has a considerable impact on the ball's motion, which is to say that the required timing and extent of the subsequent (sub) movement is highly constrained by this inclination angle. At inclination angle zero, however, the ball rolls without gravity-induced acceleration. As such, the ball is no longer increasing speed and the constraints on the timing and extent of the subsequent movement are thus lower than at the extremes. This is reflected in the larger coefficient of variation of the beam movement of middle-stoppers (P10: M±SD: 0.14±0.02) than of extreme-stoppers (P2: M ± SD: 0.10 ± 0.02). To acquire a high average ball speed on a trial and score many points, the middle- stopper is forced to produce large inclination angles to compensate for the relatively long time that is spent around inclination angle zero. Yet, one could also turn this argument around. To prevent the ball from rolling too fast, participants might have had to compensate for large inclination angles by slowing down the beam around inclination angle zero, leading to a middle-stop strategy. Either way, the two-phased beam dynamics constituted a significantly different approach to the perceptuomotor problem posed by the ball-and-beam system than the one-phased dynamics. In other words, it reflected a qualitatively different intrinsic pattern of coordination on the task, a different 'preferred' behavioral organization.

In the framework of coordination dynamics, the process of learning such stable patterns of coordination has also been conceptualized as the convergence onto certain attractors in the solution space of a task (Schöner et al., 1992; Zanone and Kelso, 1992; Kostrubiec et al., 2012). Intriguingly, both of the two reported strategies in the ball-and-beam task allowed for the achievement of task success, since the adopted strategy was not significantly correlated with the performance measures of target hits, ball speed or ball accuracy (except for the smallest target size condition, see below for a possible explanation for this). Thus, multiple loci in the solution space could function as an attractor in the task performance. Although this does not explain why individuals converged onto one rather than the other solution, it may explain why the intrinsic

differences between individuals were stable and invariant over practice: Since neither of the two strategies appeared to be better than the other, the drive for participants to transition to another pattern, either abruptly or through a gradual change of location in the solution space (Jacobs and Michaels, 2007; Pacheco et al., 2019), was absent. In this respect, the task differed fundamentally from traditional rhythmic task paradigms as used in the domain of coordination dynamics, in which often only one pattern of coordination is the optimally stable (e.g., the in-phase pattern of coordination for rhythmic interlimb movements, Haken et al., 1985). It is also in contrast with other complex and continuous perceptuomotor tasks, in which also only one optimal strategy usually emerges from practice (e.g., pedalo task, Chen et al., 2005; ski-simulation task Vereijken et al., 1992, 1997). We note that over extended and intensive practice on the ball-and-beam task, the lower energetic efficiency of the middle-stop strategy might eventually bring participants to adopt the more efficient extreme-stop strategy. This, however, remains but speculative for the time being.

If participants did not change their movement strategy to adapt to the different target size conditions, then the question arises as to what caused the speed-accuracy trade-off at the level of the rolling ball. First of all, we found that the range of motion (ROM) of the beam varied in accordance with the accuracy demands, such that smaller target sizes gave rise to smaller ROMs of the inclination angle, regardless of the adopted strategy (**Fig 3.6**). The beam's ROM was strongly correlated with the ball speed, implying that participants used it directly to modulate the speed of the ball (see also Hafkamp et al., 2023). Moreover, the ROM was highly correlated with the number of target hits—in particular in the large target condition—suggesting that the ROM was a strong indicator for task success when the accuracy demands were low. Secondly, the relative variability of the beam motion (CV) was significantly larger when the target size was smaller, even though its correlation with the number of target hits was low in these conditions. A possible reason for this apparent contradiction could be that the larger variability of the beam was caused by a lack of control of the ball for some participants, but for others gave rise to an increased use of corrective sub-movements to enhance control under the high accuracy constraints. This hypothesis is supported by the finding that in small target size conditions, a middle-stop strategy was associated with a higher accuracy of the ball motion, while an extreme stop strategy led to a lower ball accuracy ratio. The use of sub-movements has been found as a task solution in goal-directed pointing tasks as well (e.g., Keele and Posner, 1968; Meyer et al., 1990, for a review: Plamondon and Alimi, 1997) and it might reflect a general strategy to preserve accuracy in a goal-directed movement. This conclusion should be drawn with caution here, however, as the indirect form of control operating in this ball-and-beam paradigm may be fundamentally different from more direct forms of control, such as in manual aiming tasks.

The beam's range of motion and variability also played a crucial role in the performance progression over blocks. The process of skill acquisition was characterized by two distinct phases of learning. In the first phase, participants explored the ball-beam relationship to establish a general movement strategy. This exploratory phase was accompanied by a decrease in variability and an increase in the correlation between the

ball position and beam inclination (**Fig 3.3C**). In the literature, increases in the correlation between action-related and perception-related variables have been associated with improvements of the perceptuomotor coupling on a task (e.g., Jacobs et al., 2012). After this exploratory stage, the correlation between ball and beam motions stabilized and the established movement strategy—either an extreme-stop or a middle-stop dynamics—no longer changed over the duration of practice. To further improve performance in the second stage of learning, participants gradually increased the beam's range of motion, while decreasing its relative movement variability (**Fig 3.6**). In other words, they performed with more risk and higher consistency. Although this process of refinement was most clearly visible for the large target sizes, it took place in all task conditions. Such a two-staged process of skill acquisition is characteristic of de novo learning and has been found in many other perceptuomotor tasks before (Newell and McDonald, 1994; for a review see Guimarães et al., 2020). In studies using a cyclical ski-simulation task, for instance, Vereijken et al. (1997) demonstrated that in a first exploratory stage participants moved the platform from left to right with a very high variability and a low range of motion, while participants found a stable and consistent movement pattern with a larger range of motion in a second stage of learning. Similar to the findings of the present study, they reported that participants gradually increased their range of motion to improve performance in this latter stage of learning.

We conclude that individual skill acquisition in the solo setting of the manual ball-and-beam task is characterized by a gradual refinement of one of two alternative movement strategies that emerges in an early stage of learning. The chosen strategy can best be defined by the locus of stopping or slowing down in the beam's movement cycle and reflects the behavioral dynamics that arise from the perceptuomotor coupling on the task. In other words, the movement strategy is an expression of how each player coordinates the cyclical motion of the beam with the continuous motion of the ball rolling on that beam. These results are particularly interesting for our broader purpose of understanding interpersonal coordination through a joint action version of the ball-and-beam task. In joint action, both individuals not only have to coordinate their movements with the rolling ball on the beam, but also with the concurrent actions of another individual. Given the stable differences in the behavioral dynamics between individuals, we expect that dyadic performances are shaped by the idiosyncrasies of the individuals that constitute the dyads. In other words, based on the present results we expect that the adopted strategy (either extreme-stop or middle-stop) will be among the pertinent characteristics that are transferred from the solo to the joint action setting of the ball-and-beam task. This would imply that who interacts with whom may be relevant to the form as well as the stability of the interpersonal coordination. In future work we will investigate this interaction by combining the currently presented insights into individual skill acquisition with the study of joint action performances on the ball-and-beam task.

3.6. Supplementary material

The supplementary material for this chapter can be found online at https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1436099/full#supplementary-material

4. Interpersonal coordination in a ball-and-beam paradigm: Transfer of skill from solo to joint action

4.1. Abstract

Interpersonal coordination is paramount to the success of a joint action. Yet, while the stability of interpersonal coordination is well understood, current models lack attention on functionality. In a two-step study using the ball-and-beam paradigm, we investigated this dimension. Participants rolled a ball back-and-forth between two targets on a beam, by manipulating the beam inclination, either individually or dyadically. In an (earlier reported) first step, 16 participants performed two solo action sessions of the task, allowing us to identify pertinent performance characteristics. Here, those participants were paired into 8 dyads to perform a joint action session, allowing us to assess the solo-to-joint transfer of those characteristics. Over blocks, dyads improved their performance by increasing the ball speed and accuracy. While the relative variability of the beam's inclination angle decreased, the range and the timing of the beam motion remained unchanged. Variables (indirectly) related to ball speed, such as the range and timing of the beam motion, were strongly propagated from solo to joint action, while the variables related to ball accuracy, like the beam variability, were only moderately transferred. Most dyads established an anti-phase mode of coordination, with a significant decrease in phase variability over blocks. We also observed significant asymmetries in the coordination. Dyad members with a better solo-action performance were more likely to lead the interaction in joint action. We concluded that interpersonal coordination in the ball-and-beam paradigm emerged from the interaction, while being constrained by the goal of the task.

4.2. Introduction

Many of our daily life activities cannot be accomplished without some form of coordination with other individuals. Consequently, the interpersonal coordination of movement behavior is at the heart of our behavioral repertoire. Without much effort, we are able to tune into the actions of others and to establish a spatiotemporal coupling between our movements and those of our co-actors. Think, for instance, about the ease with which we do the dishes together. Or consider the apparent fluency with which we carry a heavy table to the other side of the room together, often without even talking to one another. According to Interpersonal Synergies Theory (IST, Riley et al., 2011), we can achieve such spatiotemporal coupling of movement by linking the degrees of freedom (DFs) of our own perceptuomotor system with those of other individuals, thereby

establishing a single coordinative structure. This structure is known as an interpersonal synergy. The core claim of IST is that an interpersonal synergy is established and sustained by the informational and/or mechanical coupling between the two or more perception-action systems. With this position, IST falls within a broader theoretical framework which holds that structures (or modes) of coordination emerge from a process of pattern formation (Schmidt & Richardson, 2008; Schmidt et al., 2011). This so-called ecological-dynamical approach is in large part based on the HKB model of coupled oscillators, initially developed in the domain of intra-individual coordination (Haken et al., 1985). According to this model two rhythmically moving limbs, when coupled, are dynamically constrained to display only two modes of coordination: in-phase (relative phase 0 degrees) or anti-phase (relative phase 180 degrees). This is to say that the dimensionality of the inter-limb coordination is reduced in the same way that two coupled metronomes are entrained in their swinging. In a paradigmatic study, Schmidt et al. (1990) showed that such pattern formation also occurs in inter-individual coordination. Dyads of seated and visually coupled participants could only stably oscillate their lower limbs in in-phase and anti-phase with respect to each other. In line with the HKB model, in-phase coordination was found to be more stable than anti-phase coordination and an involuntary transition from the anti-phase mode to the in-phase mode occurred when the frequency of the limb oscillations was stepwise increased. Although the stability of interpersonal coordination was found to be somewhat lower than that of intrapersonal coordination, the work of Schmidt et al. (1990) formed the basis for IST as a new perspective on human interactions.

In the decades following the work of Schmidt et al. (1990), the finding of spontaneous inter-individual synchronization was replicated in various other settings in- and outside the laboratory. From side-to-side pendulum swinging (Schmidt & O'Brien, 1997), chair rocking (Richardson, Marsh, Isenhower, et al., 2007) and treadmill walking (Van Ulzen et al., 2008) to elite level sprinting at the World Championships (Varlet & Richardson, 2015): rhythmic interpersonal coordination consistently turned out to abide by the laws of non-linear dynamics. Moreover, extended versions of the coupled oscillator model provided new predictions with respect to human interactions (Fuchs & Kelso, 1994). One of these predictions concerned a systematic deviation from synchrony, also known as detuning. When the intrinsic (eigen)frequencies of two oscillators differ from each other, the stability of their coordination will be lower and the phase locking will occur on a relative phase that slightly deviates from anti-phase or in-phase. In particular, the oscillator with the higher intrinsic frequency will take the lead over the other, with a phase lag between the two that is proportional to the difference in the eigenfrequencies. In a series of experiments with hand-held pendulums of different lengths, these predictions were shown to hold in the case of inter-individual coordination (Schmidt & Turvey, 1994; Schmidt et al., 1994; Amazeen et al., 1995). That is, the participant swinging the shorter pendulum □with the higher intrinsic frequency□ systematically led the interaction with a proportional phase lag. These experiments not only provided further support for the conceptualization of interpersonal coordination in terms of frequency entrainment and phase locking of coupled oscillators (De Poel, 2016). They also suggested that key

phenomena such as who will lead and who will follow are (at least partially) dictated by the dynamical constraints governing the interaction.

However, despite its unprecedented accounts for stability and (deviations from) synchronicity (see Schmidt & Richardson, 2008, for a review), the coupled oscillator model has its limitations in explaining interpersonal coordination as well. Most prominently, it lacks a functional dimension that is so typical of joint actions (Fusaroli et al., 2014). In daily life, we rarely coordinate our movements with others for the sake of the synchronization itself. On the contrary, interpersonal coordination occurs most often in function of a common goal among the participants (Lagarde, 2013; Richardson et al., 2015; Huys et al., 2018). Indeed, the coordination of our actions with other individuals often allows us to achieve goals that we could not have achieved individually. Together, we can carry heavier and larger pieces of furniture than we can carry alone. Likewise, we can row faster in a crew than we can row individually (in a so-called skiff). In other words, our action capabilities increase when we decide to coordinate our movements with other individuals, making available a greater range of affordances in the environment (Baron, 2007; Richardson, Marsh, & Baron, 2007). In this perspective, we argue that an interpersonal synergy is more than only a stable mode of coordination constrained by a dynamical process of pattern formation. An interpersonal synergy is also an expression of the functionality of a team of collaborating individuals pursuing a common goal. In an effort to meet that goal, each individual brings something to the interaction, while also leaving something behind. Or, in the words of Baron (2007, p. 186), cooperation involves "a symmetry-breaking process whereby organisms shift from individual to collective action (..) an 'unfreezing' process or qualitative change". Given that a goal-related dimension is lacking in the model of coupled oscillators, it seems unlikely that the functional transition from individual to collective action can be entirely understood in terms of oscillator properties (e.g., eigenfrequencies, phase progression profiles). As such, a new level of description seems to be required to describe a synergy – one that is more directly related to the purpose of the joint action.

In recent years, a number of studies have explicitly investigated the tenability of the coupled oscillator model as an account for purposeful joint actions (e.g., Huys et al., 2018; Cuijpers, 2019). For instance, in her dissertation work Cuijpers (2019) investigated the rhythmic coordination of crew rowers. Rowers are coupled not only visually but also mechanically, through the boat in which they are seated, and the coordination of their strokes is subordinate to the goal of moving the boat as fast as possible from start to finish. Analogous to coupled oscillators, Cuijpers et al. (2015) found that crew rowers can stably produce both in-phase and anti-phase coordination patterns. But in contrast with the HKB model, in crew rowing both phase modes were equally stable, although the anti-phase coordination deviated somewhat from the intended phase. Furthermore, the anti-phase mode of coordination led to lower fluctuations in the boat velocity and to less detrimental boat movements, and increases in the stroke frequency resulted in a higher consistency of the crew synchronization (Cuijpers et al., 2017). Thus, the mechanical coupling provided by the boat led to an interpersonal coordination that deviated from what was predicted by the HKB model. Also, what counted as stability on the level of the

coordination between the rowers, did not necessarily count as stability at the level of the boat in its interaction with the water, which is nevertheless crucial to the purpose of racing. Examining a dyadic rope-turning task, Huys et al. (2018) found results similar to those of Cuijpers (2019). The task for participants in this study, either individually or as a dyad, was to turn a rope regularly and at a comfortable pace. Although the turning frequency was higher in joint action than in solo action, the regularity of the rope's motion was higher in the joint action. Moreover, the regularity of the rope improved when the frequency of the turning increased, even though the relative phase between dyad members became more variable. Both findings were attributed to the mechanical coupling provided by the rope, not unlike the boat-mediated coupling in crew rowing. Together, these studies brought out two key insights. First of all, each task setting comes with additional mechanical constraints that may lead to deviations from the HKB model predictions. And secondly, stability in the interpersonal coordination is related to but not the same as stability on the outcome level of the joint performance (e.g., the regularity of boat or rope motion).

The work of Cuijpers (2019) and Huys et al. (2018) highlights the necessity for including and distinguishing (at least) two levels of description in a joint action. One level pertaining to the interpersonal coordination, which may or may not conceptualize the agents as pairs of coupled oscillators. And another level pertaining to the purpose of the activity, which describes the (mediated) interaction of the team or dyad with its environment. It is only at this second level of description that the functional dimension of a joint action is expressed. In the aforementioned examples of crew rowing and rope turning, the common goal among the participants was closely related to the stability of their coordination. That is, accomplishment of the respective tasks was not possible without some stable form of synchronization between the participants. In fact, the stability of the coordination was sometimes even implicitly included in the instructions (e.g. "the participants were instructed to turn the rope *regularly*", Huys et al., 2018, p. 58). It is important to realize, however, that the goal of a joint action often demands entirely different qualities of the performance than only coordinative stability. For instance, the purpose of a collaboration could be to perform fast, accurately or both at the same time. Think in this context about the passing of a ball in team sports, which generally needs to be performed at high speed and preferably with clinical precision. While the stability of the interpersonal coordination serves as a boundary condition on meeting such goals, a description of ball passing in terms of the spatiotemporal relationship between the players does not suffice to capture the joint action. It minimally requires a description of the ball motion, as well as the legs in relation to the ball. At the same time, the stability of the players' interpersonal coordination may be affected by the goal to pass the ball fast. The interpersonal coordination in a joint action can never be fully understood in isolation from the action's functional levels. Thus, the dimensions of stability on the one hand and functionality on the other hand need to be addressed *together* to provide an IST account for purposeful joint action. Here we deployed the recently introduced manual ball-and-beam task (Hafkamp et al., 2023, 2024) as an experimental entry into this issue.

In the ball-and-beam task, participants have to control a ball rolling on a long and hand-held beam. By continuously tilting the beam up and down, participants aim to roll the ball back and forth between two indicated targets on the beam. More specifically, they aim to hit the targets as often as possible within the timespan of a two-minute trial by reversing the direction of the ball motion in the target zones. While the task can be performed individually (i.e., in a solo action setting, **Figure 4.1A**), the current contribution focused on dyadic task performances (i.e., in a joint action setting, see **Figure 4.1B**). In joint action, each of the two beam extremities is handled by a different participant such that dyads have to collaborate to control the ball. In doing so, they are not allowed to communicate with each other in our protocol. With this set-up, the ball-and-beam paradigm constitutes a clear example of a purposeful joint action. Collaborating participants have the goal to roll the ball as fast as possible from target to target, in order to be able to score as many points as possible. To achieve this, they have to manipulate the beam inclination in such a way that the force of gravity is optimally exploited, to produce large ball accelerations and decelerations for its motion from one target to another. Such exploitation requires beam inclination excursions with a large range of motion but also with an efficient timing, so that a relatively large part of the cycle of motion can be spent at high inclination angles. On the other hand, collaborating participants aim to roll the ball back-and-forth with sufficient accuracy to ensure that they hit the targets and thereby actually score points on the task. To achieve this, dyads have to move the beam in a consistent manner, that is,

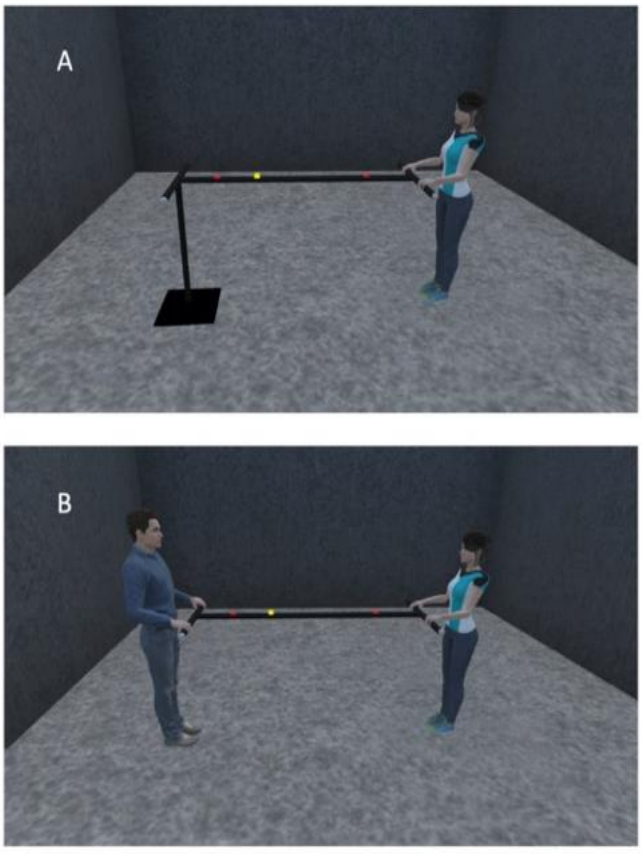


Figure 4.1: Schematic illustration of the ball-and-beam task configuration used in the solo action setting (A) and in the joint action setting (B).

with a relatively low amount of cycle-to-cycle variability. That requires a stable mode of interpersonal coordination with a strong spatiotemporal coupling between participants' respective movements.

In a first experiment exploring joint action in this ball-and-beam paradigm (Hafkamp et al., 2023), we found that the task goal could be achieved through at least two different modes of interpersonal coordination. In the experiment, one group of participants first performed a joint action session and then a solo action session (J/S), while another group started with a solo action session, followed by a joint action session (S/J). In the J/S group, most of the dyads moved the beam handles sequentially and in a turn-taking fashion – each freezing their motion while the other moved. In the S/J group, most of the dyads moved the beam handles simultaneously and in opposite directions – one moving up while the other moved down. Even though both modes of coordination were stable, only the latter mode enhanced the action capabilities of the two individuals. That is, by moving the beam handles simultaneously instead of sequentially, dyads could produce larger beam inclination angles than what they could have produced individually, implying the possibility of more target hits as a team than as a soloist. The results of Hafkamp et al. (2023) revealed an intricate relationship between interpersonal coordination and task accomplishment. Dyads were not only striving for stability, but also for a functional mode of coordination that allowed them to achieve a large number of target hits. In addition to this, the results showed that collaborating dyads needed some individual task experience to discover an optimal task solution (discovered by the S/J group, but not by the J/S group). This indicates a particular transfer of skill from the solo action setting to the joint action setting. Even though the two task settings are different in terms of the coordination (i.e., intra- versus interpersonal), they are equivalent in terms of the goal (i.e., control the ball via the beam). This suggests that a transfer of skill is more likely to be understood on a functional level than on the level of interpersonal coordination. At the same time, frequency entrainment and phase locking of the two beam extremities seem, at least to some extent, required for them to set up a stable mode of coordination. This suggests that adjustments in terms of a participant's frequency and phase progression may be required in the transfer from solo action to joint action.

In a two-step follow up study, of which the current contribution formed the second step, we set out to investigate the solo-to-joint transfer in the ball-and-beam paradigm. In the first step (Hafkamp et al., 2024) we focused on the individual task execution in a solo action setting, with the goal to identify the pertinent characteristics of the performances on a functional level. A group of 16 participants performed two solo action sessions, including trials with different target sizes to vary the accuracy demands of the task. In capturing the participants' performances, we distinguished between the level of the ball motion and the level of the beam motion. On the level of the ball, performances were characterized by the number of target hits on each trial, but also by the number of (ball) half cycles and by the ratio between the number of hits and the number of half cycles. In other words, the ball level performances featured speed as well as accuracy, which both improved over practice. On the level of the beam, the performances were characterized by three aspects of the inclination angle motion. First of all, the range of motion of the

beam. Over practice, individual participants moved the beam extremity up and down with increasingly large excursions so as to increase the speed of the ball. In second place, the consistency of the beam behavior. From trial to trial, participants enhanced the consistency of the beam movements so as to roll the ball more accurately and hit the targets more often. Third and last, the timing of the beam. A within-cycle analysis of the beam motion revealed two different timing (i.e. phase progression) strategies to set the ball in motion with the beam. While most participants tended to maintain the beam at peak inclination angles for brief, but noticeable, durations (denoted extreme-stop strategy), some were more inclined to briefly halt the beam movement between two peaks, at inclination angle zero (denoted middle-stop strategy). Although the extreme-stop strategy exploits the force of gravity more efficiently than the middle-stop strategy, and thus may lead to more target hits, the timing strategies were found to remain invariant over practice.

In the current contribution we investigated to what extent the earlier identified individual performance characteristics were propagated from the solo action setting into a joint action setting. To this end, we paired all individuals from Hafkamp et al. (2024) into dyads and had them perform a subsequent joint action session of the ball-and-beam task. Similar to the solo action, the joint action session consisted of trials with different target sizes, again to vary the accuracy demands on the level of the ball. In assessing the dyadic performances, we attended to both the functional levels (i.e., the behavior of the ball and the beam) as well as to the level of the interpersonal coordination (i.e. the behaviors of two beam extremities). Our first research question concerned the functional levels. To what extent can the rolling of the ball and the tilting of the beam in the joint action setting be understood from (that is, explained by) the corresponding individual's performances in solo action? Given that the solo and joint action setting of this task are functionally equivalent, we hypothesized a significant transfer of behavior from one setting to the other. That is, we expected the speed, accuracy and hits of the ball as well as the range, timing and consistency of the beam in the joint action setting to be at least partly predictable from the corresponding individual's solo action performances. Our second research question concerned the level of interpersonal coordination. To what extent are the (vertical motions of the) two beam extremities frequency entrained and phase locked in the joint action performance? Based on earlier research within this paradigm (Hafkamp et al., 2023), we hypothesized that frequency entrainment, dictated by the rhythm of the ball, was required for dyads to hit the targets. With respect to the relative phase of the interpersonal coordination, we hypothesized that the solo-to-joint transfer of individual participants' timing strategy would prevent a stable phase locking to occur. That is, we expected each dyad member to retain a unique phase progression profile in their timing, implying a variable phase relationship between the two extremities. Moreover, we expected that the mean relative phase would be affected by inter-participant differences at the functional levels of the task. In analogy to frequency-induced phase detuning in coupled oscillators (Schmidt & Turvey, 1994; Amazeen et al., 1995), we tentatively hypothesized that the dyad member with the larger number of target hits or half cycles in solo action would take the lead in joint action.

4.3. Materials and method

Although the research methods deployed in this two-step study were already partially reported in Hafkamp et al. (2024), for reasons of stand-alone readability of the present contribution we here provide a full description of all relevant methodological aspects.

4.3.1. Participants

A group of 16 students and junior staff members from Aix Marseille University (7 women, 9 men, with an average age of M ± SD: 23.3 ± 2.9 years) participated voluntarily in these studies. None of them had any experience on the task. All participants were free from known motor impairments and reported normal or corrected-to-normal vision. Before the start of the first experimental session the participants were informed about the aim and procedure of the experiment. All participants provided written informed consent before participating in the study. The study was approved by the French National Ethics Committee for Research in Sports and Movement Sciences (CERSTAPS 15/12/2022 IRB00012476-2022-15-12-213) and conducted according to University regulations and the Declaration of Helsinki.

4.3.2. Task and procedure

The task equipment consisted of a standard golf ball (diameter 4.3 cm, weight 46 g) that could roll over a 2-m long, 3 by 3 cm V-shaped iron beam, with tubular handles (length 54 cm, diameter 3 cm) perpendicularly attached to its extremities. Participants' task was to roll the ball as fast and accurately as possible back-and-forth between two targets clearly visible on the beam. Participants received one point for every time that the ball reversed its direction within a target's boundaries, with the objective of achieving as many points as possible within every 2-minute duration trial. With both target centers located 50 cm from the beam's midpoint, the center-to-center inter-target distance was 100 cm in all trials. The size of both targets varied from trial to trial and was either small (6 cm), medium (12 cm) or large (24 cm). Bimanually holding one handle allowed a participant to lift or lower a beam extremity and thereby change its inclination angle so as to accelerate or decelerate the ball (see **Figure 4.1**). In the solo action setting, the participant manipulated one handle while the other was attached to a hinge on a static pole, the height of which was adjusted to the participants' hip height. In the joint action setting, each handle was manipulated by a different participant. In order to compensate for more than 10 cm height differences between participants within a dyad, the smaller of the two participants was placed on a wide and stable wooden platform that allowed 2-cm stepwise height adjustments.

The first part of this two-step study consisted of two sessions of solo action practice on the ball-and-beam task that were completed on two different days, with one or two days between the sessions. A detailed description of findings obtained during these solo action sessions is provided in Hafkamp et al. (2024). The relevant results are recapitulated and provided with the necessary context in the Results section of the current contribution. For

the second part of the study, the 16 participants were subsequently paired into 8 dyads (referred to as D1 to D8) . Each dyad then performed a session of joint practice on the ball-and-beam task. The present contribution focusses on this joint action session, which was performed three to four weeks after the second solo action session. Pairing of the participants into dyads was based on the average number of target hits of each individual in the second solo action session, such that in each dyad a high performer (HP) was paired to low a performer (LP). Similar to each of the two solo action sessions, the joint action session comprised six blocks of practice. Each block consisted of three trials: one trial with small targets, one with medium targets and one with large targets. The three conditions within a block were presented in a pseudo-randomized order, such that all possible orders of conditions were presented once during a session. Each dyad thus performed a total of 18 trials. After every two blocks of trials, participants were given a short break of 2-3 minutes. During the trials, dyads were not allowed to talk or communicate otherwise. Talking was allowed during the breaks but could not concern the task.

At the start of each 2-minute trial, the ball was placed in the middle of the beam. Verbal signals from the experimenter signaled the beginning ('Go') and the end ('Stop') of a trial. After each trial, participants received verbal feedback on their score, based on experimenter observation. Participants were regularly encouraged to try to improve their score on each new trial, in order to reach the highest score possible in each target size condition. In both the solo and the joint settings, participants/dyads competed indirectly with the others via a leaderboard that expressed the high scores of the other participants or dyads on each target size condition. All of this was in function of motivating the participants to perform optimally on each new trial.

4.3.3. Data acquisition

All sessions took place in a darkened room. To capture the motion of beam, small reflective markers were attached to each handle through a thin, rigid and 10-cm long aluminum rod. In order to capture the motion of the ball, we used a bright yellow colored golf ball. Participants wore dark clothes and black gloves to ensure sufficient contrast with the ball and the two beam markers. All trials were filmed with a GoPro9 camera that was positioned at a 2-m perpendicular distance from the midpoint of the beam. The camera, set in linear lens mode so as to obtain minimal image deformation, was placed on a tripod at a 1-m height. All trials were recorded with a (recalculated) sample frequency of 29.97 Hz and a resolution of 2.7K.

Video recordings of all trials were imported into Kinovea (open-source software https://www.kinovea.org/), which was used to track the two-dimensional (X, Y) motion of the ball and the two reflective beam markers. X and Y position time series were then analyzed using MATLAB. All timeseries were first filtered using a fourth-order low pass Butterworth filter (cut off frequency of 3 Hz) and trimmed to the 120-second trial duration. The ball's trajectory was subsequently transformed from motion in a two-dimensional space to one-dimensional motion along the beam's longitudinal axis. To do this, we calculated the ball's motion along the virtual vector between the two beam markers, with the inter-marker distance used for calibration. From the trajectories of the

two beam markers we derived a single beam inclination angle at each timestep by taking the inverse tangent (atan) of the X and Y coordinates of both markers. The one-dimensional timeseries of the ball position on the beam, on the one hand, and the timeseries of beam's inclination angle, on the other hand, formed the basis of all further analyses of ball and beam behavior in this contribution. The timeseries of the vertical motions of the two hand-held beam extremities were used to analyze interpersonal coordination.

4.3.4. Dependent variables

The dependent variables in this study were related to three distinct levels of the ball-and-beam system. First of all, we addressed the level of the ball's motion between the two targets (section 2.4.1.). In second place, we analyzed the level of the beam's inclination angle (section 2.4.2.). In the third place, we investigated the level of coordination between the individuals in each dyad (section 2.4.3.).

Ball motion. Using a peak finding algorithm that split the ball position timeseries into separate half cycles, we computed three variables to assess the ball's motion between the targets. Firstly, we counted the number of target hits (TH) on each trial, which we defined as the number of ball motion reversals within the (recalculated) target zones of each task condition. Secondly, we counted the total number of ball half cycles (HC) on each trial. Given that the trials were time-constrained, this number was proportionally related to the average ball speed on a trial. Thirdly, we divided the number of target hits by the number of half cycles on a trial. Since the TH/HC-ratio indicated the accuracy on a trial, we refer to this variable as the ball's accuracy ratio (AR).

Beam motion. From the timeseries of the beam's inclination angle, we derived three variables to capture the relevant characteristics of the beam behavior. Firstly, we computed the beam's range of motion (ROM), which we defined as the average peak-to-peak amplitude of the beam inclination timeseries. Using a peak-finding algorithm, we determined the mean angular distance between the maximum and minimum beam inclination angles in each half cycle. Secondly, we assessed the relative variability of the beam's angular motion using the coefficient of variation (CV). To compute the CV, we divided the inclination angle timeseries into separate cycles on the basis of the ball position peaks. We used the ball's cycles because these were more consistent in comparison to the beam's cycles. We then time-normalized all cycles to 100 timepoints and calculated the standard deviation (std) of beam inclination across cycles at each timepoint. We averaged all std's to come to one std, which we then divided by the ROM on that trial to compute the trial's CV. Thirdly, we quantified the shape of the beam's inclination angle motion using the Shape ratio (SR). This measure was inspired by the shape of the inclination angle frequency distributions and provided an indication of the time structure of the beam's motion pattern (see Hafkamp et al., 2024, for examples). We computed SR as the ratio of the average absolute inclination angle over half of the ROM

(i.e., peak-to-peak amplitude) of the beam, with higher shape ratios thus indicating longer time spent at large inclination angle magnitudes.

Interpersonal coordination. As a first assessment of the dyadic coordination, we analyzed the relative direction of the vertical motions of the two beam extremities (each extremity being controlled by a different participant). More specifically, we calculated the proportion of the total trial duration (120 s) during which both participants moved in the opposite direction (complementarity ratio, CompR), in the same direction (supplementarity ratio, SuppR) or that at least one of the two individuals moved slower than a threshold value of 0.05 m/s (freezing ratio, FreezR) (see Hafkamp et al., 2023). To investigate the spatiotemporal characteristics of this interpersonal coordination in more detail, we computed the continuous relative phase (CRP) between the vertical movements of the two beam extremities. To this end, we first centered the two vertical extremity position timeseries, removed any linear trends and normalized the signals by dividing them by their standard deviation. We then transformed them into analytic signals using the Hilbert transform (Lamb & Stöckl, 2014) and derived the continuous phase angles (in degrees) from that. As a last step, we subtracted the phase angle of the LP from the phase angle of the HP to arrive at the CRP. Given this definition, a CRP > 180 deg indicated a leading role for HP, while a CRP < 180 deg indicated that a leading role for LP. In addition to computing the mean CRP on each trial, we also assessed the within-trial variability of the coordination by calculating the standard deviation of the CRP on each trial (CRP_{STD}) and we assessed the mean absolute deviation of the CRP from anti-phase (CRP_{DEV}).

4.3.5. Statistical analyses

In order to compare the dyad's performances across target size conditions and over practice blocks, we performed 3 x 6 repeated measures ANOVAs on all dependent variables. Each ANOVA contained the within-participant factors Condition (3 target sizes) and Practice (6 blocks). The dependent variables to which these analyses were applied included TH, HC, AR, ROM, CV, SR, CompR, SuppR, FreezR, CRP_{STD} and CRP_{DEV}. For all analyses the significance level was set to $\alpha = 0.05$. Greenhouse-Geisser corrections were applied when violations of the sphericity assumption were detected. Post-hoc tests were performed using Bonferroni corrections. Where appropriate means and standard deviations are reported as $M \pm SD$.

