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PLAYING PONG TOGETHER

A NEW EXPERIMENTAL PARADIGM TO STUDY SOCIAL COORDINATION IN A DOUBLES INTERCEPTION TASK

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A NEW EXPERIMENTAL PARADIGM TO STUDY SOCIAL COORDINATION IN A DOUBLES INTERCEPTION TASK

THESIS BY

Niek H. BENERINK

Abstract

We studied the way two individuals coordinate their actions in order to intercept an approaching ball by moving individually-controlled paddles along a common interception-axis in a video game-like doubles interception task. With contact between paddles leading to their immediate disintegration, the doubles-pong task required team members to decide on each trial who would be the one to actualize the interception. Because overt communication was precluded, these decisions were informed exclusively by vision of the on-screen movements of paddles and ball. In three experiments, manipulating initial conditions (i.e., initial paddle positions) and individual skill differences within teams, we examined how teams organized their joint interception behavior. Results revealed that all teams spontaneously demonstrated a division of labor, characterized by individual interception domains separated by fuzzy (i.e., overlapping) boundaries. While boundary locations could vary over teams within a given experimental condition, they were nevertheless systematically affected for each team by initial paddle positions. Skill differences between individual team members did not appear to have such an effect. Overall, our findings provided converging evidence that, instead of being based on any geometrically-inspired criterion for dividing up space, the observed division of space emerged from both team members' interdependent interception behaviors. An action-based definition of the (time-evolving) expediency with which, at each moment in time, each player moved towards the future interception position allowed predicting which of the two players would end up intercepting the ball and which would abandon the interception attempt. Overall, our studies suggest that the decision of who will intercept the ball emerges from an informational coupling between team members, with the division of space being an emergent result.

Key-words: Joint-action, decision-making, cooperation, social coordination, interception, perception-action, doubles-pong

RÉSUMÉ

Dans une tâche virtuelle d'interception, nous nous sommes intéressés à la façon dont deux individus, pouvant déplacer chacun une raquette le long d'un axe d'interception commun, coordonnaient leurs actions dans le but d'intercepter une balle qui s'approchait. La tâche de double-pong demandait aux participants de décider à chaque essai quel allait être celui qui allait réaliser l'interception, tout en sachant qu'un contact entre leurs raquettes entrainait leur désintégration immédiate et rendait l'interception impossible. Parce que toute communication orale leur était interdite, seules les informations visuelles provenant du mouvement des raquettes et de la balle sur l'écran pouvaient être utilisées lors processus décisionnel. A travers trois expériences, en manipulant les conditions initiales (c'est-à-dire la position initiale des raquettes) et les différences individuelles de niveaux au sein des équipes, nous avons examiné comment ces équipes organisaient conjointement leur comportement d'interception. Les résultats ont révélé que toutes les équipes établissaient spontanément une division du travail caractérisée par des domaines d'interception individuels séparés par des frontières floues, illustrant des surfaces de recouvrement non-négligeables de ces domaines d'interception. Bien que les positions des limites puissent varier d'une équipe à l'autre dans une condition expérimentale donnée, celles-ci ont néanmoins été systématiquement affectées, pour chaque équipe, par les positions initiales des raquettes. Les différences de niveaux entre les membres d'une équipe ne semblaient pas avoir un tel effet. Dans l'ensemble nos observations fournissent des preuves convergentes selon lesquelles la division de l'espace observée émergerait de comportements d'interception interdépendants aux deux membres de l'équipe, plutôt que d'être basé sur un critère purement géométriquement inspiré de répartition de l'espace. Une définition basée sur l'action de l'opportunité selon laquelle, à chaque instant chaque joueur se déplace vers la future position d'interception, a permis de prédire lequel des deux joueurs finirait par intercepter la balle et lequel abandonnerait la tentative d'interception. Dans l'ensemble, nos études suggèrent que la prise de décision de qui va intercepter la balle émerge d'un couplage informationnel entre les membres de l'équipe, considérant que la division de l'espace est un résultat émergent.

Mots-clés: action conjointe, prise de décision, coopération, coordination sociale, interception, pong

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Niek H. Benerink

EXTENDED SUMMARY

When you are walking on the pavement and someone is approaching you head on, do you ever wonder how both of you effectively adapt your movements to avoid colliding? Or when driving onto a highway and try to merge your car in front or behind a car already on the road, do you ask yourself the question what information you use to decide to speed up or to slow down? Most likely you do not, as in the majority of situations the coordination of our actions with those of others plays out fine. Such spatiotemporal interpersonal movement coordination, however, demands a lot from our perceptual-motor system in order to quickly adapt to changing circumstances. Although research into joint-action gained attention over the last 20 years, much is still unknown about the way we coordinate our actions with those of others. In this thesis we, therefore, did ask the question how actions are being coordinated in cooperative joint activities as outlined above and, additionally, what information individuals use to (jointly) decide who will perform what action where and when.

To study joint decision behavior in a cooperative activity, we found a paradigmatic example in serve reception in beach volleyball. With two individuals ready to receive the oncoming ball but *in fine* only one player that will actualize the interception, decision-making here is an integral part of a successful play. However, as going about studying interactive behavior in real-life settings is still technically challenging and, moreover, might not offer the necessary experimental control, we decided to take a step back and developed a new experimental paradigm to study joint decision making in a virtual joint interception task. Our experiment required two participants performing a video game-like interception task together to decide on every trial who had to intercept a downward moving virtual ball as the constraint not to collide impeded the two team members to both get to the ball's future arrival position. Our doubles pong task was taken to represent a variety of daily life social encounters in which cooperation follows from the joint responsibility to attain a common goal and the constraint

not to collide with each other. It allowed us to study –in a systematic fashion– how two individuals coordinate their actions when deciding who intercepts an approaching ball.

The social situation under study is unique in the sense that it includes a decision-making operation about who should perform a certain action and who should not. Typically, such decision making for action is studied at the level of the individual. A cognitive perspective to human behavior, for instance, considers decisions for actions as the output of a mental operation in which action alternatives (and their expected outcomes) are compared and a decision is made favoring one alternative over the other. Such an approach, however, is challenged when considering decision-making –and action coordination in general– as something between two individuals and, therewith, two brains. It would require a certain amount of shared knowledge about the task to perform to be able to predict the consequences a co-actor's actions and to align both individuals' action plans. For the task at hand this would imply a shared understanding of interception areas and the ability to predict the arrival position of the ball to jointly decide, among the two of them, who should perform the interceptive action and who should get out of the way. Instead of considering action selection beyond the individual as the output of a decision-making operation pointing out who performs what action where and when, deciding on a proper action might be better considered as a continuous process emerging from the lawful interactions between individuals and their environment, whether this environment concerns an object or another individual. From such an ecological perspective on human behavior, observed coordinated movement patterns reflect the continuous decision process as to how we should adjust our actions to successfully achieve a given goal (based on occurrent information specifying opportunities for action in the environment). Especially in the dynamic and fast-paced situations under study, where communication is often limited, impeded or a means too slow to quickly adapt to changing circumstances, considering joint decision making as emergent social coordination might provide a more parsimonious approach to the same problem that is action selection beyond the individual. Our main purpose of this thesis was to find out if joint action coordination and the decision as to who performs an interception where and when might indeed be an emergent property of the time-evolving interactions between cooperating individuals or, alternatively, that coordination (i.e., division of labor) between team members follows from a predefined division of interception space and a shared understanding of who performs what actions where.

Over the course of this thesis, different experiments were conducted with the same experimental set-up to find out how labor between team members cooperating on a virtual doubles interception task is divided. Our set-up had two participants sitting side-by-side at a large table, separated by a curtain, in front of a large screen positioned at the other end of the table. With two separate in-house constructed positioning devices participants were able to manually control their on-screen paddles. The paddles could move freely along a shared horizontal interception axis to intercept the downward moving virtual balls or to get out of the way to let their partner intercept the ball. Critically, verbal communication was precluded, implying that any division of labor between team members was based on visual information only. This allowed us to study if the decision to intercept a ball or not followed from the close spatiotemporal coordination of both team members' actions or from any tacit agreements about a separation of interception space, possibly predicated upon geometrically-defined boundary (e.g., the center of the screen or a location halfway both participants' initial paddle positions). The adoption of a video game-like doubles-pong task allowed us to easily capture the time-evolving spatiotemporal interactions between the participants' paddles and the ball, measure interception performance and identify the places where the left and right participant intercepted balls, that is, it allowed us to characterize how labor between team members was divided. Whereas in a first experiment both members of the teams were initially positioned at the middle of their screen half and matched based on comparable skill levels, later experiments allowed to study the effect of different initial paddle positions and skill differences between team members in order to find out how such factors influenced the team's division of labor (i.e., the decision of who intercepted which balls where).

Results showed that all teams demonstrated clear patterned interception behavior in all doubles sessions. That is to say, all teams showed a clear division of labor in that both team members intercepted balls in demarcated interception domains resulting in an (experimentally defined) boundary separating both domains. Boundaries, however, were rather fuzzy instead of clear-cut as there was some overlap between the interception domains, indicating that in a (small) area (i.e., the overlap) both team members intercepted some balls. Overall, division of interception space could vary considerably over teams within conditions, but appeared to change systematically as a function of both team members' initial paddle positions. Although some of our findings suggested that skill differences between members of a team also systematically influenced the division of interception domains, a manipulation of individual skill differences within teams did not provide the experimental evidence needed to support this claim. Given that communication upfront and in-situ was precluded, our findings point out that division of labor likely emerged from the interactions between team members during the trials instead of being based on any geometrically-defined division of space.

To support aforementioned suggestions, a simulation of the teams' interception behavior based on the (time-evolving) expediency with which, at each moment in time, each participant moved towards the future interception position provided an interesting means to unveil how behavior during the trials was related to its outcome. Based on a simple criterion 'the first paddle to attain a positive angular velocity with respect to the ball will be the one to actualize the interception' we were able to successfully predict trial outcomes in the large majority of trials of all teams participating in the different experiments. These results showed that the decision for an interception of the left or right playing participant was highly related to the participants' interdependent interception behavior (captured by both angular paddle-ball relations) during the trials. Moreover, the findings imply that in trails in which both participants initiated a movement, the participant not (being the first) to attain a positive angular velocity necessarily abandoned its interception attempt to allow a partner to actualize the interception. As attaining a positive AV with respect to the ball indicates that a participant's paddle will arrive at the future interception location ahead of the ball (and, thus, that it is engaged in an expedient interceptive action), the success of these simulations suggest that participants might actually use information about the expediency with which a partner engaged in its interceptive actions –optically available in a partner's paddle-ball relation– when deciding to intercept a ball or not.

An alternative way of accounting for observed division of labor that relied on an individual prediction of the location of ball arrival appeared far less parsimonious. Besides the finding that division of space did not seemed to be boundary-based, statistically modelling observed division of labor revealed that for a successful prediction of the trial outcome factors like ball arrival position, ball speed, lateral ball movement (i.e., lateral distance between ball departure and arrival position), and the session in which the team performed together with several between-factor interactions all significantly contributed. Taking such a model as an account for observed decision behavior implies that both team members are able to perceive, among other things, the exact ball arrival position, ball speed and lateral ball movement early during the trial that need to be integrated as 'building blocks' to come to a decision of an interception by the left or right playing participant. Considering that all this happens within one second, such a computational approach to observed division of labor might not be the most parsimonious explanation for observed decision behavior. All the more since the analysis revealed that lateral ball movement was an important predictor as well, the analysis showed that for a successful prediction of trial outcome not only where the ball arrived at the interception axis, but also how it arrived there appeared important. The observation of this so-called angle of approach effect points out that an account for observed division of labor based on a prediction of the arrival position of the ball –left or right of a tacitly agreed upon boundary– is not able to explain all behavioral characteristics observed.

In all, findings in this thesis provide converging evidence that the decision to intercept a ball or not emerges from the information coupling between participants. An action-based account, that confines the interception to the first attaining a positive AV with the ball, provides a parsimonious explanation for observed division of interception space as being the emergent result of both participants' interdependent interceptive actions following from the constraint not to collide. Without any prior division of tasks or predefined interception domains, all the team members have to do for a successful cooperation is act in such a way that if one is engaged in an expedient interceptive action (i.e., attains a positive AV), the other abandons its own interception attempt. Our studies point out that for a complete and parsimonious account of joint decision making and observed coordinated behavior in our doubles interception task it is important to consider the system of both paddles and the ball as whole with a focus on the way the spatiotemporal relations between those dynamic elements develop over time. Future studies should point out if similar emergent coordination phenomena might recur in other lab tasks and, importantly, real-life social interactions as well.

TABLE OF CONTENTS

1

GENERAL INTRODUCTION

"Do not follow where the path may lead. Go instead where there is no path and leave a trail"

- Ralph Waldo Emerson

1.1 Preliminaries

Like most animals on our planet, we, humans, possess the admirable ability to interact with the environment and others around us. From an early age we are surrounded by other individuals and learn to coordinate our actions with them in large variety of daily life activities. Indeed, whether we are walking on a crowded pavement, toasting with a friend or playing ball together, we coordinate our actions with others with seemingly ease. Those joint-actions highlight the capacity of our perception-action system to quickly adapt to changing circumstances allowing for close spatiotemporal coordination of our actions with those of others.

Consider for instance a walk on a pedestrian crossing. In order to arrive safely at the other side of the road we continuously have to pay attention to the movements of others around us and adapt our actions accordingly in a timely fashion so as to minimize the awkward dances we perform to avoid other pedestrians. We have all been in a situation in which another pedestrian is approaching head on, emphasizing the need for at least one of us to change your selected walking path in order to avoid colliding. Remarkably, coordination plays out fine in most situations. Similar situations can be observed in a traffic context. Consider for example the situation where two cars simultaneously approach an intersection requiring a coordinated order of crossing, or the moment you are speeding up to turn onto the highway while deciding to merge your car in front of or behind the car already on the road. Whereas the coordinative actions in the former situation typically follow from conventions or pre-defined interaction rules (i.e., the first to arrive will be the first to cross) the latter situation demands a decision of the drivers based on the interactions between both cars (e.g., difference between driving speeds). Similar situations abound in sports contexts in which we have to coordinate our actions with our team mates and opponents so as to achieve a common (sub)goal like delivering a successful pass in basketball, scoring a try in rugby and successfully receiving the serve in volleyball. Although all aforementioned situations are seemingly different, they have in common that they are comprised of goal directed actions that require coordination between individuals to result in an effective or successful outcome.

Whereas acting with others might result in new possibilities for action (e.g., displacing a heavy table; e.g., Marsh, Richardson, Baron, & Schmidt, 2006), in many situations joint-action is more about the coordinated interactions of multiple individuals acting in the same situation. Indeed, two cars driving close to each other on the highway do not acquire new possibilities for action, but their actions need to be coordinated closely in order to avoid colliding. Similarly, the decision of the aforementioned driver to merge in front or behind the car driving on the highway is influenced by its own driving speed, but also by the driving speed of the other car. Another situation highlighting the need of coordinated interaction is the case of two individuals loading a dishwasher together. While the task on itself (e.g., placing dishes in a dishwasher) can be performed by one individual, it can be done quicker when performing the action together. Critically, such cooperation brings along constraints that do not exist when performing an action individually. It is because of these new constraints (e.g., the possibility of colliding with one another) that individuals are demanded to make decisions about the behavior they should perform or, in some cases, they should better *not* perform. Taking turns while loading a dishwasher, hence, is a good example of joint decision behavior necessary for a productive cooperation.

In this thesis it is such joint decision behavior in a goal directed cooperative activity that we address. The activities are characterized by two individuals cooperating on a task in which in the end only of them will perform a particular action or in which both individuals will perform a similar action but have to take turns in order to avoid colliding. Two individuals leaving a room through a small door, hence, is another example describing the need of one of the individuals to perform a goal-directed action before the other. The question in this particular situation is how both individuals coordinate their actions so as to get through that door without bumping into each other. More generally, we are interested in how two individuals overcome the problem of action coordination in situations that demand a sequence of actions in order to avoid colliding. One way of looking at such a problem is that both individuals decide, among the two of them, who performs a particular action first and who should wait. Such a decision-making perspective thus considers the observed coordination as the result of a decision-making operation between the individuals. Alternatively, a social coordination perspective considers coordination as an emergent property of the interactions of both individuals over time. Such a perspective emphasizes the lawful relations that exist between interacting individuals that give rise to coordinated patterns of movement. In the following sections I will discuss some of the accepted frameworks for studying decision making for action and I will dive deeper in a way of accounting for social coordination in goal-directed joint-actions that is tailored to the purpose of this thesis.

1.2 Decision making perspective

From a decision making perspective to joint-action the goal is to describe how individuals decide who should perform what action at what moment in time. That is to say, they try to describe how individuals decide on a course of action together in which each member of a collective aligns one's actions with the actions of the other, or at least, performs an (complementary) action that least interferes with a successful performance of the task. For the goal-directed situations under study, this implies that individuals need to decide on an action plan that specifies who performs the goal-directed action (first) and who gets out of the way in order to avoid colliding. A decision, from this perspective, should be seen as the commitment to a certain kind of action with decision-making being the 'the [mental] process of solving a particular type of problem, arriving at a good decision' (Yates, 2001, p. 17).

This process of how individuals go about deciding what particular action suits task demands best has been subject to of a vast amount of studies. Typically, these studies focused on how individuals compute and select an action among a given set of action possibilities. Such a traditional view on decision making considers our brain as a central controller constructing mental representations to decide and, subsequently, act upon (e.g., Glimcher, 2003; Gold & Shadlen, 2001). By adopting such an egocentric perspective on decision making and, more generally, human cognition these studies place the origin of human behavior in the brain, therewith, largely ignoring its context (cf. Richardson, Marsh, & Schmidt, 2010). Hence, it may come as no surprise that most studies into decision making focused on the process of action selection in the individual. Although this thesis focusses on goal-directed behavior beyond the individual, I feel that an understanding of traditional approaches to human cognition, and decision making in particular, within the individual might provide the necessary context for an account of joint-action from a decision-making perspective.

1.2.1 Cognitive approach

Traditional approaches to perceptual decision making for action and, more generally, human cognition, consider human behavior as the output of a computational system (see e.g., Stillings et al., 1987; Von Eckardt, 1993). Behavior is said to be controlled by cognitive processes that mediate between the perception of sensory information (i.e., stimulus) and the selection of an appropriate action (i.e., response). Central in these information-processing approaches is the notion that sensory information is impoverished and, therefore, needs to be integrated with stored knowledge to construct semantic representations of the environment in order to give meaning to one's perceptions. These representations, or 'mental images' or 'internal models' as they are also referred to, are not imaginary pictures of an external event but comprise a symbolic structure in the central nervous system on which processes can be performed to retrieve more useful and important information (Paivio, 1986; Pinker & Mehler, 1988; Simon & Newell, 1971; Wood & Grafman, 2003). While there is still debate on how and where the representations are constructed (see e.g., Wood & Grafman, 2003), cognitive scientists generally agree that these temporally active meaningful representations are used for subsequent motor response selection (e.g., Cisek, 2007; Gold & Shadlen, 2001; Newell & Simon, 1972; Wolpert & Ghahramani, 2000; Wolpert, Miall, & Kawato, 1998). Perceiving the environment and acting within the same environment are thus treated as segregated (and serially arranged) internal processes (Newell & Simon, 1972). In what is to follow I will first describe how such a dualistic view on perception and action lies at the basis of decision making within the individual, whereupon I will elaborate more on how the information-processing approach left his mark on accounts of joint decision behavior.

1.2.1.1 On the individual

The aforementioned dualistic view on perception/action implies that decisions for actions are the result of mental processes in the brain, which is said to be a 'powerful decision-maker' (c.f., Glimcher, 2003; Gold & Shadlen, 2001). Indeed, in many decision making and judgement studies, humans are typically modeled as rational decision makers; computing and selecting an action from multiple action possibilities to maximize outcome performance (e.g., Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Gergely, Bekkering, & Király, 2002; Mellers, Schwartz, & Cooke, 1998). An appropriate action in a goal-directed task emanates from a decision making process that integrates information about previous experiences, expected outcome reward, individual needs and information retrieved from the semantic representation (e.g., Cisek, 2007; Newell & Simon, 1972). During this process mediated sensory evidence is accumulated over time in a 'decision variable' to allow for a discrimination of sequentially presented input (e.g., Gold & Shadlen, 2007; Johnson, 1980; Ratcliff & Mckoon, 2008). Actions will be executed at the time of decision completion where a decision is 'completed' when accumulated perceptual evidence in the decision variable reaches a threshold favoring one alternative over another (cf. Lepora & Pezzulo, 2015; Usher & McClelland, 2001; for a formalization of these ideas for instance see Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Carpenter & Williams, 1995; and Gold and Shadlen, 2001). With decision completion, a pragmatic representation is activated in which the goals for action are translated in motor schemata that are consequently used for movement execution and control (for details for instance see Jeannerod, 1997).

These processes represent theoretical views concerning the serial processing stream of a single decision variable that, although serving as a comprehensive explanation for behavior, often fall short to account for the more complex underlying neural structure. It is therefore that, over time, several researchers proposed alternative parallel views on the action selection in the decision-making process (see e.g., Cisek, 2007; Cisek & Kalaska, 2005; DeSoto, Fabiani, Geary, & Gratton, 2001; Ewert et al., 2001; Lepora & Pezzulo, 2015). Instead of first accumulating evidence and calculating situational probabilities before arriving at an action plan and subsequent execution, multiple action plans are prepared simultaneously (i.e., parallel) and with the accumulation of new information this leads to the execution of one action while preparation of the other is being suppressed. From this view, a cognitivist approach to decision making for action might better be conceived of as a continuous competition between action possibilities and appropriate movements instead of distinct serial processes of sensory encoding, decision formation and motor execution (Cisek, 2007; Lepora & Pezzulo, 2015).

In sum, the traditional approaches consider decision-making as a computational process connecting sensations and behavior in order to choose the best action among available alternatives (e.g., Glimcher, 2003; Wolpert & Ghahramani, 2000). To come to such rational decisions, individuals continuously integrate (sensory) evidence in a decision variable in order to thoroughly assess a situation. Once that decision variable reaches a certain threshold, an action is selected that best fits the situational needs. This way, the process of action selection places a large emphasis on computational processes in the brain. A vast amount of studies provided support for such an information processing approach to decision making.