Next, we analyzed the relationship between the dyadic performances in the joint action setting and the dyad members' individual performances in the (second) solo action setting. For each performance variable related to the ball motion (TH, HC, AR) and the beam motion (ROM, CV and SR), we did this via a Pearson correlation analysis between the joint action performances of each dyad and the sum of the corresponding individual's solo action performances. Per correlation analysis, we took the mean of all 6 blocks in the (solo/joint action) session, and we performed the analyses separately for each target size condition. In our exploratory analyses, we also conducted the same analysis by only taking the first three or last three blocks of either session, but this did not lead to significantly different results. Hence, we decided to report only the analysis in which we took the mean

of all 6 blocks per (solo/joint action) session. We used the proportion of explained variance captured by R^2 as the measure of strength of the solo-joint relation. Given that each Pearson correlation was based on 8 datapoints (dyads) and $p = 0.05$ for $r(6) = 0.707$, we interpreted a $R^2 > 0.50$ (i.e., explaining more than 50% of the variance) as indicative of a significant explanatory value of that variable in the transfer from solo to joint task performance.

Finally, at the level of interpersonal coordination, we analyzed (again using Pearson correlation analyses) the relation between the mean relative phase observed for each dyad and the mean performance differences (in TH, HC, AR, ROM, CV and SR) of the dyad members in the solo action setting, again performing these analyses separately for each target size condition. In doing so, we assessed whether any potential leader-follower dynamics could be explained from inter-individual differences in the preceding solo action setting.

4.4. Results

In presenting the results of this study, we progressively move along the three above-defined levels of the ball-and-beam system: the level of the ball motion (section 3.1.), the level of the beam motion (section 3.2.) and the level of interpersonal coordination (section 3.3.). At each level, we first report the results from the Condition (3 target sizes) x Practice (6 blocks) repeated measures ANOVAs on the dependent variables. Thereafter, we relate the dyad's performances in the joint action session to the individual's performances in the preceding solo action sessions. On the levels of the ball motion and the beam motion, we did this via correlational analyses between the indicator scores observed in the joint action session (JAS) and the (sum of the) indicator scores of the corresponding individual in the second solo action session (SAS). On the level of the interpersonal coordination, we related the dyad's mean relative phase –indicative of a leader-follower dynamics– to differences in the dyad members' performances in the solo action session.

4.4.1. Ball motion

Target hits. As shown in the upper left panel of **Figure 4.2**, the number of target hits (TH) increased significantly over practice blocks ($F(5, 35) = 9.95$, $p < 0.001$, $\eta^2_p = 0.59$). A post-hoc test revealed that the number of target hits was higher in the last (B6) than in the first (B1) block ($p < 0.001$). The TH was significantly different between target sizes ($F(2, 14) = 102.97$, $p < 0.001$, $\eta^2_p = 0.94$), such that larger targets allowed for more target hits per trial. The increase in TH over blocks was not significantly different per target size ($F(10, 70) = 1.17$, $p = 0.329$, $\eta^2_p = 0.14$).

Half cycles. The number of half cycles (HC) increased significantly over practice blocks (upper middle panel of **Figure 4.2**, $F(2.20, 15.38) = 7.04$, $p = 0.006$, $\eta^2_p = 0.50$, B1-B6 post hoc: $p < 0.001$). The HC was significantly higher in the larger target size conditions ($F(2,$

14) = 170.57, $p < 0.001$, $\eta^2_p = 0.96$), while the increase in the HC over blocks was not significantly different per target size ($F(10, 70) = 1.67$, $p = 0.105$, $\eta^2_p = 0.19$).

Accuracy ratio. The accuracy ratio (AR) increased significantly over practice (upper right panel **Figure 4.2**, $F(5, 35) = 4.76$, $p = 0.002$, $\eta^2_p = 0.41$, B1-B5 post-hoc $p = 0.003$), while revealing a slight decrease in block 6 (B1-B6 post hoc: $p = 0.333$). The AR was significantly higher for larger target sizes ($F(2, 14) = 43.24$, $p < 0.001$, $\eta^2_p = 0.86$). The changes in the AR over practice were not significantly different per target size ($F(10, 70) = 0.94$, $p = 0.560$, $\eta^2_p = 0.12$).

In summary, all ball-level variables (i.e., TH, HC and AR) increased significantly over blocks and were higher when the target sizes were larger. None of these variables showed an interaction effect between target size conditions and practice blocks.

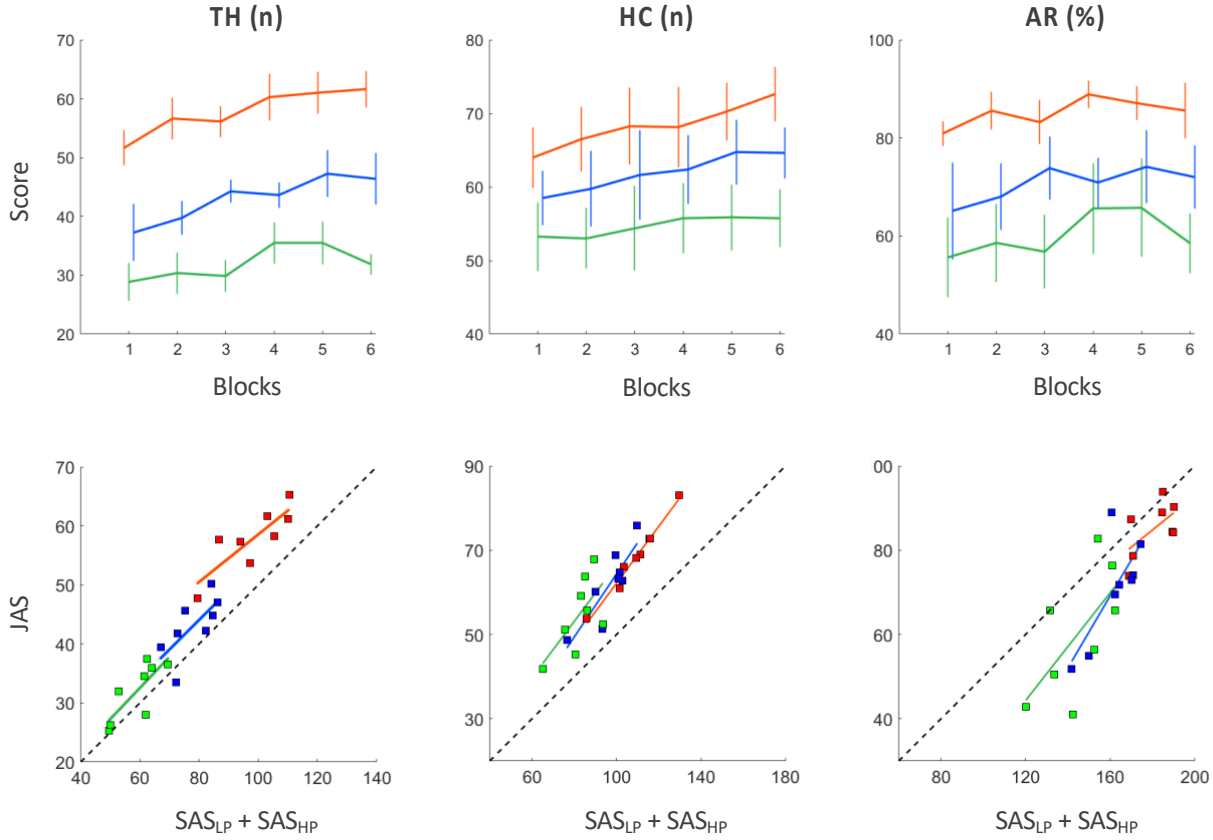


Figure 4.2: Ball motion variables: number of target hits (TH, left column), number of ball cycles (HC, middle column) and the accuracy ratio (AR, right column). The upper row of panels shows the evolution of each dependent variable across practice blocks, split per target size condition (small: green, medium: blue and large: red). The lower row of panels displays the dyad's joint action session (JAS) performances as a function of the sum of the low and high performing individual's solo action session (SAS_{LP} + SAS_{HP}) performances. Separate regression lines are fitted through the data points for each target size condition, whereas the dotted line represents JAS performance equal to the mean of SAS_{LP} and SAS_{HP} performances.

Solo-to-joint transfer. Next, we investigated how the dyad's joint performances were related to the preceding solo performances of the two dyad members. Using correlation analyses we evaluated how much of the variance in the dyad's performances could be explained from the sum of the corresponding individuals' performances on the second (and last) solo action session. For each dyad **Table 4.1** reports the average performances of the low and high performing individual in the (second) solo action session (SAS_{LP} and

Table 4.1: The average ball-level performances of each dyad (D1-D8) split per target size condition (Large: L, Medium: M, Small: S). Column 3-5 display the number of target hits (TH), column 6-8 the number of half cycles (HC) and column 9-11 the accuracy ratio (AR). For each variable, the table shows the mean of the 2nd solo action session of the low performer (SAS_{LP}), the high performer (SAS_{HP}) and the mean of the joint action session of the dyads (JAS).

		TH (n)			HC (n)			AR (%)		
Dyad	**Cond**	**SAS_{LP}**	**SAS_{HP}**	**JAS**	**SAS_{LP}**	**SAS_{HP}**	**JAS**	**SAS_{LP}**	**SAS_{HP}**	**JAS**
D1	**L**	48.2	57.2	58.3	50.7	60.5	69.0	95.1	94.5	84.4
	M	39.8	44.8	44.8	48.0	54.8	62.7	83.0	81.3	71.8
	S	28.8	32.7	34.5	44.2	49.3	52.5	65.4	66.1	65.7
D2	**L**	42.0	55.2	53.7	47.7	68.0	72.8	88.0	80.9	73.9
	M	29.5	42.7	33.5	41.8	59.8	64.7	70.6	71.3	51.9
	S	20.8	28.7	25.3	33.2	50.0	59.2	63.0	57.2	42.8
D3	**L**	49.5	53.7	61.7	49.7	59.7	68.2	99.7	90.4	90.3
	M	40.0	46.2	47.0	46.3	54.7	63.3	86.4	84.6	74.1
	S	34.3	35.2	36.5	42.7	43.3	55.7	80.6	81.9	65.7
D4	**L**	51.3	58.7	61.2	54.0	62.0	72.7	95.1	94.6	84.2
	M	41.2	43.0	50.2	44.8	54.7	68.8	91.9	78.3	72.9
	S	31.5	32.5	36.0	37.0	48.2	63.8	85.3	67.4	56.4
D5	**L**	32.0	47.5	47.8	38.2	47.7	53.7	85.0	99.6	88.9
	M	27.2	39.8	39.5	33.3	43.2	48.7	82.0	92.4	81.5
	S	21.0	31.8	32.0	27.3	37.8	41.8	76.9	84.2	76.3
D6	**L**	43.5	50.5	57.3	47.8	53.8	61.0	91.0	93.8	93.9
	M	33.0	42.2	45.7	43.2	50.0	51.3	76.6	84.3	88.9
	S	27.2	35.2	37.5	37.5	43.0	45.3	72.5	81.7	82.7
D7	**L**	37.2	49.5	57.7	41.7	61.8	66.0	89.3	80.6	87.3
	M	31.5	41.3	41.8	39.2	50.7	60.2	80.5	81.9	69.5
	S	19.7	30.3	26.2	39.2	36.3	51.2	50.2	83.4	50.5
D8	**L**	51.3	59.2	65.3	61.0	68.5	83.0	84.4	86.6	78.7
	M	36.5	45.7	42.2	54.8	55.0	75.8	67.0	82.8	54.9
	S	29.3	32.7	28.0	48.2	41.2	67.8	61.7	80.8	41.1

SAS_{HP}), together with the dyad's average joint action session performance (JAS). The results are reported for dependent variables TH, HC and AR.

In order to visualize the relations between dyadic and summed individual performance scores, we plotted for each indicator the JAS performance of a dyad against the sum of the corresponding SAS_{LP} and SAS_{HP} performances (lower row of panels in **Figure 4.2**). As can be appreciated from these graphs, the TH and the HC were generally higher in the joint performances than in the solo performances, while the reverse was true for the AR, in particular for dyads with a low accuracy ratio. Yet, for all three dependent variables the joint performances were positively correlated with the sum of the solo performances. **Table 4.2** reports the proportion of explained variance of each regression analysis, split per target size (L: large; M: medium, S: small). On average, the majority ($R^2 = 0.60$) of the variance in the dyads' number of target hits TH could be explained by the solo action performances, with an $R^2 > 0.50$ in two of the three target size conditions. The solo action performances had an even higher explanatory value with respect to the number of half cycles HC (average $R^2 = 0.73$, with $R^2 > 0.50$ in two of the three conditions). The variance in the dyads' accuracy ratio, in contrast, was only moderately explained by the solo sessions (average $R^2 = 0.46$), with an $R^2 > 0.50$ in only one condition.

Taken together, we conclude that the variance in the dyads' ball-level performances could be rather well explained by the (sum of) the corresponding individual's solo performances. In particular, it appeared that it was the speed of the ball rather than its accuracy that was propagated from the solo to the joint action setting.

Table 4.2: The proportions of explained variance (R^2) derived from the correlation analyses between the dyad's joint action performances and the sums of the dyad members' solo action performances at the ball motion level. The rows are split per target size condition (L: Large, M: Medium, S: Small). The lower row reports the average over target size conditions, while the columns show respectively the number of target hits (TH), the number of half cycles (HC) and the accuracy ratio (TH/HC). Asterisks (*) denote R^2 values > 0.50.

Condition	TH	HC	AR
L	0.70*	0.98*	0.36
M	0.49	0.75*	0.59*
S	0.62*	0.45	0.42
Average	0.60*	0.73*	0.46

4.4.2. Beam motion

Range of motion. As can be seen in the upper left panel of **Figure 4.3**, the beam's range of motion (ROM) did not change significantly over blocks ($F(1.78, 12.42) = 1.49$, $p = 0.262$, $\eta^2_p = 0.18$). The ROM was significantly different over target size conditions ($F(2, 14) = 40.58$, $p < 0.001$, $\eta^2_p = 0.85$), such that the ROM was higher when the target size was larger. The interaction effect was not significant ($F(10, 70) = 1.66$, $p = 0.109$, $\eta^2_p = 0.19$).

Coefficient of variation. The beam's motion coefficient of variation (CV) decreased significantly over blocks, as shown in the upper middle panel of **Figure** 4.**3** ($F(2.19, 15.31) = 4.87$, $p = 0.021$, $\eta^2_p = 0.41$). A post-hoc analysis demonstrated that the CV was significantly lower in B6 than in B1 ($p = 0.013$). The CV was different over target size conditions, with the CV being lower when the target size was larger ($F(2, 14) = 18.20$, $p < 0.001$, $\eta^2_p = 0.72$). The Condition x Practice interaction was not significant ($F(10, 70) = 0.45$, $p = 0.917$, $\eta^2_p = 0.06$).

Shape ratio. The beam's motion Shape ratio (SR) did not change significantly over blocks (**Figure 4.3**, upper right panel, $F(1.75, 12.25) = 0.58$, $p = 0.553$, $\eta^2_p = 0.08$). The SR was significantly higher in larger target sizes ($F(1.16, 8.11) = 24.05$, $p < 0.001$, $\eta^2_p = 0.76$). The Condition x Practice interaction was not significant ($F(10, 70) = 0.65$, $p = 0.768$, $\eta^2_p = 0.09$).

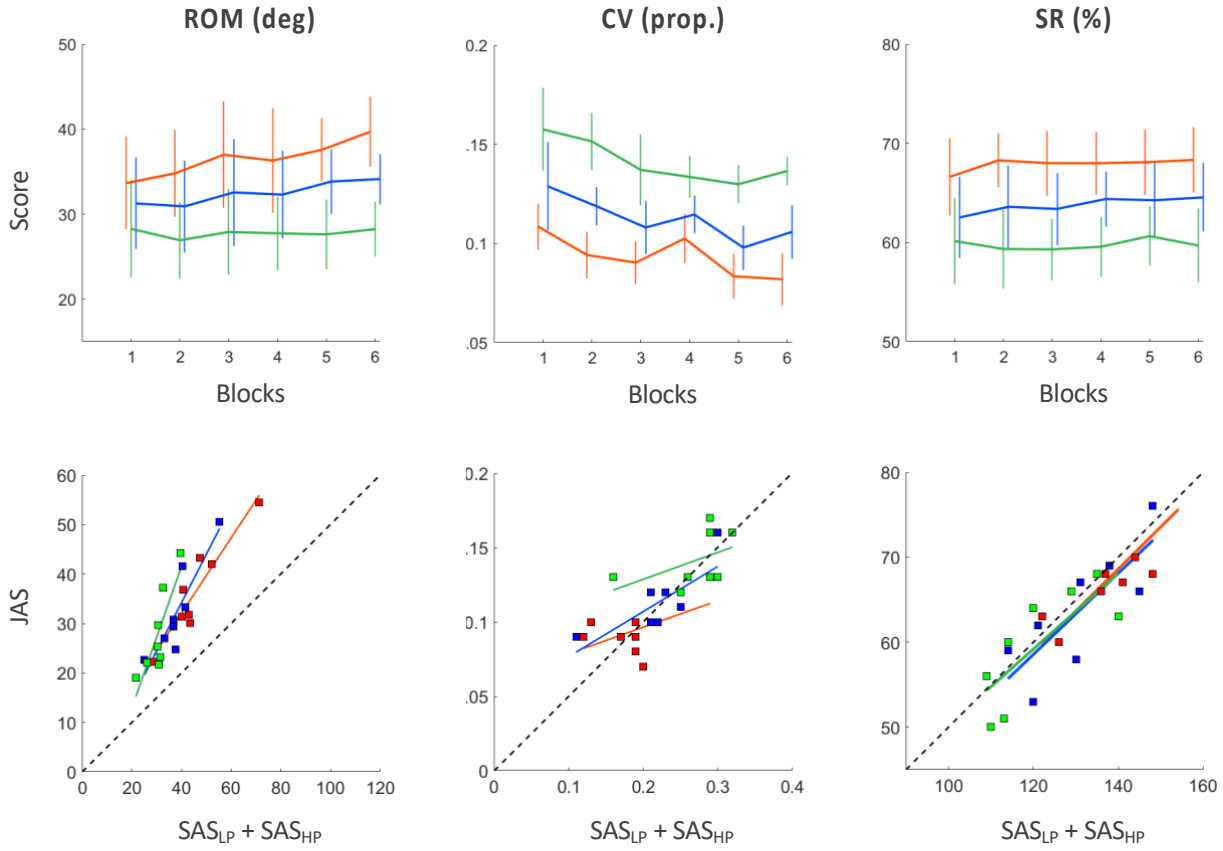


Figure 4.3: Beam motion variables: range of motion (ROM, left column), coefficient of variation (CV, middle column) and shape ratio (SR, right column). The upper row shows the evolution of each dependent variable across practice blocks, split per target size condition (small: green, medium: blue and large: red). The lower row displays the dyad's joint action session (JAS) performances as a function of the sum of the low and high performing individual's solo action session (SAS_{LP} + SAS_{HP}) performances. Separate regression lines are fitted through the data points for each target size condition, whereas the dotted line represents JAS performance equal to the mean of SAS_{LP} and SAS_{HP} performances.

All in all, only the CV decreased somewhat over blocks, while the ROM and the SR did not change significantly with practice. Thus, only the relative variability of the beam's inclination decreased over practice. All beam-related variables were different across target sizes, without statistically significant evolutions of these differences over practice.

Table 4.3: The average beam-level performances of each dyad (D1-D8) split per target size condition (Large: L, Medium: M, Small: S). Column 3-5 display the range of motion (ROM), column 6-8 the coefficient of variation (CV) and column 9-11 the shape ratio (SR). For each variable, the table shows the mean of the 2nd solo action session of the low performer (SAS_{LP}), the high performer (SAS_{HP}) and the mean of the joint action session of the dyads (JAS).

		ROM (deg)			CV (prop.)			SR (%)		
Dyad	**Cond**	**SAS_{LP}**	**SAS_{HP}**	**JAS**	**SAS_{LP}**	**SAS_{HP}**	**JAS**	**SAS_{LP}**	**SAS_{HP}**	**JAS**
D1	**L**	17.5	23.1	36.8	0.066	0.047	0.091	70.5	78.3	67.7
	M	16.9	19.7	30.8	0.062	0.050	0.086	67.1	78.2	65.6
	S	15.1	16.2	23.2	0.077	0.081	0.129	63.8	76.4	62.5
D2	**L**	16.6	35.6	42.0	0.077	0.088	0.087	71.5	64.8	67.9
	M	14.1	27.3	33.3	0.111	0.096	0.101	65.9	64.7	66.7
	S	10.7	20.0	29.7	0.138	0.118	0.131	56.1	63.8	63.8
D3	**L**	16.2	23.8	31.3	0.111	0.085	0.071	76.4	77.8	81.3
	M	15.2	21.5	29.4	0.106	0.119	0.115	76.2	71.7	76.2
	S	13.8	16.6	25.3	0.150	0.173	0.163	73.0	62.4	68.4
D4	**L**	21.8	25.6	43.3	0.094	0.045	0.096	63.7	71.7	66.4
	M	18.2	22.1	41.6	0.125	0.076	0.118	52.1	69.5	62.2
	S	14.2	18.2	37.2	0.132	0.123	0.120	47.0	67.0	60.5
D5	**L**	12.8	15.9	22.2	0.178	0.113	0.127	68.5	72.6	67.2
	M	10.2	14.8	22.6	0.179	0.118	0.156	64.8	65.4	58.4
	S	7.8	13.8	19.0	0.136	0.151	0.158	55.9	57.1	51.2
D6	**L**	17.4	26.0	30.1	0.080	0.108	0.094	66.5	59.5	60.2
	M	15.1	22.4	24.7	0.117	0.131	0.110	62.4	57.8	53.4
	S	13.0	17.9	21.6	0.142	0.145	0.129	55.0	55.3	50.0
D7	**L**	11.9	30.9	31.7	0.087	0.100	0.082	81.8	61.8	69.6
	M	10.5	22.5	27.0	0.095	0.133	0.101	83.0	55.0	68.8
	S	10.7	15.4	22.1	0.117	0.174	0.171	82.0	46.5	65.8
D8	**L**	30.1	41.2	54.5	0.103	0.094	0.100	65.3	57.2	62.8
	M	27.5	27.8	50.5	0.138	0.109	0.111	61.9	52.2	58.9
	S	22.1	17.4	44.2	0.157	0.136	0.127	59.4	49.6	56.0

Solo-to-joint transfer. For each beam-level dependent variable, we subsequently assessed how much of the variance in the joint performances could be explained by the sum to the dyad members' performances on the last solo action session. **Table 4.3** reports the average performances of the low and high performing individual in the (second) solo action session (SAS_{LP} and SAS_{HP}), together with the dyad's average joint action session performance (JAS). The results are reported for variables ROM, SR and CV.

In the lower row of panels in **Figure 4.3**, we plotted the JAS beam-level performance indicators of each dyad against the sum of the corresponding SAS_{LP} and SAS_{HP} indicators. While the ROM was consistently larger in the joint performances than in the solo performances, the CV and SR were similar in size for both sessions. For all three dependent variables, the joint performances were positively correlated with the sum of the solo performances. **Table 4.4** reports the explained variance from each correlation analysis, split per target size. The ROM of the dyads could be well explained by the solo action sessions (average $R^2 = 0.79$), with an $R^2 > 0.50$ in all three target size conditions. The beam's variability as captured by CV was only moderately (average $R^2 = 0.52$) explained by the solo performances, with an $R^2 > 0.50$ in two of the three conditions. The beam's timing, in the form of the shape ratio SR, could be well explained (average $R^2 = 67$) from the solo conditions, with $R^2 > 0.50$ in all three conditions.

In summary, the variance in the dyad's beam-level performances could be well explained by the sum of the solo action performances. The solo-to-joint transfer of beam behavior was the largest for the range (ROM) and the timing (SR) of the movement. The transfer was notably smaller for the relative variability (CV) of the beam movement, with exception of the smallest target size condition.

Table 4.4: The proportions of explained variance (R^2) derived from the correlation analyses between the dyad's joint action performances and the sums of the corresponding individual's solo action performances at the ball motion level. The rows are split per target size condition (L: Large, M: Medium, S: Small). The lower row reports the average over target size conditions, while the columns show respectively the range of motion (ROM), the coefficient of variation (CV) and the shape ratio (SR). Asterisks (*) denote R^2 values larger than 0.50

Condition	Range of motion	Coeff. of variation	Shape ratio
L	0.88*	0.27	0.74*
M	0.80*	0.59*	0.65*
S	0.70*	0.70*	0.61*
Average	0.79*	0.52*	0.67*

4.4.3. Interpersonal coordination

For some dependent variables, notably those (indirectly) related to the ball's speed, like TH and HC, but also ROM and SR, the joint performances were quite well accounted for by the corresponding individual's solo performances. For other variables, like those

(indirectly) associated with the ball's accuracy, the AR and the CV, the joint performances were less well accounted for by the solo performances. However, for none of the indicators could the solo action performances *fully* predict the outcome of the joint action session. Thus, an important part of the dyadic performances emerged from the interaction between the two individuals. To capture this interaction, we proceeded to the level of the interpersonal coordination. All analyses on this level were based on the timeseries of the vertical motions of the two hand-held beam extremities.

The beam extremities. In **Figure 4.4** the time evolutions of the two beam extremities (i.e., the two handles) are visualized for block 6 of the joint action session. More specifically, the graphs display the vertical positions (i.e., the height) of the two beam extremities as a function of the standardized position of the ball on the beam. These graphs reveal that the two agents generally moved the beam extremities in opposite directions as a function of the ball's motion, leading to X-shaped evolutions. At the same time, the graphs show notable differences between the eight dyads. While some dyads moved the beam handles in a symmetrical fashion (e.g., D2 and D3), others moved asymmetrically (e.g., D6), implying that one of the individuals adopted a larger handle range of motion than the other. What remains invisible in **Figure 4.4**, however, is how both individual's contributions related to each other in a spatiotemporal sense. To unravel this, we employed two different analyses. First, we computed the relative amount of motion of the two handles and thereafter we assessed the relative phase between them.

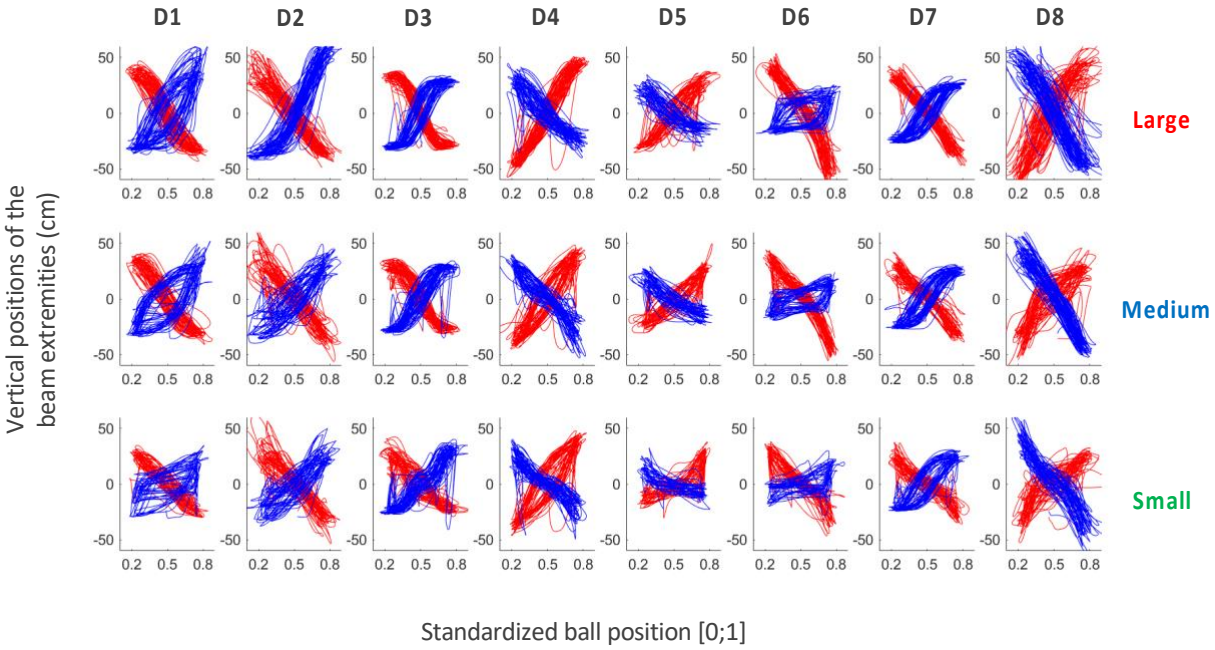


Figure 4.4: The vertical positions (in cm) of the two beam extremities as a function of the standardized [0 to 1] ball position on the beam in block 6 of the session. Each row represents one target size conditions (large, medium, small), while the columns represent the eight dyads (D1-D8). In each graph, the extremity of the high performer is in red, and the extremity of the low performer is in blue. Generally, dyad members moved the beam extremities in opposite directions as a function of the position of the ball, leading to crossing trajectories.

Freezing and freeing. We calculated the proportional amount of time that both beam extremities moved in the opposite direction (Complementarity Ratio CompR), in the same direction (Supplementarity Ratio SuppR) or that at least one of them moved slower than a threshold value of 0.05 m/s (Freezing Ratio FreezR). The evolution of these three variables over blocks, split per target size condition, is shown in **Figure 4.5**. Using a 3 x 6 repeated measures ANOVA, we compared all ratios across target size conditions and practice blocks. As can be seen in the left panel of **Figure 4.5**, CompR increased significantly over blocks ($F(2.16, 15.14) = 4.37$, $p = 0.029$, $\eta^2_p = 0.39$). CompR tended to be lower for the smallest target size ($F(1.13, 7.91) = 5.18$, $p = 0.050$, $\eta^2_p = 0.43$) while CompR's evolution over blocks was not significantly different across target sizes ($F(10, 70) = 0.72$, $p = 0.703$, $\eta^2_p = 0.09$). The change in FreezR over the 6 blocks did not reach statistical significance ($F(2.10, 14.70) = 3.36$, $p = 0.061$, $\eta^2_p = 0.32$), despite showing a decreasing trend over practice (**Figure 4.5**, middle panel). A comparison between the target sizes revealed that the FreezR was not significantly different across the conditions ($F(1.12, 7.87) = 2.49$, $p = 0.153$, $\eta^2_p = 0.26$). Lastly, the SuppR (**Figure 4.5**, right panel) did not change significantly over practice blocks ($F(1.21, 8.44) = 3.82$, $p = 0.417$, $\eta^2_p = 0.35$) and was not significantly different across target sizes ($F(1.62, 11.37) = 0.89$, $p = 0.080$, $\eta^2_p = 0.11$).

In summary, the results show that the dyads in this experiment moved complementary to each other for the majority of the trial duration. Moreover, the proportional amount of time that they did so increased over blocks, showing an increased tendency to display a mutually dependent form of interpersonal coordination. The comparisons across target sizes did not indicate any noteworthy differences in the between-agent mode of coordination.

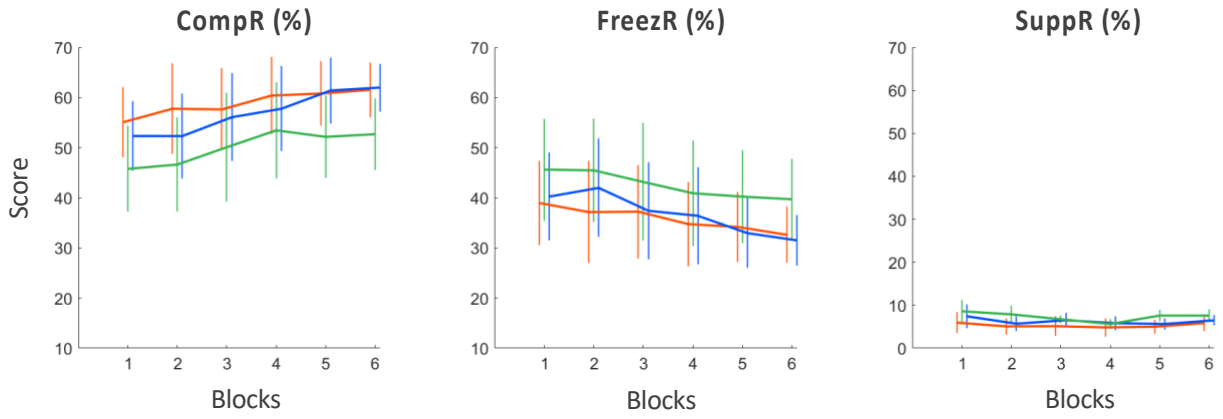


Figure 4.5 : Complementarity ratio (CompR), freezing ratio (FreezR) and supplementarity ratio (SuppR) as a function of practice blocks under each of the three target size conditions (small: green, medium: blue, and large: red).

Continuous Relative Phase. We assessed the continuous relative phase between the vertical positions of the two beam extremities. To provide an indication of the variability in the CRP over the course of a trial, **Figure 4.6** presents examples of the CRP timeseries of two representative dyads (D1 and D3) under the large and small target size condition of block 6. As can be appreciated from these graphs, the variability was generally higher for the smaller targets. In **Figure 4.7**, we show the distributions of the CRP of all dyads in block 6 of the session. The relative phase in most dyads varied around 180 degrees. This confirms that most dyads, indeed, roughly moved the beam handles in opposite directions. However, the bandwidth of variability with which they did so varied strongly between the dyads. While some like D3 and D7 displayed a low CRP variability, others like D5 and D8 showed a much larger variability. To compare the variability across target size conditions (3 levels) and blocks of practice (6 levels), we performed a 3 x 6 repeated measures ANOVA on the CRP_{STD}. As shown in the left panel of **Figure 4.8**, the CRP_{STD} decreased significantly over practice blocks ($F(2.73, 19.11) = 8.76$, $p < 0.001$, $\eta^2_p = 0.56$). Also, the CRP_{STD} was significantly different across conditions ($F(1.33, 9.30) = 39.90$, $p < 0.001$, $\eta^2_p = 0.85$), such that the smaller target sizes evoked a larger variability in the coordination. The decrease in the CRP_{STD} was not significantly different across conditions ($F(10, 70) = 0.68$, $p = 0.744$, $\eta^2_p = 0.09$).

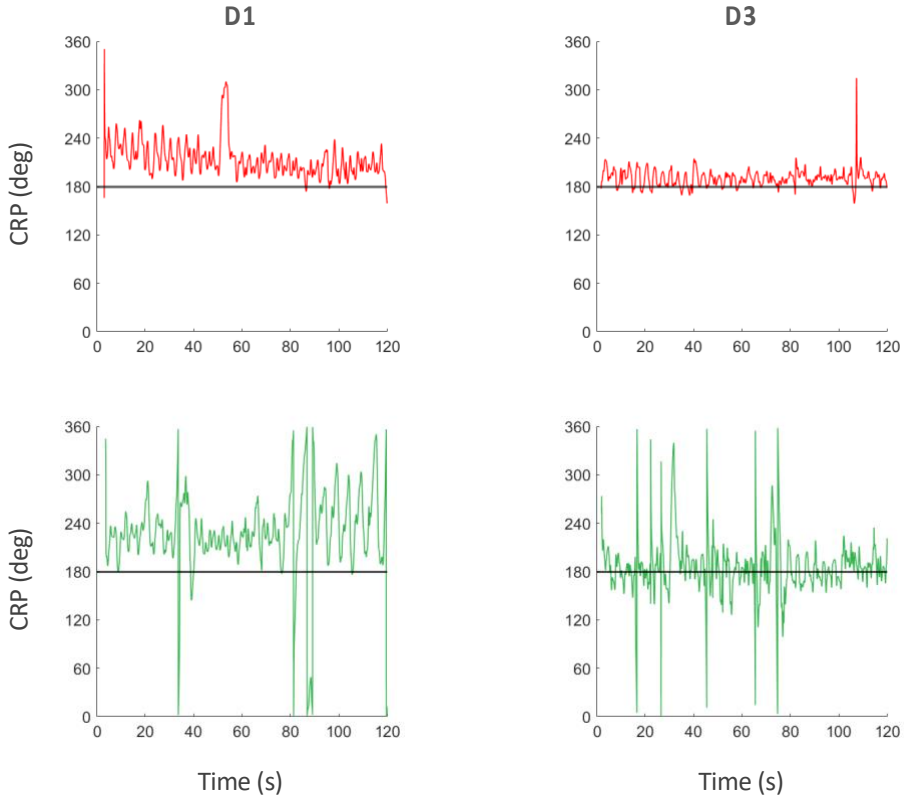


Figure 4.6 : Timeseries of the continuous relative phase (CRP, deg) of two representative dyads in block 6 of the joint action session, for the largest (red) and smallest (green) target size. D1 (left) displayed a large variability, while D3 (right) had a smaller variability. The black line indicates a CRP of 180 deg.

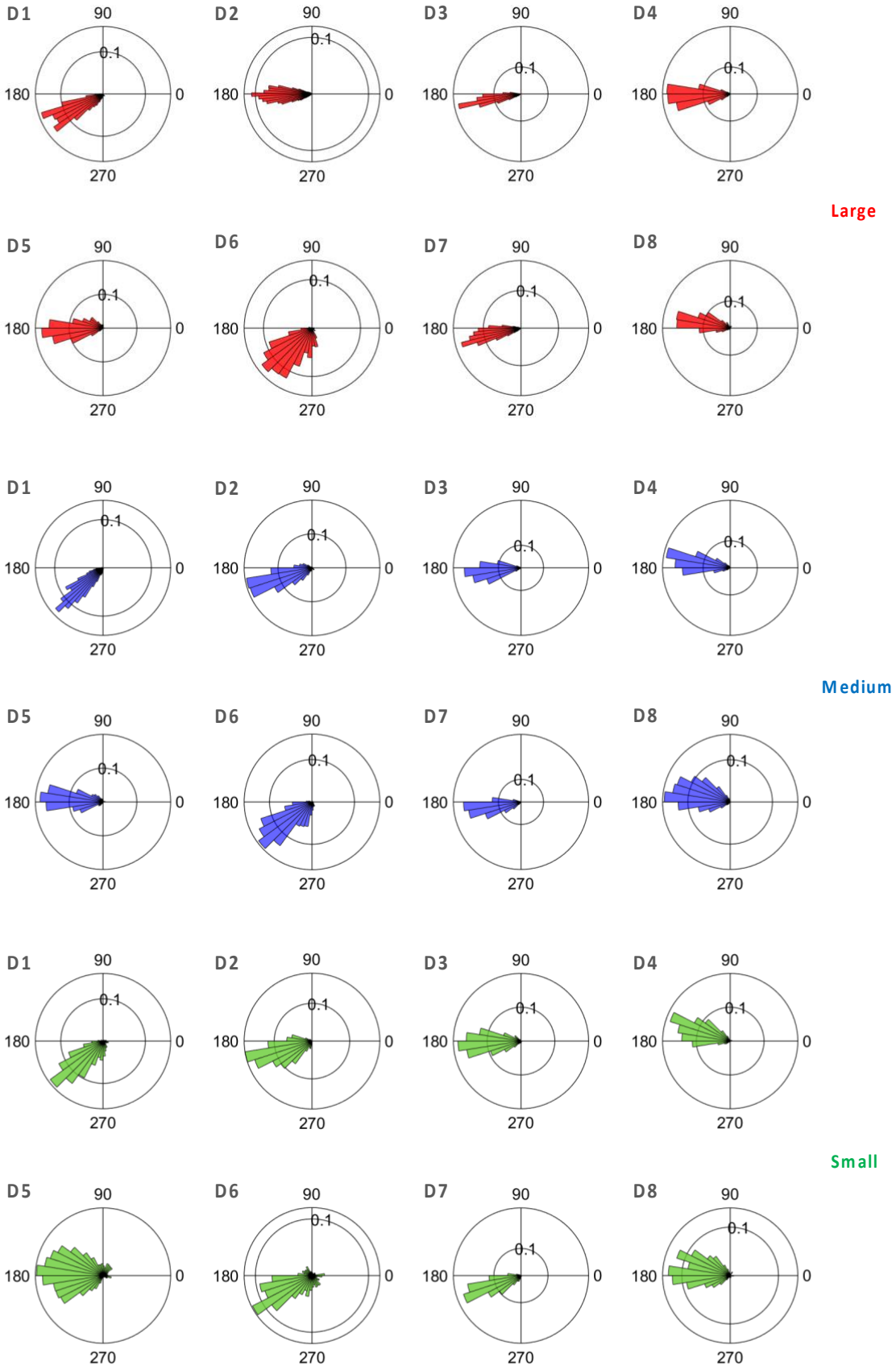


Figure 4.7 : Polar histogram distributions of the CRP (deg) between the beam extremities of all dyads (D1-D8) in block 6, split per target size condition (red: large, blue: medium, green: small). The r-axis varies in scale, with scale provided by a circle of proportional frequency 0.1.

The graphs in **Figure 4.7** not only show differences in the bandwidth of the CRP distributions. They also provide an indication of the symmetry of the interaction in each dyad's performance. Any systematic deviation from 180 degrees (i.e., anti-phase) suggests that the two individuals did not move symmetrically, but that one took the lead, while the other followed. To compare such asymmetries across conditions (3 levels) and blocks (6 levels), we conducted a 3 x 6 repeated measures ANOVA on the CRP_{DEV}, the mean absolute deviation from anti-phase. As can be seen in the right panel of **Figure 4.8**, the CRP_{DEV} did not significantly change over practice blocks ($F(172.32, 11.42) = 0.33$, $p = 0.684$, $\eta^2_p = 0.05$). Moreover, this variable was not significantly different between target size conditions ($F(1.33, 9.35) = 3.50$, $p = 0.085$, $\eta^2_p = 0.34$), although in the first blocks the deviation from symmetry in the large target sizes appeared larger than in the other two target size conditions. In addition to the absolute deviations from symmetry, we also considered the directionality of the deviation. We recall that a CRP > 180 deg indicated a leading role for high performer HP, while a CRP < 180 deg indicated a leading role for the low performer LP. Following this convention, **Figure 4.7** demonstrates that in for instance D1 and D6 the HP was leading, while in D4 and D8 the LP was leading. To investigate whether this directionality in the leader-follower dynamics could somehow be predicted from (that is, explained by) their individual differences in solo action, we conducted a final solo-to-joint transfer analysis.

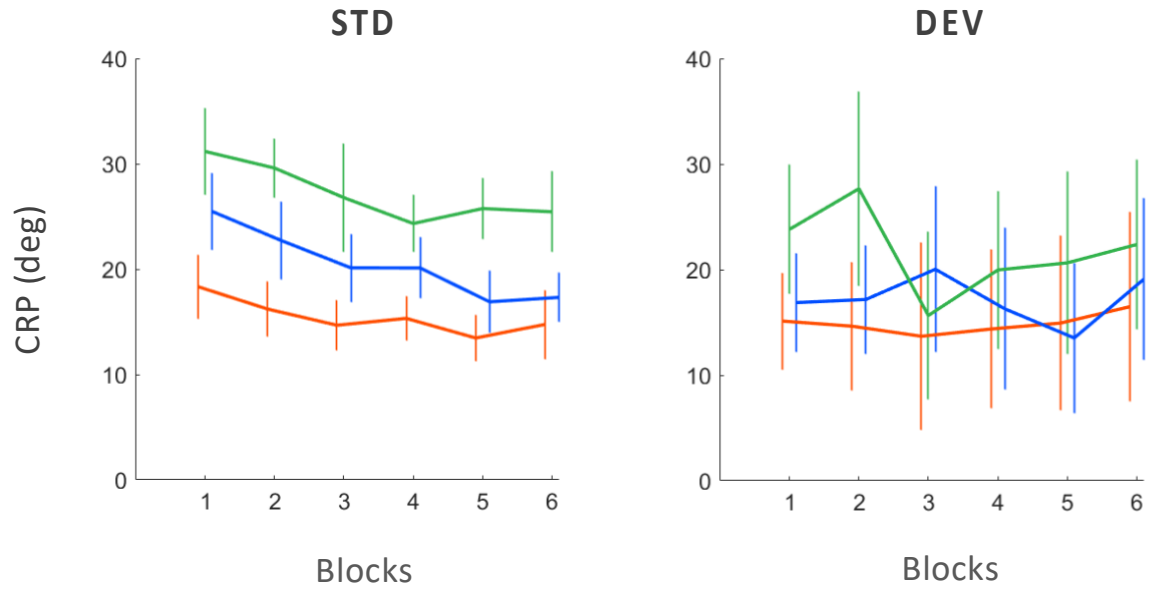


Figure 4.8 : The standard deviation (STD, left) and the mean deviation from anti-phase (DEV, right) of the continuous relative phase between the two beam extremities (CRP). Both variables are plotted as a function of the practice blocks, under each of the three target size conditions (small: green, medium: blue and large: red). The CRP_{STD} decreased significantly over blocks and was significantly higher for smaller target sizes. The CRP_{DEV} did not change significantly over blocks and was not significantly different across target size conditions.

Solo-to-joint transfer. We assessed whether the dyads' mean CRP in the joint action session could be related to any (ball and beam level) differences in the dyad members' solo action performances. In other words, we analyzed whether the leader-follower dynamics of dyads could be partially explained by their differences in the number of target hits, beam variabilities or any other dependent variable. In **Figure 4.9**, we plotted the dyad's mean CRP values as a function of their inter-individual differences in the (second) solo action session. We did not observe a consistent linear relationship between the inter-individual differences in the dependent variable and the directionality of the phase relationship in any of these six graphs ($0.00 < R^2$'s < 0.42). Nevertheless, for some variables the (positive/negative) sign of the inter-individual solo difference was congruent with the directionality (leader/follower) of the joint action CRP. This was, for instance, the case for the ball's number of target hits and the beam's range of motion. **Table 4.5** shows, for each variable and per target size condition, the percentage of the datapoints located within congruent quadrants (white/white or gray/gray). Notably, in 75% of the cases (18/24) the individual with a larger number of target hits (TH) took the lead in the interaction. This was also true for the number of half cycles (HC) of the ball, in 67% of the cases (16/24). The individual with the highest range of beam motion (ROM)

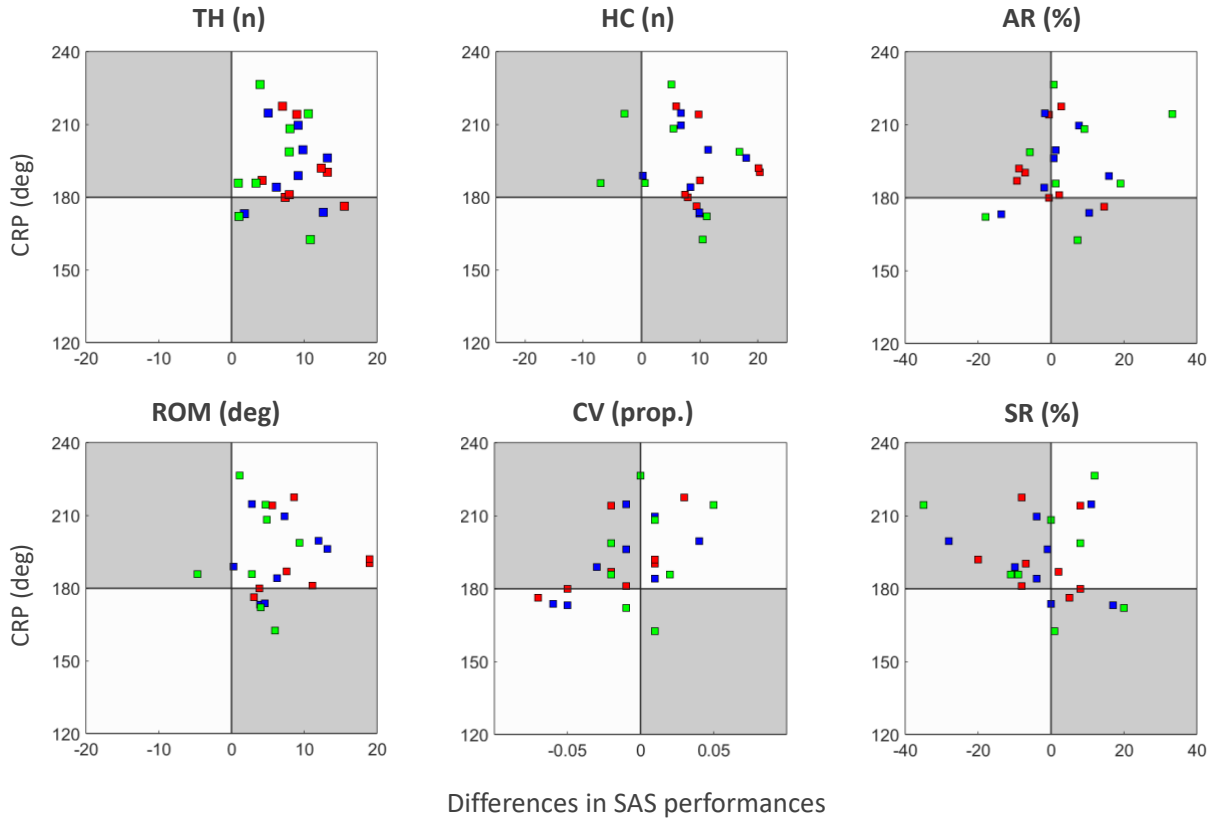


Figure 4.9: The relationship between differences in the solo action performances between dyad members and the mean continuous relative phase (CRP) in the joint action performance. Each panel represents a different dependent variable (target hits TH, half cycles HC, accuracy ratio AR, range of motion ROM, coefficient of variation CV and Shape ratio SR) and the colors refer to the different targets size conditions (small: green, medium: blue and large: red)

in the solo condition took the lead in in 71% of the joint action cases (17/24). At the same time, the individual with the higher ball accuracy ratio (AR) and relative beam variability (CV) only took the lead in 58% of the cases (14/24), suggesting no relationship between the solo action accuracy or variability and the joint action leadership. For the shape ratio, we found a negative relationship: In 79% (19/24) of the cases the individual with the *lower* shape ratio in solo action took the lead in the joint action.

Table 4.5: The percentage of dyads (%) in which the directionality of the CRP (leader/follower) was congruent with the sign (positive/negative) of the inter-individual differences in the solo action session performances on each of the six dependent variables (TH: target hits, HC: half cycles, AR: accuracy ratio, ROM: range of motion, CV: coefficient of variation and SR: Shape ratio).

Condition	TH	HC	AR	ROM	CV	SR
L	75	75	38	75	63	75
M	75	75	63	75	63	87
S	75	50	75	63	50	75
Average	**75**	**67**	**58**	**71**	**58**	**79**

4.5. Discussion

In this contribution we studied the task performances of dyads in the joint action setting of the ball-and-beam paradigm. In a two-step study, of which the current contribution formed the second step, we investigated the transfer of skill from a solo action to a joint action setting of this novel experimental paradigm. In the first step, reported in Hafkamp et al. (2024), individual participants performed two solo action sessions of the ball-and-beam task. This allowed us to identify the pertinent performance characteristics on the level of the ball and the level of the beam. In the second step, those same participants were paired into dyads to perform a subsequent joint action session, allowing us to assess the solo-to-joint propagation of these characteristics. In discussing our results, we start by addressing the general performances of the dyads in the joint action session of this study. Thereafter, we discuss the transfer of skill from the solo to the joint action context, thereby moving progressively from the level of the ball, via the level of the beam, to the level of the interpersonal coordination. By touching upon each of these levels, our aim is to provide an account of joint action in which the stability and the functionality of interpersonal coordination are covered together, as two dimensions of one and the same performance. In the remainder of the discussion we reflect on the repercussions of our account for future research into joint action.

In the ball-and-beam paradigm participants had to control a ball rolling on a long and hand-held beam. By continuously adjusting the beam's inclination angle, they were to roll the ball fast and accurately between two targets, with the goal to hit these targets as often as possible during a trial. In general, dyads were increasingly successful in accomplishing

that goal. Over blocks of practice, they improved the number of target hits (TH) per trial, by increasing not only the average speed of the ball (as revealed by an increase in the number of half cycles, HC) but also its average accuracy (as demonstrated by an increase in the accuracy ratio, AR) (**Fig. 4.2**, upper row). This outcome performance enhancement over practice was in alignment with earlier research into the solo and joint action versions of this paradigm (Hafkamp et al., 2023), as was the finding of a significant speed-accuracy trade-off in the motion of the ball (Hafkamp et al., 2024). When the target sizes were reduced, the speed of the ball decreased accordingly –in both a solo and a joint action context. This suggests that the relevant behavioral organization occurred at the level of the ball in relation to the targets. This frame of reference, in which the pertinent dynamics of a task are defined, is also known as a *task space* (Saltzman & Kelso, 1987; Mottet et al., 2001; Fernandez & Bootsma, 2008). When considering the ball motion variables of each dyad, we found a strong transfer of skill from the solo to the joint action context. In particular, we found that the TH and the HC of a dyad were quite well predicted by the solo action performances of the two dyad members (mean R^2's of 0.60 and 0.73, respectively, **Fig. 4.2**, lower row). The AR, in contrast, was less well explained by the corresponding individual's solo performances (mean $R^2 = 0.43$). Together, this suggests that each participant contributed a particular ability to bring the ball up to speed, while a dyad's capacity to be accurate emerged primarily from the interaction. This interpretation turned out to be confirmed by what we found at the underlying level of the beam.

Across dyads, the relative variability of the beam's angle of inclination (coefficient of variation, CV) decreased over blocks of practice. That is, dyads were increasingly consistent in tilting the beam up and down to roll the ball back-and-forth. The range of motion (ROM) and the timing (shape ratio, SR) of the average beam each cycle, however, did not change significantly over blocks (**Fig. 4.3**, upper row). The improvements in the ball speed and accuracy over blocks were thus not caused by large adaptations in the jointly produced beam movements, but by subtle improvements in the consistency and accuracy of the performance. The speed-accuracy trade-off on the level of the ball was also reflected in the beam's motion. A smaller target size resulted in a lower ROM and SR, but a *higher* CV. This suggests that dyads used more compensatory movements to control the ball motion when the demands on accuracy increased. This was in line with what we found earlier in the solo action setting (Hafkamp et al., 2024). In fact, the dyadic performances could to quite a large extent be explained by the individual performances of the dyad members in solo action. The ROM and the SR, in particular, were strongly propagated from the solo to the joint action context (mean R^2's of 0.79 and 0.67, respectively, **Fig. 4.3**, lower row). Given that the range and the timing of beam's cycle of motion were crucial to the production of the ball speed, this finding explained why the ball's speed (or more specifically, its number of half cycles) was well predicted by the solo performances. The transfer of the beam's CV was notably smaller (mean $R^2 = 0.52$), especially in the small target size condition ($R^2 = 0.27$). This implied that each dyad's variability was relatively poorly predicted by the corresponding individual's solo action performances. How variable the two dyad members manipulated the beam was thus an emergent property of their interaction, rather than a combination of each of their solo

contributions. It is no coincidence that the same was true for the ball's accuracy, for which we saw earlier that it was only moderately explained by the participant's solo action performances, with a mean $R^2 < 0.50$. But as the beam's variability decreased over blocks, the ball's accuracy increased with practice, suggesting that dyads somehow learned to coordinate their movements. To confirm whether this was indeed the case, we proceeded to the level of the interpersonal coordination.

To begin with, we found that dyads generally moved the beam extremities simultaneously and in opposite directions, with one dyad member moving up while the other moved down (**Figs. 4.4 and 4.5**). On average, this resulted in an anti-phase mode of coordination with a continuous relative phase (CRP) between the handle heights of somewhere around 180 degrees (**Figs. 4.6 and 4.7**). As such, the interpersonal coordination was compliant with earlier research into the ball-and-beam paradigm. In Hafkamp et al. (2023), we found that a complementary task solution, in contrast with a sequential solution, prevailed under dyads that had already practiced the task individually in a solo action setting. This was the case for the dyads in the current contribution as well. The coordination between the two vertical movements of the beam extremities also reflected the speed-accuracy that we found on the level of the ball. A reduction in the size of the targets not only evoked a lower ball speed, but also a significant increase in the standard deviation of the CRP between the beam handles (CRP_{STD}, **Fig. 4.8**, left panel). This aligned with the increased coefficient of variation we found on the level of the beam. Over blocks of practice, however, the CRP_{STD} decreased significantly, while the amount of trial time that dyad members moved complementary to each other increased. Thus, dyads managed to improve the stability of their interpersonal coordination. Notwithstanding these improvements, we note that a stable phase locking of the two beam handles for long durations –let alone for the entire duration of a trial– was particularly rare. Even though the dyad members were usually entrained in their frequency, the relative phase between their movements remained variable, also in the latter stages of practice (**Fig. 4.6**). As hypothesized, fully stable phase locking did not occur. Each dyad member retained its unique phase progression profile (at least partially), as evidenced by the high solo-to-joint transfer of the SR. Moreover, the CRP of some of the dyads considerably deviated from anti-phase ($CRP_{DEV} > 0$). The mean absolute CRP_{DEV} decreased nor increased over blocks of practice (**Fig. 4.8**, right panel), suggesting a systematicity in the leader follower-dynamics of the interactions. As a last step, we investigated whether the phase lag between the dyad members in the joint action setting was statistically related to any differences in their performances in the solo action setting.

For none of the ball/beam performance indicators was the difference in the dyad members' solo action performances proportionally related to the mean phase lag in the interaction of a dyad ($0.00 < R^2 < 0.42$). It was thus not possible to accurately predict who would lead and who would follow (and with what phase lag) on the basis of differences in the corresponding individual's solo performances. Nevertheless, for some variables the (positive/negative) sign of the solo action difference between a dyad's members was congruent with the CRP directionality (leader/follower) in joint action (**Fig. 4.9**). This congruency was most prominent for those parameters that were (indirectly) related to

the speed of the ball, such as TH (75%), but also ROM (71%) and SR (79%). Those individuals that had scored more target hits in the solo action session, or that had moved with a larger range of motion and a stronger inclination for a middle-stop strategy, were more likely to lead the interaction in joint action. The congruency was smaller, however, for those variables that were (indirectly) related to the ball's accuracy, such as the AR (58%) and the CV (58%). Earlier, we already noted that the AR and the CV were only moderately propagated from solo to joint action, in contrast with the other variables (TH, HC, ROM and SR), which were strongly transferred from one setting to another. Each dyad member contributed a particular strategy to bring the ball up to speed, expressed in the range and timing of their (beam) movements. Now we show that this contribution not only determined the jointly produced range and timing of the beam motion, but that it also had an impact the leader-follower dynamics in their interaction. The variability and the accuracy of a dyadic performance, in contrast, arose from the interaction of those contributions. This suggests that the stability of the interpersonal coordination was indeed an emergent property of the interaction, while being constrained by the task's goal to speed up the ball.

The standard ecological-dynamical model for dyadic interpersonal coordination comprises two self-sustained and non-linearly coupled oscillators (Haken et al., 1985; Schmidt & Richardson, 2008; De Poel, 2016). This (HKB) model can account for various aspects of the interpersonal coordination reported in this study. For instance, the dyads in the ball-and-beam setting displayed frequency entrainment and intermittent phase locking of their movements. Also, the common frequency and the phase lag of their interaction was partially dependent on what each dyad member had learned to do individually, that is, in a solo action setting (Hafkamp et al., 2024). This resonates with the model, in which the dynamic properties of the oscillators are known to be constitutive of the outcome of the interaction (Schmidt & Turvey, 1994). At the same time, our results deviated from the HKB model for coordination in at least two ways. In the first place, the common frequency of motion in joint action was not located in the middle of the two participant's (preferred) solo action frequencies, but on average 1.3 times higher than that. This was caused by the set-up of the ball-and-beam task. In our paradigm, dyads could produce larger inclination angles than soloists, presumably leading to larger ball speeds and thus to a higher frequency of motion. Huys et al. (2018) made a similar observation in their study of dyadic rope turning. They, too, found that in the majority of the dyads the common frequency of turning in joint action was higher than the individually preferred frequencies of turning in solo action. Not unlike the ball-and-beam setting, Huys et al. (2018) attributed that result to the doubled input of energy in joint action, as compared to solo action. The second deviation from the HKB model was that the phase lag between the dyad members was not proportionally, nor systematically, related to any differences in the solo action performances, an effect known as detuning (Schmidt et al., 1994; Schmidt & Turvey, 1994; Amazeen et al., 1995). Nevertheless, we found a global tendency for dyad members with more target hits or a higher range of beam motion in the solo action context to take the lead in the interaction. This tendency was not found

in the previously cited rope turning study of Huys et al. (2018), suggesting that leader-follower dynamics are highly contingent on the setting of the task.

Perhaps the most fundamental difference with the HKB model of coordination, however, is that the interaction in our task paradigm was constrained by a supra-coordinative goal. Dyads first and foremost had to hit the targets. Given this goal, they not only settled upon a (moderately) stable mode of interpersonal coordination. They also aimed to establish a particular relationship with the task environment of the ball and the beam. In the pursuit of this goal, each dyad member contributed a strategy for speeding up the ball to the interaction, which was expressed in the beam's ROM and SR and which served as a constraint on the interpersonal coordination. By highlighting the functional dimension of the joint action, we underscored that an interpersonal synergy –as theoretical construct (Riley et al., 2011)– is more than a stable mode of coordination emergent from a process of pattern formation. An interpersonal synergy is also an expression of functionality that allows the individuals to achieve more together than what they could have achieved individually. This dimension can only be brought to the fore when the joint action is assessed at multiple levels of observation, from the coordination between agents to their (mediated) interaction with the environment. In our view, such a multi-level assessment is paramount to future research into joint action for which interpersonal coordination is always in function of the goal among the interactants (see also Lagarde, 2013; Richardson et al., 2015; Huys et al. 2018). It allows one to see how the range and the timing of a dyad's joint behavior can be adapted to the environment, while the stability of its interpersonal coordination is emergent from the dyad members' interaction. It enriches, in other words, the HKB model for (interpersonal) coordination with the functional context in which a joint action takes place.

5. Is constrained practice in a solo action setting beneficial to the stability and symmetry of the interpersonal coordination in a joint action setting?

5.1. Abstract

In this thesis, we introduced a new experimental paradigm to study the interpersonal coordination of movement during functional joint action. In this paradigm participants have to roll a ball reciprocally between two targets on a hand-held beam, by continuously adjusting the inclination angle of that beam. Prior research into this task revealed that the coordination between dyad members is significantly affected by the task strategies that both dyad members brings to the interaction. This suggests that an increased homogeneity in the task strategies can improve the stability and symmetry of the interpersonal coordination. In a two-step study, we investigated this hypothesis. In the first step, we had 22 participants perform a solo action session of the ball-and-beam task (6 blocks, 3 trials per block) with a soft constraint on the beam's range of motion. This constraint not only led to a smaller ROM but also to a more efficient timing strategy. In the second step, we paired the participants into 11 dyads to perform a joint action session of the task, without any additional constraints (6 blocks, 3 trials per block). We found that the release of constraints resulted in a weak transfer of skill from solo to joint action, in particular in the range and timing of the beam's movement. Consequently, the constrained solo action practice did not significantly affect the stability and symmetry of the interpersonal coordination in the joint action setting. Given the explorative nature of this study and the low number of participants, we concluded that more research is required to determine whether the interpersonal coordination can, indeed, be improved by constrained practice in an individual setting.

5.2. Introduction

In joint actions, two or more individuals have to coordinate their movements with each other to achieve a common goal (Sebanz et al., 2006). In this thesis, we introduced a new experimental paradigm to study such interpersonal coordination. In this paradigm, participants have to roll a ball reciprocally between two targets on a long and hand-held beam. By continuously adjusting the inclination angle of the beam, their goal is to hit the targets as often as possible in the timespan of a trial. This ball-and-beam task can be performed individually, in solo action, but also dyadically, in joint action. In the latter setting, interpersonal coordination is required for the dyads to control the ball. In **Chapter 2** of this thesis, we showed that this interpersonal coordination was qualitatively

affected by the task experience of the participants. When the members of a dyad had no experience with the task, they moved the beam handles sequentially, in a turn taking fashion. However, when dyad members had acquired some individual experience in a prior solo action session, they tended to move the beam handles antagonistically, in a complementary fashion. This suggested a particular transfer of skill from solo action to joint action, which we further investigated in **Chapters 3** and **4** of this thesis.

In a two-step study, we had participants first perform a set of solo action sessions (**Chapter 3**) before pairing them into dyads to do a joint action session (**Chapter 4**). This design allowed us to identify the pertinent indicators of a performance and to assess whether these indicators were propagated from the solo to the joint action context. On the level of the ball, we computed the number of target hits (TH), the number of half cycles (HC) and the number of hits per half cycles (TH/HC, accuracy ratio AR). On the level of the beam, we computed the beam inclination angle's range of motion (ROM) and its coefficient of variation (CV). Moreover, we assessed the beam's shape ratio (SR), a variable that indicated the timing strategy of each participant. With the SR, we captured a continuum of strategies, ranging from a middle-stop to an extreme-stop timing. A middle-stop strategy was characterized by a brief but noticeable stopping of the beam motion *between* two inclination peaks, at inclination angle zero. This led to a relatively low shape ratio, around 0.5 on scale from 0 to 1. An extreme-stop strategy was characterized by a short halting of the beam *at* a peak inclination angle, leading to a SR of 0.7 or higher. In **Chapter 3**, we found large differences in the timing strategies of individual participants, revealing idiosyncrasy in the beam's phase progressing profiles.

In **Chapter 4**, we assessed to what extent the identified performance characteristics were propagated to the joint action context. We found that those variables (indirectly) related to the ball's speed, such as the TH and HC but also the ROM and SR, were strongly transferred from the individual to the dyadic setting. Conversely, the variables related to the ball or beam accuracy, like the AR and the CV, were only moderately transferred to the joint action performance. Moreover, we found that those dyad members that produced a higher ball speed in solo action were more likely to take the lead in the joint action. That is, in some dyads the continuous relative phase between the beam handles deviated systematically from anti-phase (180 degrees) and these asymmetries were related to how each dyad member had performed individually. Together, these results suggested that not only the stability but also the symmetry of the interpersonal coordination was constrained by the task's goal to bring the ball's up to speed. In other words, the coordination between the dyad members was, as already implied in **Chapter 2**, affected by the range of motion and the timing strategy that each member brought to the interaction. This suggests that the stability and symmetry of the interpersonal coordination might be *improved* by constraining the contributions of each dyad member, so that they act more complementary to each other. If diversity in the individual task strategies (**Chapter 3**) leads to instability and asymmetry of the interpersonal coordination (**Chapter 4**), then homogeneity in the task strategies may lead to more stability and symmetry in the interpersonal coordination. Here, in **Chapter 5**, we explore this hypothesis for the first time.

A stable and symmetrical mode of interpersonal coordination can only be achieved when the phase progression profiles of the two beam extremities exhibit a certain degree of synchronicity. This implies that the two dyad members need to bring similar timing strategies to the interaction. One way to achieve such similarity is to train participants in a constrained solo action setting, such that they are all guided towards the most efficient task solution. This is also known as a Constrains Led Approach to perceptuomotor learning (CLA, Newell et al., 1989; Gray & Sullivan, 2023; Liu, 2023). In the case of the ball-and-beam paradigm, the most efficient task solution is the extreme-stop timing strategy. By stopping the beam at the extremes rather than in between them, participants optimally exploit the force of gravity to set the ball into motion. As a result, they can produce high ball speeds with a relatively low range of motion, implying the possibility of a large number of target hits with minimal effort. For middle-stoppers, this is more difficult. Due to an inefficient exploitation of gravity, they are forced to adopt a large peak-to-peak beam amplitude to produce high ball speeds, which costs more energy. This suggests that a limitation on the beam's range of motion may guide participants towards an extreme-stop strategy. After all, this constraint would preclude the combination of a middle-stop strategy with a large ROM and make the extreme-stop strategy (with a small ROM) more salient. If this CLA training would be successful, the next step would be to investigate whether participants also bring this strategy from the solo to the joint action setting. If so, we hypothesize that the larger homogeneity in timing strategies would result in a more stable and more symmetrical interpersonal coordination.

This study consisted of two parts. In the first part, we investigated the hypothesis that constrained practice would result in a more efficient timing strategy in the ball-and-beam paradigm. One group of participants performed a solo action session of the task with a (soft) limitation on the beam's range of motion (denoted the constrained group), while another group performed a solo action session under regular conditions (denoted the unconstrained group). We expected participants in the constrained group to adopt not only a smaller ROM, but also a more efficient timing strategy with a higher SR. In the second part, we tested the hypothesis that the constrained solo action practice would improve the stability and symmetry in the interpersonal coordination in a dyadic setting. To this end, we paired the participants in both groups into dyads and had them perform an *unconstrained* joint action session. Based on the results of **Chapter 4**, we expected a significant transfer of task strategies from solo action to joint action, both in terms of the range and the timing of the beam's cycle of motion. Depending on the results of the first part of the experiment, we tentatively hypothesized that dyads formed by individuals that practiced the task in the constrained solo action setting would display a more stable and symmetrical interpersonal coordination in joint action.

5.3. Materials and method

5.3.1. Participants

A total of 22 students and junior staff members from Aix Marseille University (6 women, 16 men, with an average age of 23.0 ± 3.3 years, M ± SD) participated voluntarily in this study. None of them had any experience with the ball-and-beam paradigm. All participants were free from known motor impairments and reported normal or corrected-to-normal vision. Before the start of the experiment, we informed the participants about the aim of the project and about the procedure of the experiment. Accordingly, all participants provided written informed consent for their participation. They were randomly divided into one of two groups, which we denoted the constrained group (n = 12) and the unconstrained group (n = 10). All participants, however, were naïve to the purpose of this experimental design.