Support. Aforementioned information processing approach to decision making received a considerable amount of support from neurophysiological decision-making and judgement studies performed with animals (e.g., monkeys; for a review see e.g., Gold & Shadlen, 2007; Glimcher, 2003) and, more recently, also with humans (see e.g., Heekeren et al., 2008; Kelly & O 'connell, 2014). Typically, these studies monitored neural dynamics to show the relationship between activation of neural substrates in various cortical areas and the subject's performance on a given task (e.g., saccadic eye movements; e.g., Glimcher, 2003; Gold & Shadlen, 2001) or a button press (e.g., DeSoto et al., 2001; Sebanz, Knoblich, Prinz, & Wascher, 2006). Whereas in animal studies invasive techniques could be used to asses firing rates of neural populations, recent technologies like electroencephalography (EEG), magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) allowed researchers to study cortical systems related to the to-be-build decision variables and the interactions between areas for the encoding, retrieval and processing of information in humans as well. This way, various studies revealed candidate brain structures presumably playing a role in the process of accumulation of sensory evidence and the subsequent action selection (see e.g., Liu & Pleskac, 2011; Tosoni, Galati, Romani, & Corbetta, 2008).

Besides the observed activity in neural substrates associated with stimulus perception and action selection, reaction time is another (performance) variable said to provide support for the information-processing approach to cognition; the more difficult the discrimination between two (or more) stimuli, the longer the neural populations associated with accumulation of sensory evidence are activated and the longer it takes a subject to perform an appropriate response (see e.g., Bogacz et al., 2006; Busemeyer & Townsend, 1993; Ratcliff & Mckoon, 2008; Ratcliff & Smith, 2004). Together with the measured neural dynamics, these reaction time studies are converging to support a variety of information-processing models to decision making linking theory and empirical support in order to account for the neural mechanisms underpinning decision making.

Box 1. Two-alternative forced-choice task.

A task often adopted in neurophysiological studies to perceptual decision making is the (two-alternative) forced-choice task (TAFC; see e.g., Bogacz et al., 2006; Ratcliff & Mckoon, 2008) as studying real-life decision making does not offer the necessary experimental control. In such often highly simplified decision-making conditions, animals or human subjects are forced to make a choice between two responses based on limited information about which one is correct (that is, which one will be rewarded) with both the speed and accuracy of the response affecting the reward. Important assumptions for TAFC models dictate that information favoring each action alternative is integrated over time and that a decision is made once sufficient evidence favors one alternative over the other. An example of TAFC for human subjects is a visual lexical decision task in which individuals have to classify stimuli as words or non-words (e.g., Lepora & Pezzulo, 2015); when the stimulus is perceived as a word the subject, for example, has to point to a target on the left and when the stimulus is perceived as a non-word the subject is required to point to a target on the right. The subject's decision hence is reflected in its action.

Challenges. The aforementioned models and experimental findings, however, are challenged when looking for a valid and complete account for decision behavior, notably in more dynamical contexts. First, some concerns are raised regarding the level of (or actually, the absence of) complexity in the experimental tasks performed. Indeed, most scientific support comes for simple and highly controlled forced-choice tasks (e.g., Bogacz et al., 2006; Ratcliff & Mckoon, 2008; see Box 1). Although simplifying task demands can be useful, and is sometimes necessary, to capture elementary processes underlying task performances, the often used static decision tasks might not be very representative for decision behavior in a dynamical context. Indeed, where decisions in dynamic situations depend on a meaningful context, interactions with the environment and foregoing decisions, such static decision tasks instead only focus on recognition of a stimulus followed by a response without further consequences (Brehmer, 1992; Busemeyer & Townsend, 1993). In addition, these simple decision tasks are performed over and over by the subjects. This way, the lack of context and repetitiveness of the task leads to a certain degree of automaticity in action execution and behavioral control not representative for natural decision behavior (Gold & Shadlen, 2007).

A second concern regarding classical theories on decision making is that they typically aim at describing how individuals choose one action alternative over the other (e.g., Bogacz et al., 2006; Ratcliff & Mckoon, 2008). In order to maximize behavioral output (i.e., its utility), many theoretical models focused on how an individual decision maker surveys a known set of action alternatives, and congruently evaluates the consequences of choosing each, before deciding on the most optimal action alternative for achieving a known goal (cf. Orasanu & Connolly, 1993). Although such classical models might perfectly account for the stimulus-response mappings in stereotyped laboratory tasks, they probably fall short when accounting for decisions made in more meaningful situations where action goals are not clearly defined, like is the case in many daily life situations (Beach & Lipshitz, 1993). Indeed, in natural-world situations were stakes are often high and time is limited, a thorough assessment of the situation and utility estimates of action alternatives are generally impeded making optimality in dynamic decision behavior a mere illusion. Moreover, the computational load for optimizing decisions and subsequent actions would be too high if humans need to analyze all action possibilities in uncertain and time-constrained dynamic environments (cf. Simon, 1955). Consequently, this brings out the question to what extent human decision behavior in a dynamic context fits into the mold of classical decision theory (e.g., Brehmer, 1992). Klein and colleagues, therefore, proposed an alternative naturalistic approach to decision making, making it more sensitive to the constraints of the environments in which decisions arise.

1.2.1.2 Naturalistic Decision Making

The Naturalistic Decision Making approach (NDM; see e.g., Klein, Orasanu, Calderwood, & Zsambok, 1993) has been introduced to account for individual decision behavior in more dynamic and natural contexts. Besides the lack of process-level accounts for decisions in real-world situations, critique from the NDM approach towards the more traditional approaches concerned the fact it focused on choosing between action alternatives, meanwhile ignoring the process by which individuals generate the action alternatives from which to choose (e.g., Johnson & Raab, 2003; Zsambok & Klein, 1997). NDM, therefore, focused on how this so-called option generation process lies at the basis of decision making in complex situations. Besides the focus on option generation, the approach aims at describing how individuals use their experience to categorize situations in order to make satisfactory (instead of optimal; Simon, 1955) decisions without the need to compare multiple courses of action.

A prototypic model op the NDM is the Recognition Primed Decision model (RPD; Klein, 1993). The RPD model focusses on how individuals recognize the typicality of a situation through a comparison with similar situations contained in their memory. This way, when individuals need to make a decision they can match the situation to patterns they have learned and, hence, know from implicit 'rules' what behavior is appropriate. The RPD model consists of various stages of situation recognition of which the simplest stage indicates that individuals clearly recognize a situation and can select a typical course of action. Consequently, they can make rapid decision without the need to compare other options. In other stages the situation is not recognized immediately, but after a better diagnoses a typical action might be selected or the individual first needs to simulate the consequences of an action in order find out if the chosen action fits the situational needs. If a chosen action does not result in the desired outcome, the decision-maker generates another course of action which will be mentally simulated again before being put into action. Decision-makers, hence, only determine few options (Johnson & Raab, 2003) and most of the time only one (Yates, 2001). This way, NDM claims that individuals most of the time are simply reacting to situations based on experience and training.

In order to gain an understanding in the process of option generation for decisions NDM typically uses retrospective interviews. Indeed, studies into decision making for action used self-confrontation interviews based on video recordings of an athlete (e.g., rugby player) during an activity in a dynamic context (e.g., a rugby match). In a typical experimentation, video recordings of the play were frozen at the moment the player had to decide what to do next. Through structured questions the players were invited to recall thoughts and feelings and explain their behavior and activity at that particular moment. In the case of the rugby player, questions might concern the moment he receives a pass from a team mate; what actions come to mind in that particular situation (e.g., run forward or pass the ball to another team mate)? This way, such interviews are said to provide insights in the number of decisions generated in dynamic performance contexts, notably in sports (see e.g., Johnson & Raab, 2003; Macquet, 2009). Besides the decisions generated, such interviews gave the experimenter insights in particular aspects of the decision-making process like the relevant cues decision-makers attended to (e.g., ball trajectory or position of significant others), anticipated events (e.g., possible actions of others), and plausible goals providing a rationale behind their choice for a particular course of action.

The aforementioned way of assessing decision-making skills in individuals has its roots in the temporal occlusion paradigm of Abernethy & Russell (1984). The occlusion paradigm involves having an individual looking at a live or videotaped event while occluding action sequences for some period time requiring the individual to report what he/she expects would happen next and what action alternative would have been chosen. Using this method, several studies have shown that expert 'decision-makers' have the ability to detect important cues (i.e., information) at an earlier point in time (see e.g., Williams & Ericsson, 2005). In a similar way, the spatial occlusion paradigm (in which particular arrangements of information are omitted like for example the hips of a soccer player in a penalty shoot-out; e.g., Williams & Davids, 1998) shows how the loss of information components constrains decision-making efficiency and action selection, especially in novices. Taken together, the occlusion paradigm provides a way to show how the pick-up or the lack of information constraints the choice for a to-be-performed actions. In doing so, the approach mainly has been used as a tool to understand individual differences in the use of information, therewith emphasizing expertise differences in decision making skills and anticipation behavior in dynamic situations (see e.g., Farrow, Abernethy, & Jackson, 2005; Williams & Ericsson, 2005).

Challenges. NDM gained some plaudits for its strong emphasis on the individuals' surroundings in the process of decision-making and the identification of other neglected areas in traditional approaches to decision making. In and on itself, however, the approach is kind of limited as a general account for the complex process that is decision making in a dynamic environment. As an explanation of their choices athletes might refer to information about particular positions and possible movements of obstacles and other players around them used to act upon. Consequently, most studies provide a mere description of when and where the athletes detected the information instead of describing how they used that information throughout a certain course of action. Indeed, NDM typically faces criticisms concerning their lack of explanatory power and corresponding tools to capture general mechanisms instead of particular descriptions of decisions (see e.g., Yates, 2001). Besides, in case of studies concerning RPD, an exclusive reliance of NDM on the utterances of individuals as an account for complex processes of decision-making in the brain might, at least, be questionable when considering the fast-paced decisions made in dynamic and uncertain time-constrained environments.

Thus far, we only considered decision making within the individual. Like NDM, cognitive approaches are being challenged when considering decision making as a process beyond the individual, that is, between two (or more) individuals and therewith two (or more) brains. Considering its egocentric perspective to perception and action (which confines the causality of behavior to the in isolation studied computational and representational processes occurring in the brain; cf. Richardson, Marsh, & Schmidt, 2010), the presence of two brains in any joint activity, therefore, is a major challenge researchers faced and still face today to come up with an account for the observed coordination and cooperation in joint actions and joint decisions from an information processing perspective on cognition. In what follows I will elaborate on how information processing approaches to decision-making go about to account for the jointly coordinated movements as observed in many daily life situations.

1.2.1.3 Beyond the individual

Success in any joint-action depends on how a collective can overcome the problem that in many complex situations a variety of complementary behaviors exist to achieve a given goal. From a decision-making perspective, joint-actions thus necessarily involve a decision-making operation to decide who performs what action where and when. Scoring a goal in soccer, for example, can be done over the right wing or left wing and when displacing a sofa together there are many options as to what height and at which side the sofa might be best seized. The question then is how a collective of two or more individuals decides on a particular course of action so as to achieve a given goal. That is, how do both individuals decide (upfront or *in-situ*) on a proper action to align one's actions with the actions of the other, or at least, decide on a (complementary) action that least interferes with a successful performance of the task. Joint decision-making, this way, becomes a coordinated activity.

Like aforementioned models on decision-making for action in the individual, it is a (socio) cognitive approach that underpins the decision-making perspective on joint action.

Consequently, in an account for the process of action selection in dyads the focus mainly lies on internalized processes of cognition held responsible for the observed coordination in joint actions. Deciding on an appropriate (joint) action, here, is said to follow from a dynamic process that, over time, continuously integrates information about the inferred goal of the co-actor (obtained through motor simulation), shared knowledge about what the two actors should do (construction plan), and contextual information (e.g., the spatial distribution of objects in the working area; Bicho, Erlhagen, Louro, & Costa Silva, 2011).

Central in a socio-cognitive approach to joint-action is the concept of shared knowledge stored in shared mental models (Cannon-Bowers, Salas, & Converse, 1993; D. W. Eccles & Tenenbaum, 2004; Reimer, Park, & Hinsz, 2006). Shared knowledge is all of the knowledge that is held in common between both members of a dyad necessary to perform an action together, like the joint action goal and a plan with the to-be-performed tasks of all actors involved (Sebanz & Knoblich, 2009; Vesper et al., 2017). Based on shared knowledge dyad members create a joint task representation in which they not only represent their own task but also incorporate their co-actors task in a functional equivalent way (Sebanz, Knoblich, & Prinz, 2003, 2005; Sebanz, Knoblich, et al., 2006). Put simply, when a task is shared between two individuals, for example you and me, this implies that I have the same knowledge about what you and I are going to do and when we are going to do it, as the knowledge you have about what you and I are going to do and when we are going to do it. Such joint task representations allow for simulations of both our actions and leads to a shared understanding of the situation that dictates what action should be pursued for a successful coordinated joint performance (Reimer et al., 2006). With this in mind, cognitive scientists argue, shared knowledge is said to provide a means for each member of a collective to accurately monitor task progress and anticipate the behavior of others in order to decide on a proper action to achieve a common held goal.

A shared understanding of the task is thus a prerequisite for a successful team performance. Most studies dedicated to decision-making and coordination beyond the individual focused on how shared knowledge comes about from explicit coordination, typically in sports contexts. Here, shared knowledge about a collective performance typically follows from (verbally) communicated action plans (e.g., instructions of a coach prior to a match or the playbook in football specifying all game plans for a team) or conventions (e.g., when multiple cars arrive at a crossover it is typically the first to arrive, the first to cross; e.g., Eccles, 2010; Eccles & Tenenbaum, 2004; Ward & Eccles, 2006). Consider for example the game of volleyball where the coach in a time-out might give instructions to the setter to set all balls to the outside position as the power hitter in place is sure to score that last important point. All players heard the instructions resulting in a shared understanding of the play, that is, a serve reception and subsequent pass, the set to the outside and a smash to finish the play, and, therefore, the team can act accordingly. Verbally communicating an action plan, specifying one's actions upfront, hence, is a powerful and important tool necessary for shared task representation to allow for a task division and successful coordination (Clark, 1996; Eccles & Tenenbaum, 2004; Knoblich, Butterfill, & Sebanz, 2011; Sebanz, Bekkering, & Knoblich, 2006).

Nevertheless, not all actions can be coordinated in an explicit fashion. Indeed, plenty of situations ask for fast adaptations in rapidly changing circumstances, where slower forms of communication like deliberation would not be sufficient to achieve the fine-grained spatio-temporal coordination like, for instance, seen between two individuals shaking hands. Another pertinent example follows from the aforementioned volleyball play, where things get interesting when the pass (i.e., reception of the serve) does not end at the setter's position at the net. When an explicitly coordinated action sequence does not start according to plan, the instructions for any subsequent actions might be useless and members of a team, in this particular case the setter, quickly needs to decide on an alternative course of action. Such adaptive behavior is part of many daily life encounters with others, often involving strangers and no clearly defined action goals. Whereas a (new) action plan might be communicated verbally, in many of such dynamic and time-constrained situations, verbal communication is too slow to act in a timely fashion (Tenenbaum, 2003) or absent altogether, specifying the need for another type of coordination. Cognitive scientists argue it is the implicit (i.e., unconscious) coordination that accounts for behavioral adaptations *in-situ*. As communication is impeded and without any *a priori* action plans, implicit coordination is said to be based on pre-existing knowledge and unspoken assumptions about the behavior a co-actor is likely going to perform (Cannon-Bowers & Bowers, 2006; Espinosa, Lerch, & Kraut, 2002). Similar to explicit coordination, a mental model is constructed containing (shared) knowledge about a possible goal and actions that the co-actor is likely to perform. In order to form adequate representations of their co-actors and their roles they must process relevant information and cues from their environment. Importantly, for a shared understanding of the situation, both actors should attend to the same information and cues, as, otherwise, their mental models differ too much in order to accurately anticipate the co-actor's actions and needs (see e.g., Reimer et al., 2006). So, like in explicit coordination strategies, shared knowledge is said to provide a crucial role in implicit coordination as well.

In a recent study on doubles tennis Blickensderfer, Reynolds, Salas, & Cannon-bowers (2010) tried to find support for the concept of implicit coordination in a dynamic sports context. Implicit coordination, here, was operationalized as the (maintenance of a) relative position between both players assuming that a low variability in relative position corresponded to a high rate of implicit coordination as players constantly stayed half a court apart and responded immediately to a partner's repositioning. No immediate responses and large fluctuations in the relative position of players would indicate a low level of implicit coordination. Measuring the (change of) relative position between players was done by raters that watched video recording and rated the way players moved with respect to each other in a predefined scoring system. Together with a questionnaire measuring constructs like shared expectations of tennis players about each other, Blickensderfer and colleagues showed that a better shared understanding of the task might indeed be related to better implicit coordination in teams.

Aforementioned situation, a game of doubles tennis, resembles quite the dynamic and time-constrained task at the focus of this thesis. Typically, such situations require fast on-the-fly decisions and a dynamic course of action as the environment is constantly changing. Most studies from a socio-cognitive perspective, however, have difficulties to account for such in-situ decisions and action coordination. Indeed, like in the study of Blickensderfer et al., the conceptual frameworks proposed as an account for team behavior do not provide any answers to questions concerning the when, how and why some of the observed plays are created (cf. Eccles, 2010). Although they contribute a great deal to identifying concepts important in decision-making and joint-action coordination, these studies are mainly concerned with thinking and communicating about acting together instead of studying the *in-situ* action coordination of multiple individuals in dynamic situations (but see Vesper, 2010, 2017 and Box 2).

Box 2. Socio cognitive approach to joint action.

From an socio-cognitive perspective on joint action, smooth coordination could never be achieved if individuals only responded to what they observed others doing (e.g., Sebanz, Bekkering, et al., 2006). Prediction and anticipation of each other's intentions and actions, are critical aspects for knowing when and where to act in order to adequately perform a joint action (Sebanz & Knoblich, 2009). Action prediction is said to be achieved by creating shared task representations in which individuals not only represent their own task but also incorporate their co-actors task in a functional equivalent way (Sebanz et al., 2003, 2005; Sebanz, Knoblich, et al., 2006). This way, representational structures not only allow for a simulation of one's own actions, but also provide a basis for the simulation of the actions of others which, subsequently, can be used for a prediction of the co-actor's intentions and (the consequences of) its actions (Bicho, Erlhagen, Louro, & Costa Silva, 2011; Pezzulo & Dindo, 2011; Vesper, Butterfill, Knoblich, & Sebanz, 2010).

Such shared representations are said to result from the common coding of perception and action (see e.g., Prinz, 1990, 1997) which means that the same representational structures are used for movement perception and the action itself. Evidence at functional level for such a common coding system comes from mimicry studies (Chartrand & Bargh, 1999) and behavioral experiments (e.g., Brass, Bekkering, & Prinz, 2001; Kilner, Paulignan, & Blakemore, 2003) which showed that observing someone performing a certain action, activates our own motor system in a comparable way and facilitates (or interferes with) one's own action performance and planning. For example, seeing another individual perform a grasping movement decreases the time it takes to perform a comparable grasping movement (Kilner et al., 2003; Stürmer, Aschersleben, & Prinz, 2000). Additional evidence for shared representational structures comes from studies at the neurophysiological level that reveal the presence of the so-called mirror neurons in several areas of the brain (e.g., Gallese & Goldman, 1998; Rizzolatti & Craighero, 2004) that discharge both when an individual performs an object-directed action itself or when it perceives another individual performing the same action (see also Newman-Norlund, Noordzij, Meulenbroek, & Bekkering, 2007). Mirror-neurons in the premotor and parietal cortex, hence, would provide the neural mechanism to understand the actions of another and, subsequently, offer the means to engage in joint-actions. This way, a socio-cognitive approach advocates a neuromechanistic account for social behavior in which the activity of brain structures constitutes the causal organization of social interaction.

Consider for example the previous mentioned volleyball play where an erroneous serve reception impedes a further execution of the predefined action sequence. This, however, does not mean that the game is lost. On the contrary, if a ball bounces of a player's arms, other players respond immediately with an action to bring the ball back in the game. Typically, it is the setter that is the second player to touch the ball (out of three possible touches before the ball has to go over the net). Nevertheless, when the ball is too far away another player might decide to go and get it instead of the setter. The question then is to what extend shared knowledge about the what, when and where of a team's actions is sufficient to enable such fine-grained temporal and spatial coordination observed in such time-constrained situations (e.g., Sebanz & Knoblich, 2009). Here, saying that that particular player already anticipated to go and get the ball after mental simulating all possible courses of action for him- or herself and for others might not tell the whole story.

This brings me to another concern regarding the representationalist view on decision-making and joint action in that it focusses on internally generated structures which, researchers argue, are highly ego-centric and do not seem to fully appreciate the highly-adaptive and complete behavioral context we daily perform in (e.g., Coey, Varlet, & Richardson, 2012; Richardson et al., 2010). Indeed, by confining all human (inter)actions to the outcome of processes in the brain such an approach might not be best suited for an experimental paradigm that has the coordination of human interactions in a dynamic environment as principal object of study. For present purposes, we therefore opt for a more functionalistic approach to decision making, and perception and action in general, that emphasizes the emergence of behavior from the performer-environment interactions rather than from inferential process on representational structures in the brain: the ecological approach. In the next section I will discuss some of the nuts and bolts of the ecological approach to human behavior and elaborate on how the ecological approach considers the problem of decision-making for action, in the individual and, importantly, beyond the individual. This way, I hope, we might agree on taking a different perspective to account for the problem of decision-making for action in a dynamic and time-constrained social context.

1.2.2 Ecological approach

It was not until late in the 70's of the previous century that the ecological approach to perception (cf. Gibson, 1979/1986) was extended to account for observed control of goal-directed behavior without referring to internal mechanisms or representational structures in the brain (e.g., Turvey, Shaw, & Mace, 1978). While the established information processing approach to cognition and action was flourishing (see e.g., Chomsky, 1980; Fodor, 1975; Schmidt, 1975), critique swelled with respect to some of its basic (meta-theoretical) departure points (e.g., Michaels & Carello, 1981; Turvey & Shaw, 1979), including agent-environment dualism, and the subservient role of perception and action, that confines perceiving, knowing and acting to largely separated (and subjective) processes, only indirectly linked through mental representations. This lead researchers to develop an ecological approach to behavior that considers the act of perceiving (properties of) the environment as meaningful and direct (i.e., unmediated) and does justice to the inherent link between perception and (the control of) action (e.g., Michaels & Carello, 1981; Turvey & Kugler, 1984; Turvey, Shaw, Reed, & Mace, 1981). Combining the work of Bernstein (1967) on the reduction of the (redundant) degrees of freedom for the control of human movement and the theory of Gibson on direct perception (Gibson, 1979/1986), the unorthodox ecological approach to perception and action offered a serious alternative challenging the traditional representational views on cognition.