5.3.2. Task and apparatus

The task equipment consisted of a standard golf ball (diameter 4.3 cm, weight 46 g) that could roll over a 2-m long, 3 by 3 cm V-shaped iron beam, with tubular handles (length 54 cm, diameter 3 cm) perpendicularly attached to its extremities. Participants' task was to roll the ball as fast and accurately as possible back and forth between two targets clearly visible on the beam. Participants received one point for every time that the ball reversed its direction of motion within a target's boundaries, with the goal to achieve as many points as possible within every two-minute trial of a session. The size of both targets was 12 cm and the target centers were located 50cm from the beam's midpoint. Thus, the center-to-center inter-target distance was 100 cm in all trials. Bimanually holding one handle allowed a participant to lift or lower the beam's extremity and thereby change its inclination angle so as to accelerate or decelerate the ball. In solo action, the second of the two handles was attached to a hinge on a static pole, the height of which was adjusted to the participant's hip height. In joint action, on the other hand, both beam extremities were handled by another participant.

The participants were randomly divided into a constrained and an unconstrained group. While both groups followed the same procedure, the constrained group performed the session with a (soft) physical limitation on the beam's range of motion. This constraint had the form of an upper and a lower cord attached to two static poles placed left and right of the participant's standing position (**Figure 5.1A**). The tightly stretched cords crossed the (semi-circular) path of motion of the beam handle and thus served as an upper and a lower boundary on the beam's movement trajectory. While participants were instructed not to touch either of the two cords, the experimenter verbally indicated any (un)intentional violations of this rule. Violations only occurred occasionally over the course of the experiment. With a vertical distance of 75 cm between upper and lower cord and a horizontal distance of 200 cm from the beam's center of rotation (hinge) to either of the two cords, the ROM of the beam was effectively limited to a peak-to-peak amplitude of approximately 20 degrees. Participants in the unconstrained group were free to move

the beam as high and as low as desired (**Figure 5.1B**). The same was true for the dyads in the joint action session, who all performed the task unconstrained (**Figure 5.1C**). In order to compensate for more than 10 cm height differences between members of a dyads, the smaller of the two participants was placed on a wide and stable wooden platform that allowed 2-cm stepwise height adjustments.

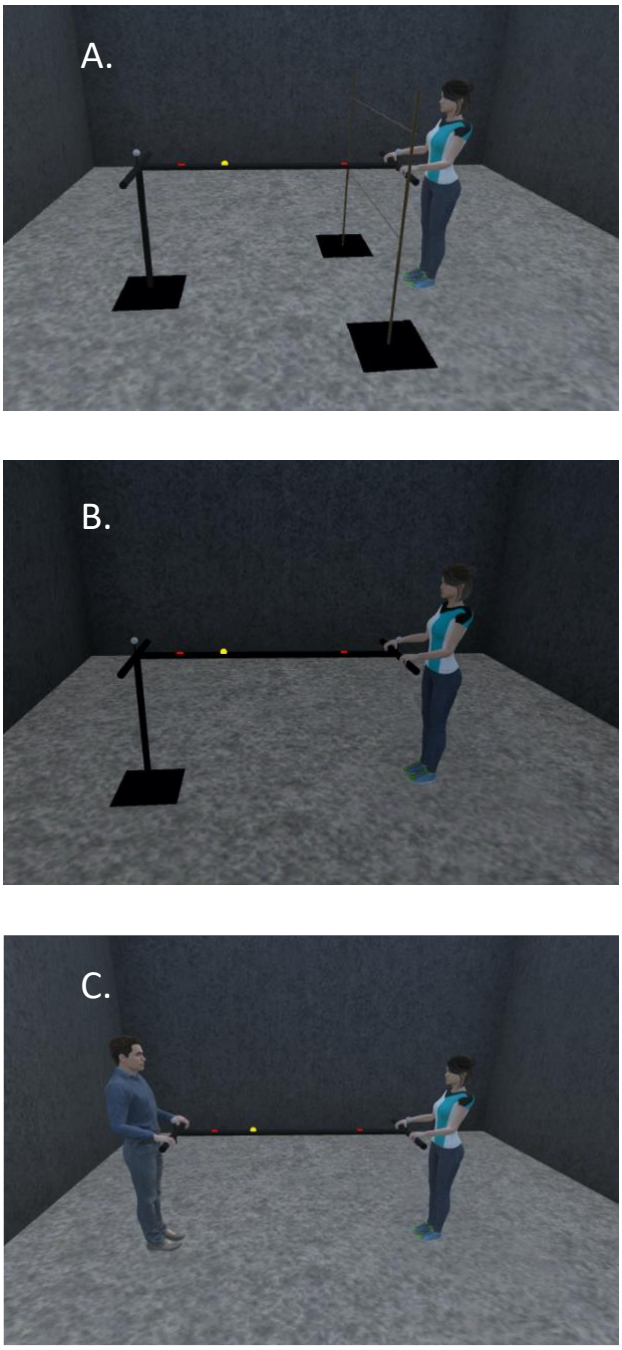


Figure 5.1: Graphical illustration of the three conditions of the experiment. A: The solo action setting with a soft constraint on the beam's range of motion. B: The solo action setting without any constraints. C: The joint action setting without any constraints.

5.3.3. Procedure

The experiment consisted of two sessions, with approximately one or two weeks between the sessions. The first session concerned solo action, meaning that participants performed the task individually, either with a constrained ROM (constrained group) or without it (unconstrained group). The second session concerned joint action, meaning that the participants were paired into dyads to perform the task collaboratively. In contrast with the solo action, all dyads performed the task without any constraints on the beam's range of motion. Each session started with a short warm-up trial of ~1 min, during which participants were given the chance to familiarize themselves with the task. This was followed by 6 blocks of practice on the task. Each block consisted of three two-minute trials, with regular breaks between the blocks. This resulted in a total of 18 trials per solo/joint action session.

At the start of each trial, the ball was placed in the middle of the beam. A verbal indication from the experimenter signaled the beginning ("Go") and the end ("Stop") of a trial. After each trial, participants received verbal feedback on their score, based on experimenter observation. We regularly encouraged participants to try to improve their score on each trial, in order for them to reach their highest score possible within a session. All participants competed indirectly with the each other via a leaderboard that expressed the high scores of the other participants. During the trials, participants were not allowed to talk or communicate otherwise. Talking was allowed during the breaks but could not concern the task.

5.3.4. Data acquisition

All sessions took place in a darkened room. To capture the motion of the ball and of the beam, we attached a reflective marker to each beam handle and we used a bright yellow colored golf ball. Participants wore dark clothes and black gloves to ensure sufficient contrast with the ball and the two beam markers. We filmed all trials with a tripod-mounted GoPro9 camera that was positioned at a 1-m height and a 2-m perpendicular distance from the midpoint of the beam. This ensured that all relevant ball and beam motion occurred well within the field of view. In the joint action task setting, we asked participants to take place on fixed locations 2.5 m apart, holding the beam in between them. The camera, set in linear lens mode so as to obtain minimal image deformation, was placed on a tripod at a 1-m height. We recorded all trials with a (recalculated) sample frequency of 29.97 Hz and a resolution of 2.7 K. Video recordings of the trials were imported into Kinovea (https://www.kinovea.org/), which we used to track the two-dimensional (X, Y) motion of the ball and the two reflective beam markers. We then analyzed the X and Y position timeseries using MATLAB, after filtering them with a fourth-order low pass Butterworth filter (cut off frequency of 3 Hz) and trimming them to the 120-s trial duration. We subsequently transformed the ball's trajectory from motion in a two-dimensional plane to motion along the beam's longitudinal axis. To do so, we calculated the ball's motion along the virtual vector between the two beam markers, with the inter-marker distance used for calibration. From the trajectories of the two beam

markers we derived a single beam inclination angle at each timestep by taking the inverse tangent (atan) of the X and Y coordinates of both markers. The one-dimensional timeseries of the ball motion, on the one hand, and the beam's inclination angle, on the other hand, formed the basis of all further analyses in this contribution.

Due to technical issues, the timeseries of 8 out of the 396 trials in solo action (2.0%) and 11 out of the 198 trials in joint action (5.6%) were excluded. To deal with these exclusions, we used the averages of each block for our analyses. In all blocks, for all participants, at least 2 of the 3 trials were included.

5.3.5. Dependent variables

We analyzed the performances on three levels of the system: the ball's motion between the targets, the beam's angle of inclination and the dyad's interpersonal coordination (in joint action only). For each level, we identified a set of pertinent variables to characterize the behavior. Although we addressed these variables in earlier chapters of this thesis (**Chapter 3, 4**), we here provide a full description of all variables, for reasons of stand-alone readability.

Ball motion. Using a peak finding algorithm that split the ball position timeseries into half cycles, we computed three variables. Firstly, we counted the number of target hits (TH) on a trial, which we defined as the number of ball motion reversals within the (recalculated) target zones of each task condition. Secondly, we counted the total number of ball half cycles (HC) on a trial. Given that the trials were time-constrained, this number was proportionally related to the average ball speed on a trial. Thirdly, we divided the number of target hits by the number of half cycles on a trial. Since the TH/HC-ratio indicated the accuracy on a trial, we refer to this variable as the ball's accuracy ratio (AR).

Beam motion. From the timeseries of the beam's inclination angle, we derived three variables. Firstly, we computed the beam's range of motion (ROM), which we defined as the average peak-to-peak amplitude of the beam inclination timeseries. Secondly, we assessed the relative variability of the beam's angular motion, using the coefficient of variation (CV). To compute the CV, we divided the inclination angle timeseries into cycles on the basis of the ball position peaks. We used the ball's cycles because these were more consistent in comparison to the beam's cycles. We then time-normalized all cycles to 100 timepoints and calculated the standard deviations of the beam inclination across the cycles at each timepoint. We averaged all standard deviations and divided the mean by the ROM on the trial. Thirdly, we quantified the shape of the beam's inclination angle motion using the shape ratio (SR). The SR was inspired by the shape of the inclination angle frequency distributions (**Chapter 3**) and provided an indication of the time structure of the beam's motion pattern. We computed SR as the ratio of the average absolute inclination angle over half of the ROM (i.e., peak-to-peak amplitude) of the beam.

Interpersonal coordination. We computed the continuous relative phase between the vertical positions of the two beam extremities, each handles by another participant.

To compute the CRP, we first centered the two signals and removed any linear trends. Then, we normalized the signals by dividing them by their standard deviation. Subsequently, we transformed the vertical positions into analytic signals using a Hilbert transform and derived the continuous phase angles in degrees (Lamb & Stöckl, 2014). Lastly, we subtracted the phase angle of the left participant from the right participant to come to a continuous relative phase angle. From the CRP timeseries, we derived two additional variables. First of all, we computed the standard deviation of the CRP, to which we shall referred as the CRP_{STD}. This variable was indicative of the stability of the interpersonal coordination, with a higher CRP_{STD} suggesting lower stability. In the second place, we computed the mean absolute deviation from anti-phase (CRP_{DEV} = |CRP_{MEAN} − 180 deg|). When anti-phase is defined as a symmetrical mode of interpersonal coordination, the CRP_{DEV} is indicative of the symmetry in the interpersonal coordination. That is, a larger CRP_{DEV} suggests that dyads interact more asymmetrically, with one dyad member taking the lead while the other follows.

5.3.6. Statistical analysis

To compare all dependent variables between the two groups (between-participants factor) and across the six blocks of practice (within-participants factor), we conducted several 2 × 6 repeated measures ANOVAs. We applied this analysis to the following dependent variables: TH, HC, AR, ROM, CV, SR, for the solo as well as the joint action session, and CRP_{STD} and CRP_{DEV} for the joint action session. For all analyses the significance level was set to $\alpha = 0.05$. Greenhouse–Geisser corrections were applied when violations of the sphericity assumption were detected. Post-hoc tests were performed using Bonferroni transformations.

In addition to this, we analyzed the relationship between the dyad's joint action session (JAS) performances and the sum of the dyad members' solo action session (SAS) performances, denoted the solo-to-joint transfer (**Chapter 4**). For the TH, HC, AR, ROM, CV and SR, we computed separate Pearson correlations between the JAS and the SAS of the constrained and the unconstrained group. Per analysis, we took the mean of the last three SAS blocks and the mean of the first 3 JAS blocks, because we observed significant changes in some of the variables over blocks of practice. We used the proportion of the explained variance R^2 as a measure of the strength of the solo-to-joint action transfer. We interpreted an $R^2 > 0.50$ (that is, explaining more than half of the variance) as indicative of a (moderately) strong transfer of skill on the corresponding indicator of performance.

5.4. Results

The Results section is divided into two parts. In the first part, we discuss the individual performances in the solo action session of the experiment. We report the results of a series of 2 (Group) x 6 (Block) repeated measures ANOVAs, on the performance indicators at the level of the ball (TH, HC and AR) and the level of the beam (ROM, SR, CV). In the second part, we address the dyadic performances in the joint action session of the

experiment. We report the results of the 2 x 6 repeated measures ANOVAs on the level of the ball and the beam and also conduct a solo-to-joint transfer analysis on each of the indicators. Moreover, we assess the stability and symmetry of the interpersonal coordination, through an analysis of the continuous relative phase (CRP) between the two beam handles.

5.4.1. Solo action

Ball motion. Overall, the individual performances improved over practice, as indicated by a significant increase in the number of target hits TH over blocks (**Figure 5.2** upper left, $F(5, 100) = 37.28$, $p < .001$, $\eta^2_p = 0.65$). Although the main effect of Group was not significant ($F(1, 20) = 0.31$, $p = 0.587$, $\eta^2_p = 0{,}02$), the increase in TH over blocks was larger for the unconstrained group than for the constrained group, in particular towards the end of the trial ($F(5, 100) = 3.16$, $p = 0.011$, $\eta^2_p = 0.14$). The improvement in hits was for a large part caused by a significant increase in the number of half cycles HC of the ball, demonstrating an increase of the average ball speed in both groups (**Figure 5.2** upper middle, $F(1.89, 37.75) = 40.53$, $p < 0.001$, $\eta^2_p = 0.67$). The number of hits per half cycles, indicative of the ball's accuracy, did not change significantly over blocks (**Figure 5.2**

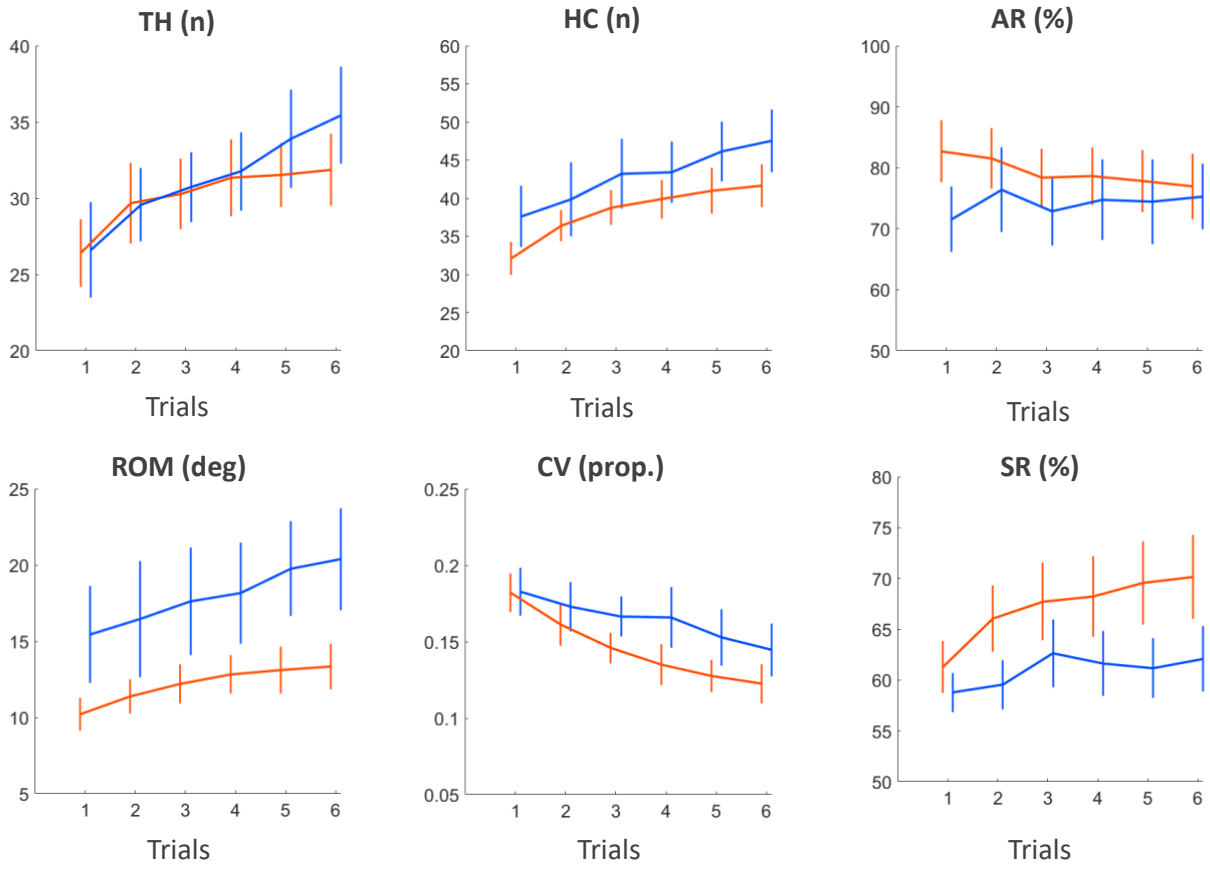


Figure 5.2: Number of target hits (upper left), ball half cycles (upper middle) and accuracy ratio (upper right) and beam range of motion (lower right), coefficient of variation (lower middle) and shape ratio (lower right) of individuals in the solo action session. Each panel shows the dependent variable across trials, split per group (constrained: red, unconstrained: blue).

upper right, $F(3.27, 65.4) = 0.82$, $p = 0.496$, $\eta^2_p = 0.04$). Both the HC and the AR were not significantly different between the constrained and the unconstrained group and the changes over blocks in both variables were not significantly different between both groups. In other words, at the end of the session only the number of target hits was smaller for the constrained than for the unconstrained group.

Beam motion. In both groups the beam's range of motion ROM increased significantly over blocks (**Figure 5.2** lower left, $F(1.69, 33.87) = 12.50$, $p < 0.001$, $\eta^2_p = 0.39$), which contributed to the increased speed of the ball. The beam's coefficient of variation CV also increased significantly over blocks (**Figure 5.2** lower middle, $F(5, 100) = 25.91$, $p < 0.001$, $\eta^2_p = 0.56$) demonstrating that participants moved the beam more consistently over practice as well. Participants in the constrained group had a significantly smaller ROM ($F(1, 20) = 8.69$, $p = 0.008$, $\eta^2_p = 0.30$) and showed a tendency towards a lower CV, even though this last effect did not each significance ($F(1, 20) = 3.00$, $p = 0.099$, $\eta^2_p = 0.13$). The reported changes in the ROM and CV over practice were not significantly different between groups ($p > 0.05$). The shape ratio, indicative of the participants' timing strategy, generally increased over blocks (**Figure 5.2** lower right, $F(2.16, 43.15) = 12.59$, $p < 0.001$, $\eta^2_p = 0.39$). The constrained group had a significantly larger SR than the unconstrained group ($F(1, 20) = 5.58$, $p = 0.028$, $\eta^2_p = 0.22$), demonstrating that they were more inclined to adopt an extreme-stop strategy. The increase in SR over blocks seemed to be stronger

Table 5.1: ANOVA results for solo action

Variable	Effect	F	df	p	η^2_p
TH	Practice	37.28	5, 100	< 0.001*	0.65
	Group	0.31	1, 20	0.587	0.02
	Practice*Group	3.16	5, 100	0.011*	0.14
HC	Practice	40.53	1.89, 37.75	< 0.001*	0.67
	Group	2.93	1, 20	0.102	0.13
	Practice*Group	0.82	1.89, 37.75	0.443	0.04
AR	Practice	0.82	3.27, 65.41	0.496	0.04
	Group	1.54	1, 20	0.228	0.07
	Practice*Group	1.54	3.27, 65.41	0.209	0.07
ROM	Practice	12.50	1.69, 33.87	< 0.001*	0.39
	Group	8.69	1, 20	0.008*	0.30
	Practice*Group	0.93	1.69, 33.87	0.389	0.05
CV	Practice	25.91	5, 100	< 0.001*	0.56
	Group	3.00	1, 20	0.099	0.13
	Practice*Group	2.37	5, 100	0.065	0.11
SR	Practice	12.59	2.16, 43.15	< 0.001*	0.39
	Group	5.58	1, 20	0.028*	0.22
	Practice*Group	2.89	2.16, 43.15	0.062	0.13

*Significant with $\alpha > 0.05$

for the constrained group, even though this effect did not reach significance (F(2.16, 43.15) = 2.89, p = 0.062, η^2_p = 0.13). Together, these results show that the experimental constraint not only limited the beam's ROM, as intended, but also significantly affected the participant's timing strategy on the task. The complete results of the 2 x 18 mixed design ANOVAs on all variables in solo action can be found in **Table 5.1**.

5.4.2. Joint action

Ball motion. The dyadic performances improved over practice, as reflected in a significant increase in the number of target hits over blocks (**Figure 5.3** upper left, F(5, 45) = 7.06, p < 0.001, η^2_p = 0.44). The mean TH was not significantly different between groups and neither was the increase in TH over blocks. The improvement the performances were partly caused by an increase in the number of ball half cycles (**Figure 5.3** upper middle, F(1.77, 15.89) = 10.96, p < 0.001, η^2_p = 0.55). Across the two groups, there was no significant difference in the HC (F(1.77, 15.89) = 3.17, p = 0.074, η^2_p = 0.26), even though the constrained group seemed to have a stronger increasing trend in HC over blocks (F(1.77, 15.89) = 3.17, p = 0.074, η^2_p = 0.26). The ball's accuracy showed a small

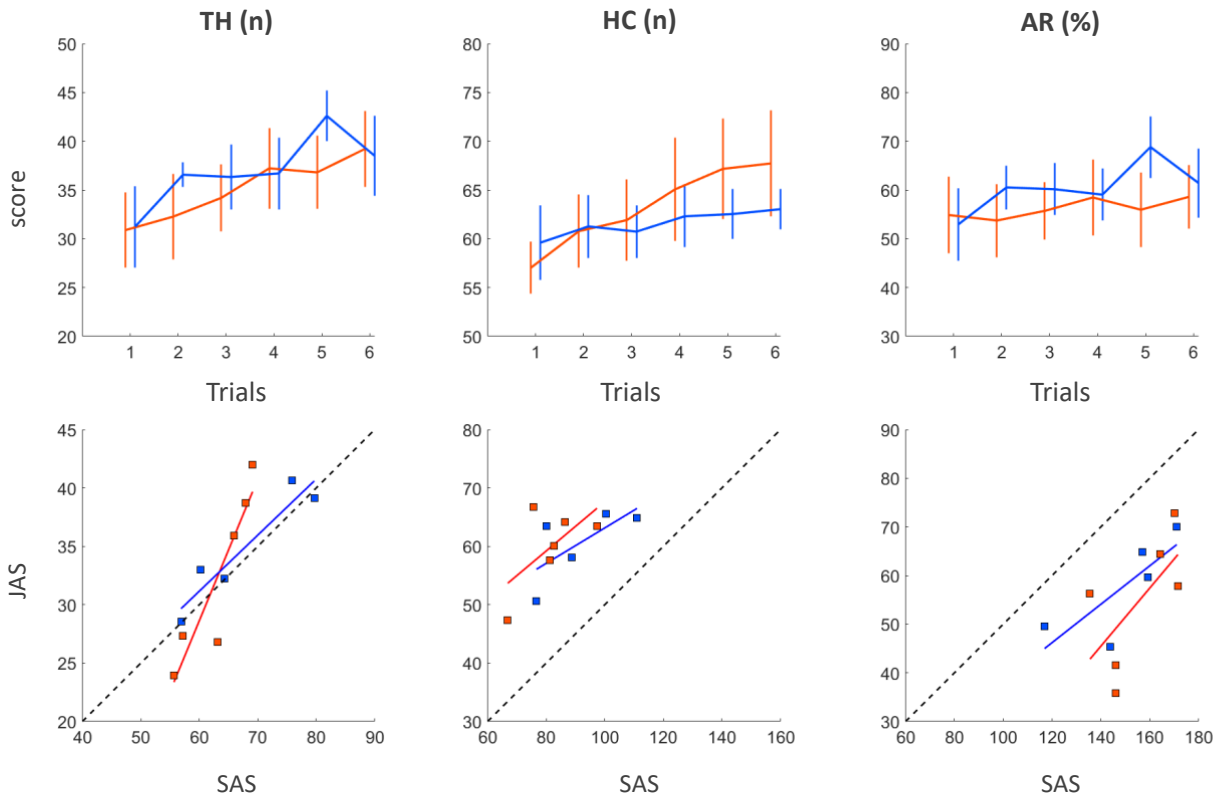


Figure 5.3: Number of target hits (left), ball half cycles (middle) and accuracy ratio (right) of dyads in the joint action session. The upper row of panels shows the evolution of each dependent variable across trials, split per group (constrained: red, unconstrained: blue). The lower row of panels displays the dyad's joint action session (JAS) performances as a function of the sum of the solo action performances (SAS) performances. Separate regression lines are fitted through the data points for each group. The dotted line represents JAS equal to the SAS.

increasing trend over blocks, which was nevertheless not significant (**Figure 5.3** upper right, $F(5, 45) = 2.39$, $p = 0.052$, $\eta^2_p = 0.21$). The AR was not significantly different between groups and neither were the changes in AR over blocks. The complete results of the 2 x 18 mixed design ANOVAs on all variables in joint action can be found in **Table 5.2**.

The dyad's number of target hits in joint action strongly correlated with the sum of the dyad member's target hits in solo action, with R^2's > 0.80 in both groups (**Figure 5.3** lower left). This was not the case for the number of half cycles, of which the solo action performances explained less than half of the joint action variance in the constrained and the unconstrained group (**Figure 5.3** lower middle). For the accuracy ratio, the R^2 was lower than 0.50 in the constrained group, but higher than 0.50 in the unconstrained group (**Figure 5.3** lower right). See **Table 5.3** for all R^2's.

Beam motion. Averaged across groups, the beam's range of motion did not significantly change over blocks (**Figure 5.4** upper left, $F(1.70, 15.26) = 0.68$, $p = 0.497$, $\eta^2_p = 0.07$). The adaptations over blocks, however, were significantly different for both groups ($F(1.70, 15.26) = 0.54$, $p = 0.019$, $\eta^2_p = 0.38$). While dyads in the constrained group started with a lower ROM and increased their beam excursions over practice, dyads in the

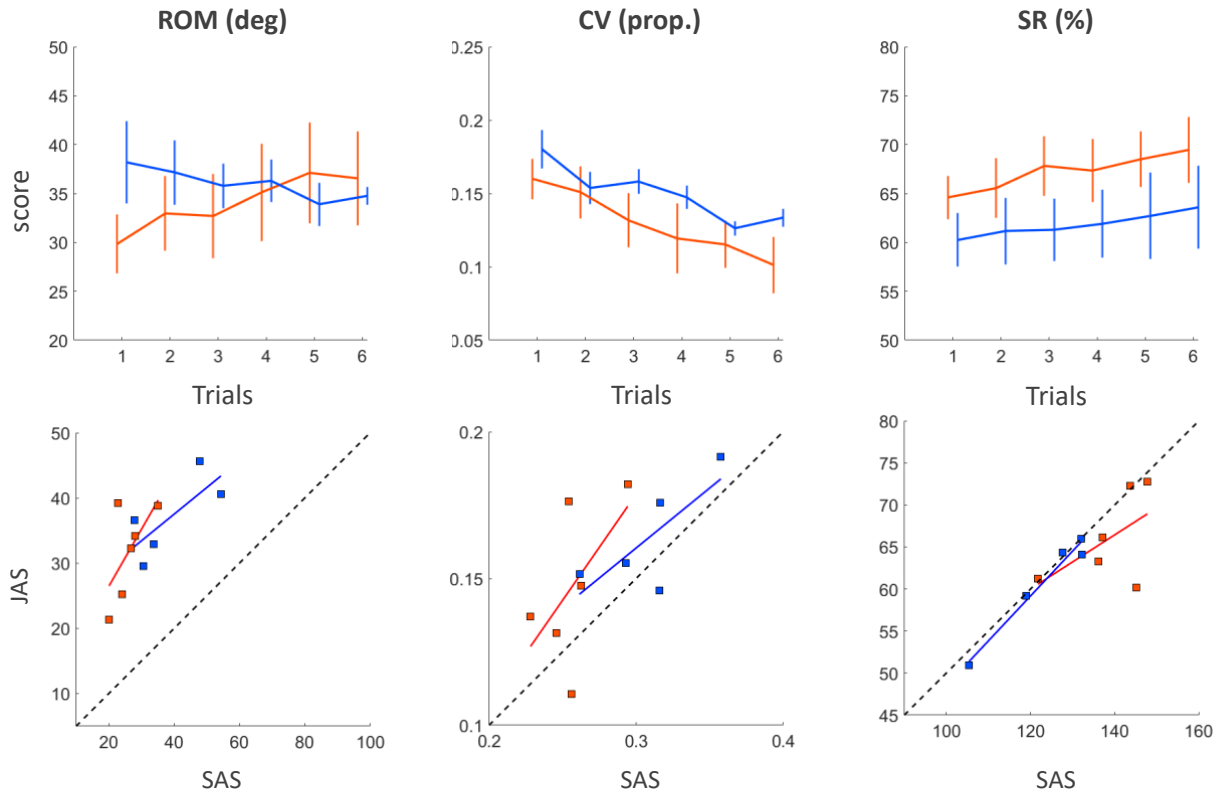


Figure 5.4: Beam range of motion (left), coefficient of variation (middle) and shape ratio (right) of dyads in the joint action session. The upper row of panels shows each dependent variable across trials, split per group (constrained: red, unconstrained: blue). The lower row of panels displays the dyad's joint action session (JAS) performances as a function of the sum of the solo action performances (SAS) performances. Separate regression lines are fitted through the data points for each group. The dotted line represents the JAS equal to the SAS.

unconstrained group started with a higher ROM and decreased that over blocks. As such, the mean ROM was not significantly different between the groups ($F(1, 9) = 0.22$, $p = 0.653$, $\eta^2_p = 0.02$). The coefficient of variation decreased significantly over blocks (**Figure 5.4** upper middle, $F(5, 45) = 11.77$, $p < 0.001$, $\eta^2_p = 0.57$), indicating that dyads moved the beam more consistently over practice. This decrease was not significantly different between groups, nor was the mean CV statistically different. The shape ratio increased over blocks (**Figure 5.4** upper right, $F(1.80, 16.20) = 6.33$, $p = 0.011$, $\eta^2_p = 0.41$) which indicated that dyads were more inclined to adopt an extreme-stop strategy towards the end of the session. The SR was not statistically different between the constrained and the unconstrained group ($F(1, 9) = 1.99$, $p = 0.192$, $\eta^2_p = 0.18$). The changes in SR over practice were also not significantly different ($p > 0.05$). See **Table 5.2** for the complete results.

For the beam's ROM, the solo action performances explained less than 50% of the variance of the joint action performances in the constrained group, but more than 50% of

Table 5.2: ANOVA results joint action

Variable	Effect	F	df	p	η^2_p
TH	Practice	7.06	5, 45	< 0.001*	0.44
	Group	0.24	1, 9	0.638	0.03
	Practice*Group	1.27	5, 45	0.294	0.12
HC	Practice	10.96	1.77, 15.89	< 0.001*	0.55
	Group	0.14	1, 9	0.714	0.02
	Practice*Group	3.17	1.77, 15.89	0.074	0.26
AR	Practice	2.39	5, 45	0.052	0.21
	Group	0.33	1, 9	0.581	0.04
	Practice*Group	1.98	5, 45	0.100	0.18
ROM	Practice	0.68	1.70, 15.26	0.497	0.07
	Group	0.22	1, 9	0.653	0.02
	Practice*Group	0.54	1.70, 15.26	0.019*	0.38
CV	Practice	11.77	5, 45	< 0.001*	0.57
	Group	1.87	1, 9	0.205	0.17
	Practice*Group	0.93	5, 45	0.473	0.09
SR	Practice	6.33	1.80, 16.20	< 0.011*	0.41
	Group	1.99	1, 9	0.192	0.18
	Practice*Group	0.55	1.80, 16.20	0.569	0.06
CRP_{STD}	Practice	10.07	1.35, 12.17	0.005*	0.53
	Group	0.52	1, 9	0.491	0.05
	Practice*Group	0.69	1.35, 12.17	0.466	0.07
CRP_{DEV}	Practice	1.08	2.18, 19.57	0.365	0.11
	Group	2.49	1, 9	0.149	0.22
	Practice*Group	0.91	2.18, 19.57	0.428	0.09

*Significant with $\alpha > 0.05$

it in the unconstrained group (**Figure 5.4** lower left). This was also the case for the CV, with an R^2 = 0.33 in the constrained group and R^2 = 0.57 in the unconstrained group (**Figure 5.4** lower middle). The same was true for the third and last beam variable, the shape ratio. While the R^2 was only 0.31 in the constrained group, it was 0.97 in the unconstrained group (**Figure 5.4** lower right). Thus, if participants were unconstrained in their movements, almost all of the variance in the timing of the beam in joint action was explained by the timing of the beam in solo action, See **Table 5.3** for all R^2s

Interpersonal coordination. To assess the interpersonal coordination in the joint action session, we computed the continuous relative phase (CRP) between the heights of the two beam extremities. To illustrate, **Figure 5.5** displays the polar histogram distributions of the CRP in the 14th trial (block 5) of the session, which was representative of the dyad's behavior in this session. As can be appreciated from these graphs, most dyads moved the beam handles roughly symmetrically, that is, in an anti-phase mode of coordination of 180 degrees. A notable exception to this is dyad 5 in the unconstrained group (**Figure 5.5** lowest panel middle), which adopted a relative phase of approximately 270 degrees. From these graphs, we derived two indicators of the interpersonal coordination. In the first, place, we computed the standard deviation of the CRP (CRP_{STD}). The CRP_{STD} decreased significantly over blocks (**Figure 5.6** left, $F(1.35, 12.17) = 10.07$, $p = 0.005$, $\eta^2_p = 0.53$), indicating that the stability of the coordination increased over practice. The CRP_{STD} was not significantly different between groups and neither was the decrease over blocks ($p > 0.05$). In the second place, we derived the mean absolute deviation from anti-phase (CRP_{DEV}), as a measure for the symmetry of the interpersonal coordination. The CRP_{DEV} did not significantly change over practice, in neither of the two groups (**Figure 5.6** right, $F(2.18, 19.57) = 1.08$, $p = 0.365$, $\eta^2_p = 0.11$). The CRP_{DEV} was also not significantly different between the constrained and the unconstrained group ($F(1, 9) = 2.49$, $p = 0.149$, $\eta^2_p = 0.22$). The complete results of the 2 x 18 mixed design ANOVAs on all variables related the interpersonal coordination in the joint action session can be found in **Table 5.2**.