Fundamental to the ecological approach to behavior is the notion of direct perception. The theory of direct perception (Gibson, 1979/1986, Michaels & Carello, 1981) implies, quite simply, that properties of the environment can be perceived directly. That is to say, instead of the need for inferences and memories to mediate (i.e., enrich) the impoverished perceptual input (i.e., stimuli), information is said to be extremely rich, because (change in) the structure of stimulation provides a precise and meaningful specification of the environment. These fundamental differences between the established theories on perception and action and Gibson's work are perfectly summarized by Turvey and Kugler (1984):

"Rather than founding perceptual theory on brain states that are related tenuously to the environments and activities of animals, Gibson founds perceptual theory on structured energy distributions that are lawfully related to the environments and actions of animals. Rather than asking how accurate objective inferences from brain states to the facts of environments and actions are made, Gibson asks how information specific to the facts of environments and actions

is detected. Rather than assuming that the conventional variables of physics provide the only legitimate basis for describing the environment, Gibson advances the idea that the environment can be legitimately described in terms that are referential of the activity capabilities of animals" (p. 213).

Information in the ecological approach to perception and action, thus, is assigned a different and far more important role then it has in information processing approaches to cognition, as the detection of specifying information allows for the perception of environmental properties and, this way, bridges the conceptual gap between the agent and its environment.

1.2.2.1 On the individual

Information, from Gibson's point of view, is the structured pattern of energy flow that lawfully specifies an environment to an agent. It is an objective (lawful) variable that mirrors (and hence unequivocally carries) the specific and meaningful properties of the agent-environment system (AES). For our visual system, for example, it is in the (changing) optical structure of light (i.e., the ambient optic array) reflecting from substances (e.g., water) and surface layouts (e.g., a pavement) that properties of the environment relative to the agent are specified. Detecting the pertinent information (by means of appropriate perceptual systems), hence, allows for the perception of corresponding AES properties. Because the structured energy flow is univocal and carries properties specific for the complementary agent-object relation, Gibson's notion of information provides a lawful basis for knowing what activities the situation offers (e.g., water is drinkable when it's in a glass or swimmable when it is in a lake). This way, he provided a description of the environment that is directly relevant for behavior; knowing what substances or surfaces are and what they mean are not separate. Hence, it is the perception of these possibilities for action (i.e., affordances), through the detection of specifying information of a substance or surface layout, that can be used to decide and act upon.

Affordances are defined as the possibilities for actions permitted by objects, places and events in the environment (Michaels & Carello, 1981). Following Gibson, perceiving affordances is perceiving what the environment means to us. A cup of tea, for example, affords grasping so when perceiving that cup of tea one knows that it can be held in our hands. For an affordance to be perceived, first and probably most obvious, a property of the AES must be specified as an invariant combination of substances and surfaces. Second, the actor must be able to detect the information, that is, it must possess senses that are tailored to the kind of information to-be-detected, as is, for example, our haptic system for mechanical forces. Ultraviolet radiation, for that matter, carries no information for humans as we do not possess the senses to detect it, whereas for honeybees, for example, it is. Third, affordances are referential to an agent's action capabilities in that an agent must be able to exert the specified action in order to perceive it as such, like stairs afford climbing and a palm tree (for most of us) does not. Taken together, as Michaels & Carello (1981) put it, it is information that specifies afforded behaviors belonging to the complementary relationship in a particular AES and nothing less. Affordances, therefore, are the central notion in the ecological approach to perceiving and acting (Turvey, 1992).

From an ecological perspective, acting in a dynamic environment constitutes a continuous process in which one adapts one's behavior to currently specified possibilities for action (i.e., affordances). Indeed, as one is moving with respect to one's surroundings, opportunities for actions emerge, persist and dissolve over time (Turvey & Shaw, 1995). Consider for this matter a rugby play where "A gap between opposing players can open to afford passing through at one moment and then collapse into an impenetrable barrier at the next moment" (Fajen, Riley, & Turvey, 2009, p. 80). A (slight) change in one's position and movement speed or in the kinematics of the other alters the interpersonal relation reflected in a transformation of the optic array (i.e., optic flow), resulting in information specifying different opportunities for action. Consequently, an agent continuously needs to attend to specifying information about its environment to control its actions in an on-line fashion, that is, prospectively (Turvey, 1992; Turvey & Shaw, 1995). This way, the agent adapts its actions based on time-evolving information specifying the state of a particular relationship with the environment, with a pertinent AES state of the relation implying success if the relation prevails (e.g., Chapman, 1968; Peper, Bootsma, Mestre, & Bakker, 1994; Turvey, 1992). Similarly, negative outcomes can be prevented if one avoids AES states that specify unwanted events (e.g., collisions; for more information on invariants see e.g., Michaels & Carello, 1981). Put simply, without needing to mentally predict future situations from the present situation, information about the 'current future' (i.e., what will happen if things do not change; Bootsma, 2009) emanating from a robust perception-action coupling enables a continuous modification of one's actions to successfully achieve a given goal under changing circumstances.

With multiple affordances available for each subsequent moment in time, the goal-directed actions we perform on daily basis are 'inherently forms of true choice behavior' (Shaw, 2001, p. 283). That is to say, in order to succeed in such goal-directed behavior we are constantly deciding between the action possibilities afforded in the current situation that suit our intentions best. And, as mentioned earlier, with the constantly changing action possibilities around us we are thus continuously deciding if and, if so, how we need to adapt our behavior to successfully achieve a given goal. Deciding on a proper action, from an ecological perspective, hence, does not merely happen at a given moment in time but is a continuous process emerging from the interaction between the agent and its environment (Araújo, Davids, & Hristovski, 2006; Barsingerhorn, Zaal, De Poel, & Pepping, 2013; Fajen & Warren, 2003). In this framework, the decision to grasp an object is not separate from and does not precede the grasping itself but, instead, comprises the whole performance from movement initiation until the moment the object is located in one's hand. This implies that decisions are expressed by (a change in one's) actions (Turvey & Shaw, 1995). Analyzing human-environment interaction at the ecological scale, hence, is said to be a grounded way to understand the decision-making process (Araújo et al., 2006).

1.2.2.2 Dynamical approach to human movement

Considering decision making as the result of interactions at the agent-environment level places the origin of action selection (i.e., the emergence of behavior) in the direct (informational) coupling between an agent and its environment. Consequently, many studies focused on identifying the information that specifies the action-relevant properties of the environment and how this information is used in the control of action. In doing so, they adopted a dynamical approach to human movement to relate the adaptive behavior in the environment (i.e., the temporal and spatial coordination) to the available perceptual information.

The dynamics of perception and action in complex behavior can be described at two levels; a first level that considers the interaction between the agent and its environment and a second level that characterizes the temporal evolution of the observed behavior, the so-called behavior dynamics[1] (Fajen & Warren, 2003; Warren, 2006). At this second level, physical principles and concepts from non-linear dynamics are used to formally describe the temporal evolution and qualitative characteristics of observed behavior. That is, concepts of non-linear dynamics help characterizing the stable movement patterns and qualitative transitions observed in human behavior (e.g., Kelso, 1997; Kugler & Turvey, 1987). The goal here is to identify a system of differential equations to formalize the human-environment interactions in terms of a dynamical system that expresses patterns of stability and changes in the system's behavior (see e.g., Warren, 2006). Preferred modes of behavior (i.e., stabilities), hence, correspond to attractors and behavioral states to avoid (i.e., instabilities) correspond to repellers in the system's dynamics with bifurcations corresponding to the qualitative transitions of one stable movement solution to the other. This way, non-linear dynamics provide a theoretical framework to characterize the stabilities and instabilities governing observed behavior.

Besides intrinsic attractor/repeller dynamics, (the limited amount of) stable behavioral solutions in goal directed activities typically result from a confluence of physical and informational constraints acting on a system. The first level of analysis, therefore, emphasizes the perception-action cycle between the agent and (the interactions with) its environment (Kugler & Turvey, 1987). Specifically, it focusses on how the actions of an agent in its environment allow for the detection of new information, and how this information, reciprocally, can be used in the control of action through the so-called laws of control (Warren, 1988). This way, studies concerned with the dynamics of perception and action revealed laws of control in which task-specific information modulates the dynamics of our action system. An overarching goal of a dynamical approach to human behavior, hence, is to

[1] Whereas other terms have been proposed to best capture the set of control laws underlying the observed behavior at functional level (e.g., task dynamics (Saltzman & Kelso, 1987), behavioral dynamics (Fajen & Warren, 2003; Warren, 2006) and ecological dynamics (Araújo et al., 2006)), key to these approaches is the use of dynamics as an universal language in a description of the world, the body and sensory and neural couplings involved in behavioral organization.

describe how aforementioned stable patterns of movement (at the second level of analysis) recur in different situations from the interaction between human and environment under a confluence of physical and environmental constraints. In doing so, they showed that stable movement solutions do not reside a priori in the human or its environment, but that they result from the interaction between both. Moreover, opposite to information-processing approaches to human cognition, the dynamical approach to human behavior has the tools to focus on the continuity of a system allowing for a characterization of temporal evolution of a system's behavior as a whole.

In sum, a dynamical approach to human movement provides an account for human behavior that focusses on the way the structure of occurrent information (i.e., informational variables), whether optic, acoustic, chemical etc., directly governs naturalistic behaviors like hitting, grasping, obstacle avoidance and interception in a lawful way. Such an information-based approach to perception and action, hence, is able to explain and predict how goal-directed behavior emerges from known control laws at the agent-environment level.

Support. Following a dynamical approach, over time many studies have been performed focusing on what information might be specifying, and how they might be specific for (i.e., lawfully control) a certain kind of goal-directed human behavior. One of the first to show that humans might indeed use a specifying variable to act on was Lee (1976) in his study on visually-guided braking. He argued that the decision to start braking and controlling the ongoing braking was closely tied to information about time-to-contact (TTC) optically specified as the ratio of an approaching object's optical size and the rate of optical expansion (referred to as tau τ). The detection of optical variable τ allowed the agent to decide when it was a proper time to start braking without making any mental calculations or inferences. In a similar fashion, a study of Benerink, Bootsma, & Zaal (2015) suggested that the initiation of locomotor actions (i.e., whole-body displacements) in volleyball serve reception was tied to the start of the serve, whereas initiation of arm movements (i.e., the decision to prepare the arms for ball reception) was related to information about TTC. Recently, studies on steering, obstacle avoidance and, more complex, route selection showed that the dynamics of behavior depend on information about the observer's movements relative to the next few objects in its environment (e.g., change of distance or optical angle with respect to an object) to decide on an appropriate road for achieving a given goal (e.g., Fajen & Warren, 2003, 2004, 2007). In a series of experiments Fajen and Warren let participants walk towards stationary and moving objects (while sometimes avoiding in-path obstacles) in controlled environments. These experiments showed that the observed route was not determined in advance based on explicit planning, but instead emerged from the participant's interactions with the environment. A model based on local attractor and repeller dynamics was able to capture steering behavior and obstacle avoidance and, importantly, to make predictions about typical route selection in goal-directed locomotor interception tasks.

In a similar vein, studies investigating sports contexts tried to model observed decision behavior and to capture information individuals used to decide on. In doing so, they pointed out that, for example, in rugby union it was in the interpersonal distance and the relative velocity between players involved that the decision of an attacker resided to pass by a defender to score a try (Correia et al., 2012; Passos et al., 2008), that the start position in a sailing regatta seemed to follow from an interplay of wind direction and starting line (Araújo, Davids, et al., 2015), that the emergence of specific punching actions in boxing depended on a scaled boxer-target distance (Hristovski, Davids, Araújo, & Button, 2006) and that the type of pass in volleyball serve reception followed from the player's initial position and serve characteristics (Paulo, Zaal, Fonseca, & Araújo, 2016). All of the previous-mentioned studies focused on the agent-environment interactions and showed that it is the agent's position with respect to a to-be-interacted-with object or individual that underlies the emergence of particular behaviors. Similarly, Travassos and colleages (2012) showed in a study on the interception and passing behavior in a game of futsal, that the decision of a defender to intercept a passed ball was constrained by its position relative to the ball's trajectory. These latter findings are of particular interest as the complex game of futsal has comparable characteristics to the dynamic nature of the task under study in the present thesis. Taken together, these studies addressed how (changes in) informational constraints influence the emergent goal-directed behavior of a player and, importantly, revealed that a focus on the overt agent-environment interactions over time provides a functional way to capture emergent behavior in a complex and dynamic environment (see also Correia, Araújo, Vilar, & Davids, 2013).

In sum, the detection of affordances allows for a prospective control of our actions in complex and dynamic situations. Studying the complementary interactions between an agent and its environment, hence, allows for a characterization of the available information governing goal-directed behavior. This way, many studies into decision-making for action showed that the decision process is reflected in the actualization of these affordances and (transitions in) each performer's course of action.

However, although the theoretical underpinnings and the way of studying complex behavior in dynamic contexts is appealing for the problem under study, some caution is required regarding the conclusions drawn from some of these studies into decision-making as the studies following the aforementioned line of research, typically did not attempt to manipulate the spatiotemporal information argued to be responsible for the observed behavior (cf. Correia et al., 2013).

Consider for example a study described by Araújo et al. (2006) in which they capture the decision behavior of an attacker dribbling with the ball to get past the defender in a game of basketball. The attacker-defender dyad is taken as a typical one-on-one situation observed in many invasive sports like football and rugby. Inspired by work of e.g., Kelso (1995) on symmetry breaking in dynamical systems, Araújo and colleagues argued that the dyad's organization could be seen as a micro-system with the interpersonal distance as a collective variable capturing the system's stability. The defender, on the one hand, tried to keep a stable distance between both players (i.e., a symmetry in both player' movements) while the attacker, on the other hand, persisted with dribbling to create an opening (i.e., a symmetry-break) so as to get past the defense. They showed that when the interpersonal distance changed from a steady positive value towards a negative value when the attacker tried to get past the defender (i.e., when symmetry was broken), the decision emerged. This way, the decision of the attacker to 'go' was reflected in a transition of the system from the initial steady state into a dynamic state. Araujo and colleagues pointed out there were certain critical values of interpersonal distance at which the attacker-defender dyad became more destabilized, resulting in more symmetry-breaks and therewith the decision of an attacker to get past the defender. Nevertheless, Araujo and colleagues did not manipulate the interpersonal distance or distance until the target (i.e., basket) to study if interpersonal distance is indeed the informational variable resulting in the decision to get passed the defender. Constraining the attacker's behavior by forcing it to get passed the defender before or after a critical distance with respect to the target, for instance, might have been a manipulation to test if the same critical values of interpersonal distance would give rise to destabilization of the attacker-defender dyad at different phases of the game as well.

Another concern for this particular situation is that for an attacker to get past the defender, the interpersonal distance necessarily has to go from a (steady) positive value towards a negative one and, consequently, results in a symmetry break. The question then rises to what extent the variable interpersonal distance and the symmetry breaking observed in the study of Araujo et al. (2006) explains the attacker's decision behavior instead of being a mere post-hoc description of the situation. Indeed, as a symmetry break is a prerequisite of successful task performance, interpersonal distance, here, tells us that it happened (i.e., when) instead of why. So, although the overt agent-agent interactions might be well captured by the interpersonal distance, the extent to which it explains the attackers decision behavior, I feel, is arguable.

This brings to the surface another, more general concern regarding a decision-making perspective to account for dynamic agent-environment interactions in complex situations. Although Turvey and Shaw (1995; Shaw, 2001) argued that all (transitions in) actions express decision behavior, generally, they provide a mere description of the decision as it is performed. Indeed, when somebody decides to put a glass on the table we can tell he/she decided doing so after we have seen him/her put the glass on the table. More interestingly, however, is to know how that glass was being put on the table and why. Following an ecological approach, the problem of decision making in neurobiological systems then, fundamentally, becomes continuous with the problem of perception and action (Araújo et al., 2006). That is, the study of knowing how the emergence of (goal-directed) behavior is lawfully related to perceptions. This way, we might take a different approach to study action selection in the individual, and importantly, as something between two or more individuals.

1.2.2.3 Beyond the individual

From an ecological perspective, decision-making for actions beyond the individual may be considered as an emergent property of the interaction in a social system, instead of being the result of a separately ongoing decision-making process pointing out who performs what action at what moment. Coordination in dynamic and complex situations, hence, is said to result from the pick-up and exchange of information with others under individual, task and environmental constraints (Marsh et al., 2006; McGarry, Anderson, Wallace, Hughes, & Franks, 2002). Especially in the fast-paced situations under study, where communication is often hampered, considering joint-action as emergent social coordination provides a different perspective to the same problem that is action selection beyond the individual. In what follows I will elaborate on studies investigating the organizational principles underlying the observed coordination in various (goal-directed) joint activities, so as to show how a social coordination perspective might account for the joint decision behavior observed in many joint activities we perform on a daily basis.

1.3 Social coordination

In a dynamics-based social coordination approach to joint-action, the emphasis lies on the self-organizing nature of a system of two (or more) co-acting individuals. Instead of being controlled by a centralized controller, coordinated behavior emerges from a balance of constraints that channels and guides informational and physical couplings between a system's components (here, the agent-agent interactions; e.g., Richardson et al., 2010; Riley, Richardson, Shockley, & Ramenzoni, 2011; Warren, 2006). As the activity of components in a system is constrained (i.e., dependent) on the activity of the other components in the system, the interaction itself is critical for an account of the observed behavior (Coey et al., 2012). As mentioned above, the study into joint-action thus bears similarities with studies into perception-action couplings in the individual, as both studies aim at finding patterns and regularities underlying the interactive behavior of an individual and its environment (Marsh et al., 2006; Marsh, Richardson, & Schmidt, 2009; Richardson et al., 2010). Indeed, whether this environment is a moving obstacle or another individual, an ecological approach focusses on the (perceptual) information governing one's actions with its environment in a lawful way (Warren, 2006). This way, focusing on the couplings between an agent and its environment has proven to be able to account for the organization of emergent behavior at the level of the individual and, more importantly, in a system consisting of two co-acting individuals as well (Harrison & Richardson, 2009; Marsh et al., 2009; Richardson, Marsh, Isenhower, Goodman, &

Schmidt, 2007; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994; Schmidt, Fitzpatrick, Caron, & Mergeche, 2011).

In accounting for the dynamic and self-organized nature of social interactions, the ecological approach goes hand in hand with a dynamic-systems framework to movement coordination. As previously mentioned, a dynamical approach to human behavior provides a way to describe the lawful principles that govern the causal unfolding of the observed intra- and interpersonal movements rather than looking for neurophysiological areas that generate behavior (Kelso, 1997; See also Box 2 for a socio-cognitive acount to joint-action). A dynamic approach thus provides a parsimonious way to account for the control of (joint) behavior that is ‘regular without being regulated’ (p.225, Gibson, 1979). Although there is no general dynamic theory of social coordination yet, studies into coordination dynamics have provided a particularly interesting example of self-organization processes in rhythmical coordination tasks.

1.3.1 On rhythmic coordination

Many studies concerned with the emergence of movement patterns at interpersonal level focused on the coordination of rhythmical movements. Rhythmic coordination (i.e., synchronization or entrainment of oscillatory movements), Bernstein (1996) argued, is a fundamental type of coordination in biological systems. Consider for example the rhythmic coordination of limbs that is omnipresent in organisms propelling themselves in their respective environment (e.g., the fins of a fish for swimming and the legs of humans for walking). Besides coordination within biological systems, rhythmical movements of organisms have shown to be lawfully constrained by conspecifics as well. Such rhythmic coordination becomes apparent in one or a small number of stable coordination patterns. Fireflies, for example, gather at dusk and, although starting off blinking at an individual frequency, their own rate of blinking is pulled into the blinking rate of others around them resulting, with a sufficient number of fireflies around, in a pulsing mass of synchronized blinking fireflies (e.g., Buck, 1988; Strogatz & Stewart, 1993). More directly related to human behavior, the synchronous applause of a satisfied crowd (Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000) and the entrainment of individuals walking side-by-side (van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008) are examples of rhythmical coordination resulting in few stable coordination patterns within humans as well. A vast amount of studies, therefore, focused on capturing the dynamics of behavioral organization in rhythmic coordination tasks for an understanding of the emergence of stable movement patterns out of a wealth of movements possible, first within the individual and later also between individuals.

1.3.1.1 On the individual

The first studies concerned with the stability phenomena observed in rhythmical activities focused on bimanual coordination within the individual. Following a dynamic-systems perspective, Haken, Kelso and colleagues showed that the rhythmical movement patterns observed in bimanual coordination tasks typically could be modeled using non-linearly coupled oscillator dynamics (e.g., Haken et al., 1985; Kelso, Holt, Rubin, & Kugler, 1981). When asked to voluntary wiggle their fingers, participants showed a behavioral organization that was characterized by two preferred stable coordination patterns; the oscillating fingers moved at a relative phase relation of either 0° (in-phase) or 180° (anti-phase). The latter coordination pattern was less stable and showed a sudden transition into the more stable in-phase coordination patterns when movement frequency was increased. Like a system of two coupled oscillators, both characteristics could be modeled by capturing the dynamics of the relative phase angle between both moving limbs (see e.g., Haken et al., 1985 for a theoretical underpinning of their model). These findings enabled researchers to capture the dynamical processes of self-organization governing rhythmical coordination and, consequently, to make lawful predictions about the emergence of coordination of rhythmic movements at different scales of nature. This way, rhythmic coordination tasks served as an experimental paradigm for an understanding of the processes governing intrapersonal coordination from a dynamics perspective (e.g., Kelso, 1997; Kugler & Turvey, 1987, Schmidt & Richardson, 2008). The challenge for studies into social coordination, hence, was to demonstrate the recurrence of stable movement patterns in rhythmical activities performed by more than one individual as well.

1.3.1.2 Beyond the individual

Schmidt and colleagues (1990) were the first to show that dynamical principles underlying intrapersonal rhythmic movement coordination could also account for the observed coordination patterns at interpersonal level. In their study on leg swinging they showed that the phasing of limbs within and between individuals revealed the same distinct modes of coordination (i.e., symmetric in-phase and alternate anti-phase) and that the alternate mode was less stable, giving rise to a sudden transition into a symmetric mode of coordination when an increased oscillation frequency was demanded. These findings showed that the observed rhythmic movements between two informationally coupled individuals could be understood and modeled using the same coupled oscillators' dynamics known to account for the observed interlimb coordination within the individual (e.g., Haken et al., 1985; Kelso et al., 1981).

The study of Schmidt et al. (1990) was of particular significance as it demonstrated that the principles of stability underlying the emergence of coordinative patterns operate whether the elements of a system are coupled neurally (i.e., intrapersonal) or informationally (e.g., through vision). Indeed, the same stability-related phenomena were observed when a single person coordinated two legs or when two persons both contributed one leg to the coordinated action. This so-called similitude principle was viewed as providing evidence for the existence of general lawful principles underlying human behavior at different scales of nature, implying that a neural substrate is not the determining factor for understanding coordination patterns (Schmidt et al., 2011). This way, Schmidt and colleagues showed that the dynamic-systems approach could account for the observed coordination of rhythmical movements at different behavioral levels, independent of the nature of coupling between the elements of a system (e.g., neural or informational; see also Schmidt & Richardson, 2008).