Table 5.3: Solo to joint transfer of the performance indicators on the level of the ball (Target hits TH, half cycles HC, accuracy ratio AR) and the beam (range of motion ROM, coefficient of variation CV, shape ratio SR). For each indicator, we computed the explained variance (R^2) of the linear regression analyses between the dyad's joint action performances and the sums of the dyad members' solo action performances.

Group	TH	HC	AR	ROM	CV	SR
Constrained	0.85	0.39	0.42	0.40	0.33	0.31
Unconstrained	0.89	0.48	0.62	0.56	0.57	0.97

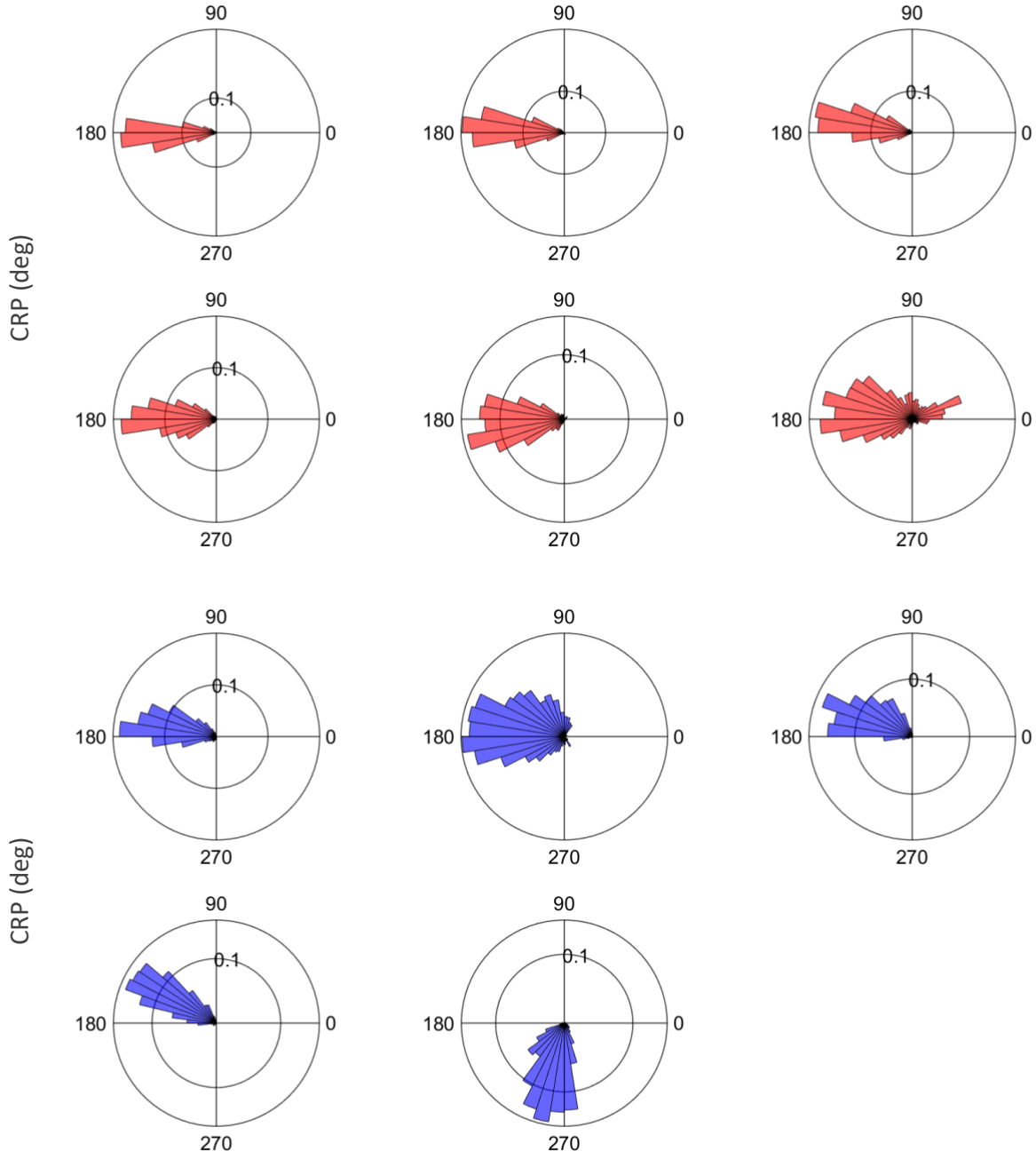


Figure 5.5: Polar histogram distributions of the continuous relative phase (deg) between the beam extremities of all dyads in trials 14 (block 5) of the joint action session. Panels in red belong to the constrained group, while panels in blue belong to the unconstrained group. For reasons of visibility, the r-axis varies in scale, with a circle of proportional frequency 0.1.

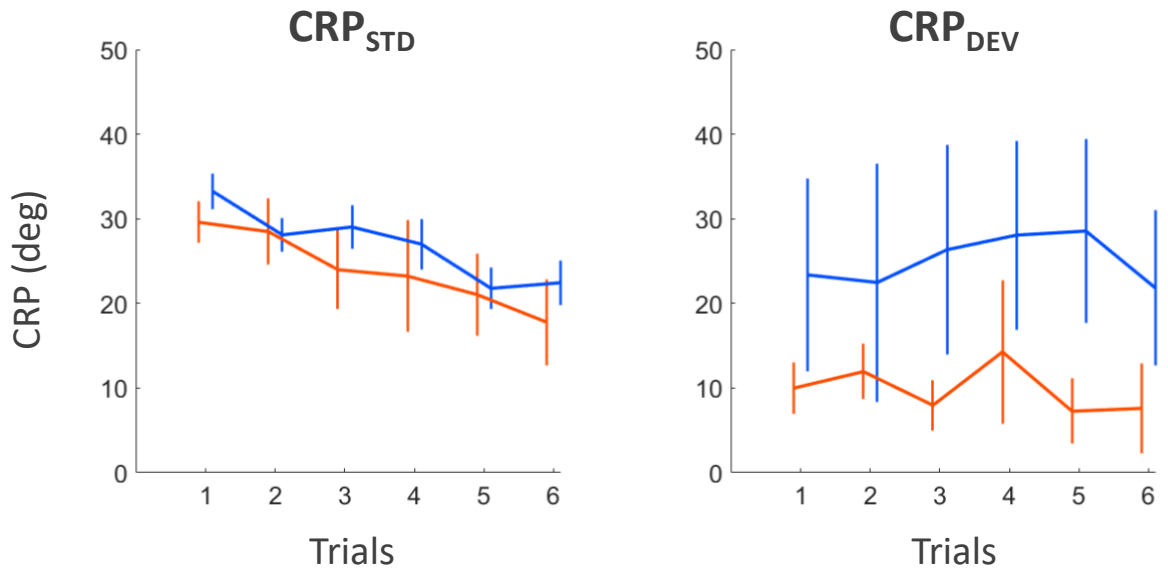


Figure 5.6: The standard deviation (left) and the average absolute deviation from anti-phase (right) of the continuous relative phase of dyads in the joint action session. Both panels show the evolution of the variables over trials, split per group (constrained: red, unconstrained: blue).

5.5. Discussion

In this experiment, we investigated individual and dyadic performances in the manual ball-and-beam paradigm. In a two-step study, we explored the hypothesis that constrained practice in a solo action setting would improve the stability and symmetry of the interpersonal coordination in a joint action setting. In the first step, we had two groups of participant perform the task individually in a solo action session. While one group performed the task with a soft constraint on the beam's range of motion (denoted the constrained group), another group performed the task under regular conditions without additional constraints (denoted the unconstrained group). In the second step, the participants within both groups were paired into dyads to perform a subsequent and unconstrained joint action session. In discussing the results of this study, I will first interpret the outcomes of the solo action session, before moving towards the findings in the joint action session. That is, I will first address the question whether constrained solo action practice resulted in a more efficient timing strategy, before addressing the question whether this constrained practice also led to a more stable and symmetrical interpersonal coordination in the ensuing joint action session.

5.5.1. Solo action

To compare the solo action performances of the constrained and the unconstrained group, we assessed several performance indicators on two levels of the ball-and-beam system. On the level of the ball, we found that participants improved their performances over practice, with a significant increase in the number of target hits and half cycles per

block (**Fig. 5.2**). This result was in line with earlier studies into this paradigm, although we did not find an increase in the accuracy ratio over blocks in this study (Hafkamp et al., 2023; 2024 or **Chapter 2** and **3**). The increase in target hits suggests that participants, as intended, learned to control the rolling ball on the beam. Participants in the unconstrained group showed a stronger increase in the target hits over blocks, in particular towards the end of the session. At the same time, we found no significant differences in the number of half cycles or the ratio of hits per half cycles between the two groups. This suggests that participants were, at least to some extent, able to overcome the experimental constraints imposed on their performance. To understand how they were able to do so, we proceeded to the motion of the beam – the level at which the constraint was applied.

In the motion of the beam's inclination angle, we observed significant differences between the constrained and the unconstrained group. In the first place, the range of motion in both groups was different. Even though all participants enhanced their average peak-to-peak amplitude over blocks, the ROM of the constrained group was significantly smaller and less variable than that of the unconstrained group. This demonstrated that the experimental constraint was strong enough to limit participants in their freedom to move. Participants in the constrained group also had a significantly higher shape ratio, indicating that they were more inclined to stop the handles at the extremes than participants in the unconstrained group. The shape ratio increased significantly over blocks in both groups, with a (non-significant) tendency towards a higher rate in the constrained group. The higher SR in the constrained group showed that the experimental manipulation had the intended effect: practice with a limited ROM resulted in the emergence of a more efficient timing strategy. Moreover, the fact that the ball speed and accuracy were not significantly lower for the constrained group suggested that the adaptation in the timing *compensated* for the limitation in the range of motion. The beam's coefficient of variation, in the third place, was not significantly different between groups, although we found a trend towards less variability in the constrained group. Participants in both groups improved the consistency of their movements, supporting the conclusion that they were increasingly skilled in controlling the ball. Taken together, these results confirmed out first hypothesis. Practice in a constrained setting resulted in a more efficient timing strategy, as predicted by Constraints Led Approach (Newell et al., 1989; Gray & Sullivan, 2023). In the second part of this study, we investigated the repercussions of this constrained practice session for the joint action performances.

5.5.2. Joint action

One the level of the ball, we found a significant increase in the dyad's number of target hits and half cycles, but not in the ratio between these two (**Fig. 5.3**). This was in line with earlier studies into this task paradigm and showed that dyads improved their performances (**Chapter 2** and **4**). The observed increases were not significantly different between the two groups, even though both the HC and AR showed a stronger increasing trend in the unconstrained group than in the constrained group. Yet, on average there were no significant differences in the ball level performances of dyads that had trained in a constrained and in an unconstrained setting. From solo to joint action, we found a large

transfer in the TH in both groups, meaning that the dyadic performances were strongly correlated with the dyad members' individual performances. This transfer of skill was markedly lower for the half cycles and accuracy ratio, especially in the constrained group. For dyads that had practiced in a constrained condition, the HC and AR of the solo action session explained less than 50% of the variance in the joint action session. Conversely, for dyads that had practiced in unconstrained conditions, the explained variance was around or above 50%, suggesting a moderately strong transfer of skill. This was in accordance with what we had found in **Chapter 4** of this thesis. All in all, constrained individual practice did not have strong repercussions for unconstrained dyadic performances, at least not on the level of the ball. But what about the motion of the beam, the level at which the constraints had been applied?

The beam's range of motion, to begin with, *did* reflect the constraints that had been imposed in the preceding solo action session. While dyads in the constrained group started with a small range of motion, which they enlarged over blocks, dyads in the unconstrained group did the reverse. They started with a (very) large ROM, which they gradually reduced over practice (**Fig. 5.4**). Again, we found a stronger transfer of skill in the constrained than in the unconstrained group. While the individual ROMs explained less than half of the variance of the dyadic ROMs in the constrained group, it explained more than half of the variance in the unconstrained group. This was similar to what we found in **Chapter 4**. The beam's shape ratio, as a second indicator, increased over blocks in both groups, suggesting that most dyads learned to move the beam more efficiently over practice. A comparison of groups, however, did not reveal any significant differences between the dyads. Thus, constrained solo action practice did *not* significantly affect the timing of dyads in the joint action session. The reason for this was revealed by the transfer analysis. We found that in the constrained group less than half of the variance of dyad's SR was explained by dyad members' SR in solo action. Apparently, the transfer of the timing strategy was weak when the constraints on the range of motion were released from solo to joint action. In the unconstrained group, in contrast, the transfer was remarkably high: no less than 97% of the variance in the joint action was explained by what each dyad member had done individually in solo action. This was in accordance with what we had found in **Chapter 4**. In other words, a transfer of strategy *only* occurred when the conditions of the task remained the same from solo to joint action. The third indicator, the beam's coefficient of variation, decreased significantly over blocks: dyads moved the beam more consistently over blocks. Between groups, however, there were no significant differences in the CV. Thus, constrained practice had no noticeable effect on the relative variability of the jointly produced beam movements.

Last, but not least, we investigated the interpersonal coordination between dyad members. We computed the continuous relative phase between the two beam extremities and assessed its standard deviation (CRP_{STD}) and its mean absolute deviation from anti-phase (CRP_{DEV}) (**Fig. 5.6**). Overall, we found that the CRP_{STD} decreased significantly over blocks, suggesting that the stability of the interpersonal coordination improved over practice. This aligned with earlier studies into the ball-and-beam paradigm (**Chapter 4**). The CRP_{DEV}, in contrast, did not decrease over blocks. This showed that the asymmetry in

the interpersonal coordination remained invariant over practice, even though there were strong deviations from anti-phase (180 deg) in some dyads. Both the CRP_{STD} and the CRP_{DEV} were not statistically different between groups. Thus, both the stability and the (a)symmetry in the interpersonal coordination in joint action were not significantly affected by the constrained practice in solo action. The average asymmetry was larger in the unconstrained group, as expected, but analyses per dyad revealed that this mean was strongly affected by one dyad that had an average deviation from anti-phase of almost 90 degrees (**Fig. 5.5**). Thus, the constraints imposed in the solo action were not strong enough for the stability and the symmetry of the interpersonal coordination to be improved or the group of dyads was too small to demonstrate this effect. In either case, follow up research is required to further explore how the interpersonal coordination in the ball-and-beam paradigm can be improved.

5.5.3. Conclusion

Our goal in this study was to investigate whether constrained practice in a solo action setting of the ball-and-beam task would be beneficial to the stability and symmetry of the interpersonal coordination in the joint action setting. The results were ambiguous and only partially supported our hypothesis. On the one hand, we found that a limitation on the beam's range of motion in solo action successfully modified the timing strategies of participants, leading to a more efficient (extreme-stop) strategy to fulfill the task. This was in line with CLA and demonstrated that constraining the task environment can lead to the acquisition of a better task solution. On the other hand, we found that the modified timing strategy was weakly transferred from the solo action to the joint action context. As a result, neither the stability nor the symmetry of the interpersonal coordination between dyad members was significantly affected by the constrained individual training. Given the small group of participants and the explorative nature of this study, we conclude that further research is required to determine whether the interpersonal coordination can, indeed, be improved by prior practice under constrained conditions.

6. General discussion

6.1. This chapter

In this thesis we investigated the interpersonal coordination of movement behavior. More specifically, we studied how two individuals manage to coordinate with each other in the context of a functional, that is, a goal-directed joint action. In addressing this question, we introduced a new experimental paradigm: the manual ball-and-beam task. In this task, participants had to control a ball rolling on a long and hand-held beam. By continuously adjusting the inclination angle of the beam, they had to roll the ball reciprocally between two targets, with the aim to hit these targets as often as possible in the timespan of a trial. This required them to learn a particular form of indirect control, in which the relationship between their own movements and those of the to-be-controlled ball was yet to be discovered. While the ball-and-beam paradigm could be performed individually, in solo action, our main interest in this thesis was the dyadic performance of the task, in joint action. There, participants had to coordinate with each other to control the rolling ball, in the absence of any verbal communication between them. The study of which modes of interpersonal coordination emerged from this setting, and under what constraints, is reported in this thesis. This last chapter serves as a reflection on that work.

First, I will summarize the main findings of this thesis. We employed the ball-and-beam paradigm in three related but independent experiments, the results of which I recapitulate at the start of this chapter. Thereafter, I will interpret the results in the context of an ecological approach to perception and action. In particular, I reflect on the experiments of this thesis in the light of two foundational concepts: the (social) affordance and the (interpersonal) synergy. In doing so, I will develop an ecological account of joint action that brings these two concepts together, such that the issue of interpersonal coordination is placed in a functional context. In the third place, I will evaluate the ball-and-beam task as a paradigm for the study of joint action. I reflect on its strengths and its weaknesses and provide concrete suggestions for how the set up can be improved. Fourth, I will discuss the implications and applications of this thesis. I address the question of how the scientific theory developed in this thesis can be translated to the societal practice of today. By way of illustration, I discuss some potential repercussions of our work for the rehabilitation of patients with mild arm paresis after stroke. In the last sections of this chapter, I will close off with some concluding remarks on the topics addressed in this thesis, facing forward to future pathways of research.

6.2. Summary of findings

6.2.1. General observations

For the purpose of this thesis, we conducted three experiments with the ball-and-beam paradigm. In **Chapter 2** we described the first experiment, in **Chapter 3** and **4** the second and in **Chapter 5** the third. Together, these experiments produced a wealth of motion capture data. 62 individuals volunteered as a participant in one of three experiments, each partaking in at least one solo action and one joint action session. This participation produced a total of 1332 solo action trails and 522 joint action trials. With a duration of two minutes per trial, this amounted to no less than 61 hours and 48 minutes of raw data. The data consisted exclusively of the timeseries of three carefully identified markers: the ball, beam handle 1 and beam handle 2, with each handle either being manipulated by a participant or being attached to a hinge (in solo action). We analyzed all of this data with customized MATLAB algorithms and thereby distinguished between three levels of observation. The level of the ball, the level of the beam's inclination angle and the level of the interpersonal coordination. Although intricately related, each level revealed different aspects of the performance, allowing us to identify a set of pertinent performance characteristics that recurred in all of the studies that we conducted. But before going into detail about each of the three experiments, I would like to say a few general words about the performances of our participants.

To begin with, all participants managed to acquire some form of control over the rolling ball, whether they performed the task individually or in dyads. Over blocks of practice, they learned to control ball, to the extent that they could hit the targets – no matter how small they were. Although some participants and dyads were better than others, this suggests that the ball-and-beam task is, as intended, well suited to study issues of perception, action and interpersonal coordination. That said, I note that the variability between the participants' performances was remarkably large. While some participants found a successful task solution within the first few trials, others were struggling to control the ball until the last trial. As such, the target hit scores ranged from a meagre 20 points in two minutes, to a spectacular 70 points in the same amount of time. The difficulty of the task especially came to the fore in the joint action setting. There, participants had to coordinate their movements not only with a ball, but also with the movements of another participant with whom they could not speak. As fascinating as it was for me as experimenter to observe this challenge, it was also difficult for them as participants to rise to that challenge. Nevertheless, most of them managed to do this quite successfully, up to the point that they acquired more target hits in joint action than in solo action. For most dyads, the increase in ball speed outweighed the decrease in ball accuracy, leading to better scores in the joint action setting. In the following section, I will briefly recapitulate **Chapter 2** to **5** of this thesis. I will focus on the results of the experiments, while refraining – for the moment – from interpretating them. This I will do in later sections of this chapter, from both theoretical and practical perspectives.

6.2.2. The experiments

In **Chapter 2**, we conducted a first study with the ball-and-beam paradigm. 24 participants performed two sessions of the task, with one or two days between the sessions. Group S/J first performed a solo action session, followed by a joint action session. Group J/S started with a joint action session and subsequently performed a solo action session. Each session consisted of 15 two-minute trials, with a target size of 15 cm and an inter-target distance of 120 cm. The number of target hits generally increased over trials, caused by an increasing ball speed and accuracy and a growing beam range of motion over practice. Dyads generally outperformed soloists and dyads in the S/J group acquired significantly more target hits than dyads in the J/S group. Dyads in the S/J group adopted a simultaneous mode of interpersonal coordination, one participant moving up while the other moved down. Dyads in the J/S group opted for a sequential mode of interpersonal coordination, one participant freezing their motion whenever the other moved. We concluded that a complementary, more successful mode of interpersonal coordination was more likely to emerge when participants had acquired some individual practice (by means of the preceding solo session) before performing in the joint action session. That is, individual practice stimulated a freeing of degrees of freedom in the multi-individual system. Reversely, dyadic practice before performing in the solo action session did not lead to a significant improvement in the individual performance.

In **Chapter 3** and **4** we followed up on Chapter 2's conclusion that joint action performances were affected by prior individual practice in solo action. In a two-step study, we investigated the transfer of skill from solo action to joint action. In the first step, reported in **Chapter 3**, we focused in the individual skill acquisition in the solo ball-and-beam paradigm, with the goal to characterize the behavioral dynamics that arose from learning the task. 16 participants performed two solo action sessions, with one or two days between the sessions. Each session consisted of six blocks, with a small (6 cm), medium (12 cm) and large (24 cm) target size per block (inter-target distance 100 cm). Overall, the number of target hits (TH) increased over trials, due to a larger number of ball half cycles (HC) and more hits per half cycles (AR). This improvement was caused by an increasing range of motion (ROM) and consistency (CV) of the beam's inclination angle, as well as an increased correlation between the ball and the beam motion. In contrast with our hypothesis, the target size did not appreciably affect the 'shape', that is, the timing of the beam's pattern of motion, which we characterized with a shape ratio (SR). Instead, we found stable inter-individual differences in the within-cycle timing strategies. While most participants were inclined to maintain the beam at peak inclination angles for brief, but noticeable, durations (denoted extreme-stop strategy), some tended to briefly halt the beam movement between two peaks, at inclination angle zero (denoted middle-stop strategy). Given that SR was uncorrelated with TH, we concluded that multiple timings strategies could lead to task success. Individual skill acquisition was thus characterized by the refinement of a behavioral dynamics that emerged in an early stage of practice.

Chapter 4 constituted the second step of the two-step study into the transfer of skill from solo to joint action in the ball-and-beam paradigm. Chapter 3 allowed us to identify

the pertinent performance characteristics on the level of the ball and the level of the beam. Here, we investigated to what extent these characteristics were propagated from the solo to the joint action setting. The 16 participants from the previous chapter were paired into 8 dyads to perform a subsequent joint action session. The session consisted of six blocks of three trials, with again small, medium and large targets. Over blocks, dyads improved their performance (TH) by increasing the speed (HC) and accuracy (AR) of the ball. While the consistency (CV) of the beam's inclination angle increased too, its range of motion (ROM) and timing (SR) remained unchanged. Those variables (indirectly) related to the ball's speed, such as the TH, HC, ROM and SR, were strongly transferred from the solo to the joint action setting. Contrastingly, the variables (indirectly) related to the ball's accuracy, like the AR and CV, were only moderately transferred. On the level of interpersonal coordination, we found that most dyads moved the beam handles simultaneously and in opposite directions. This mode of coordination was moderately stable, with a decrease in the relative phase variability over blocks. At the same time, we found significant asymmetries in the coordination that were not systematically related to the individual performances. However, dyad members that had acquired more hits or half cycles in the solo action setting, were more likely to take the lead in the joint action setting. We concluded that the stability in the interpersonal coordination emerged from the interaction, while being constrained by the task's goal to bring the ball up to speed.

In **Chapter 5** we followed up on Chapter 4's conclusion that the stability and symmetry of the interpersonal coordination was constrained by the task goal to roll the ball as fast as possible from target to target. Our goal in this chapter was to manipulate the constraints in the task setting such that participants would display a more stable and more symmetrical mode of interpersonal coordination. In line with the previous chapters, we conducted a two-step study, with first a solo action session and then joint action session. However, this time we constrained the range of motion of half of the participants (n = 12) in the solo action setting, with the goal to manipulate the timing strategy that they adopted to bring the ball up to speed. The other half (n = 10) performed the solo action setting without any constraints. We expected that this manipulation would beneficially change the SR and ROM that they brought to the interaction, once they were paired into dyads to perform in a subsequent and unconstrained joint action session. All sessions consisted of 18 trials with a target size of 12 cm and an inter-target distance of 100 cm. The results of the solo action part showed that the ROM-limitation indeed led to a smaller ROM and a higher SR, indicating a stronger tendency to stop the beam in at the extreme's rather than in the middle of the trajectory. The results of the joint action part showed, however, that this did not significantly affect the stability (CRP_{STD}) nor the symmetry (CRP_{DEV}) of the interpersonal coordination. In the dyads of the constrained group, the transfer of skill was weak in most variables, including the shape ratio, resulting in a fading away of the training effect. Given the explorative nature of the study and the small number of participants, we concluded that further research is required to determine whether the interpersonal coordination can, indeed, be improved by constrained individual training.

6.3. Ecological psychology

Ecological psychology, currently also known as the ecological-dynamical approach, was founded by J.J. Gibson in the wake of the Second World War (Lobo et al., 2018). At the time, it provided a response to the cognitive psychology that dominated in the scientific discourse. While the mainstream field of psychology was grounded in a Cartesian dualism of body and mind, ecological psychology was based on a Darwinian mutualism of animal and environment (**Chapter 1**). Humans, like any other animal on this planet, were claimed to make an inseparable pair with their surroundings (Gibson, 1979). Likewise, perception and action were argued to form two sides of the same coin, implying that they should be studied together rather than separately. But perhaps the most (in)famous contribution of this new psychology was its rejection of representations, a concept that had been central to almost any cognitive account of behavior. Gibson, instead, suggested that animals are in direct epistemological contact with their environment, an idea that has been followed by proponents of the ecological approach ever since (Michaels & Carello, 1981). Departing from this meta-theoretical standpoint, the ecological community has built a theoretical framework that, in my opinion, leans on two pillars: affordances and synergies. While the affordance was introduced by Gibson himself (Gibson, 1979), the notion of a synergy came from Nikolai Bernstein, whose work vastly contributed to the ecological account for movement coordination (Turvey 1990). In what follows, I will provide a brief background of both concepts. I will discuss their historical origin as well as their contemporary ecological interpretations. Thereafter, I will reflect on the results of this thesis in the light of both concepts, so as to develop an ecological account of interpersonal coordination during joint action. The central question around which this section revolves is this: How can ecological psychology help us to understand interpersonal movement coordination?

6.3.1. Affordances

Background. The concept of an affordance was introduced by Gibson to give hands and feet to the notion of direct epistemological contact, or direct perception in short. According to this view, animals do not perceive their environment in terms of its physical properties, such as size and mass, but in terms of how they can use it. Affordances, so Gibson defined, are "what [the environment] offers the animal, what it provides or furnishes, either for good or for ill" (Gibson, 1979, p. 127). A chair, for instance, affords the human to sit on, while the stairs afford climbing on. A leaf in the forest, in contrast, does not afford the human such activities, while it is provides a spider with the opportunity to find shelter for the night. Note, here, how the affordance is a deeply relational concept. It does not apply to the animal, nor to its environment, but it applies to both at the same time. That is, the affordance is a property of the animal-environment system as a whole. This relational character is illustrative for ecological psychology, which can be interpreted as a systemic approach to perception and action. In the decades after its introduction, a series of groundbreaking studies have given the concept of the affordance its empirical backbone. For instance, Warren (1984) showed that participants can directly perceive whether a chair is climbable, through the ratio between the stepping

height and the length of their legs. This demonstrated that our perception for action is colored by the configuration of the agent-environment system as a whole. For further elaboration on the concept of an affordance as well as its historical development, I refer the reader to the ecological literature (e.g. Bruineberg et al., 2024). For our present purpose of understanding interpersonal coordination, I will focus on the affordance in a social context.

In the interpersonal domain, research into affordances has been remarkably scarce. Although human interactions are at the order of the day, studies into how we can perceive affordances for *joint* actions have rarely been conducted. A notable exception to this is the work of Richardson, Marsh, & Baron (2007). In this study, participants had to transport planks with different lengths, either with their hands, with a tool or with the help of another participant. By varying the length of the planks, Richardson, Marsh, and Baron (2007) showed that individuals could accurately perceive the point at which they had to switch from carrying individually to carrying with someone else. Moreover, they showed that this transition occurred at exactly the same body-plank ratio as when participants had switched from one to two hands, or from manual to tool-assisted carrying. This suggested that agents can accurately perceive an opportunity for joint action, that is, a circumstance in which the coordination of their action with someone else is beneficial to the outcome of the performance. In **Chapter 1**, I proposed to use the term 'social affordance' to denote this situation, following Marsh et al. (2006, 2009). A social affordance, in my view, is that what interpersonal coordination with another individual (or multiple others) offers the individual, in terms of opportunities for a joint action. It provides an answer to the question of *why* individuals start to couple their movement behavior, rather than how they do so. The results of **Chapter 2** of this thesis make unequivocally clear why this issue needs to be addressed before one can proceed to the question of what is being coordinated, or how they do so.

Social affordances in the ball-and-beam task. In **Chapter 2**, two groups of participants performed the ball-and-beam task in consecutive sessions. One group first performed a solo action session and then a joint action session (S/J), while another group started with a joint action session, followed by a solo action session (J/S). In the J/S group, most of the dyads moved the beam handles *sequentially* and in a turn taking fashion – each freezing their motion while the other moved. In the S/J group, most of the dyads moved the beam handles *simultaneously* and in opposite directions – one moving up while the other moved down. Although both modes of coordination were at least moderately stable, only the latter mode increased the action capabilities of the participants. Moving the beam handles simultaneously allowed participants to produce larger beam inclination angles than what they could have produced individually, implying the possibility of more target hits as a dyad than as a soloist. Since the goal of the task was to acquire as many hits as possible, the simultaneous mode of interpersonal coordination was a better solution than the sequential mode. In light of the discussion above, we may say that participants who moved simultaneously more accurately perceived and enacted the social affordance of the ball-and-beam paradigm. That is, the setting of the task allowed participants to perform

better in joint action than in solo action, under the condition that dyad members did not wait for each other but that they moved complementary to one another. The question that remained, however, is why dyads in the S/J group enacted that social affordance, while dyads in the J/S-group did not.

Dyads in the S/J group, as opposed to those in the J/S group, had already performed the task individually in a preceding solo action session. As such, they were in the position to contrast their dyadic performance to what they had accomplished as soloists. I speculate that this helped them to perceive the advantages that the joint action setting brought them, in comparison to the solo action setting. By contrasting the two DFs in the dyadic context to the one DF in the individual context, they were able to discover the opportunity to move complementary to one another, with the result that they acquired significantly more target hits. A different way to say this, is that their individual task experience allowed them to perceive the *inadequacy* (Baron, 2007) of freezing one degree of freedom at a time, prompting them to exploit the full freedom that the joint action setting offered. In an intriguing study into virtual shepherding, Nalepka et al. (2017) reported a remarkably similar result. In their experiment, dyads of participants were to collect virtual herds of sheep on a two-dimensional game field, by each manually driving the sheep into a circle with a cursor. Not unlike the dyads in our experiment, the pairs of shepherd participants could be partitioned into two groups (**Figure 6.1**). Initially all dyads adopted a so-called search-and-recover strategy, in which the dyad members collected the sheep one by one on their own side of the field. After a while, however, one group of dyads switched to coupled-oscillatory containment, in which the two participants adopted an in-phase or anti-phase rhythm of motion with the cursors around the virtual herd. Another group of dyads, in contrast, persisted in the search-and-recover

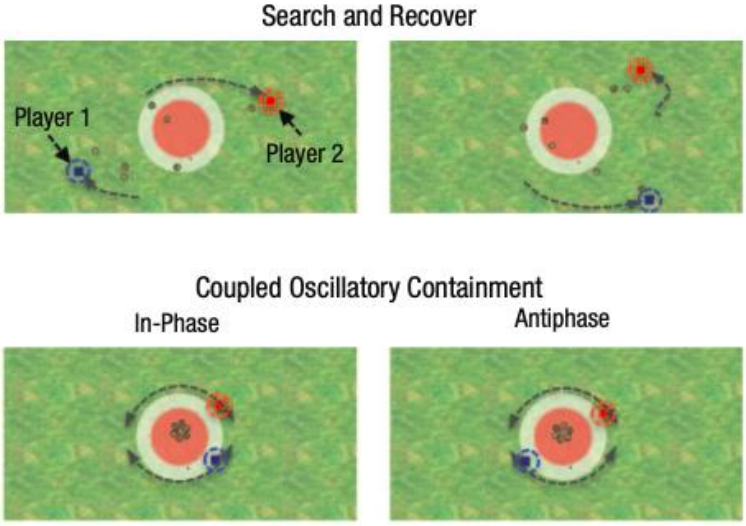


Figure 6.1: Two task strategies adopted by dyad in the virtual shepherding paradigm of Nalepka and colleagues (2017). One group dyads acted individually, also known as a search-and-recover strategy (upper graphs), while another group of dyads acted collectively, denoted a coupled oscillatory containment (lower graphs). From: Nalepka et al. (2017)

strategy that they had adopted from the start of the experiment. In my view, these two solutions are analogous to the task solutions that participants in our study found. In respectively the search-and-recover (shepherding) and sequential (ball-and-beam) modes of coordination, the members of a dyad acted *individually*, each ignoring their co-actor or waiting for them to stop moving. In the coupled-oscillatory containment and the simultaneous modes of coordination, dyad members acted *collectively*, with each member each moving complementary to the other. Furthermore, in both task settings participants first had to perceive the inadequacy of their individual task solutions before they could make the switch to a collective task solution. In other words, they first had to perceive the social affordance offered by the task before they could enact it.

Beyond this thesis. The concept of a social affordance, the 'why' of interpersonal coordination, requires further investigation. More research is needed to find out how, and under what conditions, individuals perceive and enact opportunities for joint action. Outstanding issues concern, for instance, the influence of individual action capabilities on the perception and enactment of a social affordance. To speculate, I hypothesize that the pull towards interpersonal coordination increases whenever one's own perceptuomotor capabilities on a task are low. In that case, the engagement in a joint action would provide more benefits than whenever one is equally capable of achieving a goal in solo action. The other way around, one could also hypothesize that degraded perception-action capabilities raise the threshold for joint action, since person-oriented (i.e., interpersonal) coordination is often more challenging than object-oriented (i.e., intrapersonal) coordination. An experimental paradigm required for the study of this topic should meet a number of requirements. It should be goal-oriented, challenging and it should call upon the perceptuomotor skill set of those who partake in it. But most of all, a task should be feasible for individuals as well as multi-individual configurations, while engagement in the latter setting is potentially beneficial to the outcome of the performance. The ball-and-beam paradigm, as presented in this thesis, constitutes an example of such a task. However, I foresee that other experimental set-ups like for instance the shepherding setting of Nalepka et al. (2017) may be equally viable to conduct such research.

6.3.2. Synergies

Background. The synergy, as a concept in the study of human movement, is strongly associated with the seminal work of Nikolai Bernstein (Kelso, 1995; Bongaardt & Meijer, 2000; Latash et al., 2007). In a time when animal behavior was believed to be composed of Pavlovian reflexes, Bernstein advocated a remarkably systemic approach to human movement. According to him, the coordination of movement involved an *organization* of the control of our body (Turvey 1990). Whenever we acquire a new perceptuomotor skill, we learn not to control every single degree of freedom (e.g., muscles, joints) that we have at our disposal, but we come to organize our DFs into functional units. These functional units are what Bernstein referred to as synergies. Synergies, so he proposed, are not merely groups of automated muscles that reflexively respond to a particular stimulus. In contrast, synergies are task specific modules that allow us to adapt flexibly to the current

demands of the environment. They are, in other words, dynamical systems that have an intrinsic stability, while also rapidly changing its configuration whenever that is needed. At the time, Bernstein's insights were received with fierce criticism (Meijer & Bruijn, 2007). But long after his death, early proponents of the ecological movement, most prominently Michael Turvey, acknowledged the ingenuity of his ideas. The systemic thinking of Bernstein colored well with Gibson's ecological psychology, in which the agent-environment system was central. As such, the notion of a synergy was embraced by the ecological community. Over the years, the concept was further developed along the theoretical lines of the ecological approach. In short, this development is characterized by two complementary perspectives (**Chapter 1**).

On the one hand, the synergy has been approached as a *coordinative process*. While Bernstein himself had envisioned this process as that of neuromotor integration (Bongaardt & Meijer, 2000), proponents of the ecological approach would instead draw inspiration from one of his other early intuitions: that a synergy may constitute a dynamical system (Kugler et al., 1980). A dynamical system is a time-evolving system with self-organizing properties, much like a self-sustained pendulum clock. In the early 80s, a series of groundbreaking studies would provide empirical support for this claim and establish the hypothesis that the coordination of movement is a process of self-organization (Kelso et al., 1982; Kelso et al., 1984; Schöner et al., 1986). The standard model for this process became the HKB-model of coupled oscillators (Haken et al., 1985), according to which two rhythmically moving limbs spontaneously synchronize in their movement – either at an in-phase or at an anti-phase mode of coordination. In the context of interpersonal coordination, this model would come to account for the (in)voluntary synchronization of movement between interacting agents, for instance during side-to-side walking (Van Ulzen et al., 2008) or side-to-side chair rocking (Richardson, 2007) (for review: Schmidt & Richardson, 2008). Moreover, follow-up studies modeled the interaction between oscillators with different eigenfrequencies, showing a systematic effect of detuning that could explain leader-follower relationships that occur in interpersonal coordination (Schmidt & Turvey, 1994). But above all, this research provided a process account for (interpersonal) coordination which envisioned a (social) synergy as a stable 'attractor state' of a self-sustained dynamical system. This perspective is more commonly known as coordination dynamics (Kelso, 2022) or as the dynamical systems approach (Beek et al., 1995) to human movement.

On the other hand, the synergy has been approached as a *coordinative structure*. A synergy is not only a stable state of affairs, but it also constitutes a pattern of motion that facilitates the accomplishment of a task. It preserves a functional relationship between an agent and its environment, or between multiple agents and their environment, for that matter. For long, ecological psychology's focus on dynamical modeling has been at the expense of the development of this perspective (but see Vereijken et al., 1992, 1997 for a notable exception to this). However, the advent of the Uncontrolled Manifold analysis, the UCM, brought change to this (Scholz & Schöner, 1999). With the UCM, it became possible to reveal the coordinative structure of discrete and rhythmic movements by analyzing the trial-to-trial or cycle-to-cycle variability of the degrees of freedom in the system. More

specifically, this method partitions the DF-variability in two components: one along (VUCM) and one orthogonal (VORT) to a solution manifold, with respect to a self-chosen performance variable. If the variability along the manifold is larger than that orthogonal to it (VUCM > VORT), this indicates that the DFs are structure into a pattern of coordination that stabilizes the performance variable. As such, we may say that the DFs are coordinated into a synergy (Latash et al., 2007). In the context of interpersonal coordination, the DFs can for instance be the members of a dyad or team. This way, the UCM can reveal whether the coordination among those members is facilitative of the accomplishment of a common goal between them. This method has for example been applied to dyadic pointer-to-target aiming (Romero et al., 2015), but also to team sports like rugby (Passos et al., 2018) and doubles badminton (Passos et al., 2022). In this perspective a synergy is envisioned as a coordinative structure that facilitates and sustains a functional relationship between agent(s) and their environment. .

About a decade ago, Riley et al. (2011) proposed to unify both perspectives into one definition – which came to be knowns as Interpersonal Synergies Theory. A synergy, in their definition, has two critical features. In the first place, it reduces the dimensionality of the (multi-individual) system. This is accomplished by coupling the DFs of the system so that they move together rather than independently (**Figure 6.2**). In this feature we can recognize the fingerprints of the dynamical systems approach, and of the HKB model in particular, according to which limbs synchronize spontaneously in their motion. In the second place, a synergy is characterized by reciprocal compensations of the DFs in the

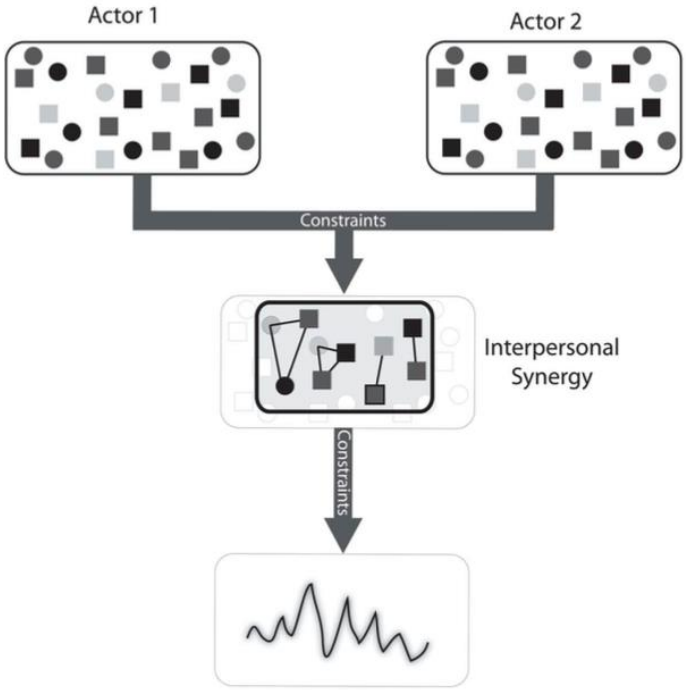


Figure 6.2: A schematic depiction of the formative process of an interpersonal synergy. Through constraints, the DFs of the two actors are coupled to each other such that they form one coordinative structure across the two individuals. This, in turn, produces a collective pattern of motion. From: Riley et al. (2011)

system, for instance between the members of a dyad. In this feature, we can recognize the UCM hypothesis, which holds that the DFs involved in synergy covary to stabilize a parameter necessary to achieve the task goal. The common thread running through this definition is the notion of *stability*. The two features provide respectively a process and a structure account of how a stable joint action is performed. In what follows, I reflect on the results of this thesis in the perspective of this two-faceted definition. By explicitly positioning our findings within this framework, I will show that the current interpretation of a synergy has its shortcomings. More specifically, it will become clear that the account lacks a functional dimension that is required to explain the coordination of a joint action. The methodology outlined in **Chapter 3, 4** and **5** of this thesis serves as way to account for this functional dimension.

Interpersonal synergies in the ball-and-beam task. In **Chapter 4**, we studied the interpersonal coordination between dyad members in the joint action setting of the ball-and-beam task. By computing the relative phase between the two beam extremities, we assessed whether the dyad members synchronized their movements (that is, in anti-phase manner). We found that most dyads adopted a common frequency of movement and that they moved the beam extremities simultaneously in opposite directions, one moving up while the other moved down. In this aspect, the dyadic coordination aligned with the HKB model for coordination: the dimensionality of the two-person system was temporarily reduced from two to one degree of freedom, being constrained by the particular demands of the task. At the same time, our results indicated significant deviations from that model. The mode of coordination was only semi-stable, meaning that dyads occasionally fell out of their synchrony and that their relative phase was variable. Although this variability reduced over trials, it did not disappear, meaning that a fully stable solution was never found. Another anomaly that remained, was the occurrence of significant asymmetries in the interaction of some of the dyads. In contrast with the predictions of coupled-oscillator models (Schmidt & Turvey, 1994; Schmidt et al., 1994), these asymmetries were not systematically related to differences in the 'eigenfrequencies' of the two members of a dyad. That is, the preferred movement frequencies of the two corresponding participants in solo action were not linearly predictive of the phase lag between the two in joint action. We did find, however, that the dyad member with the better performance in solo action was more likely to lead the interaction. As a last deviation from the HKB model, we found that a common frequency of motion of dyad was not located between the two members' solo action frequencies, but that it was 1.3 times larger than that.

The deviations from the coupled-oscillator model illustrate the relevance of the functional context in which a joint takes place. Each joint action comes with a new set of constraints that shapes the interaction. As such, a simple synchronization between individuals may sometimes not suffice to fulfill the task (Wallot et al., 2016). Similar results have been found in other joint action settings. For instance, Cuijpers et al. (2017) showed that synchronous crew rowing led to more lateral boat movements than non-synchronous rowing, which is detrimental to the rowing performance. And in a study into

dyadic rope turning, Huys et al. (2018) showed that increases in the common turning frequency led to a more regular motion of the rope, even though the HKB model predicts a *decrease* in stability at higher frequencies. Together with the findings in this thesis, such results demonstrate that the environmental context, in particular the goal of the joint action, always needs to be taken into account to explain the interpersonal coordination. The demonstration of dimensionality reduction in the performance of a joint action is not sufficient. Following the synergy definition of Riley et al. (2011), this functional dimension of the social coordination can be assessed by conducting a UCM analysis on the recorded behavior. If the members of a crew of rowers, or a dyad of rope turners, reciprocally compensate for each other's behavior, we may say that they form an interpersonal synergy. This leads us back to the manual ball-and-beam paradigm. Did the members of a ball-and-beam dyad compensate for each other's movements in the performance of the joint action?

In this thesis, we did not conduct a UCM analysis on the data of our experiments. Thus, we could not provide direct evidence for reciprocal compensations between the members of our dyads. Nevertheless, the results of **Chapter 4** suggest covariations between the collaborating participants. Dyads in that study performed the ball-and-beam task with varying accuracy requirements. The results showed that a reduction in the size of the targets led to a decrease in the variability of the ball motion, in accordance with what was demanded by the task. Yet, the results also indicated an *increase* in the variability of the relative phase between the beam extremities. This suggests compensatory behavior between dyad members, presumably with the goal to stabilize the motion of the ball to increase its accuracy. A UCM analysis with the two beam handles as DFs and the back-and-forth motion of the ball as performance parameter could confirm the presence of such reciprocal compensations. As such, it could provide further evidence for the existence of an interpersonal synergy (Riley et al., 2011). To my view, however, this conceptualization of 'function' is too narrow for the context of this task. In the ball-and-beam paradigm, dyads were not only required to roll the ball accurately from target to target. They were *also* required to roll the ball as fast as possible between those targets. In fact, it was the balance between ball speed and ball accuracy that determined the success of their performance. With its exclusive focus on coordinative stability, Riley et al., (2011)'s definition of a synergy does not do justice to the interpersonal coordination displayed in this our task paradigm. For this reason, we developed in this thesis a novel method to address the functional dimension of interpersonal coordination. In **Chapter 3, 4** and **5** we worked out this methodology step by step.

Solo-to-joint transfer. A first step in our approach, was the distinction of (at least) two levels of description in the joint action. One level pertaining to the interpersonal coordination, with the two dyad members as two DFs in the ball-and-beam system (**Chapter 2**). And another level pertaining to the purpose of the activity, describing the (mediated) interaction of the dyad with its environment. It is only at this second level that the functional dimension of a joint action is expressed. In the case of the ball-and-beam task, the functional level can even be split in two, since the task requires an indirect form

of control. In **Chapter 3**, we captured the behavior on both functional levels in a set of pertinent variables, assessed in the solo action performances. On the level of the ball, we assessed the performances in terms of the number of target hits (TH), half cycles (HC) and the hits per half cycles (accuracy ratio, AR). On the level of the beam, we computed the range of motion (ROM) and the coefficient of variation (CV) of the inclination angle. But perhaps the most interesting parameter was the shape ratio (SR), which indicated the timing strategy of participants within each cycle. In short, this measure distinguished between those who tended to stop the beam handle at peak inclination angles (denoted extreme-stop strategy) and those who tended to halt the beam between two peaks, at inclination angle zero (denoted middle-stop strategy).

The second step in the approach was the assessment of the skill transfer of each of these ball/beam-characteristics, from the solo to the joint action setting. In **Chapter 4**, we paired the participants into dyads and had them perform a joint action session of the ball-and-beam task. Intriguingly, we found that those indicators indirectly related to the ball's speed were strongly propagated from solo to joint action, while the variables related the ball's accuracy were only moderately transferred. For instance, the ROM and SR of the dyads, denoting the range and timing of the beam movement, could be quite accurately predicted on the basis of the dyad members' solo action performances. The AR and the CV of each dyad, denoting the accuracy and variability of the performance, were rather poorly predicted by the corresponding individual's solo action sessions. Crucially, these results revealed something about the interpersonal coordination that the analysis of the relative phase or a UCM could not have pointed out. It showed that the ball's accuracy was emergent from the interaction between the two participants, while its speed was largely determined in advance. Since the ball's accuracy was strongly associated with the variability in the relative phase between the two beam handles, we drew the following conclusion: The stability of the interpersonal coordination emerged from the interaction, while being constrained by the task's goal to be fast as well as accurate. This way, our two-step approach revealed with remarkable detail how the functional context of the ball-and-beam task affected the dyad's interpersonal coordination.

In **Chapter 5**, we repeated our two-step approach. Building upon the conclusions of Chapter 4, our goal was to *improve* the stability and symmetry of the interpersonal coordination by manipulating the timing strategy that participants brought to the interaction. In the first step, in solo action, we constrained the beam's range of motion for half of the participants, in order to induce a switch from the inefficient middle-stop strategy to a more efficient extreme-stop strategy. The results showed that our manipulation was successful: the participants in the experimental group had significantly larger shape ratio than those in the control group, indicating a higher prevalence of the extreme-stop timing strategy. In the second step, in joint action, we studied the solo-to-joint transfer of the performance indicators and assessed the effect of this propagation on the stability and symmetry of the interpersonal coordination. The results were ambiguous. In participants that had practiced the task under regular conditions, we found a (moderately) strong transfer for most indicators of the performance, including the range and timing of the beam. This aligned with what we had found in **Chapter 4**. In participants

that had practiced under constrained conditions, however, the transfer was notably lower. For instance, the shape ratio of dyad members in (constrained) solo action explained only half of the variance of the shape ratio of dyads in (unconstrained) joint action. Thus, the transfer of skilled only occurred when the setting of the task remained the same. As a consequence, the stability and the symmetry of the interpersonal coordination in joint action was not significantly affected by the imposed constraints in solo action.

Beyond this thesis. The experiments in **Chapter 3, 4**, and **5** of this thesis were all conducted in the context of the ball-and-beam paradigm. Although this setting is highly specific in terms of its goal and environment, I believe that the rationale set out in these chapters is applicable to other interactive settings too. As long as the task is goal-directed and performable in a solo setting as well as in a joint action setting, our solo-to-joint transfer analysis can be used. Paramount to this method, is the identification of one or more functional levels of observation. This level should pertain directly to the goal of the task and it should be distinguishable from the level of the interpersonal coordination. This way, it is possible to identify indicators of the performance that apply equally to solo and joint action. As an example, the functional level in competitive rowing may comprise the motion of the boat. The boat's movements through the water pertains directly to the goal of rowing, which is to race as fast as possible from start to finish. Moreover, the boat movements are clearly distinguishable from the interpersonal coordination between the members of a crew. Consequently, performance variables on the level of the boat motion apply not only to joint action, but also to solo action. Think, for instance, about lateral fluctuations of the boat or about the mean forward velocity. Correlational analyses such as those conducted in **Chapter 4** and **5** of this thesis can reveal to what extent the solo action performances are predictive of joint action performances. Of course, it is also possible to conduct other predictive analysis techniques, dependent on the number of participants and the quality of the data. The key point here, is that our methodology has the power to reveal the constraints under which interpersonal coordination emerges.

6.3.3. An ecological account of joint action

The results of this thesis give rise to a revision of the current ecological account of interpersonal coordination, most clearly depicted in Riley et al. (2011). Our findings lead to an account in which the notion of an interpersonal synergy can be combined with the notion of a social affordance. An account that portrays interpersonal coordination not only as a stable attractor state of a dynamical system, but also as a functional expression of a team of individuals pursuing a common goal. An account, in other words, not of interpersonal coordination per se, but of interpersonal coordination *in the context of joint action*. Throughout this thesis, we developed this ecological theory step by step, guided by the concepts of ecological psychology on the one hand and the empirical findings in our experiments on the other hand. In the passages set out above, I aimed to bring these two worlds together, in an effort to come to a more comprehensive understanding of what it means to engage in a joint action. In this last section, I will recapitulate the main tenets

of this theory, with the goal to be as clear as possible in my formulations. I will do so by considering the engagement in a joint action from the angle of the individual agent. What does participating in a joint action mean for the agent, in terms of action, perception and interpersonal coordination? Although much more research is required to fully understand the structures and processes of coordination involved in joint action, the sketched account serves as a theoretical framework for positioning such research.

The engagement in a joint action requires, first and foremost, the perception of a social affordance. The individual agent needs to perceive the opportunity for interpersonal coordination, which is created by the lay-out of the environment. More specifically, the agent needs to see that the coordination of his or her actions with someone else is *beneficial* to the accomplishment of a particular goal. For this perception to occur, it is crucial that the agent perceives the inadequacy of acting individually. The reason for joining others in their actions should be clear. In the ball-and-beam setting, this inadequacy was reflected in the number target hits acquired. In an alternative task setting, it may reveal itself in an entirely different way. The results of this thesis suggests, however, that having performed a task individually before doing it dyadically (or triadically), may facilitate the perception of the social affordance that lies ahead. After having perceived the opportunity for joint action, an agent needs to grasp it. The individual has to engage in the joint action, by forming an interpersonal synergy with the other(s). This interpersonal synergy has two faces. In the first place, it is a social tool that allows the agent to achieve something that they could not have achieved individually. This aspect of the interpersonal synergy is necessarily described at a functional level, pertaining to the goal of the activity. It involves a qualitative transition from acting individually, to acting in a team. In this thesis, we set out a methodology to assess what each individual brings to the interaction and what they leave behind, so as to adapt to their co-actor. In short, this methodology consists of two steps, involving a solo and a joint action session of the task and an analysis to determine the transfer of skill from the first to the latter session. We denoted this methodology the solo-to-joint transfer analysis.

In the second place, the interpersonal synergy is a stable solution to the multi-individual 'problem' of coordination, as posed by the joint action. In more mathematical terms, we may say that the synergy is a stable attractor state of a dynamical system that is temporarily spanned across those individuals that decided to engage in the joint action. In contrast with its functional dimension, the stability of an interpersonal synergy can only be understood at the level of the interpersonal coordination. It may involve the synchronization of movement behavior between agents, or the covariation of their actions. It may even involve both at the same time, as for instance, Black et al. (2007) pointed out. But in any case, it constitutes a way for individuals to act as a whole and to preserve the (mediated) relationship between themselves and their task relevant environment. Riley et al. (2011)'s two critical features, dimensional compression and reciprocal compensations, reside at this level of level of the joint action. Both a relative phase assessment and a UCM analysis can provide evidence for these features. One of the key insights gained from the work of this thesis, however, is that a description of this level *alone* does not suffice to understand real-world interpersonal coordination. The

functional layer is always required to map out the task level constraints under which the coordination between individuals unfolds. In this ball-and-beam context, these constraints involved the task's goal to bring the ball up to speed, leading to a high solo-to-joint transfer of the range and timing of the movement behavior. In other contexts, these constraints are likely to be entirely different. But the fact remains that a complete account of joint action needs to address both the stability and the functionality of the coordination. Only through a combination of these two perspectives can the ecological-dynamical approach foster the study of interpersonal coordination during daily life activities.

6.4. The ball-and-beam paradigm

6.4.1. A new paradigm

In this thesis, we introduced a new experimental paradigm to study interpersonal coordination. In several ways, this paradigm aligned with previous experimental tasks that have been used to study interpersonal coordination from an ecological-dynamical approach (for an overview: Passos et al., 2016). For instance, the ball-and-beam paradigm is a pseudo-rhythmic task that can be performed continuously and for a relatively long duration. In this aspect, it resembles tasks such as side-to-side pendulum swinging (e.g., Schmidt & O'Brien, 1997; Varlet et al., 2012), chair rocking (Richardson, Marsh, Isenhower, et al., 2007) or rope turning (Huys et al., 2018). Rhythmicity facilitates the emergence of a stable mode of interpersonal coordination, which can be characterized by the relative phase between the individuals (e.g., Schmidt & Richardson, 2008). Moreover, it generates repetitive or sustained timeseries that can be analyzed with non-linear timeseries analyses such as measures of fractality or entropy (e.g., Davis et al., 2016). In addition to this, the ball-and-beam paradigm is a perceptuomotor task that requires a continuous coupling between the visual, auditory and haptic perception of the ball and the individual or dyadic tilting of the beam. Such perception-action coupling is paramount to any experimental paradigm in ecological psychology, since the two are commonly considered as two sides of the same coin (Warren, 2006). In that sense, the ball-and-beam task resembles tasks such as for example virtual ball rolling on a labyrinth platform (Rigoli et al., 2015) or actual pole balancing on a finger (Jacobs et al., 2012). Last, but not least, the ball-and-beam paradigm bears strong similarities with the reciprocal pointer-to-target aiming, also known as a continuous Fitts' task (Fitts, 1954). In **Chapter 3** of this thesis, we explicitly compared the behavioral dynamics on the level of the ball and the beam to the behavioral dynamics of the end-effector in reciprocal aiming (Mottet & Bootsma, 1999; Bongers et al., 2009). Although we found large similarities between the ball (in our task) and the end-effector (in pointing), the dynamics at the level of the beam were markedly different.

The ball-and-beam paradigm, as introduced in this thesis, is in many ways unique in its sort (but see Huang et al., 2006, for a small scale version). Its indirect form of control, in which the relationship between one's own movements and those of the to-be-controlled ball are yet to be discovered, is not only challenging, but also highly intriguing. Challenging

for the participant, who has to learn how to couple its movements to an ever accelerating or decelerating ball. And intriguing for the scientist, who aims to understand how the participant manages to do so. Add to this that the task can be performed individually as well as dyadically, and the remarkable potential of this task for the study of human movement reveals itself. In this section, I will highlight some of the most notable aspects of the ball-and-beam paradigm. What makes this task so interesting, compared to the existing paradigms in the field? And how did we exploit these aspects in this thesis? In addressing these questions, I will also critically evaluate the choices we made in our research and propose alternative options. Furthermore, I will point at the potential avenues for future research into this paradigm. How may the ball-and-beam set-up be adapted and improved to facilitate the gathering of new knowledge in the upcoming years? And could the paradigm be applied in any new directions?

6.4.2. Strengths and weaknesses

To begin with, the ball-and-beam task as used in this thesis excelled in its simplicity. In our design, we brought the complexity of a joint action down to an accessible experimental set-up without losing any essential features of the interpersonal coordination. The only things required for our experimental sessions were a small golf ball, a two-meter long beam with markers, a camera on a tripod and a pair of benevolent participants. As difficult as it was for participants to perform the task, so straightforward it was for us, as scientists, to record their performance. To come to this accessible set-up, we made a number of choices in the design of our experiments. In the first place, we chose to limit the plane of motion to two dimensions. In the joint action setting, participants could only move their end of beam up and down or forward and backward. Any sideward movements (i.e., in the direction of the camera), were disallowed by the experimenter. In solo action, the plane of motion was even further limited, to one dimension. Since one of the beam extremities was attached to a static hinge, participants could only rotate the beam handle around this hinge, in a circular path of motion. The ball motion, too, was constrained to a one-dimensional plane, rolling back-and-forth on the beam. In the second place, we chose to limit the analysis to the level of the ball, the beam and the coordination between the two handles, each held by another participant. Accordingly, we only captured the two-dimensional motion of the ball and that of the two extremities, while we derived the angle of inclination from those marker locations. In the third place, we opted for a posteriori tracking of the marker positions via 'Kinovea' software, instead of real time tracking with an active or passive motion capture system. Given that accurate recording of human movement is still technically challenging, this choice contributed significantly to the speed of the data collection and allowed us to conduct several experiments with this new task, in a relatively short amount of time.

The choices we made in our experimental design had a number of downsides as well. The reduction of the ball-and-beam system to only one or two dimensions, of only a ball and two beam extremities, implied a loss in the behavioral complexity. In daily life, our movements unfold in three dimensions. Agents have the freedom to move up and down, forward and backward, left and right, and we rotate as well as translate our limbs. In the

ball-and-beam setting, however, the movement behavior of participants was heavily constrained. Although this was necessary to create a controlled experimental setting, it invertedly limited participants in their freedom. Thereby, it may have excluded potentially interesting movement behavior, like compensatory behavior in a lateral dimension. Nevertheless, we believe that the current paradigm retained the critical features of a joint action, such as a multi-modal coupling between the individuals and a mode of interpersonal coordination subservient to a particular task goal. In the future, the ball-and-beam paradigm could be expanded to a set-up with more dimensions. For instance, the beam could be replaced with a table, allowing the ball to roll on a two-dimensional plane and participants to manipulate the beam in three directions. This would also allow the study of coordination between configurations of three or four individuals, rather than two. Currently, a colleague PhD student at the Faculty of Human Kinetics, Lisbon University, is exploring such an experimental set up, to which we may refer as a ball-on-plate paradigm. Another downside of our current ball-and-beam set up, was the relatively low accuracy of our motion capture system. A posteriori tracking of markers leads to relatively large amounts of noise in the recorded trajectories. Moreover, movements perpendicular to the camera, however scarce, were not recorded. Although the reliability of the data was in my opinion sufficient for current purposes, I think that future studies with this paradigm should consider using more advanced motion capture systems, either active of passive. This would not only produce more reliable data, but also allow a richer recording of the human movement. For instance, the joint angles of the upper extremity, as well as the hip or the legs could be captured accurately with such systems. This would undoubtedly provide new and valuable insights into the coordination of human movement, whether this would be intra- or interpersonally.

6.4.3. Perception, action and direct learning

One of the things that makes the ball-and-beam task so unique, it its indirect form of control. In contrast with almost any other paradigm for joint action (but see for instance Rigoli et al., 2015, for an exception), dyads had to figure out how to exploit an external force to control a (rolling) object, without being able to communicate with each other. As a result of this indirect control, at least three levels of observation can be distinguished: from the level of ball, via the level of the beam to the level of the interpersonal coordination. If future studies would include joint angle motion of the body to the analysis, this would even constitute a fourth level of analysis. This multi-level analysis creates a unique insight into the layered coordination of a multi-individual system. While each level has its own characteristic features, all levels are related, often in a highly complex manner. In this context, the results of this thesis are just a tip of the iceberg. Much more research is required to understand how individuals coordinate their movements, but also how the beam-level movements are coupled to the ball-level motion. Which optical or acoustic variables of information do agents use to guide their movements? How do they learn to couple, in other words, their perception to their action? As we showed in **Chapter 3**, these questions are best addressed in a solo action context, at least initially. In solo action, the beam only moves in one dimension, which makes both the task of the participant and the

analysis of the scientist easier. This, however, relies on the assumption that perceptuomotor control in solo and joint action is comparable. In **Chapter 4** and **5** of this thesis, we showed that is assumption is valid. A high transfer of skill from solo action to joint action was found in either of the two experiments. Also, we found a similar speed-accuracy trade-off on the level of the ball in both contexts.

A theoretical framework that may be well suited to address the process of perceptuomotor in this task paradigm is that of Direct Learning (Jacobs & Michaels, 2007). According to Direct Learning, practice-induced changes in perception and action are ultimately specific to ecological information, that is, to properties of the ambient optical or acoustic energy arrays in relation to the perceiving agent. As a way to study such specificity, Jacobs & Michaels, (2007) introduced the notion of an information space. This is a multi-dimensional space spanned by candidate informational variables, in which a pathway of learning from the use of one variable to another can be visualized. From this pathway, a vector field can be derived which would hypothetically represent the information for learning. Jacobs et al. (2012) applied this rationale to pole balancing, a challenging task that requires a continuous coupling of what one sees and what one does. In this study, they created an information-action space that included not only variables related to ecological information, but also variables related to the action. More specifically, one dimension was related to the force that participants applied to the pole, while another was related to the angle of the pole (i.e., its angular deviation from upright stance). The results showed that learners generally followed a similar pathway through this space over trials, suggesting that information for learning was available to them. Given the resemblance of the pole balancing with ball-on-beam rolling, I speculate that this methodology may be applicable to our paradigm as well. The information-action space may be spanned by variable(s) related to ball motion on the one hand, and variable(s) related to the beam's inclination angle on the other hand. Over the past years, we have been in contact with David Jacobs to develop a Direct Learning account for the ball-and-beam paradigm. Up to date, we have not managed to do so. However, I believe that the combination of the ball-and-beam task as experimental paradigm and Direct Learning as theoretical backbone, could be fruitful in discovering lawfulness in perceptuomotor learning. This, in turn, could serve as a stepping stone to address the issue of interpersonal coordination, in which individuals not only have to coordinate their movements with respect to the rolling ball, but also with respect to someone else.

6.4.4. Other applications

Interpersonal coordination and perceptuomotor control are by no means the only issues that can be addressed with the ball-and-beam paradigm. The task can also be used for research related to for instance verbal communication in joint action (e.g., Paxton et al., 2021) or feedback-based learning (e.g., Starzak et al., 2022). Let me conclude this task evaluation by elaborating on these potential pathways for future research. In this thesis, we were interested in the emergence of interpersonal coordination under non-verbal conditions. It is also possible, however, to allow participants to communicate so as to study their verbal interaction. What are effective ways for dyads to communicate with

each other during the interaction? Should they instruct each other? Or is it better to keep quiet? As experimenter, I frequently noticed how difficult it was for participants to refrain from talking to their co-actor. More than once, participants had to resist the urge to give advice to their partner – or to express their frustration in failing to hit the targets. In could be highly insightful to record and analyze the things people say to each other. From another angle, the ball-and-beam task could be used to study the influence of feedback on the learning process. In the experiments of this thesis, we provide participants afterwards with feedback on their score (i.e., the number of target hits), in order to encourage them. It would also have been possible to refrain from giving any feedback, or to include real time feedback during the performance. Future research should point out which forms of feedback is most efficient to help participants in learning the task. All in all, I conclude that the ball-and-beam paradigm, despite of its inevitable flaws and shortcomings, provides plenty of opportunities for research into human (movement) behavior.

6.5. Implications and applications

6.5.1. From theory to practice

This thesis belongs to the category of fundamental research. Through our experiments, we developed abstract knowledge about interpersonal movement coordination, a phenomenon that nevertheless pervades human life. Multiple times a day, people are confronted with the task to coordinate their movements with other individuals. Whether we help each other in household activities, pass the ball to one another on the soccer field or shake hands with a partner to close a business deal: interpersonal coordination is part and parcel of our daily routines. Although all of these so-called joint actions are different, they share at least two critical features. First, they require a perceptual, often multi-modal coupling between individuals. And second, they would not be possible without a spatiotemporal coupling of the movement behavior between the individuals. In the ball-and-beam paradigm, we reduced the complexity of a joint action to the simplicity of a controlled experimental setting, without losing these two critical features. Even though we exclusively studied the movement behavior of participants in a highly constrained laboratory set up, we did so under the assumption that the conclusions being derived from it would be at least partially applicable to human behavior outside the laboratory. In other words, we were and are deeply convinced that our conclusions are, to some extent, generalizable to the joint actions exemplified above.

At the same time, we realize that the abstraction presented in this thesis may be difficult to apply to the reality of our daily life. Every behavioral setting brings a unique set of constraints, both in terms of the environment and in terms of the individuals and the tasks they are confronted with. This idiosyncrasy may obscure the regularities that underly our behavior, since the same ‘rules’ can lead to a different ‘game’ whenever the circumstances change. The translation from theory to practice is thus not straightforward. It would require a specification of the context in which a (joint) action takes place, to what purpose and under which conditions. This is beyond the scope of this thesis. It would

perhaps be more valuable if I would instead reflect on how our lab-based work could ultimately contribute to a societal practice that is related to the issues addressed in this thesis. An example of such a practice is perceptuomotor rehabilitation. This can be defined as the re-learning of perception and action in the context of functional impairments or perceptuomotor disabilities (https://repairs-etn.eu/). Since this thesis is about how we learn to move, in particular in an interpersonal context, our research may have important repercussions for this domain. In rehabilitation, patients often interact with their therapist. What may the findings of this thesis tell us about these types of joint actions? And can the ball-and-beam paradigm perhaps be used as a tool for rehabilitation? In this section, I will address these questions via the example of a mild arm paresis after stroke. In doing so, I hope to demonstrate the relevance of our research for society. Also, my aim is to sketch the outlines of a research program that may follow from our work.

6.5.2. Rehabilitation of mild arm paresis

A major cause of perceptuomotor disabilities among both younger and older populations is stroke (Hatem et al., 2016). A stroke can lead to the full paralysis of body parts, but also to a paresis, meaning that the motor control and muscle strength in those body parts is moderately affected. While a complete recovery after paralysis is rare, rehabilitation can lead to significant functional improvements in paresis (e.g., Hendricks et al., 2002). These improvements are crucial to preserve a high quality of life for the patient, who is impaired in its daily functioning. To date, there are numerous interventions for improving dexterity in mild (arm) paresis after stroke, ranging from neuromuscular stimulation and mirror therapy to virtual reality immersion and robot assisted therapies (Hayward et al., 2010; Pollock et al., 2014; Bertani et al., 2017). From this wealth of literature, a number of ground rules for rehabilitation practice seem to emerge. First of all, in the first 6 months after an acute stroke, intensified rehabilitation with a large amount of repetitive movements of the affected limb is beneficial to the recovery process (Oujamaa et al., 2009; Buma et al., 2013; Bertani et al., 2017). In second place, the training of goal-directed movement, with a functional or task specific coupling between perception and action, is more beneficial than non-goal-directed movement (Urton et al., 2007; Pollock et al., 2014; Bertani et al., 2017). And thirdly, the intervention needs to be tailored to the individual needs of the patient for it to be optimally efficient (Hatem et al., 2016). Research suggests that interventions which meet these requirements have a higher chance of fostering functional improvements of the affected limbs.