Later, more studies followed showing the emergence of coordinated movement patterns from lawful relations between human participants in various rhythmic coordination tasks like swinging hand-held pendulums (Black, Riley, & Mccord, 2007; Richardson, Marsh, & Schmidt, 2005; Schmidt & Turvey, 1994; Schmidt & O'Brien, 1997), rocking chairs together (Richardson, Marsh, Isenhower, et al., 2007) and when walking together (van Ulzen et al., 2008). For instance, the study of Harrison and Richardson (2009) revealed that pairs of participants showed coordinated movement patterns by virtue of a mechanistic coupling between both individuals. In their study, one individual walked or jogged behind the other while being joined together through a foam appendage. As a result of both individuals being literally joined together, the participants not just revealed coordinated movements, but showed particular gait patterns associated with quadrupeds (e.g., the pace and trot observed in horses) that do have neural linkages between both pairs of legs. Taken together, these studies showed the universal pull (intentionally and unintentionally) for movement entrainment with others in a large variety of rhythmical tasks, emphasizing the hidden unity of principles underlying behavioral organization of an agent-agent system, and nature in general (Strogatz & Stewart, 1993).

Aforementioned studies considerably contributed to a better understanding of the coordination dynamics underlying the spontaneous movement synchronization in rhythmical joint actions. Most activities in daily life, however, have supra-coordinative goals. As most of the aforementioned studies (perhaps with the exception of Harrison and Richardson (2009) addressing on gait) focused on rather simple, non-goal-directed rhythmical movements, questions were raised as to what extent the results might be generalized to observed coordination in more complex natural joint-actions (cf. Richardson et al., 2015; Schmidt et al., 2011).

Adding a goal to a reciprocal pointing task, the study of Richardson et al. (2015) showed that also in more complex and goal directed joint-actions only a few stable movement patterns emerged from the interactions between both participants over time. In their study, Richardson and colleagues asked groups of two participants to perform a repetitive targeting task in which they moved computer cursors between two sets of locations without colliding with each other. As movement axes between target locations were perpendicular to each other, participants had to coordinate their actions with one another so as to avoid colliding. Results revealed that dyads fell into stable, asymmetric movement patterns with a typical phase lag between dyad-members, essential for successful task performance. Importantly, participants could not communicate with one another, indicating that complementary joint-action roles emerged from the interaction between participants over time instead of being predefined.

As all aforementioned studies considered rhythmical and continuous coordination tasks, findings of these studies might not relate directly to the situation under study. Most of the goal-directed social interactions in daily life require the coordination of complementary and more discrete behaviors instead of continuous synchronization of rhythmical movements.

Like in the examples mentioned before, when merging into traffic on the highway it is the discrete act of merging in front of or behind a car already on the road that needs to be coordinated and in rugby passing a ball requires coordination between someone that throws the ball and someone that catches it. What is interesting about the aforementioned rhythmical synchronization studies though is that in capturing the dynamics of an agent-agent system they show the pertinence of variables that are not taken relative to each individual separately. Instead, the key variables concern the relation between both co-acting individuals. The adoption of a phase relation between both swinging legs, for that matter, is a great example that captures the spatiotemporal coordination of one moving leg with respect to another (see e.g., Schmidt et al., 1990). So, rather than focusing on the actions of both individuals separately, studies concerned with the behavioral organization in joint-action should focus on dynamic measures at interpersonal level.

All in all, studies into rhythmical coordination significantly advanced our understanding of the self-organizing nature of (social) behavior. They showed that the observed behavioral patterns have less to do with the neural substrate or a central controller causing behavior and more to do with constraints that couple parts of a system (e.g., a body and its environment) so as to act in a lawful way (Richardson et al., 2010). And, although neural substrates and processes of the central nervous system play an important role in constraining the coordinated movements of humans and animals, these studies brought out that they are not the organizational structure at the origin of coordinated behavior (Coey et al., 2012; Richardson et al., 2010). Instead, organization lies in a functional perception-action system defined and distributed across individuals. This way, dynamic-systems theory provides a parsimonious way to account for the self-organizing nature of social behavior, not only in rhythmical joint activities but, importantly, also in more discrete and goal-directed tasks.

1.3.2 On coordination in discrete joint-actions

Discrete joint-actions are said to be typical of the kind of actions we perform on a daily basis. Consider for example situations in which we reach to shake someone's hand, move a sofa together or pass a ball in a sports play. These actions are characterized by relative short interactions that are often non stationary and adaptive. Furthermore, the mutual responsiveness (i.e., who does what and when) is often asymmetrical in that both actors may need to adopt different roles. Goal-directed cooperative movements, hence, require close spatiotemporal coordination in a complementary manner. Indeed, if one throws a ball a bit too fast this requires quick compensatory movements on the part of the catcher. Here, movement coordination of both interacting individuals is done in service of a mutual task goal (Marsh et al., 2009; Sebanz & Knoblich, 2009). Considering the omnipresence of such cooperative activities, however, it is somewhat surprising that only few studies investigated coordination principles underlying such complementary joint actions.

1.3.2.1 Cooperation

Most of the studies that have been performed on discrete goal-directed social interactions have focused on the synergistic nature of dyads performing an action together (i.e., cooperate). That is to say, they focused on how multiple actors might constitute a new coordinative structure (i.e., a synergy) that lawfully emerges from the mutual influences between co-actors in the context of interaction. A synergy, here, is defined as a functional grouping of elements (e.g., neurons, muscles, limbs or individuals) that are temporally and functionally constrained to act as a single unit. The term was coined by Bernstein (1967) to account for the redundancy problem of the large number of degrees of freedom in the human movement system. In short, he proposed that elements of a system (e.g., muscles) are grouped together to form softly-coupled, function-specific units of control, where the system as a whole changes as a function of jointly and proportionally activated elements instead of all elements being controlled on their own. Evidence for the control of motor behavior in a synergistic fashion during (non-social) goal-directed tasks comes, for example, from studies into grasping (Zaal & Bongers, 2014) and pistol shooting (Scholz, Schoner, & Latash, 2000) showing variable joint configurations underlying precise movements of an end-effector (e.g., a hand or a gun). This way, a synergistic approach to behavior emphasizes the self-organizing nature of agent, agent-environment and agent-tool systems capable of producing temporally and spatially organized patterned behavior. A paradigmatic example of synergies underlying motor behavior, hence, is the previously mentioned interlimb coordination observed in rhythmical tasks (Kugler and Turvey, 1987). Interestingly, rhythmic coordination tasks did not only reveal synergistic behavior at the level of the individual but also between individuals (e.g., Black et al., 2007; Mottet, Guiard, Ferrand, & Bootsma, 2001; see also Schmidt & Richardson, 2008).

Congruent with these observations, Marsh, Richardson and Schmidt argued that in any social activity the co-actors, the environment and the task might be perceived as a single synergetic system as well (Marsh et al., 2006, 2009; Richardson et al., 2010). As such a synergetic perspective has its roots in self-organizing complex systems (Riley et al., 2011), where the emergence of coordinated social behavior is argued to result from dynamic and self-organized processes and constraints coupling the minds, bodies and environment in a lawful way. Constraints, in this sense, are said to be the 'causal' mechanisms allowing or denying certain states of the system. Consider for example the rhythmical coordination task that revealed that, both in solo and joint action, higher movement frequencies allowed for in-phase coordination of oscillating legs, whereas an anti-phase coordination patterns was denied, resulting in a transition into stable in-phase coordination pattern (e.g., Schmidt et al., 1998, 1990). Importantly, a synergistic perspective to behavior emphasizes a similarity in the way solo and joint actions are organized and constrained. This implies that, not only in rhythmical tasks, but across a wide range of acting pairs, behavior should follow from the same kind of action-scaled invariant relations as observed in individual perception-action systems (see e.g., Warren, 1984) and that dynamic properties of behavioral transitions should hold.

This claim was supported by research of Isenhower, Richardson, Carello, Baron, & Marsh (2010) and Richardson, Marsh, & Baron (2007) in their studies on individual and cooperative plank carrying. A pair of participants received light-weight planks of different sizes in a continuous sequel and they were asked to move those planks by grasping them only at the ends. Some of the planks could be grasped solo either with one hand (i.e., between index finger and thumb) or with two hands, whereas others required cooperation of both individuals grasping one end of the plank each. Results revealed that transitions between displacement modes followed from the fit between the effectors of the individual or pair (that is, the hand span or average arm span of a pair) taken with respect to the length of the planks. This shows that pairs used invariant action-scaled information to decide on cooperating or not. Moreover, the sudden transitions from one to two-handed grasping and from individual to cooperative grasping revealed similar dynamical properties showing that transitions in action modes are functionally equivalent across agent-environment and agent-agent-environment systems (like observed in the social synchrony studies; see e.g., Schmidt et al., 1990). Behavioral organization at different scales of nature thus seems to emerge spontaneously from similar action-scaled invariants relating bodily constraints to properties of the environment in a dynamic fashion.

Recently, more studies have been performed on coordination in complementary joint actions showing support for a synergistic organization of dyads performing a precision task together (e.g., Ramenzoni, Davis, Riley, Shockley, & Baker, 2011; Riley et al., 2011; Romero, Kallen, Riley, & Richardson, 2015). Consider for example the study of Romero and colleagues in which dyads had to cooperate on a discrete pointer-to-target task. Two individuals sat next to each other and each used one arm to complete a two-dimensional pointer-to-target task. More precisely, the participant that sat on the right side pointed with a pointer in its right hand to a target held in the left hand by the participant that sat left. With a focus on the variance in the joint angles of the upper limb (using the uncontrolled manifold method; Latash, Scholz, & Schöner, 2002; see e.g., Black et al., 2007, for an application in social behavior), results revealed signs of a stronger synergistic organization at interpersonal level compared to intrapersonal level. That is to say, participants showed close temporal organization of their movements at the level of the collective instead of both individuals coordinating their joint configurations at individual level. Similarly, the joint supra-postural task of Ramenzoni et al. (2011), in which dyads performed a complementary precise motor task, individuals revealed flexible coordination at intrapersonal level (i.e., change in posture) to stabilize coordination at interpersonal level (i.e., stable task performance) resulting in movement variance at collective level that was significantly lower than the sum of both movement variances at the level of the individuals. Taken together, these studies showed that also in discrete joint-actions, social behavior self-organizes in a synergistic way.

1.3.2.2 Studying emergent social behavior

All in all, aforementioned studies showed that certain aspects of the structured behavior observed in solo and joint-actions emerge from a self-organization process that binds individuals to behave as a unified functional whole. Important for the study into social coordination, hence, is describing the necessary relationships (i.e., laws) that dictate how a system of two (or more) individuals changes within the context of constraints. In order to find the laws underlying organized behavior, first and foremost, behavioral regularities must be identified at the level of the collective (e.g., synchronization when walking side-by-side). This is done by studying the system's dynamics or the lawful evolution of the system's behavior (e.g., Haken et al., 1985; Richardson et al., 2015; Schmidt et al., 1990; Warren, 2006). Note, however, that apparent coordination does not always result from a coupling between both individuals and, hence, that behavioral organization is not always organized in a synergistic way. Indeed, in some situations the observed coordination might simply reflect the coincidental activity of two individuals coordinating their actions at individual level (e.g., with a common external information source) rather than at collective level (Coey et al., 2012). Consider for this matter the example of two individuals walking side-by-side. Typically, when walking side-by-side, humans tend to fall in synchrony when faced with each other's movements or when linked in another way (e.g., when wearing tapping shoes providing auditory information or when holding hands for a physical coupling; van Ulzen et al., 2008) and, hence, show self-organized patterns of movement at the level of the collective that emerge from their mutual interactions. In a similar fashion, two individuals might show entrainment while just being coupled onto a common external rhythmical information source like the beat of music. Observed 'entrainment' in the latter situation is not a result of mutual interactions, but rather reflects the coincidental activity of both individuals without being organized as a synergistic collective. Critical for demonstrating the emergence of behavioral patterns in a synergistic way, therefore, is a mutual influence between the system's components, that is, a coupling between both individuals.

When behavioral regularities and a necessary coupling are identified using a dynamical system's framework, a last step could be the modeling of the system's dynamics to shed a light on the structural relations and self-organizing processes that give rise to successful coordinated and robust behavior. Modeling the system's behavior provides us with the ability to make testable predictions and validate hypotheses in order to uncover fundamental processes that shape and constrain cooperative actions and human behavior in general (Richardson et al., 2016). These aforementioned ideas have been applied to dynamic behavior in social situations, like movements of a crowd or in a sports context.

1.3.2.3 Examples in a dynamical context

Recent studies focused on the emergence of behavioral organization in dynamical contexts like in sports. Sports team collectives have been conceptualized as complex dynamical systems composed of many interacting parts (e.g., Davids, Araújo, & Shuttleworth, 2005) in which spontaneous coordinated patterns of movement emerge from a dynamic process of self-organization (e.g., Araújo & Davids, 2016; Duarte et al., 2012; McGarry et al., 2002). Instead of being imposed from inside (e.g., a team captain) or outside (e.g., instructions from a coach), coordinated movements follow from physical (e.g., gravity) and social (e.g., game rules) constraints and on-the-fly information specifying action-relevant properties in a situation. Sports contexts, therefore, have often been used for studies into behavioral organization of social systems.

An extensively studied sports context is the game of rugby union (see e.g., Passos et al., 2008, 2009; Rodrigues & Passos, 2013). In their studies, Passos and colleagues have begun identifying collective variables characterizing (sub) phases of the game as being self-organized. These situations typically comprised 1 versus 1 interactions (e.g., attacker vs. defender) and, therefore, mainly focused on modeling the interactive behavior in competitive situations. To model the self-organizing nature of cooperating individuals, the use of local, context dependent information possibly governing lawful interactions between team members needs to be verified as well. Passos et al. (2011), therefore, began extending their findings in more complex intra-team interactions in rugby union.

In rugby, we can identify typical subunits that are characterized by stable movement formations. An attacking subunit, for instance, involves four players that advance towards the try line in a diamond shape. In order to act as a successful attacking unit, the players must remain close to and behind the ball carrier and have to move at the same speed and in the same direction in order to afford passing to. An implication, hence, is that when the ball carrier increases or decreases ball speed, other players in the attacking subunit should adapt their velocities accordingly. Although players are made aware of the benefits of playing in a diamond shape by a coach and, hence, are encouraged to keep a stable relative position with respect to the other players they necessarily need to use functional context-dependent information to regulate their rule-governed behavior. Passos and colleagues, therefore, focused on identifying the nature of information used to acquire and maintain these functional coordination patterns.

The experiment Passos and colleagues (2011) set up required four attackers to score a try while getting past two defense lines consisting of two defenders each. They videotaped the attackers' actions with which they could reconstruct the attackers' movements in the bidirectional space. In order to assess the coordination and strength of coupling between attackers advancing towards the try line, they analyzed the continuous changing (one-dimensional) distances of attackers with respect to the try line and performed pairwise correlations on these distances between each possible pair of the subunit of four attackers (i.e., six pairs). If the distance to the try line of both individuals in a pair decreased in a similar fashion, coupling between both attackers was assumed to be strong and if there was no correlation, the coupling was said to be weak or absent altogether. This way, the study of Passos and colleagues (2011) revealed that for a significant part of the time the change in distances towards the try line were highly correlated, indicating that interpersonal distances form a crucial variable that influences the attackers' collective behaviors. They also reported the existence of functional values of interpersonal distance (i.e., stable mean interpersonal distances that altered with changes in game constraints) between members of an attacking subunit in a rugby team that collectively constrain behavior, implying that an individual sticks to a nearby teammate, runs at the same velocity and avoids colliding with their teammate. And although the patterned behavior might be de-stabilized in the vicinity of defenders, team-members showed the tendency to regroup to form stable patterns of goal-directed behavior again.

Also in basketball stable spatiotemporal movement patterns between teams (Bourbousson, Sève, & McGarry, 2010a) and selected dyads from the collective (Bourbousson, Sève, & McGarry, 2010b) have been reported. The various behavioral patterns in basketball would result from (transitions between) stable phase relations between members of teams and selected dyads in their longitudinal and lateral movements across the field, implying that individuals move at a similar speed and in the same direction as their team mate over a (short) period of time. Like in the studies in rugby of Passos and colleagues, these results point out that members of a collective are locally coupled to (one or two) team members to produce effective team behavior. Moreover, Bourbousson and colleagues argued that the dynamical relations between dyad members might be characterized as attractors and/or repellers supporting the view that a sports collective as a whole might be characterized as a complex dynamical system emerging from the interactions between its components, that is, the players. Taken together, aforementioned studies indicated that individuals seem to stick to locally-defined interaction rules resulting in the emergence of coordinated movement patterns at macroscopic level. These results highlight the use of functional information about a team member's movements in order to co-adapt to its actions, revealing the couplings that exist between members of a team.

Aforementioned co-adaptation is a mechanism proposed to account for observed coordination behavior at the collective level that demands that each agent in the system continuously needs to adapt its behavior relative to perceived actions of neighboring agents (Fajen et al., 2009; Passos, Araujo, Travassos, Vilar, & Duarte, 2014; Passos et al., 2011). This coordination phenomenon is not only observed in sports collectives like rugby and basketball. Indeed, across a wide range of self-organizing biological systems like a flock of birds, a school of fish or a group of pedestrians (see e.g., Couzin & Krause, 2003; Kiefer, Rio, Bonneaud, Walton, & Warren, 2017; Vicsek & Zafeiris, 2012), similar co-adaptation mechanisms have been observed showing that repeated interactions between elements of a group scale to global collective systems behavior (Duarte, Arajo, et al., 2012). Recently, following pedestrian models accounting for individual steering and obstacle avoidance behavior (Fajen & Warren, 2003, 2007) and interactions between pairs of walking participants (Rio, Rhea, & Warren, 2014), Kiefer et al. (2017) started to model the coordination in pedestrian groups, providing a foundation for the analysis and prediction of local and global coordination in small collectives and crowds. This way, they showed that quantifying local and global coordination offers an approach to characterize emergent collective behaviors (See also Bourbousson et al., 2010a, 2010b).

In sum, these studies bring out that also in more discrete and goal-directed joint-actions dynamical principles (may) govern the emergence of coordinative structures at the interpersonal level. Aforementioned research highlights how a functional unit emerges from simple local interaction rules, emphasizing the self-organizing nature of (sports) collectives, and social interactions in general. Instead of being the result of a separate decision-making process, it is in the agent-agent-environment interactions that give rise to coordination patterns at the level of the collective. Importantly, such coordination patterns can be captured by looking for key variables that characterize co-adaptive behaviors of individuals in a collective. From a social coordination perspective, the challenge for studies into joint-action, therefore, is to find key variables capturing the system's dynamics responsible for the observed coordination patterns and importantly, to show that it is the interactions between individuals that give rise to the joint decision behavior observed in many of our daily life activities.

1.4 This thesis

The foregoing literature overview revealed that significant advances in our understanding of human functioning in a social context have been made. Indeed, the studies discussed pointed out that decisions for actions might be the emergent result of the realization of action possibilities (i.e., affordances) offered by the situation. Moreover, they showed how a dyad or a collective might act as a self-organizing system in which the coordinated behavior emerges from the interaction between (informationally) coupled individuals. Nevertheless, most of the studies into social coordination either concerned rather simple continuous coordination tasks (e.g., leg or pendulum swinging; Schmidt et al., 1998, 1990; Schmidt & Turvey, 1994) or, when addressing a complex and dynamical context, merely concerned observations of the coordinated behavior (e.g., in sports; see e.g., Araújo, Silva, & Davids, 2015; Bourbousson, Sève, & McGarry, 2010b; Pedro Passos et al., 2008, 2011; Travassos et al., 2012). Indeed, where the former studies lacked generalizability to more discrete goal-directed behaviors observed in natural situations, the latter studies lacked experimental manipulation, thereby providing more of a (nevertheless useful) description of social behavior instead of an experimentally founded explanation. The few experimental studies that did look for an explanation of coordination between members of a dyad in goal-directed discrete movement tasks (e.g., Ramenzoni et al., 2011; Romero et al., 2015) concerned activities that did not involve the decision behavior that characterizes many of our daily life interactions. Thus, as the experiments and analyses used in those studies might not be best suited to study joint decision behavior in a cooperative action (i.e., the study how two individuals decide who is going to perform a certain action and who is not) we sought to develop a new experimental paradigm in which a dyad cooperates on a goal-directed discrete movement task, but is forced to make a decision about who is going to perform a certain action and who is not.

To this end, we found a paradigmatic example of joint decision behavior in the cooperative activity that is a serve reception in beach volleyball. In beach volleyball, a team existing of two individuals prepares themselves to intercept an oncoming serve whereas *in fine* the interceptive action can only be performed by one of the two individuals. During the serve that takes about one second (cf. Benerink, Bootsma, & Zaal, 2015), both individuals have to decide together who will be the one performing the interceptive action and who will not. This decision is even more pertinent when realizing that the non-intercepting player has to prepare the follow-up action; the earlier this player knows it will not be the one intercepting the ball, the more time it has for getting ready for a successful follow-up action (i.e., the set). With the interception of a ball being an a priori non-social activity, joint decision making, here, is an integral part of successfully performing the cooperative action that is serve reception in beach volleyball.

Whereas the situation of serve reception in beach volleyball seems rather particular, similar decision-making is seen in all situations of doubles in sports (e.g., tennis and badminton) or traffic. It, therefore, serves as an exemplary situation representing the joint decision behavior we encounter in a large variety of our daily life activities. We are interested in how members of a team decide who will be the one to intercept the ball or not and whether we should conceive coordinating individuals as a team (i.e., a coherent unit, a 'We') or as a collection of several 'I's'. Importantly, this raises the question: how does team organization come about from two cooperating individuals? And what information does a team use to decide on who will intercept the ball where?

In order to answer such questions we developed a new experimental paradigm that includes the most important features of the serve reception in beach volleyball. In our video game-like experimental set-up, teams of two participants manually intercept virtual balls together using individually-controlled on-screen paddles, that is, they play 'pong' together. In doing so, we adapted the well-known game of pong[2] (Atari, 1972). Instead of playing against each other, in this set-up both individuals play together in a cooperative interception task.

As will become clear from reading the rest of this thesis, I hope, the adoption of this game-like task allowed for a thorough analysis of action coordination and joint decision behavior in a discrete joint activity, that is, a doubles interception task. First, the task allowed for the characterization of the division of labor between individuals cooperating on a goal-directed task. In other words, it allowed for a characterization of who intercepts what balls where and when. Besides, the easy-to-obtain (unidimensional) kinematics of both participants' paddle movements offered the possibility to look for stable patterns of movement in the observed behavior of both individuals intercepting balls together. It allowed for the identification of a key variable that captures the interactions between both individuals with respect to the ball, thereby opening a window into the way individuals use information about the other participant or the ball to decide to intercept the ball or not. Moreover, the set-up provided the means to manipulate –in a controlled way– the situational or task constraints (e.g., initial positions of team members), to investigate if any observed coordination patterns recurred under different conditions as well. This way, the experimental set-up offered a way to study how informational and task constraints may lead to a (possibly) different division of labor. All in all, the introduction of this experimental paradigm opened up a wealth of possibilities for the study into joint decision-making and social coordination in general, emanating from the simple but versatile nature of the task.