In my admittedly modest view, the ball-and-beam paradigm could serve as a rehabilitation tool for mild arm paresis. In addition to being a highly enjoyable task, the paradigm has the potential to meet all three aforementioned characteristics of an efficient intervention. To begin with, a ball-and-beam performance requires repetitive rotational movements of the arm-shoulder system, with a load that can be tailored to the specific demands of the patient. The beam can be made heavier or lighter, dependent on the strength of the patient's upper extremity. Furthermore, the required movements are functionally specific, in the sense that the action of lifting or lowering the beam needs to be timely coupled to the perception of the ball to hit the targets. Again, the difficulty of

this task can be adjusted to the needs of the patient. In case of more severe paresis, for instance, the ball can be made heavier and larger such that the sensitivity of the coupling is lower and the task is easier to execute. Likewise, the size of the beam can be tailored to the range of motion of the patient, who is invertedly limited in his or her movements. And last but not least, the joint action version of the task can be performed in synergy with a therapist, which may be beneficial to the recovery. A large advantage of the ball-and-beam task, in comparison to for instance robot assisted therapy, is that the paradigm is cheap and highly accessible. Given my limited expertise in the domain of rehabilitation, however, it befits me to speculate on this matter with some caution. It would perhaps be more helpful if I were to envision some of the research steps that would be minimally required for a ball-and-beam rehabilitation tool to be developed. In my perception, follow-up studies into this issue could concern both fundamental and applied research, either at universities or at rehabilitation centers. Ideally, this work would be conducted in close collaboration with a continuous interplay between both worlds.

6.5.3. Avenues for future research

On the fundamental side, future research into the ball-and-beam paradigm could investigate the hypothesis that joint action practice of a patient together with a therapist is beneficial to the functional recovery of that patient. In this thesis, we showed that individual task practice in a solo action setting was beneficial to the perceptuomotor performance of dyads in a joint action setting. Future research should point out, however, whether the reverse is true as well. Is dyadic practice in joint action also beneficial to the performance of individuals in solo action? If so, this would provide a first indication that interpersonal coordination in the context of the ball-and-beam task may have a profitable effect on a perceptuomotor performance. In **Chapter 2** we already showed that 15 two-minute trials of joint action did *not* have a significant impact on the performance in a subsequent solo action session. I suggest that a new series of studies should build upon this result by for instance extending the amount of joint action practice to multiple sessions or by pairing experienced ball-and-beam players with unexperienced players. In such a set-up, the participant with task experience would take the role of 'therapist', while the participant without task experience would fill the role of 'patient'. An alternative design could be to experimentally constrain one of the dyad members, either by limiting their range of motion or by limiting their access to visual or auditory information. If the constrained participant (the 'patient') benefits from practice with the unconstrained participant (the 'therapist'), this would serve as an indication that joint action practice is helpful in functionally restoring that patients' capacity to move. Of course, such designs could also be applied to other experimental paradigms than the ball-and-beam set up, under the condition that these tasks can be performed individually as well as dyadically (e.g., rope turning, Huys et al., 2018).

On the applied side, future research could explore the hypothesis that the ball-and-beam task can be used as an intervention tool for the rehabilitation of impairments such as mild arm paresis. Post-stroke, patients are severely limited in their perceptuomotor capacities (Hatem et al., 2016). It is unlikely that the task, in its current form, can be useful

for those patients. As such, the physical requirements of the task need to be tailored to the needs of a patient before any intervention can be conducted. In my opinion, this should first be explored in the solo action setting of the task, preferably in close interaction with patients and therapists. In the latter stages of my doctoral project, I visited *Revalidatie Friesland*, a rehabilitation clinic in the north of The Netherlands. During this visit, I had an open conversation with two of the clinicians about the translation of scientific knowledge to rehabilitation practice. One of the valuable things I learned from this conversation is that the word 'functional', in reference to a particular task, is highly ambiguous. When a scientist speaks of functionality, they may refer to the general fact that a task can only be achieved by coupling action to perception. However, when a therapist speaks of functionality, they may refer to the fact that a task is part of the daily routine of a patient. From the grasping of a cup of coffee to getting dressed in the morning: functionality would refer to everything that is essential to the quality of life of that patient. Although the ball-and-beam paradigm complies with the scientific definition of functionality, it certainly does not meet the therapeutic definition. This example illustrates the large conceptual gap between science and practice. Before any successful translation of knowledge can be achieved, this gap first needs to be addressed, acknowledged and bridged (Di Rienzo, 2023) – a process that requires years. If, after all this time, rehabilitation clinics happen to see potential value in the ball-and-beam paradigm for the recovery of their patients, the next step could be to design a clinical experiment. But for now, it seems more fruitful to continue the conversation between science and practice, and to come closer together.

6.5.4. Augmented reality

In the potential transformation of the ball-and-beam paradigm into an intervention for rehabilitation, research could benefit from recent developments in the field augmented reality, AR in short (e.g., Schnier et al., 2011; Miller et al., 2019). Earlier, I mentioned that the ball-and-beam task should be tailored to the demands of the patients. Not only is every patient different in its clinical needs, but the perceptuomotor capabilities of a patient also change over the course of rehabilitation. The flexibility that the advancements in technology can provide us with, can help to customize the task to a patient's needs. Recently, we developed a pilot version of an augmented reality ball-and-beam task. In this 'AR game', participants wore glasses that projected a virtual ball on an actual beam. By tilting the beam up and down, participants had to roll this virtual ball back and forth between two projected targets on the beam, similar to the regular task. But by using a virtual rather than an actual ball, this AR game was much more flexible than the regular version. For example, the size and mass of the ball could be adjusted anytime, just like its color or texture. More rigorously, we could also adjust the effect of gravity or friction, which simply constituted a set of formulas and parameters in the setting of the AR game. Additionally, it became possible for us to change the location or size of the targets (or properties of the ball, for that matter) *during* the performance. And lastly, all of these changes could be personalized, in the sense that they would apply only to one of the two dyad members playing the task. This way, there is a possibility to adjust the difficulty of the task to level of the player, either in real time of between trials. The first experiments

with the pilot version of our AR game showed that the task was feasible for healthy young adults to play. In terms of the speed and accuracy of the participants' motor behavior, the results were roughly comparable to what we found in the experiments of this thesis. Future work is required to realize the full potential of this AR ball-and-beam game.

6.6. Conclusion

The main thrust of this thesis was to provide an ecological account of interpersonal coordination in the context of a functional, that is, a goal-directed joint action. To this end, we designed a new experimental paradigm in which (dyads of) participants had to control a ball rolling reciprocally between two targets on a long and hand-held beam. With this ball-and-beam task, we conducted a series of experiments that included both solo action and joint action performances. Together, these experiments led to the following conclusions. To begin with, the interpersonal coordination in joint action was qualitatively dependent on the individual task experience of the participants in solo action. While unexperienced dyads adopted a sequential mode of coordination, experienced dyads opted for the more successful simultaneous mode of coordination. In ecological terms, we interpreted this finding as whether or not the members of a dyad enacted the social affordance – the opportunity for joint action – that was offered by the lay-out of the task. Building upon this first conclusion, we further investigated the transfer of skill from the solo action to the joint action context. In a two-step study involving both solo and joint action, we proposed a new methodology to identify what each dyad member brought to the interaction and what they left behind. We denoted this the solo-to-joint transfer analysis. Using this analysis, we found that those performance characteristics that were somehow related to ball speed were strongly propagated from the solo to the joint action, while the characteristics related to ball accuracy and beam consistency were only moderately transferred. Also, the dyad members that produced a higher ball speed in solo action were significantly more likely to take the lead in the interaction. Together, this led to a second conclusion. The stability of the interpersonal coordination emerged from the dyad members' interaction, while being qualitatively constrained by the task goal to bring the ball up to speed.

This second conclusion brings out the two-faced character of interpersonal coordination during joint action. On the one hand, the dyads in our studies collectively attempted to find a stable solution to the ball-and-beam task. They synchronized their movements and compensated for each other's actions during the trial. Moreover, the stability of their interpersonal coordination was found to be emergent from the interaction, rather than determined in advance. All of this suggests that the dyads in our experiments formed an interpersonal synergy: a self-organizing mode of coordination across interacting individuals (Riley et al., 2011). On other hand, the dyads also tried to achieve a particular task goal that went beyond the stability of their interaction. In fact, the interpersonal coordination allowed them to acquire more target hits than what they could have achieved individually, via a collective strategy of moving the beam handles

antagonistically up and down. In my view, this constitutes a second feature of an interpersonal synergy. An synergy is not only a stable solution, but it *also* increases the action capabilities of the interacting individuals. Crucially, this second feature cannot be understood on the level of the interpersonal coordination itself. It necessarily appeals to a functional level of the joint action. As such, a key insight gained from this thesis is that an understanding of interpersonal coordination in a goal-directed joint action, requires at least two levels of observation. One pertaining to the stability of the interpersonal coordination and one pertaining to the goal of the joint action. In other words, an ecological account of joint action needs to address not only the stability, but also the functionality of the interpersonal coordination. The current thesis served as an illustration of this dual approach.

Epilogue

I have spoken, in this thesis, of perception and action. I have spoken of human movement, of coordination and of control. I have addressed individuals and dyads, solo and joint action, intra- and interpersonal coordination. But one thing have left untouched, is the human experience. In our experiments, we recorded hours of timeseries of a ball and two beam extremities. We reduced the 62 participants in our experiments to moving dots on a two dimensional computer screen. But by doing so, we neglected the experiences that those participants had during their performances. What the reports in this thesis do not show, is what each individual *thought* while they were tilting the beam, what they *felt*, or what they *sensed*. We could, of course, dismiss these experiences as another dimension of the behavior that is unrelated to the topic of our interest – interpersonal movement coordination. We could disregard these experiences as intangible reflections of an 'inner world' that is only vaguely connected with the 'outer world' on which we focused. I think, however, that this would be a mistake. In the first place, because the distinction between an inner and an outer world is a remnant of the Cartesian dualism of mind and body, which has no place in an ecological psychology. And in the second place, because my observations during the experiments gave sufficient reason to take the dimension of human experience seriously.

From the very first experimental session, I noticed something interesting. Almost without exception, participants were more engaged in the joint action session than in the solo action session. When playing the ball-and-beam task individually, they were calm, quiet and occasionally bored, no matter how challenging it was for them to control the rolling ball. But when playing the task dyadically, participants were energetic, passionate and seemingly entertained. Although I instructed them not communicate, they often could not resist the urge to express their emotions to each other. Whether it was the joy of hitting a target or the annoyance of missing it, they occasionally felt the need to let their co-actor known what they experienced. Also, the participants' desire to instruct each other, on what to do or what not to do, was remarkably strong. More than once, I have had to remind them of the rule not to talk to each other, in particular with respect to any task strategies. To me, this dyadic energy was revealing. It showed that people trigger something in each other, that they affect one another, whether this is positive or negative. Apparently, joint action is substantially different from solo action, in the sense that it brings an entirely different experience for those who partake in it. Technically speaking, the task for participants in both settings was exactly the same. They had to roll a ball fast and accurately between two targets on the beam. Yet, in terms of the energy it evoked, the two experimental settings were miles apart. This made me aware of a dimension of interpersonal coordination that I did not address in this thesis, but that nevertheless deserves to be highlighted here.

Interpersonal coordination is not only a matter of spatiotemporal coupling between interacting individuals, as I framed it in this thesis. It is also a matter of agreement and of trust, a matter of anticipation and of recognition. Whenever we tune into the actions of

the other, we do more than merely adapting our movements to that person, as if they were a lifeless object. We co-create our movements with that someone. Such co-creation can only be achieved when we understand what the other is doing, when we have a mutual feeling for what we intend to accomplish together. This shared experience is much more than the individual's cognitive interpretation – or representation, for that matter – of what is happening. It is an embodied understanding that is woven through the human interaction. It is *perceivable* to those who attend to it. Trust is embodied in anticipatory movements, much like recognition is visible as faint smile and understanding as a quick nod. This makes interpersonal coordination, as a phenomenon, fundamentally different from object oriented coordination. In my view, this layer of shared experience should be included if when one wishes to understand interpersonal coordination, in all of it richness. Indeed, I would go as far as to claim that the social dimension of human behavior goes beyond the type of interactions we addressed here. As I sketched in the opening pages of this thesis, most of us live in a world that is made by and made for humans. From streets to buildings, from trash cans to vending machines and from cars to bicycles: we continuously find ourselves in places that are made for us to interact with. As such, I believe that the ecological study of perception and action could benefit from the experiences we have and display whenever we interact with this inherently social world.

Bibliography

Abney, D. H., Paxton, A., Dale, R., & Kello, C. T. (2015). Movement dynamics reflect a functional role for weak coupling and role structure in dyadic problem solving. Cognitive Processing, 16(4), 325–332. https://doi.org/10.1007/s10339-015-0648-2.

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. Psychological bulletin, 101(1), 41. https://doi.org/10.1037/0033-2909.101.1.41.

Amazeen, P. G., Schmidt, R. C., & Turvey, M. T. (1995). Frequency detuning of the phase entrainment dynamics of visually coupled rhythmic movements. Biological Cybernetics, 72(6), 511–518. https://doi.org/10.1007/BF00199893.

Anderson, D. L., and Sidaway, B. (1994). Coordination changes associated with practice of a soccer kick. Research Quarterly for Exercise and Sport 65, 93–99. https://doi.org/10.1080/02701367.1994.10607603.

Araújo, D., & Davids, K. (2016). Team Synergies in Sport: Theory and Measures. Frontiers in Psychology, 7. https://doi.org/10.3389/fpsyg.2016.01449.

Aune, T. K., Pedersen, A. V., & Ingvaldsen, R. P. (2008). Dominant Paradigms in Motor Behavior Research: The Motor-Action Controversy Revisited. Perceptual and Motor Skills, 106(2), 573–578. https://doi.org/10.2466/pms.106.2.573-578.

Azaad, S., Knoblich, G., & Sebanz, N. (2021). Perception and Action in a Social Context (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009029049.

Backe, A. (2001). John Dewey and early Chicago functionalism. History of Psychology, 4(4), 323–340. https://doi.org/10.1037/1093-4510.4.4.323.

Baron, R. (2007). Situating Coordination and Cooperation Between Ecological and Social Psychology. Ecological Psychology, 19(2), 179–199. https://doi.org/10.1080/10407410701332106.

Beek, P. J., & Meijer, O. G. (1988). Chapter 5 On the Nature of the Motor action Controversy. In Advances in Psychology (Vol. 50, pp. 157–185). Elsevier. https://doi.org/10.1016/S0166-4115(08)62555-8.

Beek, P. J., Peper, C. E., & Stegeman, D. F. (1995). Dynamical models of movement coordination. Human Movement Science, 14(4–5), 573–608. https://doi.org/10.1016/0167-9457(95)00028-5.

Bernstein, N. A. (1967). The Co-ordination and Regulation of Movements. Oxford: Pergamon Press.

Bertani, R., Melegari, C., De Cola, M. C., Bramanti, A., Bramanti, P., & Calabrò, R. S. (2017). Effects of robot-assisted upper limb rehabilitation in stroke patients: A systematic review with meta-analysis. Neurological Sciences, 38(9), 1561–1569. https://doi.org/10.1007/s10072-017-2995-5.

Bizzi, E., Cheung, V. C. K., d'Avella, A., Saltiel, P., & Tresch, M. (2008). Combining modules for movement. Brain Research Reviews, 57(1), 125–133. https://doi.org/10.1016/j.brainresrev.2007.08.004.

Black, D. P., Riley, M. A., & McCord, C. K. (2007). Synergies in Intra- and Interpersonal Interlimb Rhythmic Coordination. Motor Control, 11(4), 348–373. https://doi.org/10.1123/mcj.11.4.348.

Bolívar-Vincenty, C. G., and Beauchamp-Báez, G. (2014). Modelling the ball-and-beam system from Newtonian mechanics and from Lagrange method. in Twelfth LACCEI Latin American and Caribbean Conference for Engineering and Technology (LACCEI'2014) (Guayaquil, Ecuador). Available at: http://laccei.org/LACCEI2014-Guayaquil/RefereedPapers/RP176.pdf.

Bongaardt, R. (1996). Shifting focus: The Bernstein tradition in movement science (Doctoral dissertation). Vrije Universiteit, Amsterdam.

Bongaardt, R., & Meijer, O. G. (2000). Bernstein's Theory of Movement Behavior: Historical Development and Contemporary Relevance. Journal of Motor Behavior, 32(1), 57–71. https://doi.org/10.1080/00222890009601360.

Bongers, R. M., Fernandez, L., & Bootsma, R. J. (2009). Linear and logarithmic speed–accuracy trade-offs in reciprocal aiming result from task-specific parameterization of an invariant underlying dynamics. Journal of Experimental Psychology: Human Perception and Performance, 35(5), 1443–1457. https://doi.org/10.1037/a0015783.

Bootsma, R. J. (1988). The timing of rapid interceptive actions: Perception-action coupling in the control and acquisition of skill (Doctoral dissertation). Free University Press.

Bootsma, R. J. (1998). Ecological movement principles and how much information matters. In A. A. Post, J. R. Pijpers, P. Bosch, & M. S. J. Boschker (Eds.), Models in Human Movement Science (pp. 51–63). PrintPartners Ipskamp. https://www.researchgate.net/publication/259591214_Ecological_movement_principles_and_how_much_information_matters.

Bootsma, R. J., & van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table tennis. Journal of Experimental Psychology: Human Perception and Performance, 16(1), 21–29. https://doi.org/10.1037//0096-1523.16.1.21.

Bootsma, R. J., Fernandez, L., & Mottet, D. (2004). Behind Fitts' law: kinematic patterns in goal-directed movements. International Journal of Human-Computer Studies, 61, 811–821. https://doi.org/10.1016/j.ijhcs.2004.09.004.

Borelli, G. A. (1680). De Motu Animalium (On the Motion of Animals). Rome: Ex Typographia Ciriaca.

Borooghani, D., Casanova, R., Zaal, F. T. J. M., & Bootsma, R. J. (2024). Toward an Operational Dynamical Model of Lateral Manual Interception Behavior. Motor Control, 1–16. https://doi.org/10.1123/mc.2024-0036.

Bregman, R. (2020). Humankind: A hopeful history (De meeste mensen deugen). Bloomsbury Publishing (De Correspondent).

Brennan, S. E., Chen, X., Dickinson, C. A., Neider, M. B., & Zelinsky, G. J. (2008). Coordinating cognition: The costs and benefits of shared gaze during collaborative search. Cognition, 106(3), 1465–1477. https://doi.org/10.1016/j.cognition.2007.05.012.

Brette, R. (2022). Brains as Computers: Metaphor, Analogy, Theory or Fact? Frontiers in Ecology and Evolution, 10, 878729. https://doi.org/10.3389/fevo.2022.878729.

Bruineberg, J., Withagen, R., & Van Dijk, L. (2024). Productive pluralism: The coming of age of ecological psychology. Psychological Review, 131(4), 993–1006. https://doi.org/10.1037/rev0000438.

Buma, F., Kwakkel, G., & Ramsey, N. (2013). Understanding upper limb recovery after stroke. Restorative Neurology and Neuroscience, 31(6), 707–722. https://doi.org/10.3233/RNN-130332.

Butterfill, S. (2012). Joint action and development. The Philos Q 62, 23–47. https://doi/10.1111/j.1467-9213.2011.00005.x.

Carruthers, G. (2008). Types of body representation and the sense of embodiment. Consciousness and Cognition, 17(4), 1302–1316. https://doi.org/10.1016/j.concog.2008.02.001.

Chemero, A. P. (2009). Radical Embodied Cognitive Science. The MIT Press. https://doi.org/10.7551/mitpress/8367.001.0001.

Chen, H.-H., Liu, Y.-T., Mayer-Kress, G., & Newell, K. M. (2005). Learning the pedalo locomotion task. Journal of Motor Behavior, 37(3), 247–256. https://doi.org/10.3200/JMBR.37.3.247-256.

Cisek, P. (n.d.). Beyond the computer metaphor: behavior as interaction. d'Avella, A., & Lacquaniti, F. (2013). Control of reaching movements by muscle synergy combinations. Frontiers in Computational Neuroscience, 7. https://doi.org/10.3389/fncom.2013.00042.

Coey, C. A., Varlet, M., & Richardson, M. J. (2012). Coordination dynamics in a socially situated nervous system. Frontiers in Human Neuroscience, 6. https://doi.org/10.3389/fnhum.2012.00164.

Costall, A. (1995). Socializing Affordances. Theory & Psychology, 5(4), 467–481. https://doi.org/10.1177/0959354395054001.

Cuijpers, L. S. (2019). Coordination dynamics in crew rowing [Doctoral Thesis, University of Groningen]. https://doi.org/10.33612/diss.94906482.

Cuijpers, L. S., Passos, P. J. M., Murgia, A., Hoogerheide, A., Lemmink, K. A. P. M., & De Poel, H. J. (2017). Rocking the boat: Does perfect rowing crew synchronization reduce detrimental boat movements? Scandinavian Journal of Medicine & Science in Sports, 27(12), 1697–1704. https://doi.org/10.1111/sms.12800.

Cuijpers, L. S., Zaal, F. T. J. M., & De Poel, H. J. (2015). Rowing Crew Coordination Dynamics at Increasing Stroke Rates. PLOS ONE, 10(7), e0133527. https://doi.org/10.1371/journal.pone.0133527.

Darwin, C. (1859). The Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life. 150th Anniversary Edition (2003). New York: Signet Classics.

Davis, T. J., Brooks, T. R., & Dixon, J. A. (2016). Multi-scale interactions in interpersonal coordination. Journal of Sport and Health Science, 5(1), 25–34. https://doi.org/10.1016/j.jshs.2016.01.015.

De Poel, H. J. (2016). Anisotropy and antagonism in the coupling of two oscillators: Concepts and applications for between-person coordination. Frontiers in Psychology, 7. https://doi.org/10.3389/fpsyg.2016.01947.

Debono, D., and Bugeja, M. (2015). Application of sliding mode control to the ball and plate problem: in Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics (Colmar, Alsace, France: SCITEPRESS - Science and Technology Publications), 412–419. http://doi.org/10.5220/0005569804120419.

Descartes, R. (1644). Principia philosophiae [The principles of philosophy]. In C. D. Broad (Ed.), The philosophical works of Descartes (Vol. 1, pp. 1–198). Cambridge University Press, 1911.

Dewey, J. (1896). The reflex arc concept in psychology. Psychological Review, 3(4), 357–370.

Di Rienzo, G. (2023). Situating the KTA gap in clinical research: Foregrounding a discontinuity in practices. Frontiers in Psychology, 13, 1058845. https://doi.org/10.3389/fpsyg.2022.1058845.

Didier, J. J., Li, L., and Magill, R. A. (2013). Environmental context affects outcome and kinematic changes at different rates during skill learning. Percept Mot Skills 116, 953–968. https://doi.org/10.2466/25.23.PMS.116.3.953-968.

Dijksterhuis, E. J. (1950). De mechanisering van het wereldbeeld. Noord-Hollandsche Uitgeversmaatschappij.

Domkin, D., Laczko, J., Djupsjöbacka, M., Jaric, S., & Latash, M. L. (2005). Joint angle variability in 3D bimanual pointing: Uncontrolled manifold analysis. Experimental Brain Research, 163(1), 44–57. https://doi.org/10.1007/s00221-004-2137-1.

Fan, X., Zhang, N., and Teng, S. (2004). Trajectory planning and tracking of ball and plate system using hierarchical fuzzy control scheme. Fuzzy Sets Syst 144, 297–312. https://doi.org/10.1016/S0165-0114(03)00135-0.

Fernandez, L., & Bootsma, R. J. (2008). Non-linear gaining in precision aiming: Making Fitts' task a bit easier. Acta Psychologica, 129(2), 217–227. https://doi.org/10.1016/j.actpsy.2008.06.001.

Fishburn, F. A., Murty, V. P., Hlutkowsky, C. O., MacGillivray, C. E., Bemis, L. M., Murphy, M. E., Huppert, T. J., & Perlman, S. B. (2018). Putting our heads together: Interpersonal neural synchronization as a biological mechanism for shared intentionality. Social Cognitive and Affective Neuroscience, 13(8), 841–849. https://doi.org/10.1093/scan/nsy060.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol 47, 381–391. https://doi.org/10.1037/h0055392.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67(2), 103–112. https://doi.org/10.1037/h0045689.

Floegel, M., Kasper, J., Perrier, P., & Kell, C. A. (2023). How the conception of control influences our understanding of actions. Nature Reviews Neuroscience, 24(5), 313–329. https://doi.org/10.1038/s41583-023-00691-z.

Foo, P., Kelso, J. A. S., and De Guzman, G. C. (2000). Functional stabilization of unstable fixed points: Human pole balancing using time-to-balance information. J Exp Psychol Hum Percept Perform 26, 1281–1297. https://doi.org/10.1037/0096-1523.26.4.1281.

Fuchs, A., & Kelso, J. A. S. (1994). A theoretical note on models of interlimb coordination. Journal of Experimental Psychology: Human Perception and Performance, 20(5), 1088– 1097. https://doi.org/10.1037/0096-1523.20.5.1088.

Fusaroli, R., Rączaszek-Leonardi, J., & Tylén, K. (2014). Dialog as interpersonal synergy. New Ideas in Psychology, 32, 147–157. https://doi.org/10.1016/j.newideapsych.2013.03.005.

Gallese, V. (2003). The roots of empathy: The shared manifold hypothesis and the neural basis of intersubjectivity. Psychopathology, 36(4), 171–180. https://doi.org/10.1159/000072786.

Ganesh, G., Takagi, A., Osu, R., Yoshioka, T., Kawato, M., & Burdet, E. (2014). Two is better than one: Physical interactions improve motor performance in humans. Scientific Reports, 4(1), 3824. https://doi.org/10.1038/srep03824.

Gibson, J. J. (1979). The Ecological Approach to Visual Perception: Classic Edition (1st ed.). Psychology Press. https://doi.org/10.4324/9781315740218.

Godfrey-Smith, P. (2024). Living on Earth: Life, Consciousness, and the Making of the Natural World. William Collins.

Gomez-Marin, A., & Ghazanfar, A. A. (2019). The Life of Behavior. Neuron, 104(1), 25–36. https://doi.org/10.1016/j.neuron.2019.09.017.

Gray, R. (2020). Changes in movement coordination associated with skill acquisition in baseball batting: freezing/freeing degrees of freedom and functional variability. Front. Psychol. 11, 1295. https://doi.org/10.3389/fpsyg.2020.01295.

Gray, R., & Sullivan, R. (2023). A Constraints-Led Approach to Baseball Coaching (1st ed.). Routledge. https://doi.org/10.4324/9781003274490.

Green, C. D. (2009). Darwinian theory, functionalism, and the first American psychological revolution. American Psychologist, 64(2), 75–83. https://doi.org/10.1037/a0013338.

Guimarães, A. N., Ugrinowitsch, H., Dascal, J. B., Porto, A. B., & Okazaki, V. H. A. (2020). Freezing degrees of freedom during motor learning: A systematic review. Motor Control, 24(3), 457–471. https://doi.org/10.1123/mc.2019-0060.

Hafkamp, M. S. J., Casanova, R., & Bootsma, R. J. (2023). Freezing and freeing of degrees of freedom in joint action learning. Frontiers in Psychology, 14, 1287148. https://doi.org/10.3389/fpsyg.2023.1287148.

Hafkamp, M. S. J., Casanova, R., & Bootsma, R. J. (2024). Perceptuomotor skill acquisition in a solo manual ball-and-beam task with varying accuracy requirements. Frontiers in Psychology, 15, 1436099. https://doi.org/10.3389/fpsyg.2024.1436099.

Haken, H. (1983). Synergetics: An introduction. Nonequilibrium phase transitions and self-organization in physics, chemistry, and biology (3rd ed.). Springer.

Haken, H., & Wunderlin, A. (1990). Synergetics and its paradigm of self-organization in biological systems. In: The natural-Physical Approach to Movement Control, pp. 1-36 H.T.A. Whiting, H.T.A., Meyer, O.G & Van Wieringen, P.C.W. VU University Press.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. Biological Cybernetics, 51(5), 347–356. https://doi.org/10.1007/BF00336922.

Hamilton, A. F. D. C. (2021). Hyperscanning: Beyond the Hype. Neuron, 109(3), 404–407. https://doi.org/10.1016/j.neuron.2020.11.008.

Harari, Y. N. (2014). Sapiens: Een kleine geschiedenis van de mensheid (A brief history of humankind). Thomas Rap.

Harrison, S. J., & Richardson, M. J. (2009). Horsing Around: Spontaneous Four-Legged Coordination. Journal of Motor Behavior, 41(6), 519–524. https://doi.org/10.3200/35-08-014.

Hasanbarani, F., & Latash, M. L. (2020). Performance-Stabilizing Synergies in a Complex Motor Skill: Analysis Based on the Uncontrolled Manifold Hypothesis. Motor Control, 24(2), 238–252. https://doi.org/10.1123/mc.2019-0049.

Hasson, U., Ghazanfar, A. A., Galantucci, B., Garrod, S., & Keysers, C. (2012). Brain-to-brain coupling: A mechanism for creating and sharing a social world. Trends in Cognitive Sciences, 16(2), 114–121. https://doi.org/10.1016/j.tics.2011.12.007.

Hatem, S. M., Saussez, G., Della Faille, M., Prist, V., Zhang, X., Dispa, D., & Bleyenheuft, Y. (2016). Rehabilitation of Motor Function after Stroke: A Multiple Systematic Review Focused on Techniques to Stimulate Upper Extremity Recovery. Frontiers in Human Neuroscience, 10. https://doi.org/10.3389/fnhum.2016.00442.

Hauser, J., Sastry, S., and Kokotovid, P. (1992). Nonlinear control via approximate input-output linearization: The ball and beam example. IEEE Trans. Automat. Contr. 37, 392–398. doi: https://doi.org/10.1109/9.119645.

Hayward, K., Barker, R., & Brauer, S. (2010). Interventions to promote upper limb recovery in stroke survivors with severe paresis: A systematic review. Disability and Rehabilitation, 32(24), 1973–1986. https://doi.org/10.3109/09638288.2010.481027.

Heft, H. (2007). The Social Constitution of Perceiver-Environment Reciprocity. Ecological psychology. 19:2, 85-105. https://doi.org/10.1080/10407410701331934.

Heft, H. (2020). Ecological psychology as social psychology? Theory & Psychology, 30(6), 813–826. https://doi.org/10.1177/0959354320934545.

Hendricks, H. T., Van Limbeek, J., Geurts, A. C., & Zwarts, M. J. (2002). Motor recovery after stroke: A systematic review of the literature. Archives of Physical Medicine and Rehabilitation, 83(11), 1629–1637. https://doi.org/10.1053/apmr.2002.35473.

Hickok, G. (2009). Eight Problems for the Mirror Neuron Theory of Action Understanding in Monkeys and Humans. Journal of Cognitive Neuroscience, 21(7), 1229–1243. https://doi.org/10.1162/jocn.2009.21189.

Hodges, N. J., Hayes, S., Horn, R. R., and Williams, A. M. (2005). Changes in coordination, control and outcome as a result of extended practice on a novel motor skill. Ergonomics 48, 1672–1685. https://doi.org/10.1080/00140130500101312.

Hofmans, J., Dóci, E., Solinger, O. N., Choi, W., & Judge, T. A. (2019). Capturing the dynamics of leader–follower interactions: Stalemates and future theoretical progress. Journal of Organizational Behavior, 40(3), 382–385. https://doi.org/10.1002/job.2317.

Hong, S. L., and Newell, K. M. (2006). Change in the organization of degrees of freedom with learning. J Motor Behav 38, 88–100. https://doi.org/10.3200/JMBR.38.2.88-100.

Houterman, A. (2019). Wij zijn ons lichaam: Een zoektocht naar de verbinding tussen geest en lichaam. Ambo Anthos Uitgevers.

Huang, F. C., Gillespie, R. B., & Kuo, A. D. (2006). Human Adaptation to Interaction Forces in Visuo-Motor Coordination. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14(3), 390–397. https://doi.org/10.1109/TNSRE.2006.881533.

Huys, R., Fernandez, L., Bootsma, R. J., & Jirsa, V. K. (2010). Fitts' law is not continuous in reciprocal aiming. Proceedings of the Royal Society B: Biological Sciences, 277(1685), 1179–1184. https://doi.org/10.1098/rspb.2009.1954.

Huys, R., Kolodziej, A., Lagarde, J., Farrer, C., Darmana, R., & Zanone, P.-G. (2018). Individual and dyadic rope turning as a window into social coordination. Human Movement Science, 58, 55–68. https://doi.org/10.1016/j.humov.2017.12.015.

Huys, R., Perdikis, D., & Jirsa, V. K. (2014). Functional architectures and structured flows on manifolds: A dynamical framework for motor behavior. Psychological Review, 121(3), 302–336. https://doi.org/10.1037/a0037014.

Innocenti, A., De Stefani, E., Bernardi, N. F., Campione, G. C., & Gentilucci, M. (2012). Gaze Direction and Request Gesture in Social Interactions. PLoS ONE, 7(5), e36390. https://doi.org/10.1371/journal.pone.0036390.

Jacobs, D. M., & Michaels, C. F. (2007). Direct learning. Ecological Psychology, 19(4), 321–349. https://doi.org/10.1080/10407410701432337.

Jacobs, D. M., Vaz, D. V., & Michaels, C. F. (2012). The learning of visually guided action: An information-space analysis of pole balancing. Journal of Experimental Psychology: Human Perception and Performance, 38(5), 1215–1227. https://doi.org/10.1037/a0027632.

James, W. (1890). The principles of psychology (Vols. 1 & 2). Henry Holt and Company.

Jennings, et al. (Austin TX: Cognitive Science Society), 1997–2002. Available at: https://mindmodeling.org/cogsci2015/papers/0345/paper0345.pdf.

Karlinsky, A., and Hodges, N. J. (2018). Turn-taking and concurrent dyad practice aid efficiency but not effectiveness of motor learning in a balance-related task. J Motor Learn Dev 6, 35–52. https://doi.org/10.1123/jmld.2017-0029.

Keele, S. W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. Journal of Experimental Psychology, 77(1), 155–158. https://doi.org/10.1037/h0025754.

Kelso, J. A. (1984). Phase transitions and critical behavior in human bimanual coordination. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 246(6), R1000–R1004. https://doi.org/10.1152/ajpregu.1984.246.6.R1000.

Kelso, J. A. S. (1995). Dynamic patterns: The self-organization of brain and behavior. MIT Press.

Kelso, J. A. S. (2009). "Synergies: Atoms of Brain and Behavior," in Progress in Motor Control Advances in Experimental Medicine and Biology., ed. D. Sternad (Boston, MA: Springer US), 83–91. https://doi.org/10.1007/978-0-387-77064-2_5.

Kelso, J. A. S. (2021a). The Haken–Kelso–Bunz (HKB) model: From matter to movement to mind. Biological Cybernetics, 115(4), 305–322. https://doi.org/10.1007/s00422-021-00890-w.