In elaborating this thesis, we decided to first take a step back from studying joint decision making in real-life settings (and, notably, from the mere observation of natural situations). As studying real-life settings is still technically challenging and often does not allow for the necessary experimental control, the adoption of this video game-like task provided a way to

[2] For those that do not know the game pong (and probably have been living under a stone for years), it was in 1972 one of the earliest multiplayer electronic arcade games made after a sports setting. Based on ping-pong, the idea was very basic; one ball, two paddles, a score and nothing else. With a black background, two inch-long white lines and a small white circle representing the ball, the instructions were simple, ''Avoid missing ball for high score" (for details see, for instance, Kent, 2001).

reveal some of the basic principles underlying joint decision making in a carefully controlled experimental set-up. Although our observations and results might not directly apply to the complex problem of social coordination in a real-life settings (like the serve reception in beach volleyball), the experimental paradigm proposed, turned out to allow first answers regarding the how, what, where and when of decision making and a division of labor in joint activities. In this thesis, we were particularly interested in the question whether coordination (i.e., division of labor) between team members cooperating on a doubles interception task must be predefined, following from (tacit) agreements about who intercepts balls where, or if division of labor might be the emergent result of the interactions between members of a team. In so doing, this thesis takes the first steps in a new direction to reveal the coordination dynamics underlying cooperative joint activities.

1.4.1 Outline thesis

The remainder of this thesis is roughly organized in three parts. First, *Chapter 2* provides a detailed description of the experimental set-up used for the present series of experiments. This way, this chapter serves as an introduction of the experimental paradigm proposed. Alongside the experimental set-up, *Chapter 2* provides a detailed analysis of our findings in a first experiment. The analysis concerns a way of looking at the macroscopic coordination patterns (i.e., who intercepts balls where) and provides a way to visualize the time-evolving interactions between members of a team with respect to the ball. It moreover includes some first suggestions concerning the coordination principles and decision-making process underlying the coordinated patterns of movement at team level (i.e., the division of labor).

The subsequent *Chapters 3* and *4* present two experimental manipulations following up on findings of our first study presented in *Chapter 2*. These two chapters allow for a further understanding of factors influencing division of labor between co-acting individuals. *Chapter 3* addresses the effect of different initial positions on the division of labor and *Chapter 4* is dedicated to the effects of skill differences between members of a dyad on the division of labor. Moreover, *Chapters 3* and *4* allow testing some of the suggestions made in *Chapter 2* with respect to the coordination principles underlying the observed division of labor by means of an action-based simulation and a prediction of the trial outcomes, both accounting for observed division of labor in their own way.

Finally, *Chapter 5* serves as a general discussion that provides an overview of the main findings of this thesis. Moreover, this section is dedicated to answering some of the questions raised above. In doing so, I tried to provide answers to questions as to how labor is divided between individuals cooperating on an interception task and whether such a division necessarily follows from (tacit) agreements or may fall out of an effective information-based coordination of the team members' interceptive actions. To wrap up, I discuss some implications of our findings for further studies into joint action and joint decision behavior that could foster our understanding of social coordination in daily life activities.

2

EMERGENT COORDINATION IN A DOUBLES INTERCEPTION TASK

In order to study joint decision behavior of two individuals cooperating on a doubles interception task in a controlled way, a new experimental paradigm was developed. This chapter provides a detailed explanation of the experimental set-up used throughout this thesis. Besides, it introduces a way of looking at a team's division of labor (i.e., the division of the space domains in which both participants performed interceptions) and the on-going paddle-ball relations that allows for a first analysis of the team members' time-evolving interception behaviors. This way, this chapter provides some first suggestions as to how labor between team members might be divided.

Published as

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2.1 Abstract

In this contribution we set out to study how a team of two players coordinated their actions so as to intercept an approaching ball. Adopting a doubles-pong task, six teams of two participants each intercepted balls moving downward across a screen towards an interception axis by laterally displacing participant-controlled on-screen paddles. With collisions between paddles resulting in unsuccessful interception, on each trial participants had to decide amongst them who would intercept the ball and who would not. In the absence of possibilities for overt communication, such team decisions were informed exclusively by the visual information provided on the screen. Results demonstrated that collisions were rare and that 91.3 ± 3.4% of all balls were intercepted. While all teams demonstrated a global division of interception space, boundaries between interception domains were fuzzy and could moreover be shifted away from the center of the screen. Balls arriving between the participants' initial paddle positions often gave rise to both participants initiating an interception movement, requiring one of the participants to abandon the interception attempt at some point so as to allow the other participant intercept the ball. A simulation of on-the-fly decision making of who intercepted the ball based on a measure capturing the triangular relations between the two paddles allowed the qualitative aspects of the pattern of observed results to be reproduced, including the timing of abandoning. Overall, the results thus suggest that decisions regarding who intercepts the ball emerge from between-participant interactions.

2.2 Introduction

Actions in our daily life often involve others. Whether we are shaking someone's hand, moving a table together or walking on a crowded pavement, we have to coordinate our actions with those of other individuals. Such social coordination, whether it is intentional or spontaneous, often requires decisions about the behavior that we should perform or, in some cases, we should *not* perform. For instance, safe driving dictates that when two drivers simultaneously approach an intersection one should cross first and the other should wait. Likewise, two individuals loading a dishwasher should take their turns when placing the dishes. Besides interacting with one another, these situations typically demand a decision of who performs an action and who does not. It is such joint decision making among individuals in goal-directed joint activities that we address in the present study. To do so, we started from a pertinent example in a sports context: serve reception in beach volleyball. When facing a serve, only one of the two players of a team should perform the actual serve reception. The non-receiving player should not interfere during the interceptive action of the teammate, while, at the same time, preparing a follow-up action. How do such individuals coordinate their actions and decide who will intercept the ball? In this contribution, we captured the essential characteristics of the beach volleyball situation in a task in which two participants play "doubles pong". The participants' task is to ensure that on each trial one of them intercepts the approaching target. Like in the situation of serve reception in beach volleyball, the players have to decide together who will be the one performing the interceptive action (and who will not). We are interested in the way the decision of 'who intercepts the balls where' is shaped and how such joint decision making may best be captured.

Rather than focusing on the neural processes that are involved in decision making within each individual (Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Cannon-Bowers, Salas, & Converse, 1993; Cisek, 2007; DeSoto, Fabiani, Geary, & Gratton, 2001; Lepora & Pezzulo, 2015; Resulaj, Kiani, Wolpert, & Shadlen, 2009), here we consider the system of the two individuals and their environment (cf. Araújo, Davids, & Hristovski, 2006; Coey, Varlet, & Richardson, 2012; Marsh, Richardson, Baron, & Schmidt, 2006; Riley, Richardson, Shockley, & Ramenzoni, 2011; Schmidt, Fitzpatrick, Caron, & Mergeche, 2011; Theiner, Allen, & Goldstone, 2010). We study how the coordinated behavior of this system gives rise to a distribution over the individuals of interception activities. Instead of understanding decisions as mental operations that precede action, we see the act of deciding as the emergent behavior of the system of the individuals and environment resulting in (un)successful task performance (cf. Araújo, Davids, & Hristovski, 2006; Barsingerhorn, Zaal, De Poel, & Pepping, 2013; Travassos et al., 2012; Turvey & Shaw, 1995). Understanding decision making among individuals as emergent is in line with a dynamic-systems approach initially developed to account for intrapersonal coordination of rhythmic movements (e.g., Haken, Kelso, & Bunz, 1985; Kugler & Turvey, 1987). From a dynamic-systems perspective on human movement the goal is to identify general laws and patterns that govern the causal unfolding of a system's behavior rather than looking for neurophysiological areas that generate behavior (J. A. S. Kelso, 1995). Importantly, the stability principles underlying the emergence of coordination in a system of coupled oscillators have been demonstrated to operate whether the coupling is neural (J. A. S. Kelso, Holt, Rubin, & Kugler, 1981), mechanical (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002) or informational (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt, Carello, & Turvey, 1990; Schmidt & O'Brien, 1997). That is to say, the same phenomena related with stability of patterns are found when a single person coordinates two body parts and when two persons contribute one body part each to the coordination (Richardson et al., 2007; Schmidt & O'Brien, 1997; see Schmidt & Richardson, 2008, for a review). This similitude principle indicates that the dynamic-systems approach can account for interactions at different behavioral levels, independent of the nature of the connections between the system's components (i.e., neural, mechanical or informational). Whereas most of the studies addressing the dynamics of joint actions concerned non-functional or stereotyped oscillatory limb or whole-body movements (such as swinging legs or rocking chairs together, Richardson et al., 2007; Schmidt et al., 1990), a few studies have shown that the interactive behavior of two individuals can also account for the observed coordinated patterns in more goal-directed tasks (Mottet, Guiard, Ferrand, & Bootsma, 2001; Richardson et al., 2015; Romero, Kallen, Riley, & Richardson, 2015).

The shared goal of the players in a beach-volleyball situation is that the approaching serve will be intercepted by one of the two. In order to understand the dynamics of joint decision-making in such a cooperative goal-directed interception task, in the doubles-pong task adopted here we explored how a team's task performance might emerge from the interactions between participants. For the present purposes, potential interactions in this video-game-like task were restricted to be uniquely information-based: without any other form of communication being available, participants only shared vision of the task space (i.e., screen) in which the target and individual participant-controlled interception paddles moved. With each of the two paddles being moreover confined to one-dimensional movement along a common interception axis, the task design ensured that successful interception could only be achieved by a single participant: contact between the two paddles immediately eliminated all future possibilities for interception. Because the task of the team of players involves the interception of the ball by one of them, and this lateral interception closely resembles tasks that have been studied extensively before (e.g., Bootsma, Ledouit, Casanova, & Zaal, 2016; Ledouit, Casanova, Zaal, & Bootsma, 2013; Michaels, Jacobs, & Bongers, 2006; Peper, Bootsma, Mestre, & Bakker, 1994), we expect that the current study might serve as a stepping stone for identifying informational variables that may underlie team behavior.

2.3 Material and Methods

2.3.1 Participants

A group of 12 right-handed students from the University of Aix-Marseille, 8 men and 4 women with an average age of 19.6 ± 1.0 years (M ± SD), took part in the experiment. They all provided written consent before participating voluntarily in our study. The study was approved by the local institutional review board of the Institute of Movement Sciences (*Comité Ethique de l'Institut des Sciences du Mouvement d'Aix-Marseille Université*) and conducted according to University regulations and the Declaration of Helsinki.

2.3.2 Task

The experiment consisted of three consecutive sessions in which participants were to manually intercept virtual balls moving downward across a screen. A ball could be intercepted by moving an on-screen paddle laterally over an invisible horizontal interception axis at the bottom of the screen. During the first experimental session participants intercepted balls individually (Fig. 2.1A). This session served to familiarize participants with the experimental set-up. In addition, by counting the number of intercepted balls, we obtained a measure of how well individual participants performed the interception task. The second experimental session was, again, an individual-participant session. This time, however, participants were assisted by a static "partner" incorporated by a large stationary paddle located at the opposite side of the interception axis (Fig. 2.1B). Balls arriving at the stationary paddle were returned upwards and counted as a successful interception. Participants had to avoid touching the static paddle; on-screen contact immediately led both paddles to disintegrate and interception was no longer possible. In the third experimental session participants performed the interception task in teams (Fig. 2.1C). We composed teams of two participants with similar interception scores on the first two sessions. Like in Sessions 1 and 2, participants were able to move all along the interception axis and, comparable with Session 2, they should avoid touching one another; both paddles would disintegrate if they did. No communication in any form was allowed.

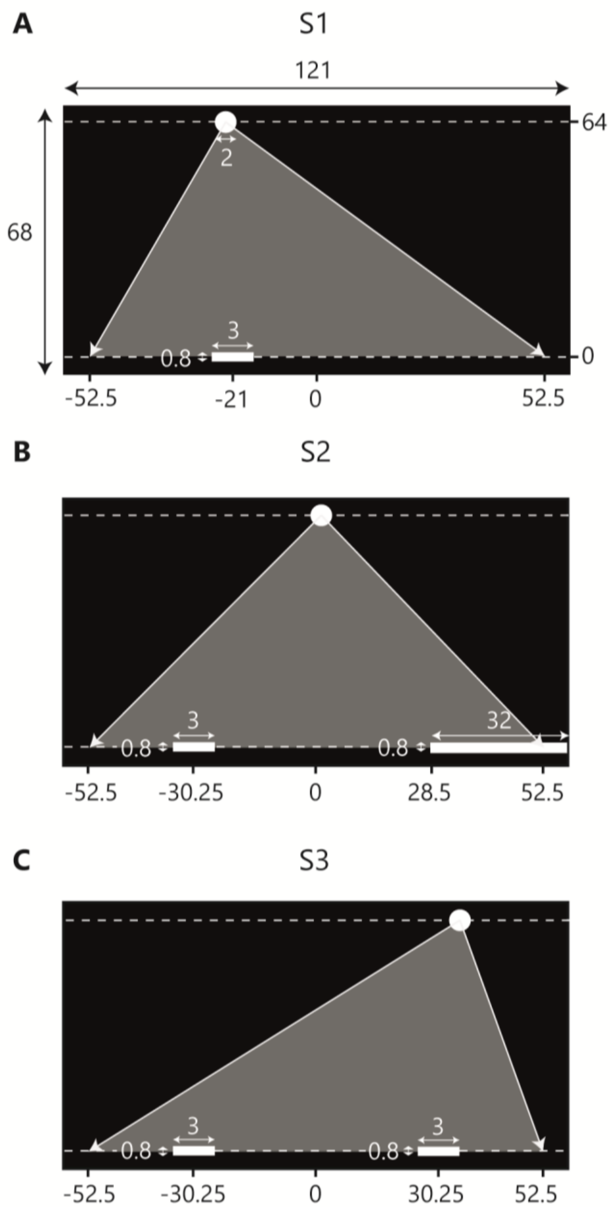


Figure 2.1 | Schematic overview of the set-up of the three consecutive experimental sessions. Screen dimensions and other metrics are in cm. Note that the figures are not scaled to actual size. Balls appeared at the top of the screen (Y = 64) and moved downward towards the interceptions axis (Y = 0) at one of two constant vertical velocities. Grey triangles indicate the range of potential ball arrival positions. **(A)** During the first session (S1) participants intercepted balls individually. The situation depicted here represents the initial conditions for LP. **(B)** In the second session (S2) participants were assisted by a stationary partner, incorporated by a static paddle covering the final 24 cm of the range of potential ball arrival positions on the opposite side of the interception axis. The situation depicted represents the initial conditions of LP. **(C)** During the third session (S3) participants intercepted ball in dyads where LP started on the left side of the screen and RP started on the right side of the screen.

2.3.3 Experimental set-up

The experiment took place in a darkened room without windows. Figure 2.2 present the experimental setting for the session in which two participants performed the task together. Participants were seated at one of the two possible seats on one end of a table. They were facing a large television screen (Samsung 55" LED ED55C, with a 1920 x 1080 pixels resolution) that was positioned two meters away at the other end of the table. When seated, the participants faced the screen at eye height. Six participants were always seated at the right side of the table during each of the three sessions and are referred to as Right-side Participants (RPs); the other six participants always sat left and are referred to as Left-side Participants (LPs).

Figure 2.2 | Representation of the experimental set-up used in Session 3. Participants were sitting side by side facing a large television screen. They were separated by a black curtain and wore headphones and earplugs so as to avoid overt communication between them. To intercept the balls moving downward across the screen, both participants could move an on-screen paddle along the (non-visible) interception axis by displacing a handheld knob on a linear positioning device placed on the table in front of them. In Sessions 1 and 2 only one of the participants was present.

Using their right hand, participants displaced the on-screen paddle by laterally displacing a handheld knob on top of an in-house-constructed linear positioning device placed on the table in front of them. The knob was firmly attached to a small (3 by 6 cm) aluminum cart that could slide along two (75-cm long) parallel iron bars. The cart's position was sampled at a frequency of 100 Hz using a linear magnetic potentiometer (MP1-L-0750-203-5%-ST, Spectra Symbol, West Valley City, UT, USA) connected to the computer (HP ZBook 15) controlling the experiment. The digitally-sampled electrical output of the potentiometer was converted by in-house developed ICE® (ISM, Aix-Marseille Université, France) software into a paddle position using a constant gain, such that the two extreme knob positions corresponded to (virtual) screen positions slightly beyond the physical screen. This allowed participants to cover the full (121 cm) length of the interception axis on the screen without ever reaching the extremities of the 75-cm long positioning device. Unless specified otherwise, positions and distances reported from here on correspond to distances on the screen, with the origin corresponding to the horizontal center of the interception axis. The screen thus extended horizontally (X-axis) from –60.5 cm to +60.5 cm and vertically (Y-axis) from –2 cm to +66 cm.

2.3.4 Procedure

Participants had to intercept virtual (2-cm diameter circles) white balls depicted against a black background, moving downward across the screen at various angles and speeds, by making them bounce back upwards after contact with their white (3-cm wide and 0.8-cm high) paddle.

For a trial to start, participants moved the paddle to a designated start position (see Fig. 2.1) positioned at ±21 cm from the center of the screen in Session 1 and at ±30.25 cm from the center of the screen in Sessions 2 and 3. Start positions were marked by a 3-cm wide translucent red rectangle that would turn green when the center of the paddle was located at a horizontal distance of less than 0.3 cm from the center of the rectangle. After the participant(s) had remained in place for 2 s, the rectangle disappeared and after another 2 s the appearance of a ball at the top of the screen marked the beginning of the trial. Balls immediately moved downward with vertical velocities of 0.40 or 0.64 m/s corresponding to movement durations until reaching the interception axis of 1.6 and 1.0 s, respectively.

Ball trajectories were constructed with the use of five standard ball departure positions (Y = 64 cm) and five standard arrival positions (Y = 0 cm), both at X = –42, –21, 0, +21 and +42 cm. Combining the five departure positions with the five arrival positions gave rise to a total of 25 standard rectilinear trajectories. To avoid participants becoming familiarized with the arrival positions of the ball, a random distance between -10.5 cm and +10.5 cm was added to both the standard departure and arrival positions of a trajectory. This way, balls could appear and arrive everywhere between X = –52.5 cm and X = +52.5 cm while trajectory angles were kept the same. In a single block, all 25 trajectories appeared with two different vertical ball velocities, for a total of 50 fully randomized trials per block. All participants performed four blocks per session, adding up to a total of 200 trials per participant in a one-hour session.

Successful interception required that the paddle touched the ball when it crossed the interception axis. After a successful interception, the paddle turned green and the ball moved back up. In an unsuccessful trial the ball continued moving downward and the paddle turned red. Three seconds after ball arrival at the interception axis, the paddle returned to its original white color and the translucent red triangle would appear again to indicate the start of a new trial.

All sessions started off with ten practice trials. During these practice trials participants were asked not only to intercept a number of balls but also to purposely miss a ball so they would have experienced all the possible actions and their outcomes. In Sessions 2 participants were also asked to touch the stationary paddle during a trial, so as to experience what would happen if they did during the experiment. For the proper experimental sessions participants were instructed to intercept as many balls as possible, without any further information being provided. To motivate the participants, the experiment was organized as a competition in which all participants competed anonymously.

In Session 3 participants were seated next to each other (see Fig. 2.2). They were separated by a black cloth, hanging from the ceiling, that effectively prevented each participant from seeing (any part of) the other. Moreover, they wore headphones (3M Peltor Optime2) and earplugs (DEXTER Lm30215-10) so they could not hear each other either. No communication in any form was allowed (both before and during the experiment). The participants were explicitly instructed that the number of interceptions per individual did not matter and that their performance as a team was the only thing that counted.

Kinematic data of the participants' paddles and the ball was sampled at a frequency of 100 Hz and stored on an external disk. Along with the kinematic data, we registered trial characteristics including whether a participant intercepted the ball or not and, in Session 2 and 3, the time of a collision, if any. Before further analysis, the kinematic data was filtered with a second-order Butterworth filter with a cut-off frequency of 5 Hz ran through twice in order to negate the phase shift (Ledouit et al., 2013).

2.3.5 Dependent measures

Interception scores were calculated per block as the percentage of balls intercepted from the total number of 50 balls presented. The score used to assemble the teams was the mean value of interception scores obtained during the first and second individual sessions.

Movement initiation time was defined as the first moment a participant crossed a velocity threshold of 3.0 cm/s provided that the participant's movement amplitude reached at least 1 cm. Based on this criterion we determined for each individual trial whether, and if so when, a participant initiated a movement. Velocity-time series were obtained using a three-point central difference method. Peak velocity was determined as the maximum velocity reached during a movement.

Defining angles β_{LP} and β_{RP} according the definition provided in Fig. 2.3A, allowed deriving time-series of the rates of changes of these angles (i.e., angular velocities) for the LP and the RP. As demonstrated in Fig. 2.3B-D, the manner in which a participant's paddle movement affects the pattern of change of the angle β (i.e., the state of the angular velocity) is lawfully related to the future outcome of the ongoing action (also see, for instance, Fajen & Warren, 2004). As we will detail later, this prospective character of the (visual) information provided by the LP's and RP's angular velocities may be used to develop an account of emergent decision making.

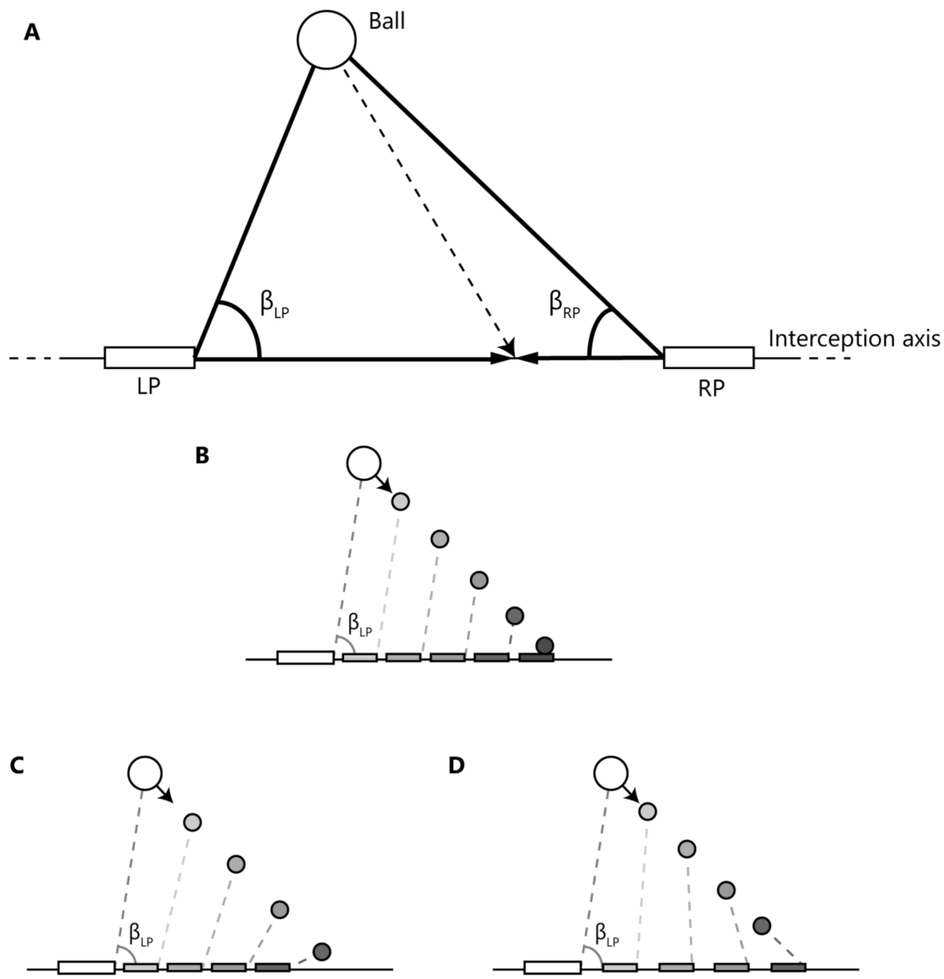


Figure 2.3 | Definition and time course examples of angles used to capture the relations between the paddles and the ball. (A) LP and RP represent the paddles of the left and right participant, respectively, that could freely move along the interception axis. β_{LP} and β_{RP} are the angles formed by the line connecting both paddles and the lines connecting each paddle with the ball. **(B)** When the paddle moves at a speed that will bring it to reach the ball arrival position when the ball (moving at constant velocity) gets there, β_{LP} is constant over time (i.e., AV is zero). **(C)** When the paddle moves at a lower speed, β_{LP} closes (decreases) over time (i.e., AV is negative). **(D)** When the paddle moves at a higher speed, β_{LP} opens (increases) over time (i.e., AV is positive).

2.4 Results and Discussion

2.4.1 Performance on the task

We begin by examining performance on the interception task, operationalized by the percentage of balls intercepted, in each of the three experimental sessions (see Table 2.1).

Table 2.1 | Interception scores of the 12 individual participants in Sessions 1 (S1) and 2 (S2) and the 6 teams in Session 3 (S3), together with the number of collisions observed in Sessions 2 and 3.

Team	Side	Gender	Interception score (%)			Collisions (number)	
			S1	S2	S3	S2	S3
1	LP	M	91.5	93.0	92.5	0	1
	RP	M	92.5	95.0		1	
2	LP	M	90.0	89.5	92.5	0	1
	RP	M	91.0	94.0		3	
3	LP	M	87.5	91.5	95.5	1	0
	RP	M	85.0	91.5		0	
4	LP	F	82.0	92.0	89.5	0	2
	RP	F	85.5	92.5		0	
5	LP	M	82.5	91.0	92.0	1	1
	RP	M	85.0	88.5		2	
6	LP	F	73.0	82.5	85.5	3	1
	RP	F	83.0	93.5		2	
Mean			*85.7*	*91.2*	*91.3*	*1.1*	*1.0*

During the first session individual participants had to cover the full 105-cm range of potential ball arrival positions with their paddle initially positioned at an eccentricity of 21 cm (to the left for the LPs and to the right for the RPs) with respect to the center of the screen. With an average interception performance of 85.7 ± 5.4 % for the total of 200 trials completed by each participant, performance was overall quite good. A repeated-measures one-way ANOVA on the evolution of performance over the 4 blocks of 50 trials revealed a significant effect of Block (F(3, 33) = 18.51, $p < 0.001$, $\eta^2 = 0.63$), reflecting an initial increase from Block 1 (78.2 ± 8.9 %) to Block 2 (88.8 ± 4.2 %), followed by a leveling off of performance during Blocks 3 (87.2 ± 6.3 %) and 4 (88.7 ± 5.6 %). Post-hoc Newman-Keuls analyses confirmed that performance in Block 1 was significantly different from performance in Blocks 2, 3, and 4 (p's < 0.001), while no significant differences were observed among the latter.

During the second session the individual participant's paddle was initially positioned at an eccentricity of 30.25 cm (to the left for the LPs and to the right for the RPs) with respect to the center of the screen. Participants were assisted by a static partner (32-cm wide stationary paddle) covering the final 24-cm range of potential ball arrival positions on the opposite side of the full 105-cm range. They therefore needed to cover an 81-cm range of potential ball arrival positions while avoiding contact with the static partner's paddle. Collisions with the stationary paddle occurred only sporadically (on average on 0.5 ± 0.6 % of the trials, see Table 2.1), with only three participants colliding once during the first block. Interception scores were stable over blocks (89.3 ± 4.5, 91.7 ± 5.2, 93.0 ± 5.9, and 92.0 ± 4.5 %, for blocks 1, 2, 3, and 4, respectively); a repeated-measures ANOVA did not reveal significant differences in performance over the four blocks (F(3, 33) = 1.61, $p = 0.205$, $\eta^2 = 0.13$). These results indicate that participants performed well from the beginning of the session.

In order to examine potential differences between LPs and RPs in Sessions 1 and 2, we conducted a mixed two-way ANOVA on interception scores with Side (LP and RP) as a between-participant factor and Session (1 and 2) as a within-participant factor. This analysis did not reveal significant differences between LP and RP (F(1, 10) = 1.22. $p = 0.296$. η^2_p = 0.11). Inspection of individual means (cf. Table 2.1) confirmed that performance was comparable for left and right participants in both sessions.

Having thus characterized the performance of individual participants in Sessions 1 and 2, we now turn to the third session in which the 12 participants were combined into 6 teams, each consisting of an LP and an RP. Paddles were initially positioned 30.25 cm to the left (LP) and to the right (RP) with respect to the center of the screen. Together, the two participants needed to cover the full 105-cm range of potential ball arrival positions while avoiding contact between their paddles. As in Session 2, collisions were rare (6 out of the total of 1200 trials, see Table 2.1), with only two teams colliding once within the first block. Interception scores were quite high from the start and stable over blocks (90.7 ± 4.3, 92.3 ± 3.9, 92.3 ± 5.1, and 89.7 ± 7.0 %, for blocks 1, 2, 3, and 4, respectively); a repeated-measures one-way ANOVA did not reveal significant differences in performance over the four blocks ($F(3, 15) = 0.50$, $p = 0.688$, $\eta^2 = 0.09$). Interestingly, team performance could not be predicted on the basis of its members' scores observed in Session 2. Indeed in two cases team performance in Session 3 was better than the best team member's score in Session 2 (teams 3 and 5, see Table 2.1). In two other cases the opposite pattern was observed (teams 1 and 4, see Table 2.1).

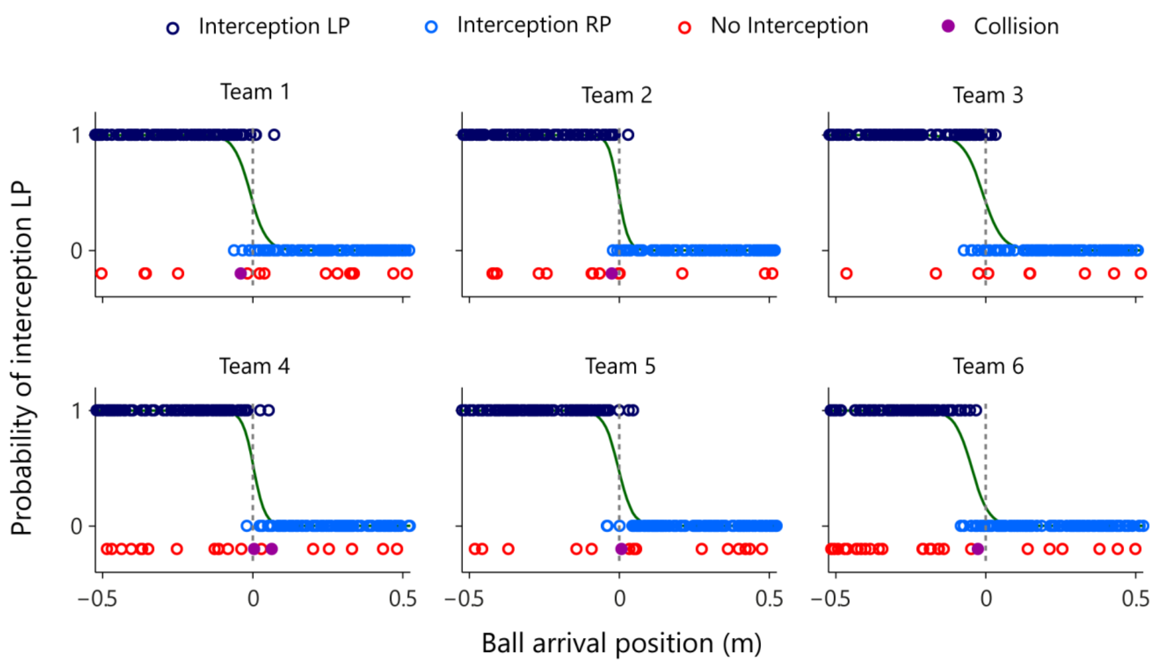


Figure 2.4 | Graphical summary of interception performance as a function of ball arrival position for all six teams separately. Ball arrival positions for each successful trial are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of unsuccessful trials are indicated by red circles (errors) and purple dots (collisions). The green curves depict the logistic curves representing the probability that LP ($P = 1$) or RP ($P = 0$) will intercept the ball as a function of ball arrival position. The horizontal dashed gray lines at ball arrival position 0 cm indicate the center of the interception axis.

Figure 2.4 provides a graphical summary of the interception results as a function of the ball's arrival position on the interception axis for all 200 trials of each team. Interceptions accomplished by the LP (dark blue circles) and by the RP (light blue circles) were plotted on two separate axes, so as to allow visual discrimination of who intercepted the balls where. These intercepted trials were completed with the trials in which both participants failed to intercept the ball (red circles, referred to as errors) and with the trials in which the LP and RP paddles made contact with one another (purple dots, referred to as collisions). The (rare) collisions occurred for balls arriving at locations near the center of the screen. Errors, on the other hand, were generally distributed over the full range of ball arrival positions. Indeed, errors for ball arrival positions located within the interval between both participants' initial positions (n = 53) occurred as often as errors for ball arrival positions outside this interval (n = 52), indicating that the majority of errors seemed to result from individual mistakes. Together with the high interception scores (on average 91.3 ± 3.4 %) and the low number of collisions (on average 0.5 ± 0.3 %), these results demonstrate that participants succeeded remarkably well in coordinating their interceptive movements with one another.

Visual inspection of Figure 2.4 revealed that all six teams exhibited a quite well-defined distribution of who intercepted the ball where, with the LP intercepting the grand majority of balls arriving on the left half of the interception axis and the RP intercepting the grand majority of balls arriving on the right half. Interestingly, however, the interception performance of all teams also included an area where both participants could intercept balls. In order to quantify the separation of interception domains, for each team we computed a logistic regression equation with ball arrival position as the explanatory variable. Using a logit link function (Nelder & Wedderburn, 1972), logistic probability curves were derived for the balls intercepted by the LP (P = 1) and by the RP (P = 0) for all teams independently. The boundary between both interception domains was defined as the Median Effective Level (MEL), that is, the position on the interception axis where the probability of the LP intercepting the ball is equal to the probability of the RP intercepting the ball (i.e., P = 0.5). As can be seen from Table 2.2 (observed interception performance), teams 1 to 5 revealed MEL values close to zero with a maximum absolute deviation of 1.08 cm, indicating that in these teams the boundary between both interception domains laid close to the exact (and yet unmarked) middle of the interception axis. Team 6, on the other hand, was characterized by a

MEL value of –4.66 cm, indicating that the boundary between both interception domains was shifted almost 5 cm to the left. Of potential interest here is the fact that team 6 was the team with the largest difference in individual performances, as observed in Sessions 1 and 2 (see Table 2.1). The boundary shifted towards the participant with the lowest interception score, resulting in a 19.5 % difference in the ranges of both participants' interception domains. Note, however, that even in the presence of a shift in the location of the boundary team 6 still demonstrated a rather well-defined separation of interception domains.

Table 2.2 | Logistic regression results for observed and predicted interception performance

	Observed		**AV Predicted**	
Team	MEL (cm)	Overlap (cm)	MEL (cm)	Overlap (cm)
1	-0.88	16.1	-1.14	23.7
2	-0.31	9.7	-1.19	14.9
3	-1.08	19.3	-2.17	33.2
4	0.34	11.3	-1.27	20.9
5	-0.32	14.2	-0.25	15.1
6	-4.66	16.9	-4.24	22.0
Mean	*-1.15*	*14.6*	*-1.71*	*21.6*

The degree of separation between both interception domains is reflected in the steepness of the slopes of the logistic curve and the amount of overlap may be calculated as the distance between the 5% and 95% points of the logistic curve (Cox & Snell, 1989). On average, overlap thus defined amounted to a non-negligible 14.6 ± 3.6 cm. Interestingly, the amount of overlap between interception domains was not related to a team's performance (r = 0.13, $t(4)$ = 0.263, p > 0.8). While team 6 (characterized by the leftward boundary shift discussed above) demonstrated an above-average overlap (16.9 cm, see Table 2.2) as well as the lowest team performance (85.5 % of all balls intercepted, see Table 2.1), team 3 not only revealed the largest overlap (19.3 cm) but also the highest team performance (95.5 % of all balls intercepted).

2.4.2 Movement kinematics

We first examined initiation times for all interception movements in all three sessions. As can be seen from Table 2.3, whereas average initiation times were similar for Sessions 1 (428 ± 38 ms) and 2 (437 ± 44 ms), they appeared longer for Session 3 (534 ± 51 ms). However, this observation was difficult to interpret because the different sets of initiation times refer to different ranges of movement in the three sessions. For Sessions 2 and 3 we therefore calculated the initiation times for the subset of all interception movements that were directed to ball arrival positions between the initial paddle position and the middle of the screen (i.e., between –30.25 cm and 0 cm for the LPs and between 0 cm and +30.25 cm for the RPs). As can be seen from the last two columns of Table 2.3, even for these range-corrected interception movements a difference in initiation time occurred (paired t-test: $t(11) = 3.56$, $p < 0.01$) with movements being initiated later in the presence of a dynamic partner (Session 3: 518 ± 50 ms) than in the presence of a static partner (Session 2: 459 ± 61 ms).

Table 2.3 | Mean initiation times of individual participants in Sessions 1 (S1), 2 (S2), and 3 (S3). Range-corrected initiation times only concern movements initiated for balls arriving between the initial position (-30.5 cm for the LP and +30.5 cm for the RP) and the center of the screen (0 cm).

			Initiation Times (ms)				
Team	**Side**	**Gender**	Full range			Range-corrected	
			S1	S2	S3	S2	S3
1	LP	M	409	477	581	479	645
	RP	M	404	344	492	371	487
2	LP	M	438	493	581	538	537
	RP	M	414	412	524	368	481
3	LP	M	412	423	483	421	518
	RP	M	462	462	499	467	540
4	LP	F	385	393	469	575	544
	RP	F	470	446	504	454	499
5	LP	M	364	393	508	478	513
	RP	M	451	474	556	406	449
6	LP	F	498	471	642	482	475
	RP	F	425	453	566	468	527
Mean			*428*	*437*	*534*	*459*	*518*

In Session 3, interception on a given trial could *in fine* only be accomplished by a single participant but this did not necessarily imply that the other participant did not move at all. For every single trial and independent of the result, we therefore determined for both LP and RP whether they initiated a movement. Figure 2.5 summarizes the resulting frequency distribution of observed movement initiations for the LPs and RPs as a function of the arrival position of the ball, with the full 105-cm range of potential ball arrival positions divided into 20 (5.25-cm wide) bins. Each trial was classified into one of four categories: initiation LP only (dark blue), initiation RP only (light blue), initiation both LP and RP (green), and no initiation, that is, neither LP nor RP (red) initiated a movement. Of all 1200 trials, 436 (i.e., 36.3 %) revealed LP initiation only, almost exclusively associated with balls arriving on the left side of the interception axis. Similarly, 421 (i.e., 35.1 %) of all trials revealed RP initiation only, almost exclusively associated with balls arriving on the right side of the interception axis. Of the 279 (i.e., 23.3 % of all trials) revealing both LP and RP initiations, 246 (i.e., 88.2 %) resulted in successful interception, implying that one of the participants must have abandoned the launched interception attempt at some point so as to allow the other participant to intercept the ball. The prevalence of such double initiations appeared to follow a bell-shaped distribution over the interception axis, with its peak located in the vicinity of the center of the interception axis (i.e., the center of the screen). In 5.3 % of the trials neither of the two participants initiated any movement. In 63 of these 64 trials without movement initiation, balls arrived at or close to one of the participants' initial positions (i.e., ±30.25 cm). Note that in 59 (i.e., 93.7 %) of those 63 trials the ball was in fact intercepted, making contact with one of the motionless (3-cm wide) paddles.

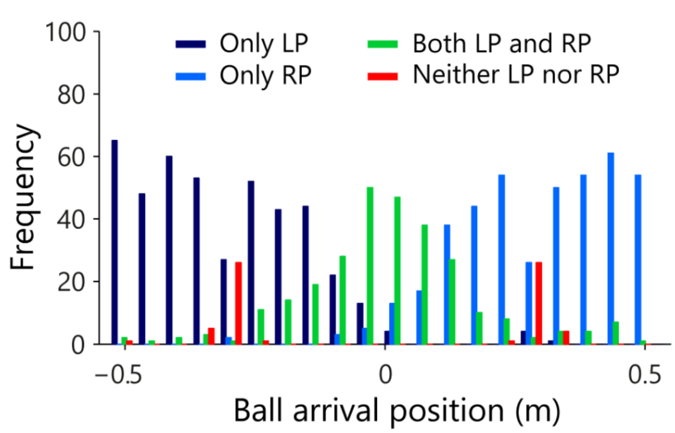
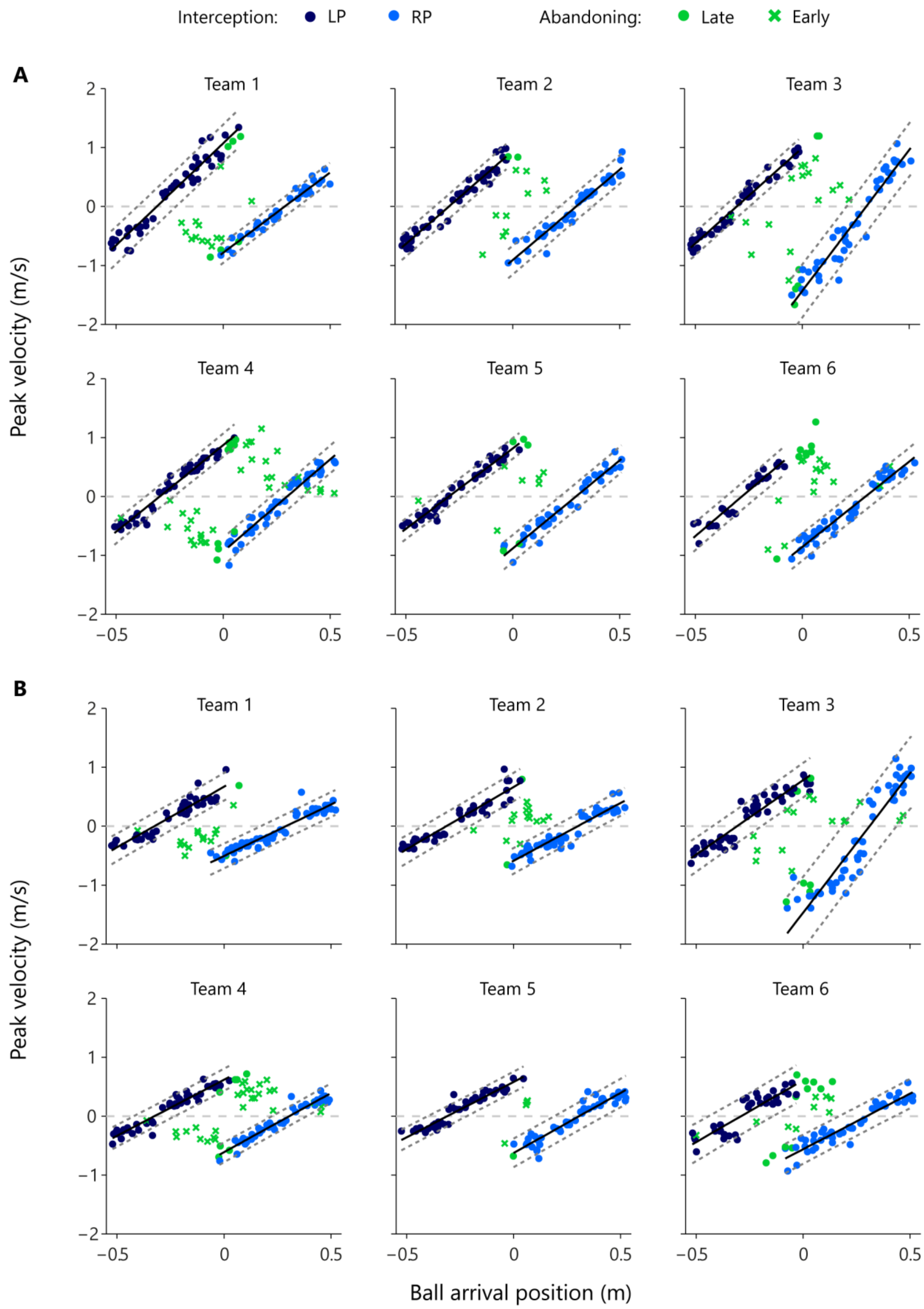


Figure 2.5 | Frequency distribution of the observed movement initiations of the LP and RP as a function of ball arrival position. Each trial arriving in one of 20 (5.25-cm wide) bins was classified as indicating initiation of only LP (dark blue), only RP (light blue), both LP and RP (green) or neither LP nor RP (red).