Kelso, J. A. S. (2021b). Unifying Large- and Small-Scale Theories of Coordination. Entropy, 23(5), 537. https://doi.org/10.3390/e23050537.

Kelso, J. A. S. (2022). On the coordination dynamics of (animate) moving bodies. J. Phys. Complex. 3, 031001. https://doi.org/10.1088/2632-072X/ac7caf.

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: Critical fluctuations. Physics Letters A, 118(6), 279–284. https://doi.org/10.1016/0375-9601(86)90359-2.

Kelso, J. A. S., Tuller, B., & Fowler, C. A. (1982). The functional specificity of articulatory control and coordination. The Journal of the Acoustical Society of America, 72(S1), S103–S103. https://doi.org/10.1121/1.2019692.

Kelso, J. S., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. Journal of Experimental Psychology: Human Perception and Performance, 10(6), 812–832. https://doi.org/10.1037/0096-1523.10.6.812.

Knoblich, G., Butterfill, S., & Sebanz, N. (2011). Psychological Research on Joint Action. In Psychology of Learning and Motivation (Vol. 54, pp. 59–101). Elsevier. https://doi.org/10.1016/B978-0-12-385527-5.00003-6.

Kostrubiec, V., Zanone, P.-G., Fuchs, A., & Kelso, J. A. S. (2012). Beyond the blank slate: Routes to learning new coordination patterns depend on the intrinsic dynamics of the learner—experimental evidence and theoretical model. Frontiers in Human Neuroscience, 6. https://doi.org/10.3389/fnhum.2012.00222.

Kourtis, D., Knoblich, G., Woźniak, M., & Sebanz, N. (2014). Attention Allocation and Task Representation during Joint Action Planning. Journal of Cognitive Neuroscience, 26(10), 2275–2286. https://doi.org/10.1162/jocn_a_00634.

Kourtis, D., Sebanz, N., & Knoblich, G. (2013). Predictive representation of other people's actions in joint action planning: An EEG study. Social Neuroscience, 8(1), 31–42. https://doi.org/10.1080/17470919.2012.694823.

Kourtis, D., Woźniak, M., Sebanz, N., & Knoblich, G. (2019). Evidence for we-representations during joint action planning. Neuropsychologia, 131, 73–83. https://doi.org/10.1016/j.neuropsychologia.2019.05.029.

Krakauer, J. W., Ghazanfar, A. A., Gomez-Marin, A., MacIver, M. A., & Poeppel, D. (2017). Neuroscience needs behavior: Correcting a reductionist bias. Neuron, 93(3), 480–490. https://doi.org/10.1016/j.neuron.2016.12.041.

Kugler, P. N., & Turvey, M. T. (1987). Information, natural law, and the self-assembly of rhythmic movement. Lawrence Erlbaum Associates.

Kugler, P. N., Scott Kelso, J. A., & Turvey, M. T. (1980). 1 On the Concept of Coordinative Structures as Dissipative Structures: I. Theoretical Lines of Convergence. In Advances in Psychology (Vol. 1, pp. 3–47). Elsevier. https://doi.org/10.1016/S0166-4115(08)61936-6.

Lagarde, J. (2013). Challenges for the understanding of the dynamics of social coordination. Frontiers in Neurorobotics, 7. https://doi.org/10.3389/fnbot.2013.00018.

Lamb, P. F., & Stöckl, M. (2014). On the use of continuous relative phase: Review of current approaches and outline for a new standard. Clinical Biomechanics, 29(5), 484–493. https://doi.org/10.1016/j.clinbiomech.2014.03.008.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), Cerebral mechanisms in behavior (pp. 112–136). Wiley.

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor Control Strategies Revealed in the Structure of Motor Variability: Exercise and Sport Sciences Reviews, 30(1), 26–31. https://doi.org/10.1097/00003677-200201000-00006.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a New Theory of Motor Synergies. Motor Control, 11(3), 276–308. https://doi.org/10.1123/mcj.11.3.276.

Leach, D., Kolokotroni, Z., & Wilson, A. D. (2021). The Ecological Task Dynamics of Learning and Transfer in Coordinated Rhythmic Movement. Frontiers in Human Neuroscience, 15, 718829. https://doi.org/10.3389/fnhum.2021.718829.

Lee, D. N. (1976). A Theory of Visual Control of Braking Based on Information about Time-to-Collision. Perception, 5(4), 437–459. https://doi.org/10.1068/p050437.

Liu, C. (2023). A Constraint-Led Approach: Enhancing Skill Acquisition and Performance in Sport and Physical Education Pedagogy. Studies in Sports Science and Physical Education, 1(1), 1–10. https://doi.org/10.56397/SSSPE.2023.06.01.

Lluc Montull, Passos, P., Lluís Rocas, Milho, J., & Natàlia Balagué. (2020). Proprioceptive Dialogue - Interpersonal Synergies During a Cooperative Slackline Task. https://doi.org/10.13140/RG.2.2.35466.70087.

Lobo, L., Heras-Escribano, M., & Travieso, D. (2018). The History and Philosophy of Ecological Psychology. Frontiers in Psychology, 9, 2228. https://doi.org/10.3389/fpsyg.2018.02228.

Loehr, J. D., Kourtis, D., & Brazil, I. A. (2015). It's not just my fault: Neural correlates of feedback processing in solo and joint action. Biological Psychology, 111, 1–7. https://doi.org/10.1016/j.biopsycho.2015.08.004.

Loehr, J. D., Kourtis, D., Vesper, C., Sebanz, N., & Knoblich, G. (2013). Monitoring Individual and Joint Action Outcomes in Duet Music Performance. Journal of Cognitive Neuroscience, 25(7), 1049–1061. https://doi.org/10.1162/jocn_a_00388.

Marom, S. (2009). On the Precarious Path of Reverse Neuro-Engineering. Frontiers in Computational Neuroscience, 3. https://doi.org/10.3389/neuro.10.005.2009.

Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social connection through joint action and interpersonal coordination. Topics in Cognitive Science, 1(2), 320–339. https://doi.org/10.1111/j.1756-8765.2009.01022.x.

Marsh, K. L., Richardson, M. J., and Baron, R. M. (2006). Contrasting approaches to perceiving and acting with others. Ecol Psychol 18, 1–38. https://doi.org/10.1207/s15326969eco1801_1.

McDonald, P. V., Van Emmerik, R. E. A., and Newell, K. M. (1989). The effects of practice on limb kinematics in a throwing task. J Motor Behav 21, 245–264. https://doi.org/10.1080/00222895.1989.10735480.

Meerhoff, L. (Rens) A., & De Poel, H. J. (2014). Asymmetric interpersonal coupling in a cyclic sports-related movement task. Human Movement Science, 35, 66–79. https://doi.org/10.1016/j.humov.2014.04.003

Meijer, O. G., & Bruijn, S. M. (2007). The Loyal Dissident: N.A. Bernstein and the Double-Edged Sword of Stalinism. Journal of the History of the Neurosciences, 16(1–2), 206–224. https://doi.org/10.1080/09647040600720979.

Meijer, O. G., Wagenaar, R. C., & Blankendaal, F. C. M. (1988). Chapter 20 The Hierarchy Debate: Tema Con Variazioni. In Advances in Psychology (Vol. 50, pp. 489–561). Elsevier. https://doi.org/10.1016/S0166-4115(08)62570-4.

Merleau-Ponty, M. (2013). Phenomenology of Perception (0 ed.). Routledge. https://doi.org/10.4324/9780203720714.

Meyer, D. E., Smith, J. E. K., Kornblum, S., Abrams, R. A., & Wright, C. E. (2018). Speed—accuracy tradeoffs in aimed movements: Toward a theory of rapid voluntary action. In M. Jeannerod (Ed.), Attention and Performance XIII (1st ed., pp. 173–226). Psychology Press. https://doi.org/10.4324/9780203772010-6.

Meyer, M., Van Der Wel, R. P. R. D., & Hunnius, S. (2013). Higher-order action planning for individual and joint object manipulations. Experimental Brain Research, 225(4), 579–588. https://doi.org/10.1007/s00221-012-3398-8.

Michaels, C. F., & Carello, C. (1981). Direct perception. Prentice-Hall.

Michaels, C. F., Withagen, R., Jacobs, D. M., Zaal, F. T. J. M., & Bongers, R. M. (2001). Information, Perception, and Action: A Reply to Commentators. Ecological Psychology, 13(3), 227–244. https://doi.org/10.1207/S15326969ECO1303_3.

Michaels, D. C., Matyas, E. P., & Jalife, J. (1987). Mechanisms of sinoatrial pacemaker synchronization: A new hypothesis. Circulation Research, 61(5), 704–714. https://doi.org/10.1161/01.RES.61.5.704.

Miller, M. R., Jun, H., Herrera, F., Yu Villa, J., Welch, G., & Bailenson, J. N. (2019). Social interaction in augmented reality. PLOS ONE, 14(5), https://doi.org/10.1371/journal.pone.0216290.

Monaco, V., Tropea, P., Rinaldi, L. A., & Micera, S. (2018). Uncontrolled manifold hypothesis: Organization of leg joint variance in humans while walking in a wide range of speeds. Human Movement Science, 57, 227–235. https://doi.org/10.1016/j.humov.2017.08.019.

Morrison, A., McGrath, D., & Wallace, E. S. (2016). Motor abundance and control structure in the golf swing. Human Movement Science, 46, 129–147. https://doi.org/10.1016/j.humov.2016.01.009.

Mottet, D., & Bootsma, R. J. (1999). The dynamics of goal-directed rhythmical aiming. Biological Cybernetics, 80(4), 235–245. https://doi.org/10.1007/s004220050521.

Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R. J. (2001). Two-handed performance of a rhythmical Fitts task by individuals and dyads. Journal of Experimental Psychology: Human Perception and Performance, 27, 1275–1286. https://doi.org/10.1037/0096-1523.27.6.1275.

Nalepka, P., Kallen, R. W., Chemero, A., Saltzman, E., & Richardson, M. J. (2017). Herd Those Sheep: Emergent Multiagent Coordination and Behavioral-Mode Switching. Psychological Science, 28(5), 630–650. https://doi.org/10.1177/0956797617692107.

Néda, Z., Ravasz, E., Brechet, Y., Vicsek, T., and Barabási, A.-L. (2000). The sound of many hands clapping. Nature 403, 849–850. https://doi.org/10.1038/35002660.

Newell, K. M., & McDonald, P. V. (1994). Learning to coordinate redundant biomechanical degrees of freedom. In Interlimb Coordination (pp. 515–536). Elsevier. https://doi.org/10.1016/B978-0-12-679270-6.50029-2.

Newell, K. M., & Vaillancourt, D. E. (2001). Dimensional change in motor learning. Human Movement Science, 20(4–5), 695–715. https://doi.org/10.1016/S0167-9457(01)00073-2.

Newell, K. M., Van Emmerik, R. E. A., & McDonald, P. V. (1989). Biomechanical constraints and action theory. Human Movement Science, 8(4), 403–409. https://doi.org/10.1016/0167-9457(89)90045-6.

Newman-Norlund, R. D., Noordzij, M. L., Meulenbroek, R. G. J., & Bekkering, H. (2007). Exploring the brain basis of joint action: Co-ordination of actions, goals and intentions. Social Neuroscience, 2(1), 48–65. https://doi.org/10.1080/17470910701224623.

Newtson, D., Hairfield, J., Bloomingdale, J., & Cutino, S. (1987). The Structure of Action and Interaction. Social Cognition, 5(3), 191–237. https://doi.org/10.1521/soco.1987.5.3.191.

Oujamaa, L., Relave, I., Froger, J., Mottet, D., & Pelissier, J.-Y. (2009). Rehabilitation of arm function after stroke. Literature review. Annals of Physical and Rehabilitation Medicine, 52(3), 269–293. https://doi.org/10.1016/j.rehab.2008.10.003.

Oullier, O., De Guzman, G. C., Jantzen, K. J., Lagarde, J., & Scott Kelso, J. A. (2008). Social coordination dynamics: Measuring human bonding. Social Neuroscience, 3(2), 178–192. https://doi.org/10.1080/17470910701563392.

Oyama, S. (2000). The Ontogeny of Information: Developmental Systems and Evolution (2nd ed.). Duke University Press.

Pacheco, M. M., Lafe, C. W., & Newell, K. M. (2019). Search strategies in the perceptual-motor workspace and the acquisition of coordination, control, and skill. Frontiers in Psychology, 10, 1874. https://doi.org/10.3389/fpsyg.2019.01874.

Pacherie, E., & Dokic, J. (2006). From mirror neurons to joint actions. Cognitive Systems Research, 7(2–3), 101–112. https://doi.org/10.1016/j.cogsys.2005.11.012.

Passos, P., Davids, K., & Chow, J. Y. (Eds.). (2016b). Interpersonal Coordination and Performance in Social Systems (0 ed.). Routledge. https://doi.org/10.4324/9781315700304.

Passos, P., Lacasa, E., Milho, J., & Torrents, C. (2020). Capturing interpersonal synergies in social settings: An example within a badminton cooperative task. Nonlinear Dynamics, Psychology, and Life Sciences, 24(1), 59–78. https://doi.org/10.1007/s11071-019-05347-0.

Passos, P., Lacasa, E., Milho, J., Diniz, A., & Torrents, C. (2022). How to Take a "Portrait" of Interpersonal Synergies Formation? – Exemplar Data with Expert Badminton Doubles. Ecological Psychology, 34(3), 71–89. https://doi.org/10.1080/10407413.2022.2075748.

Passos, P., Milho, J., & Button, C. (2018). Quantifying synergies in two-versus-one situations in team sports: An example from Rugby Union. Behavior Research Methods, 50(2), 620–629. https://doi.org/10.3758/s13428-017-0889-3.

Paxton, A., Roche, J. M., Ibarra, A., & Tanenhaus, M. K. (2021). Predictions of Miscommunication in Verbal Communication During Collaborative Joint Action. Journal of Speech, Language, and Hearing Research, 64(2), 613–627. https://doi.org/10.1044/2020_JSLHR-20-00137.

Pezzulo, G., Donnarumma, F., & Dindo, H. (2013). Human Sensorimotor Communication: A Theory of Signaling in Online Social Interactions. PLoS ONE, 8(11), e79876. https://doi.org/10.1371/journal.pone.0079876.

Pezzulo, G., Donnarumma, F., Dindo, H., D'Ausilio, A., Konvalinka, I., & Castelfranchi, C. (2019). The body talks: Sensorimotor communication and its brain and kinematic signatures. Physics of Life Reviews, 28, 1–21. https://doi.org/10.1016/j.plrev.2018.06.014.

Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. Behavioral and Brain Sciences, 20(2), 279–303. https://doi.org/10.1017/S0140525X97001441.

Pollock, A., Farmer, S. E., Brady, M. C., Langhorne, P., Mead, G. E., Mehrholz, J., & Van Wijck, F. (2014). Interventions for improving upper limb function after stroke. Cochrane Database of Systematic Reviews, 2014(11). https://doi.org/10.1002/14651858.CD010820.pub2

Prigogine, I., & Nicolis, G. (1977). Self-organization in nonequilibrium systems: From dissipative structures to order through fluctuations. Wiley.

Profeta, V. L. S., & Turvey, M. T. (2018). Bernstein's levels of movement construction: A contemporary perspective. Human Movement Science, 57, 111–133. https://doi.org/10.1016/j.humov.2017.11.013.

Rahmat, M. F., Wahid, H., and Wahab, N. A. (2010). Application of Intelligent Controller in a Ball and Beam Control System. Int J Smart Sens Intell Syst 3, 45–60. https://doi.org/10.21307/ijssis-2017-378.

Ramenzoni, V. C., Riley, M. A., Shockley, K., and Baker, A. A. (2012). Interpersonal and intrapersonal coordinative modes for joint and single task performance. Hum Movement Sci 31, 1253–1267. https://doi.org/10.1016/j.humov.2011.12.004.

Reed, E. S. (1982). An Outline of a Theory of Action Systems. Journal of Motor Behavior, 14(2), 98–134. https://doi.org/10.1080/00222895.1982.10735267.

Reed, E. S. (1988). Applying the theory of action systems to the study of motor skills. In O. G. Meijer & K. Roth (Eds.), Complex movement behaviour: The motor-action controversy (pp. 45–86). North-Holland.

Reed, E. S. (1997). From Soul to Mind: The Emergence of Psychology, from Erasmus Darwin to William James. Yale University Press. https://doi.org/10.12987/9780300147230.

Réveillé, C., Vergotte, G., Perrey, S., & Bosselut, G. (2024). Using interbrain synchrony to study teamwork: A systematic review and meta-analysis. Neuroscience & Biobehavioral Reviews, 159, 105593. https://doi.org/10.1016/j.neubiorev.2024.105593.

Reynolds, R. F., & Osler, C. J. (2014). Mechanisms of interpersonal sway synchrony and stability. Journal of The Royal Society Interface, 11(101), 20140751. https://doi.org/10.1098/rsif.2014.0751.

Richardson, M. J., Harrison, S. J., Kallen, R. W., Walton, A., Eiler, B. A., Saltzman, E., & Schmidt, R. C. (2015). Self-organized complementary joint action: Behavioral dynamics of an interpersonal collision-avoidance task. Journal of Experimental Psychology: Human Perception and Performance, 41(3), 665–679. https://doi.org/10.1037/xhp0000041.

Richardson, M. J., Marsh, K. L., & Baron, R. M. (2007). Judging and actualizing intrapersonal and interpersonal affordances. Journal of Experimental Psychology: Human Perception and Performance, 33(4), 845–859. https://doi.org/10.1037/0096-1523.33.4.845.

Richardson, M. J., Marsh, K. L., Isenhower, R. W., Goodman, J. R. L., & Schmidt, R. C. (2007). Rocking together: Dynamics of intentional and unintentional interpersonal coordination. Human Movement Science, 26(6), 867–891. https://doi.org/10.1016/j.humov.2007.07.002.

Rigoli, L., Romero, V., Shock, K. D., Funke, G. J., Strang, A. J., and Richardson, M. J. (2015). "Effects of complementary control on the coordination dynamics of joint-action.," in COGSCI 2015, eds. D. C. Noelle, R. Dale, A. S. Warlaumont, J. Joshimi, T. Matlock, C. D.

Riley, M. A., Richardson, M. J., Shockley, K., & Ramenzoni, V. C. (2011). Interpersonal Synergies. Frontiers in Psychology, 2. https://doi.org/10.3389/fpsyg.2011.00038.

Rizzolatti, G., & Craighero, L. (2004). The mirror neuron system. Annual Review of Neuroscience, 27(1), 169–192. https://doi.org/10.1146/annurev.neuro.27.070203.144230.

Rizzolatti, G., & Craighero, L. (2006). The mirror neuron system. Trends in Cognitive Sciences, 10(4), 174–179. https://doi.org/10.1016/j.tics.2005.12.009.

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations. Nature Reviews Neuroscience, 11(4), 264–274. https://doi.org/10.1038/nrn2805.

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. Cognitive Brain Research, 3(2), 131–141. https://doi.org/10.1016/0926-6410(95)00038-0.

Romero, V., Kallen, R., Riley, M. A., & Richardson, M. J. (2015). Can discrete joint action be synergistic? Studying the stabilization of interpersonal hand coordination. Journal of Experimental Psychology: Human Perception and Performance, 41(5), 1223–1235. https://doi.org/10.1037/xhp0000083.

Sacheli, L. M., Tidoni, E., Pavone, E. F., Aglioti, S. M., & Candidi, M. (2013). Kinematics fingerprints of leader and follower role-taking during cooperative joint actions. Experimental Brain Research, 226(4), 473–486. https://doi.org/10.1007/s00221-013-3459-7.

Saltzman, E., & Kelso, J. A. S. (1987). Skilled actions: A task-dynamic approach. Psychological Review, 94(1), 84–106. https://doi.org/10.1037/0033-295X.94.1.84.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. Psychological Review, 82(4), 225–260. https://doi.org/10.1037/h0076770.

Schmidt, R. A., & Lee, T. D. (2005). Motor control and learning: A behavioral emphasis (4th ed.). Human Kinetics.

Schmidt, R. C., & O'Brien, B. (1997). Evaluating the dynamics of unintended interpersonal coordination. Ecological Psychology, 9(3), 189–206. https://doi.org/10.1207/s15326969eco0903_2.

Schmidt, R. C., & Richardson, M. J. (2008). Dynamics of interpersonal coordination. In A. Fuchs & V. K. Jirsa (Eds.), Coordination: Neural, Behavioral and Social Dynamics (pp. 281–308). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74479-5_14.

Schmidt, R. C., & Turvey, M. T. (1994). Phase-entrainment dynamics of visually coupled rhythmic movements. Biological Cybernetics, 70(4), 369–376. https://doi.org/10.1007/BF00200334.

Schmidt, R. C., Carello, C., & Turvey, M. T. (1990). Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. Journal of Experimental Psychology: Human Perception and Performance, 16(2), 227–247. https://doi.org/10.1037//0096-1523.16.2.227.

Schmidt, R. C., Christianson, N., Carello, C., & Baron, R. (1994). Effects of Social and Physical Variables on Between-Person Visual Coordination. Ecological Psychology, 6(3), 159–183. https://doi.org/10.1207/s15326969eco0603_1.

Schmidt, R. C., Fitzpatrick, P., Caron, R., & Mergeche, J. (2011). Understanding social motor coordination. Human Movement Science, 30(5), 834–845. https://doi.org/10.1016/j.humov.2010.05.014.

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. https://doi.org/10.1037/xhp0000403.

Schnier, C., Pitsch, K., Dierker, A., & Hermann, T. (2011). Collaboration in Augmented Reality: How to establish coordination and joint attention? In S. Bødker, N. O. Bouvin, V. Wulf, L. Ciolfi, & W. Lutters (Eds.), ECSCW 2011: Proceedings of the 12th European Conference on Computer

Supported Cooperative Work, 24-28 September 2011, Aarhus Denmark (pp. 405–416). Springer London. https://doi.org/10.1007/978-0-85729-913-0_22.

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. Experimental Brain Research, 126(3), 289–306. https://doi.org/10.1007/s002210050738.

Scholz, J. P., Kelso, J. A. S., & Schöner, G. (1987). Nonequilibrium phase transitions in coordinated biological motion: Critical slowing down and switching time. Physics Letters A, 123(8), 390–394. https://doi.org/10.1016/0375-9601(87)90038-7.

Schöner, G. (1995). Recent Developments and Problems in Human Movement Science and Their Conceptual Implications. Ecological Psychology, 7(4), 291–314. https://doi.org/10.1207/s15326969eco0704_5.

Schöner, G., & Kelso, J. A. S. (1988). Dynamic Pattern Generation in Behavioral and Neural Systems. Science, 239(4847), 1513–1520. https://doi.org/10.1126/science.3281253.

Schöner, G., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movement. Biological Cybernetics, 53(4), 247–257. https://doi.org/10.1007/BF00336995.

Schöner, G., Zanone, P. G., & Kelso, J. A. S. (1992). Learning as change of coordination dynamics: Theory and experiment. Journal of Motor Behavior, 24(1), 29–48. https://doi.org/10.1080/00222895.1992.9941599.

Sebanz, N., & Knoblich, G. (2021). Progress in joint-action research. Current Directions in Psychological Science, 30(2), 138–143. https://doi.org/10.1177/0963721420984425.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. Trends in Cognitive Sciences, 10(2), 70–76. https://doi.org/10.1016/j.tics.2005.12.009.

Sebanz, N., Knoblich, G., & Prinz, W. (2003). Representing others' actions: Just like one's own? Cognition, 88(3), B11–B21. https://doi.org/10.1016/S0010-0277(03)00043-X.

Sebanz, N., Knoblich, G., & Prinz, W. (2005). How Two Share a Task: Co-representing Stimulus-Response Mappings. Journal of Experimental Psychology: Human Perception and Performance, 31(6), 1234–1246. https://doi.org/10.1037/0096-1523.31.6.1234.

Sevrez, V., Rao, G., Berton, E., and Bootsma, R. J. (2012). On the organizing role of nonmuscular forces during performance of a giant circle in gymnastics. Journal of Applied Biomechenics 28, 57–62. https://doi.org/10.1123/jab.28.1.57.

Shafizadegan, Z., Sarrafzadeh, J., Salehi, R., Farahmand, F., & Rasouli, O. (2022). The Effects of Challenging Walking Conditions on Kinematic Synergy and Stability of Gait in People with Knee Osteoarthritis: A Study Protocol. Advanced Biomedical Research, 11(1), 35. https://doi.org/10.4103/abr.abr_289_21.

Shea, C. H., & Wulf, G. (2005). Schema Theory: A Critical Appraisal and Reevaluation. Journal of Motor Behavior, 37(2), 85–102. https://doi.org/10.3200/JMBR.37.2.85-102.

Sherrington, C. S. (1906). The integrative action of the nervous system. Yale University Press..

Smit, H., & Hacker, P. M. S. (2014). Seven Misconceptions About the Mereological Fallacy: A Compilation for the Perplexed. Erkenntnis, 79(5), 1077–1097. https://doi.org/10.1007/s10670-013-9594-5.

Starzak, M., Biegajło, M., Nogal, M., Niźnikowski, T., Ambroży, T., Rydzik, Ł., & Jaszczur-Nowicki, J. (2022). The Role of Verbal Feedback in the Motor Learning of Gymnastic Skills: A Systematic Review. Applied Sciences, 12(12), 5940. https://doi.org/10.3390/app12125940.

Strogatz, S. H. (2003). Sync: How order emerges from chaos in the universe, nature, and daily life. Hyperion.

Swaab, D. F. (2014). We Are Our Brains: A Neurobiography of the Brain, from the Womb to Alzheimer's. Random House Publishing Group.

Takai, A., Fu, Q., Doibata, Y., Lisi, G., Tsuchiya, T., Mojtahedi, K., Yoshioka, T., Kawato, M., Morimoto, J., & Santello, M. (2023). Learning acquisition of consistent leader–follower relationships depends on implicit haptic interactions. Scientific Reports, 13(1), 3476. https://doi.org/10.1038/s41598-023-29722-6.

Tamboer, J. W. I. (1988). Chapter 18 Images of the Body Underlying Concepts of Action. In Advances in Psychology (Vol. 50, pp. 439–461). Elsevier. https://doi.org/10.1016/S0166-4115(08)62568-6.

Todorov, E. (2004). Optimality principles in sensorimotor control. Nature Neuroscience, 7(9), 907–915. https://doi.org/10.1038/nn1309.

Treffner, P. J., & Turvey, M. T. (1995). Symmetry, broken symmetry, and handedness in perceiving and performing. Advances in Psychology, 105, 247–277. https://doi.org/10.1016/S0166-4115(08)70296-3.

Turvey, M. T. (1990). Coordination. American Psychologist, 45(8), 938–953. https://doi.org/10.1037/0003-066X.45.8.938.

Turvey, M. T. (2007). Action and perception at the level of synergies. Hum Movement Sci 26, 657–697. doi: https://10.1016/j.humov.2007.04.002.

Turvey, M. T., Shaw, R. E., Reed, E. S., & Mace, W. M. (1981). Ecological laws of perceiving and acting: In reply to Fodor and Pylyshyn. Cognition, 9(3), 237–304. https://doi.org/10.1016/0010-0277(81)90002-0.

Urton, M. L., Kohia, M., Davis, J., & Neill, M. R. (2007). Systematic literature review of treatment interventions for upper extremity hemiparesis following stroke. Occupational Therapy International, 14(1), 11–27. https://doi.org/10.1002/oti.220.

Vaccari, A. (2003). The body made machine: On the history and applications of a metaphor. https://Academia.edu/.

Valk, T. A., Mouton, L. J., Otten, E., & Bongers, R. M. (2019). Synergies reciprocally relate end-effector and joint-angles in rhythmic pointing movements. Scientific Reports, 9(1), 17378. https://doi.org/10.1038/s41598-019-53913-9.

Van Der Wel, R. P. R. D., Becchio, C., Curioni, A., & Wolf, T. (2021). Understanding joint action: Current theoretical and empirical approaches. Acta Psychologica, 215, 103285. https://doi.org/10.1016/j.actpsy.2021.103285.

Van Der Wel, R. P. R. D., Knoblich, G., & Sebanz, N. (2011). Let the force be with us: Dyads exploit haptic coupling for coordination. Journal of Experimental Psychology: Human Perception and Performance, 37(5), 1420–1431. https://doi.org/10.1037/a0022337.

Van Dijk, L. (2021a). Affordances in a Multispecies Entanglement. Ecological Psychology, 33(2), 73–89. https://doi.org/10.1080/10407413.2021.1885978.

Van Dijk, L. (2021b). Psychology in an Indeterminate World. Perspectives on Psychological Science, 16(3), 577–589. https://doi.org/10.1177/1745691620958005.

Van Schie, H. T., Mars, R. B., Coles, M. G. H., & Bekkering, H. (2004). Modulation of activity in medial frontal and motor cortices during error observation. Nature Neuroscience, 7(5), 549–554. https://doi.org/10.1038/nn1239.

Van Ulzen, N. R., Lamoth, C. J. C., Daffertshofer, A., Semin, G. R., & Beek, P. J. (2008). Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side. Neuroscience Letters, 432(2), 88–93. https://doi.org/10.1016/j.neulet.2007.11.070.

Van Wieringen, P. C. W. (1988). Chapter 3 Kinds and Levels of Explanation: Implications for the Motor Systems Versus Action Systems Controversy. In Advances in Psychology (Vol. 50, pp. 87–120). Elsevier. https://doi.org/10.1016/S0166-4115(08)62553-4.

Varlet, M., & Richardson, M. J. (2015). What would be Usain Bolt's 100-meter sprint world record without Tyson Gay? Unintentional interpersonal synchronization between the two sprinters.

Journal of Experimental Psychology: Human Perception and Performance, 41(1), 36–41. https://doi.org/10.1037/a0038640.

Varlet, M., Marin, L., Capdevielle, D., Del-Monte, J., Schmidt, R. C., Salesse, R. N., Boulenger, J.-P., Bardy, B. G., & Raffard, S. (2014). Difficulty leading interpersonal coordination: Towards an embodied signature of social anxiety disorder. Frontiers in Behavioral Neuroscience, 8. https://doi.org/10.3389/fnbeh.2014.00029.

Varlet, M., Marin, L., Raffard, S., Schmidt, R. C., Capdevielle, D., Boulenger, J.-P., Del-Monte, J., & Bardy, B. G. (2012). Impairments of Social Motor Coordination in Schizophrenia. PLoS ONE, 7(1), e29772. https://doi.org/10.1371/journal.pone.0029772.

Vereijken, B., Emmerik, R. E. A. V., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing Degrees of Freedom in Skill Acquisition. Journal of Motor Behavior, 24(1), 133–142. https://doi.org/10.1080/00222895.1992.9941608.

Vereijken, B., Van Emmerik, R. E. A., Bongaardt, R., Beek, W. J., & Newell, K. M. (1997). Changing coordinative structures in complex skill acquisition. Human Movement Science, 16(6), 823–844. https://doi.org/10.1016/S0167-9457(97)00021-3.

Vereijken, B., Whiting, H. T. A., & Beek, W. J. (1992). A Dynamical Systems Approach to Skill Acquisition. The Quarterly Journal of Experimental Psychology Section A, 45(2), 323–344. https://doi.org/10.1080/14640749208401329.

Vesper, C., & Richardson, M. J. (2014). Strategic communication and behavioral coupling in asymmetric joint action. Experimental Brain Research, 232(9), 2945–2956. https://doi.org/10.1007/s00221-014-3982-1.

Vesper, C., Abramova, E., Bütepage, J., Ciardo, F., Crossey, B., Effenberg, A., Hristova, D., Karlinsky, A., McEllin, L., Nijssen, S. R. R., Schmitz, L., & Wahn, B. (2017). Joint action: Mental representations, shared information and general mechanisms for coordinating with others. Frontiers in Psychology, 07. https://doi.org/10.3389/fpsyg.2016.02039.

Vesper, C., Butterfill, S., Knoblich, G., & Sebanz, N. (2010). A minimal architecture for joint action. Neural Networks, 23(8–9), 998–1003. https://doi.org/10.1016/j.neunet.2010.06.002.

Vesper, C., Van Der Wel, R. P. R. D., Knoblich, G., & Sebanz, N. (2011). Making oneself predictable: Reduced temporal variability facilitates joint action coordination. Experimental Brain Research, 211(3–4), 517–530. https://doi.org/10.1007/s00221-011-2706-z.

Wallot, S., Mitkidis, P., McGraw, J. J., & Roepstorff, A. (2016). Beyond Synchrony: Joint Action in a Complex Production Task Reveals Beneficial Effects of Decreased Interpersonal Synchrony. PLOS ONE, 11(12), e0168306. https://doi.org/10.1371/journal.pone.0168306.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. Journal of Experimental Psychology: Human Perception and Performance, 10(5), 683–703. https://doi.org/10.1037/0096-1523.10.5.683.

Warren, W. H. (2006). The dynamics of perception and action. Psychological Review, 113(2), 358–389. https://doi.org/10.1037/0033-295X.113.2.358.

Welford, A. T. (1968). Fundamentals of Skill. London: Methuen.

Wijnberg, R. (2023). Voor ieder wat waars: Filterbubbels, desinformatie en de kracht van goede journalistiek. De Correspondent.

Winfree, A. T. (1967). Biological rhythms and the behavior of populations of coupled oscillators. Journal of Theoretical Biology, 16(1), 15–42. https://doi.org/10.1016/0022-5193(67)90051-3.

Withagen, R. (2010). Een bewogen fundament: Filosofische grondslagen van de bewegingswetenschappen (2nd ed.). 20/10 Uitgevers.

Withagen, R., & Michaels, C. F. (2005). On Ecological Conceptualizations of Perceptual Systems and Action Systems. Theory & Psychology, 15(5), 603–620. https://doi.org/10.1177/0959354305057265.

Withagen, R., & Van Der Kamp, J. (2010). Towards a new ecological conception of perceptual information: Lessons from a developmental systems perspective. Human Movement Science, 29(1), 149–163. https://doi.org/10.1016/j.humov.2009.09.003.

Withagen, R., Van Der Kamp, J., & Woods, C. T. (2024). Conceptualizing the Environment in a Time of Ecological Collapse. Ecological Psychology, 1–10. https://doi.org/10.1080/10407413.2024.2397764.

Wolpert, D. M. (1997). Computational approaches to motor control. Trends in Cognitive Sciences, 1(6), 209–216. https://doi.org/10.1016/S1364-6613(97)01070-X.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. Nature Neuroscience, 3(S11), 1212–1217. https://doi.org/10.1038/81497.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. Nature Reviews Neuroscience, 12(12), 739–751. https://doi.org/10.1038/nrn3112.

Zanone, P. G., & Kelso, J. A. (1992). Evolution of behavioral attractors with learning: Nonequilibrium phase transitions. Journal of Experimental Psychology: Human Perception and Performance, 18(2), 403–421. https://doi.org/10.1037/0096-1523.18.2.403