In order to obtain a grasp on when one of the participants abandoned the launched interception attempt, we examined the relation between the distance to be covered and the peak velocity reached during the movement on each trial. Figure 2.6 presents this relation for each successful (i.e., intercepted) trial in which at least one participant initiated a movement, for each team and each of the two vertical ball speeds separately. Successful interceptions by the LPs (dark blue dots) and the RPs (light blue dots) were characterized by proportional scaling relations between the distance covered (i.e., the distance between initial paddle position and ball arrival position) and the peak velocity reached during the movement (see Ledouit et al., 2013, for similar results). For each individual player we therefore performed a linear regression analysis of peak velocity onto distance covered for the balls intercepted by that participant. Results of these regression analyses are reported in Table 2.4 and shown graphically in Figure 2.6.

Table 2.4 | Results of regression analyses of the relations between peak velocity and distance covered during movements resulting in interception, performed for each participant separately for each of the two vertical ball speeds. n: number of trials, a: slope (s^{-1}), r: correlation coefficient, p: probability.

			High Ball Speed				**Low Ball Speed**			
Team	**Side**	**Gender**	*n*	*a*	*r*	*p*	*n*	*a*	*r*	*p*
1	LP	M	43	3.46	0.97	< .001	41	2.06	0.94	< .001
	RP	M	39	2.73	0.98	< .001	51	1.75	0.95	< .001
2	LP	M	45	3.16	0.98	< .001	39	2.12	0.96	< .001
	RP	M	41	3.08	0.97	< .001	50	1.97	0.95	< .001
3	LP	M	42	3.25	0.98	< .001	49	2.53	0.95	< .001
	RP	M	43	4.80	0.96	< .001	46	4.74	0.94	< .001
4	LP	F	42	2.94	0.98	< .001	46	1.90	0.96	< .001
	RP	F	41	3.13	0.97	< .001	43	2.01	0.97	< .001
5	LP	M	41	2.74	0.98	< .001	49	1.88	0.96	< .001
	RP	M	39	2.99	0.98	< .001	45	2.04	0.94	< .001
6	LP	F	25	3.09	0.97	< .001	35	2.10	0.89	< .001
	RP	F	49	2.90	0.97	< .001	46	1.89	0.94	< .001



Interception: LP RP
Abandoning: Late Early
A
B
Team 1
Team 2
Team 3
Team 4
Team 5
Team 6
Peak velocity (m/s)
Ball arrival position (m)
2
1
0
−1
−2
−0.5
0
0.5

Figure 2.6 | Peak velocity of movement as a function of ball arrival position for both members of each team for each vertical ball velocity separately. Dark blue dots indicate LP-interception trials and light blue dots indicate RP-interception trials. The solid black lines represent the associated regression lines of peak velocity onto ball arrival position and the dashed gray lines represent the ±2 *SD* boundaries. Green symbols indicate trials in which interception was abandoned, with dots indicating that the peak velocity reached during that trial fell within the above-defined boundaries (late abandoning) and crosses indicating that the peak velocity reached during that trial fell outside the above-defined boundaries (early abandoning). The horizontal gray dashed lines in each panel, at peak velocity = 0 m/s, indicate the borders between negative (i.e., movements to the left) and positive (i.e., movements to the right) values of peak velocity. All green dots and crosses with positive peak velocity (i.e., all green points above the zero line) represent abandoned interception attempts of the LP. Likewise, all dots and crosses with negative peak velocity (i.e., all green points below the zero line) represent abandoned interception attempts of the RP. **(A)** high vertical ball speeds (0.64 m/s, 1-s trial duration) and **(B)** low vertical ball speeds (0.4 m/s, 1.6 s trial duration).

While the slope of the relation varied both as a function of participant characteristics and as a function of vertical ball speed, individual correlation coefficients were satisfactorily high to allow the definition, for each participant at each vertical ball speed, of a "standard" relation (operationally defined by a range of ±2 *SD*s around the mean, dashed parallel lines in the panels of Fig. 2.6) between ball arrival position and peak velocity reached during an interception movement. Using this "standard" relation observed for successful interceptions, we could identify whether the 246 abandoned interception attempts (i.e., successful trials in which the participant that did not intercept the ball had nevertheless initiated a movement) occurred early or late during the trial. Late abandoning was characterized by the participant still reaching the standard peak velocity (green dots in Fig. 2.6), whereas early abandoning was characterized by the participant reaching a lower-than-standard peak velocity (green crosses in Fig. 2.6). Of the 246 successfully intercepted trials demonstrating both LP and RP initiation, 179 (i.e., 72.8 %) were characterized by early abandoning, while 67 (i.e., 27.2%) were characterized by late abandoning.

2.4.3 Team interactions

Several of the results discussed in the previous sections suggest that team performance, as observed in Session 3, cannot be satisfactorily understood as resulting from a form of organization with pairs of independent players, each covering their own half of the interception space. First, while for five of the teams the boundary between interception domains laid close to the center of the screen (with differences in the sizes of individual participant interception domains being limited to 2.3 ± 1.4 %), in team 6 this boundary was shifted by almost 5 cm, leading to a difference in domain sizes of 19.5%. Second, for all six teams the boundary between interception domains was fuzzy rather than sharp, with participants regularly entering their teammate's domain to intercept balls there without such "intrusions" leading to collisions. The observed degree of overlap between interception domains was indeed quite substantial (14.6 ± 3.6 cm), amounting to 13.9 ± 3.4 % of the full range of potential ball arrival positions. Third, balls arriving near the center of the screen (four center bins of Figure 2.5, with ball arrival positions ranging from -10.5 to +10.5 cm) more often evoked movement initiations of both participants than only initiations of the participant in whose interception domain the ball would in fact arrive. Yet, both collisions and errors were rare, as 87.9 % of the trials on which both participants initiated a movement resulted in successful interception by one the participants. Finally, while in 72.8 % of the 246 double-initiation trials one of the participants abandoned the launched interception attempt early on, in the remaining 27.2 % of the trials the interception attempt was abandoned after the participant had reached a peak velocity associated with an ongoing interception attempt. Together, these results suggest that participants took into account the ongoing actions of their partners.

Without going as far as suggesting that this is the information used by the participants (see Bootsma et al., 2016; Fajen & Warren, 2007, for further details), for the present purposes the state of the angle formed, for each participant, by the line connecting this participant's paddle with the other participant's paddle and the line connecting this participant's paddle with the ball (see Fig. 2.3) may well allow capturing the unfolding team interactions. Indeed, by physical law, a constant angle (i.e., a zero angular velocity) indicates that the player's current movement speed will lead the paddle to reach the interception point when the ball arrives there. Put differently, zero angular velocity means that an interception will occur if both ball and paddle speed remain constant over the remainder of the trial. Given that in the present study ball speed was always constant over the course of a trial, from the foregoing it follows that a positive angular velocity (i.e., an opening of the angle) implies that maintaining current paddle speed will lead to an early arrival at the interception location and, likewise, that a negative angular velocity (i.e., a closing of the angle) implies that maintaining current paddle speed will lead to a late arrival at the interception location.

When neither of the two participants has begun to move their paddle (i.e., from the beginning of a trial up to the moment of first movement initiation), for both participants angular velocity (AV) will be negative for balls arriving at a location between the two paddles. For balls arriving at locations to the left of the LP, AV will be positive for the stationary LP and negative for the stationary RP. *Mutatis mutandis*, AV will be positive for the stationary RP and negative for the stationary LP for balls arriving at locations to the right of the RP.

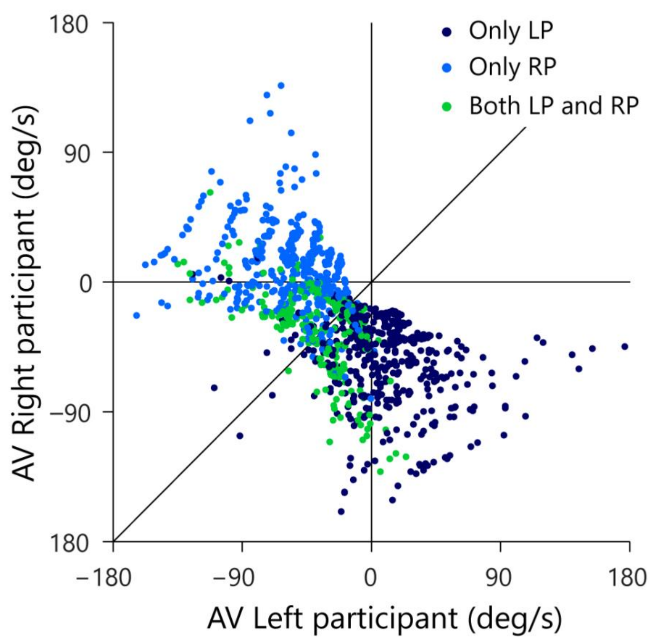


Figure 2.7 | Rate of change of β_{RP} (AV-RP) as a function of rate of change of β_{LP} (AV-LP) at the moment of first participant movement initiation. Trials with only LP initiation are indicated by dark blue dots, trials with only RP initiation by light blue dots, and trials with both LP and RP initiation by green dots. The thin vertical and horizontal lines mark zero AV for the LP and RP, respectively. The thin diagonal line marks AV-LP = AV-RP.

Each trial in which one or both participants initiated a movement is represented in Figure 2.7 as a point in space defined by the states of the AV-LP (abscissa) and the AV-RP (ordinate) at the moment of first movement initiation. Dark blue dots designate the 436 trials in which only the LP initiated a movement, light blue dots designate the 421 trials in which only the RP initiated a movement, and green dots designate the 279 trials in which both players initiated a movement. As was already visible in Figure 2.5, balls arriving to the left of the LP almost invariably evoked only movement from the LP. In Figure 2.7, these trials correspond to the (predominantly dark blue) dots in the lower right quadrant where AV-LP is positive and AV-RP is negative. Likewise, balls arriving to the right of the RP almost invariably evoked only movement from the RP. In Figure 2.7, these trials correspond to the (predominantly light blue) dots in the upper-left quadrant where AV-LP is negative and AV-RP is positive. As was also already visible in Figure 2.5, trials evoking initiation by both the LP and RP generally arrived between the initial positions of both paddles, close to the center of the screen. In Figure 2.7 these trials correspond to the green dots predominantly located in the lower-left quadrant where both AV-LP and AV-RP are negative.

The (AV-LP, AV-RP) state space allows us to scrutinize the evolution over time of the behavior of both participants with respect to the ball. The trials of interest for such scrutiny are of course the trials in which both participants initiated an interception movement (green dots in Fig. 2.7). For these reasons, the subset of 246 successfully intercepted trials in which both participants initiated a movement is once again presented in Figure 2.8, but this time coded for the player who in the end intercepted the ball (LP interception: dark blue, RP interception: light blue). When participants start moving they actively change their relation to the ball, which is functionally captured by a change in their AV. The motion through the (AV-LP, AV-RP) state space thus captures the dynamic triangular relation between both players and the ball. As in Figure 2.7, Panel A of Figure 2.8 depicts the situation at the time of first movement initiation. Panels B, C, and D depict the situation, respectively, 100, 200, and 300 ms later.

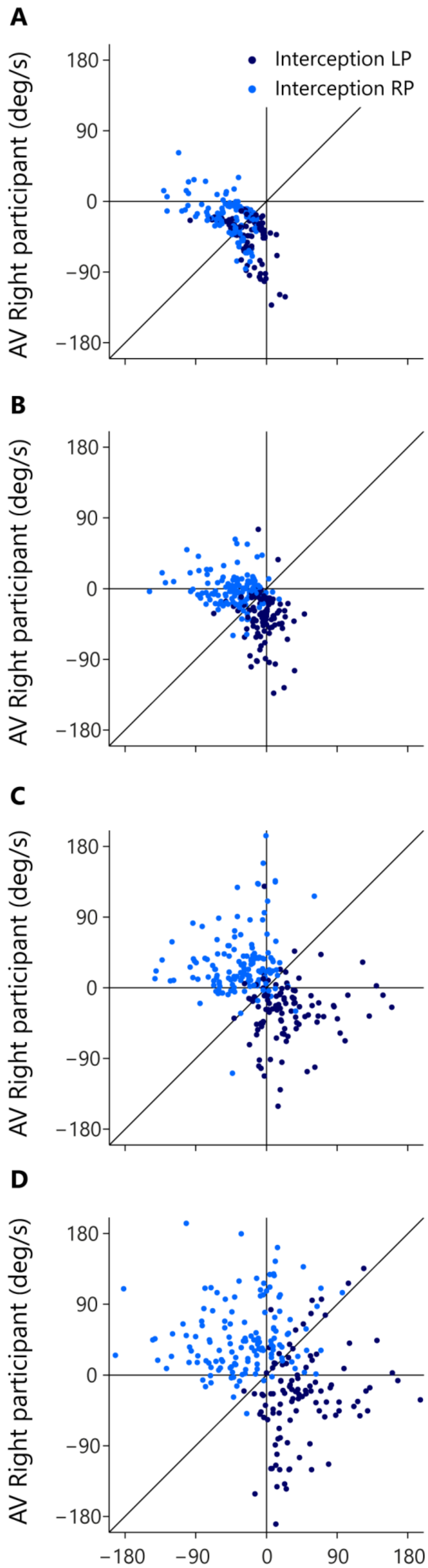


Figure 2.8 | Rate of change of β_{RP} (AV-RP) as a function of rate of change of β_{LP} (AV-LP) for the trials with both LP and RP initiation at different moments in time. Dark blue dots indicate LP-interception trials and light blue dots indicate RP-interception trials. The thin vertical and horizontal lines in each panel mark zero AV for the LP and RP, respectively. Movements of dots across these lines mark transitions from negative to positive AV. The thin diagonal line in each panel marks AV-LP = AV-RP. **(A)** at the moment the first participant initiated a movement, **(B)** 100 ms later, **(C)** 200 ms later, and **(D)** 300 ms later.

Inspection of Figure 2.8 brings out that trials that eventually gave rise to LP-interception were characterized by a change in AV-LP from negative to positive (resulting from the LP's sustained movement towards the future interception location), with dots moving from the lower-left quadrant either to the lower-right quadrant or, for a smaller proportion of trials, to the upper-right quadrant. A similar picture emerged for the trials that eventually gave rise to RP-interception. These trials were characterized by a change in AV-RP from negative to positive (resulting from the RP's sustained movement towards the future interception location), with dots moving from the lower-left quadrant either to the upper-left quadrant or, for a smaller proportion of trials, to the upper-right quadrant. Figure 2.8 thus reveals the gradual separation in the two groups of trials based on who intercepted the ball in the end. This observation suggests that the decision of who intercepts the ball in fact emerges over the course of a trial, as a function of the expediency with which both participants engaged in their interception attempts. In fact, it appeared that the first participant to reach positive AV tended to be the one that ended up intercepting the ball. Recalling (cf. Fig. 2.3) that negative AV implies that with the current movement speed the participant will be (too) late, positive AV implies that with the current movement speed the participant will in fact arrive at the interception location before the ball gets there. Even though all participants generally slowed down prior to interception (probably so as to minimize chances of colliding with the other participant), the occurrence of a positive AV for one participant may signal to the other that the interception attempt should be abandoned.

In order to test this idea, we examined the evolution over time of AV-LP and AV-RP for all 1095 trials on which the ball was intercepted. Starting from the situation at the onset of a trial, we classified the trial as LP-interception or RP-interception, as a function of the first participant to reach positive AV. Note that this rule led to correct (although immediate) classification of balls arriving to the left of the LP as LP-interception and of balls arriving to the right of the RP as RP-interception. The results of this on-the-fly decision formulation are presented in Figure 2.9 for all six teams separately.

As can be seen from Figure 2.9, attribution of interception to the LP (dark blue circles) or the RP (light blue circles) was correct in the overwhelming majority of cases. Overall, attribution errors occurred on only 2.0 % of the trials, corresponding to a total number of errors of 2, 2, 6, 7, 3, and 2, for teams 1 to 6, respectively. The on-the-fly decision criterion of interception by the "first participant to reach positive AV" not only allowed to predict which participant would intercept the ball with more than satisfactory precision, but also reproduced the qualitative aspects of the distribution of interception domains observed in each team. Deriving logistic probability curves for the predicted performance (see Table 2.2, predicted interception performance) revealed that the locations of boundaries between interception domains were well predicted (r = 0.92, $t(4)$ = 4.54, p = 0.010), laying close to the center of the screen (2.17 cm maximal absolute deviation) for teams 1 to 5 while being shifted 4.24 cm to the left for team 6. Similarly, even though somewhat overestimated, the amount of overlap between interception domains was fairly well predicted (r = 0.80, $t(4)$ = 2.63, p = 0.059).

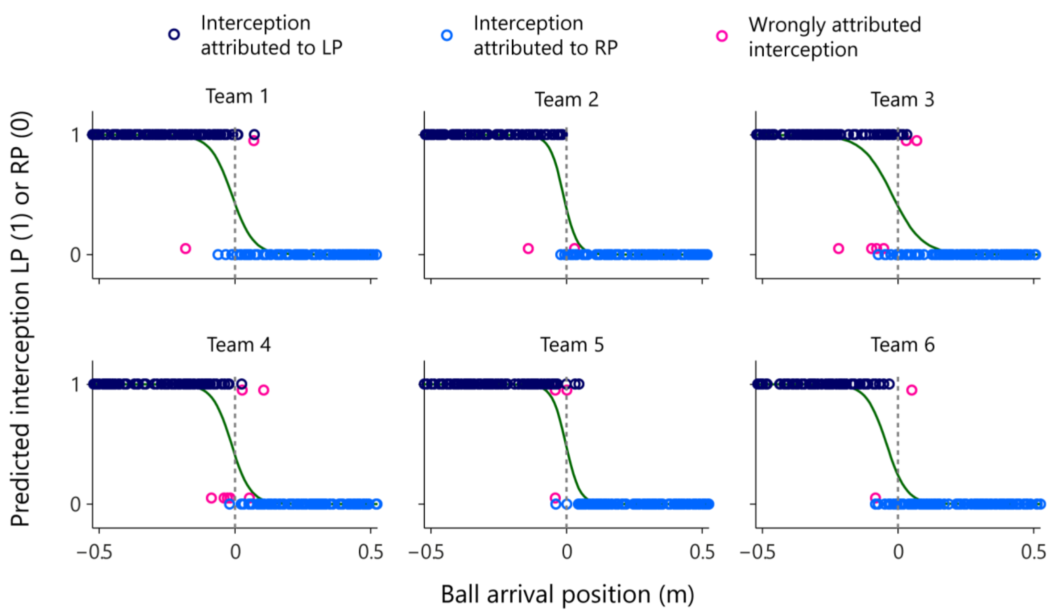


Figure 2.9 | Graphical summary of predicted interception performance as a function of ball arrival position for all six teams separately. The participant that would intercept the ball was predicted as being the participant who first reached positive AV. Ball arrival positions for correctly attributed interceptions are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of incorrectly attributed interceptions are indicated by pink circles with a slight vertical offset. The green curves depict the logistic curves representing the probability that LP (P = 1) or RP (P=0) will intercept the ball as a function of ball arrival position. The horizontal dashed gray lines at ball arrival position = 0 cm indicate the center of the interception axis.

Finally, because the moment at which the first participant reached positive AV could be detected, we examined whether this criterion also correctly predicted when the non-intercepting participant abandoned the launched interception attempt in the trials in which both participants initiated an interception movement. In 209 (i.e., 85.0 %) of the 246 double-initiation trials, the abandoning participant indeed reached peak velocity *after* the intercepting player had reached positive AV. Thus, the non-intercepting participant was already decelerating (that is, had already abandoned) before the intercepting player reached positive AV in only 15.0 % of the cases. This first analysis suggests that our on-the-fly decision criterion also captures the timing of the decision rather well. We can take the analysis one step further by also considering the information with respect to the moment of abandoning contained in the magnitude of the peak velocity reached by the non-intercepting participant, as described in section 2.4.2. If the peak velocity reached during an abandoned interception attempt corresponded to the "standard" peak velocity of a successful interception movement, the interception attempt was considered as still underway at the moment the non-intercepting participant reached this peak velocity. Abandoning was then classified as late. If, on the other hand, the peak velocity reached during an abandoned interception attempt was smaller than the standard peak velocity, the interception attempt was considered as already abandoned when the non-intercepting participant reached this lower-than-standard peak velocity. Abandoning was then classified as early. Table 2.5 presents the foregoing results in the form of a contingency table;

As can be seen from Table 2.5, of the 209 double-initiation trials in which the non-intercepting participant reached peak velocity *after* the intercepting participant had reached positive AV, 150 (i.e., 71.8 %) had been characterized as early abandoning and 59 (i.e., 28.2 %) as late abandoning. This repartition nicely mirrors the observed overall 72.8 % (179 out of 246) early abandoning and 27.2 % (67 out of 246) late abandoning. Of the 37 trials in which the non-intercepting participant had reached peak velocity *before* the intercepting participant reached positive AV, the grand majority (29 or 78.4 %) had been characterized as early abandoning. We suggest that in many of these trials the non-intercepting participant produced only a small movement, characterized by a low peak velocity (i.e., the green points close to the zero velocity axis in Fig. 2.6). Overall we conclude that the on-the-fly criterion that the ball will be intercepted by the "first participant to reach positive AV" allows the observed team interactions to be rather accurately captured.

Table 2.5 | Contingency table for double-initiation (both LP and RP) trials, combining the number of times the non-intercepting player reached peak velocity before or after the intercepting participant reached positive angular velocity with the number of times the non-intercepting player abandoned the interception attempt early or late, as determined by the magnitude of the peak velocity reached.

	Before	**After**	*Total*
Early	29	150	*179*
Late	8	59	*67*
Total	*37*	*209*	*246*

2.5 General discussion

In the present contribution we set out to study how a team of two players coordinated their actions so as to intercept a series of approaching balls. Contrary to most work performed in the field of between-participant collaboration (e.g., Isenhower, Richardson, Carello, Baron, & Marsh, 2010; Mottet et al., 2001; Romero et al., 2015), our doubles-pong task (implicitly) required the team members to decide amongst them, on every single trial, who would perform the interceptive action and who would not: continuing interception attempts realized by both players led to collisions between their paddles that subsequently disintegrated, thereby no longer allowing the ball to be intercepted. In order to be able to study how such joint decisions were made on the basis of shared visual information only, we effectively prevented participants from directly communicating between them: unable to see or hear the other participant, they only shared the visual information available on the screen in front of them, depicting the moving ball and the positions of each of the two participant-controlled paddles along the interception axis.

Before partaking in the team interception session, participants had previously been familiarized with the apparatus and task. In a first session they had practiced intercepting all balls on their own and in a second session they had practiced intercepting balls while assisted by a static partner, incorporated by a large stationary paddle covering the last part of the opposite side of the interception axis. These first two sessions not only served to allow the participants to become acquainted with the set-up but also allowed us to characterize interception performance of all 12 individual participants. After having ascertained that performance in the first two sessions was comparable for the left-positioned participants (LPs) and right-positioned participants (RPs), six teams, each consisting of an LP and a RP, were formed for the final session.

Notwithstanding the lack of possibilities for overt communication, performance during this team interception session was remarkably good, with between 85.5 % and 95.5 % of the balls being intercepted by the different teams. Collisions were extremely rare, with one team never colliding, four teams colliding once and one team colliding twice on a total of 200 trials per team. Focusing on who intercepted balls where revealed that all teams instantiated a division of the total interception space, with the LP intercepting the grand majority of ball arriving on the left half of the interception axis and the RP intercepting the grand majority of balls arriving on the right half. However, as already mentioned, a simple geometry-based division-of-space hypothesis did not satisfactorily account for the pattern of results observed. The decision of who intercepts a ball where appeared to be founded in between-participant interactions rather than in situational geometry.

A first indication hereof was the finding that, while for five of the six teams the boundary between LP and RP interception domains was located close to the (unmarked) center of the screen, for the remaining team this boundary was shifted almost 5 cm to the left (cf. Fig. 2.4). As the latter team was characterized by a large difference in individual performance scores in Sessions 1 and 2 and the LP was the participant with the lowest interception performance scores, it is tempting to suggest that the boundary shift resulted from the better (worse) player taking charge of a larger (smaller) part of the interception space. However, more systematic explorations of between-participant performance levels are required to test the hypothesis that a team's division of interception space may indeed depend on the performance levels of the individual members. By the same token, the question whether approximately equally skilled team members would also divide the interception space in halves when their initial paddle positions were not symmetrically centered around the middle of the space also needs to be addressed in future work.

A second indication of the inadequacy of a geometry-based division-of-space hypothesis was the finding that, even though all six teams of the present study revealed a division of interception space, such divisions were never absolute. Boundaries were indeed fuzzy rather than clear-cut and the interception domains of individual participants were characterized by a significant degree of overlap (cf. Fig. 2.4). Under a division-of-space hypothesis excursions into the other participant's interception space should be considered as mistakes likely to result in collisions, with the likelihood of collisions expected to increase with the magnitude of the intrusion. Yet excursions into the partner's interception domain leading to successful interception were clearly far more frequent than collisions. Collisions moreover generally occurred for balls arriving very close to the boundary between interception domains. Interestingly, overlap between interception domains was not only spatial but also temporal: initiation of interceptive movements by both participants occurred in almost a quarter of all trials (cf. Fig. 2.5). While this may be understood as resulting from uncertainty with respect to the future ball arrival position, it does require that at some point in time one of the participants abandons the launched interception attempt so as to allow the other participant to successfully intercept the ball. At least in these trials the decision to (continue to attempt to) intercept the ball on a given trial or not is thus clearly taken on the fly rather than before movement onset.

How might between-participant interactions provide an account for the patterns of results observed? In the present contribution we suggested that the dynamic triangular relations between the movements of both participants and the approaching ball may be captured by the relation between the rates of change of angles β_{LP} and β_{RP} (cf. Fig. 2.3A). Importantly, both angular velocities (AVs) are influenced by the motion of the ball. Moreover, AV-LP is influenced by the way in which the LP moves the left paddle and AV-RP is influenced by the way the RP moves the right paddle. Contrary to movement speed, that necessarily varies as a function of the distance to be covered, AV provides a functional (because future outcome-related) characterization of the relation between the ball and the participant's paddle (see Fig. 2.3B-D). As such it allows evaluation of the expediency of both participants' ongoing interception attempt. Expediency here refers to the current functionality of the engagement of a participant in an interception attempt, with an expedient movement being a movement that rapidly leads to positive AV. Because positive AV implies a paddle speed that is higher than required to ensure interception, such a relation indicates that the participant is on track to perform an interception (and may end up beyond the interception point if the ongoing movement is not decelerated). Picking up such expediency of the partner's movement would allow the other participant to timely abandon his/her own ongoing interception attempt in order to avoid the paddles to collide.

Simulating the outcome of the on-the-fly decision process on each intercepted trial by attributing the future interception to the first participant to attain positive AV allowed the qualitative aspects of the observed results to emerge for all six teams. Indeed the predictions grounded in this action-based criterion (cf. Fig. 2.9) revealed that the overlap as well as the location of the boundary between interception domains, including the boundary shift observed for team 6, could be understood as emerging from the participants' behaviors during a trial. It is worth noting that predicted overlap tended to be larger than observed overlap, emphasizing the capacity of an information-based coupling to explain such a phenomenon. Moreover, the simulation provided first evidence that not only the outcome but also the timing of the team's decision who will intercept the ball could be understood as emerging from the interaction.

In this study we took an embodied approach to joint decision making (Coey et al., 2012; Marsh, Richardson, & Schmidt, 2009; Richardson, Shockley, Fajen, Riley, & Turvey, 2008). Looking at the interactive team behavior over time provides a way to study the emerging of the decision over time, rather than focusing on the outcome of a decision making process (cf. Lepora & Pezzulo, 2015; Turvey & Shaw, 1995). With the observation that in almost a quarter of all trials both participants initiated an interceptive movement (after which one of the two was required to abandon this attempt), the results of the present study provide behavior-based empirical evidence for the argument that actions may already be underway before decisions are completed, stressing the need to consider choice of action and control of action as highly-integrated rather than serially-arranged processes (for neural accounts also proposing parallel rather than serial decision processes, see, for instance, Cisek, 2007; Lepora & Pezzulo, 2015). The results also revealed that team decisions do not necessarily call upon shared knowledge or mental models —minimally exemplified in our doubles-pong task without overt communication by a silent agreement to divide interception space— as suggested by tenants of the social-cognitive perspective (e.g., Cannon-Bowers & Bowers, 2006; Cannon-Bowers et al., 1993; Eccles & Tenenbaum, 2004; Sebanz & Knoblich, 2009; Ward & Eccles, 2006). Our results rather suggest that team decisions are information-driven: the interactions between the participants' with respect to the ball provide information (tentatively captured in the AV-LP, AV-RP space) that can be used to decide to continue or to abandon a launched interception attempt.

Taking our observations into account, how then should we perceive a team of two individuals intercepting balls together? Intercepting a moving target on itself is a nonsocial activity and, therefore, often studied as such (e.g., Bootsma & van Wieringen, 1990; Bootsma et al., 2016; Chardenon, Montagne, Laurent, & Bootsma, 2005; Fajen & Warren, 2007; Ledouit et al., 2013: Michaels et al., 2006; Peper et al., 1994). However, whereas the ball typically will be intercepted by one individual, in many (sports) situations more individuals are present, potentially intercepting the ball as well. The task under study here was inspired by and modeled after the situation of (beach) volleyball players ready to intercept an oncoming serve. In situations such as these, it is the common goal (i.e., intercepting as many balls as possible) and accompanying constraints (i.e., not colliding with one another) that bind both individuals to act as a 'social unit' (i.e., a team; Marsh et al., 2006). Nevertheless, we do not know (yet) how such a social unit comes about from two 'I's' cooperating as a 'we' on the same task. Marsh and colleagues (2006) proposed that multiple individuals acting together might be considered a so-called social synergy, in which several individuals are temporally and functionally constrained by informational linkages to act as one unit. Evidence for such a synergistic approach to joint action has been found in studies on rhythmical interpersonal coordination (see Schmidt & Richardson, 2008 for a review) and during a continuous interpersonal postural task (Ramenzoni, Davis, Riley, Shockley, & Baker, 2011) showing behavioral control at the collective level. Our study, however, does not concern continuous rhythmical movements made by an ensemble of individuals, neither do both individuals perform the same task, as only one of the two individuals will intercept the ball in the end. Our results, though, do suggest that both players act as a team when deciding to go for the ball or not.

2.6 Conclusion

In conclusion, this study offered a paradigm in which two players act as a team to realize the interception of an approaching ball without any other means of interaction than the visual information of the joint action display on the shared task space. We suggest that the decision of who of the two players realizes ball contact emerges from these interactions of both players (paddles) and the ball. The coordinated action often involves the initiation of movement by both members of a team, leading to abandoning of movement by one of the players. Of course, many questions remain. Details of the interactions, effects of the means of interacting, and the identification of the information that the players use await future experiments. Furthermore, we suggest that the task that we developed captures the essentials of real-world tasks such as the interception of a serve in beach volleyball, but also in many other situations of daily life in which individuals have to coordinate to attain a common goal. Although further testing is needed to back up these suggestions, we feel that the paradigm that we introduced holds great promise for understanding on-the-fly decision making among individuals.

3

DIVISION OF LABOR AS AN EMERGENT PHENOMENON OF SOCIAL COORDINATION

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This chapter is devoted to provide support for an account of the observed division of labor as being an emergent property of the ball-related between-participant interactions. Although findings described in *Chapter 2* point out the decision to go and intercept a ball or not in the doubles pong task appeared highly related to a partner's paddle-ball relation, it could not be excluded that the close to perfect division of labor followed from (tacit) agreements on boundary-based interception domains. This chapter, therefore, presents an experiment in which the team members' initial paddle positions were manipulated to study if the division of interception domains changed accordingly.

Article in press

Benerink, N.H., Zaal, F.T.J.M., Casanova, R., Bonnardel, N., and Bootsma, R.J. (2017). Division of labor as an emergent phenomenon of social coordination: the example of playing doubles-pong. *Human Movement Sciences*.

3.1 Abstract

In many daily situations, our behavior is coordinated with that of others. This study investigated this coordination in a doubles-pong task. In this task, two participants each controlled a paddle that could move laterally near the bottom of a shared computer screen. With their paddles, the players needed to block balls that moved down under an angle. In doing so, they needed to make sure that their paddles did not collide. A successful interception led to the ball bouncing back upwards. Importantly, all communication other than vision of the shared screen was blocked. In the experiment, the initial position of the paddle of the right player was varied across trials. This allowed testing hypotheses regarding the use of a tacitly understood boundary to divide interception space. This boundary could be halfway the screen, or in the middle between the initial positions of the two paddles. These two hypotheses did not hold. As an alternative to planned division of labor, the behavioral patterns might emerge from continuous visual couplings of paddles and ball. This was tested with an action-based decision model which considered the rates of change of each player’s angle between the interception axis and the line connecting the ball and inner edge of the paddle. The model accounted for the observed patterns of behavior to a very large extent. This led to the conclusion that decisions of who would take the ball emerged from ongoing social coordination. Implications for social coordination in general are discussed.

3.2 Introduction

Many activities in daily life involve coordination with other individuals. When walking on the street, we not only need to avoid collisions with street furniture, but also need to navigate among other pedestrians. We all have been in situations in which we approach another pedestrian head-on and are both not sure who will go in which direction. How will coordination play out? In many sports situations as well, coordination among players and objects (often balls) is needed for a successful outcome. Obviously, in team sports like soccer this is at the heart of the game. The team has to act as a coordinated system to reach their shared goal, which is to outperform the opponent team. Some of that coordination is based on rules and pre-arranged (tactical) plans (e.g., Eccles, 2010). In soccer, when dealing with an attacker approaching with the ball on the foot, the defenders typically have instructions of who will take on that player. Analogously, in an example from a traffic context, when simultaneously approaching a four-way stop, each car needs to come to a full stop, and the ensuing order of crossing is typically negotiated on a first-to-arrive first-to-cross basis. Still, much of the coordination that we are involved in takes place without any clear plan of action. For example, when entering the highway, merging into traffic behind or in front of an upcoming car usually is a matter of nonverbal communication between the drivers (often signaled only through car motion and not through visual contact between drivers per se). Similar joint action is part and parcel of numerous sports situations. The present study investigates this type of everyday social coordination.

Social coordination has been studied from many different angles. When moving together rhythmically, social coordination can be understood as entrainment, typically leading to one of a small number of stable coordination patterns (Richardson, Marsh, & Schmidt, 2005; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008). For instance, Richardson, Marsh, Isenhower, Goodman, & Schmidt (2007) showed that two individuals sitting side-by-side in rocking chairs unintentionally fall into either an in-phase or antiphase coordination pattern. The stability phenomena associated with this entrainment are fully in line with those known to exist in intrapersonal coordination (e.g., Haken, Kelso, & Bunz, 1985; Kelso, Holt, Rubin, & Kugler, 1981; Kugler & Turvey, 1987; Turvey, 1990). Of particular interest for the current purposes is the fact that the coupling between the two individuals rocking their chairs is informational, through vision. Other studies have considered physical couplings (e.g., De Brouwer, De Poel, & Hofmijster, 2013; Harrison & Richardson, 2009) and shown that resulting coordination patterns are essentially the same as those with a visual coupling, implying that the neural substrate is not the determining factor for understanding the coordination patterns. Although studying the characteristics of rhythmic social coordination patterns has been very fruitful (see Schmidt & Richardson, 2008, for an overview), many behaviors also have supra-coordinative goals. Studying two participants individually performing reciprocal pointing movements confronted with a complementary collision-avoidance task, Richardson et al. (2015) showed that also in this case a small set of stable coordination patterns can be observed, again emerging from a visual coupling of the two individuals. Whereas in daily life, gaze and verbal communication might be used to support coordination (cf. Clark, 1996; Knoblich, Butterfill, & Sebanz, 2011), these types of communication were not necessary to attain successful coordination in the reciprocal pointing task. In fact, plenty of situations ask for such fast adaptations to changing circumstances for which slower forms of communication such as deliberation or gaze signaling would not be sufficient (see, for instance, Correia et al., 2012; Craig & Watson, 2011, for examples from rugby settings). The present study considered a time-pressured, discrete task in which two participants had the shared goal of intercepting approaching targets under a collision-avoidance constraint.

Benerink, Zaal, Casanova, Bonnardel, & Bootsma (2016) recently introduced the doubles-pong paradigm to study joint decision-making. Their doubles-pong task was inspired by the task of serve reception in (beach) volleyball. Teams of two participants sat in front of a shared screen, on which a ball would move from top to bottom along a rectilinear trajectory. Each participant controlled a paddle that could move laterally along a horizontal interception axis just above the bottom of the screen. Apart from each of the two players being able to see both paddles and the ball moving across the screen, no other form of between-player communication was allowed. The task for the team of players was to intercept as many balls as possible, while avoiding contact between their paddles (as these then immediately disintegrated). In performing the task together, all teams showed a rather systematic division of interception spaces in that the left participant intercepted the majority of balls arriving at the left side of the screen and the right participant intercepted the majority of balls arriving at the right side of the screen. One way of considering the task that each pair of participants was faced with on each trial was that they needed to decide, among the two of them, who would be the one going to intercept the ball. From such a decision-making perspective, one would assume that the future ball-arrival position along the interception axis would determine the choice of the recipient. For instance, the rule could be that the ball would be for the player whose paddle's starting position is closest to the arrival position of the ball (according to the same logic underlying a characterization of spatial interactions by means of a voronoi diagram; see e.g., Fonseca, Milho, Travassos, & Araújo, 2012). For such a strategy to be feasible, players need to be able to predict with reasonable accuracy the ball arrival position from early ball motion. That is to say, players would have to know early during ball motion where the ball will pass the interception axis to be able to use this knowledge to decide among them who will intercept. Although a number of studies have indicated that the control of interception does not seem to be based on early prediction of a future interception location and time (e.g., Bootsma, Ledouit, Casanova, & Zaal, 2016; Fajen & Warren, 2007; Ledouit, Casanova, Zaal, & Bootsma, 2013; Michaels, Jacobs & Bongers, 2006; Peper, Bootsma, Mestre, & Bakker, 1994), for the present purposes we will for now leave aside this discussion and accept that one solution for the task at hand that the team of players might use is to divide up interception space and decide who should perform the interceptive action on the basis of the ball's estimated future arrival position.

An alternative to such an interception space-based division of labor would be emergent coordination. Rather than assuming the existence of a (explicit or implicit) predefined boundary between interception spaces of the two players (implying that the boundary would determine —that is, precedes— the division of space), emergent coordination would give rise to a division of space that, subsequently, happens to be accompanied by an experimentally observable boundary. In other words, the players would not base their decision of who will intercept which ball on a ball's perceived future arrival position with respect to a specific boundary; rather, due to the coordination with each other and the ball, over trials (with varying ball trajectories), interception regions for both players will become visible and, as a consequence, a post-hoc boundary can be experimentally determined. Actually, this alternative of an emergent boundary is what Benerink et al. (2016) suggested to be at play.

They provided several indications of why this was considered most probable. First, although a boundary between interception spaces could indeed be distinguished in the data of each team, this boundary was in fact quite fuzzy. Second, in many cases both players initiated an interception movement, followed by one player continuing on to make the interception and the other player abandoning the interception attempt. Finally, Benerink and colleagues presented a model of continuous interaction that accounted for a very high percentage of the observed phenomena. Their proposal started from the following consideration: if a paddle moves in such a way that angle β —formed by the line connecting the inner paddle edge and the ball, on the one hand, and the interception axis, on the other hand— remains constant during approach of the ball towards the interception axis, this (lawfully) implies that paddle and ball will meet at the interception point (e.g., Chardenon, Montagne, Laurent, & Bootsma, 2004; Fajen & Warren, 2004, 2007; Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999). Now, when at the start of a trial a ball starts to move, approaching a position on the interception axis in between the two (still stationary) paddles, this angle will initially close, giving rise to a negative rate of angular change (i.e., $d\beta/dt < 0$). Suppose that one player starts moving the paddle in such a way that the negative angular rate of change is cancelled (i.e., $d\beta/dt = 0$); this player would thus be on track for a successful interception. This would be the moment that the other player, perhaps also moving his or her paddle, but still with a negative rate of change of angle β, could know that the teammate would be able to make the interception. At this point in time, the latter player may therefore safely abandon his or her interception attempt. Applying this logic to their data, Benerink et al. (2016) showed that an action-based decision model in which the interception is attributed to the first player to reach $d\beta/dt \geq 0$ accounted for the observed distribution of interceptions over the two players to a very high degree.

To summarize, two players in a doubles-pong task (considered as a paradigmatic example for many situations in sports and daily life) appear to divide labor. They might do so based on (explicit or implicit) prior conventions or the division of labor might emerge from their social coordination. In the Benerink et al. (2016) study, participants started with their paddles located at mirror-symmetrical positions (i.e., at equal distances) with respect to the center of the screen. This configuration might have invited the two players to divide up interception spaces using the middle of the screen. In other words, the specific configuration might have tipped the situation towards one in which a tacitly-accepted boundary is used rather than that this boundary emerged from the coordination of the two players. Although the action-based decision model presented by Benerink and colleagues performed very well on their data set, stronger support for the emergence of boundaries between players would come from a study in which using the midline of the screen to separate individual interception spaces would be less obvious. Therefore, in the present study, we had teams of players perform the doubles-pong task with paddle starting positions that were either symmetrical or asymmetrical around the vertical midline of their shared screen. Moreover, while always maintaining the same paddle starting position for the left player, over trials we randomly varied the right player's paddle starting position between a symmetrical and an asymmetrical position. In this design, interception partitioning based on shared understanding of a boundary would lead to some straightforward hypotheses. Given that nothing changes over trials for the left player, one way that the players could deal with the situation is simply use the screen's vertical midline, irrespective of the paddle starting position of the right player. Alternatively, both players might partition their interceptions by (tacitly) acknowledging a boundary located right in the middle between the initial positions of both paddles. In this case, this boundary would be different across trials, varying as a function of the randomly chosen starting position of the right paddle. Finally, a third possibility would be that the boundaries would show up at other positions than at the middle of the screen or in the middle of the starting positions of the two paddles. If this turned out to be the case, applying Benerink et al.'s action-based decision model of continuous interaction to performance in these changing circumstances would allow testing the emergent boundary hypothesis.

3.3 Methods

3.3.1 Participants

A mixed group of 28 right-handed (post)graduates from the University of Aix-Marseille, 17 men and 11 women with an average age of 24.7 ± 2.2 years ($M \pm SD$), took part in the first phase of the experiment. They all provided written consent before participating voluntarily in our study. The study was conducted according to University regulations and the Declaration of Helsinki. During this first phase each participant performed the interception task in an individual session.

For the experimental manipulation described in this contribution, a subset of 16 participants (9 men and 7 women, average age of 24.6 ± 2.8 years) was selected to partake in a second experimental session. In this second session, the participants performed the interception task in pairs, with each pair composed of participants with comparable scores on the individual session. The other subset of 12 participants took part in a separate study.

3.3.2 Experimental set-up

The experimental set-up used was the same as described in Benerink et al. (2016). All experimental sessions took place in the same darkened room that contained a large table with two adjacent seats at one end and a large television screen (Samsung 55" LED ED55C, with a 1920 x 1080 pixels resolution) positioned at 2 m from the seats at the other end. Figure 1 presents the experimental set up for the session in which two participants performed the task together. When seated, participants faced the middle of the screen at eye-height. Half of the participants always performed the task while being seated at the left side of the table. These participants are referred to as Left-side Participants (LP). The other half of the participants always sat on the right side of the table and are referred to as Right-side Participants (RP). To avoid that the participants would see each other’s hand movements during the experiment they were separated by a black curtain, hanging from the ceiling. This way, we effectively prevented participants seeing (any part of) the other (see Fig. 3.1). Participants also wore headphones (3M Peltor Optime2) to avoid communication between them and preventing them to pick up (auditory) information about the other player’s movements.

To intercept the on-screen downward-moving balls, using their right hand participants displaced a handheld knob laterally over an in-house constructed linear positioning device placed on the table in front of them, to control the movement of their on-screen paddle. The knob was firmly attached to a small aluminum cart that could slide along two (75-cm long) parallel iron bars. With a magnet placed under the cart, the cart’s motion could be tracked in a contactless manner using a linear magnetic potentiometer (MP1-L-0750-203-5%-ST, Spectra Symbol, West Valley City, UT, USA). The potentiometer was connected to a computer (HP ZBook 15) that converted the digitally-sampled (100 Hz) electrical output into an on-screen paddle position, using the in-house developed ICE® (ISM, Aix-Marseille Université, France) software. During conversion of the electrical output, the signal was multiplied by a constant gain such that positions at both extremes of the linear positioning device corresponded to virtual screen positions slightly outside the physical screen. This way, participants were able to cover the full (121-cm) range of the interception axis without reaching the extremities of the 75-cm long device. Unless specified otherwise, positions and distances reported from here on correspond to distances on the screen, with the origin corresponding to the horizontal center of the interception axis. The screen thus extended horizontally (X-axis) from -60.5 cm to +60.5 cm and vertically (Y-axis) from -2 cm to +66 cm.

Figure 3.1 | Representation of the experimental setting used in the doubles sessions. Participants were sitting side by side facing a large television screen. They were separated by a black curtain and wore headphones so as to avoid overt communication between them. To intercept the balls moving downward across the screen, both participants could move an onscreen paddle along the (non-visible) interception axis by displacing a handheld knob on a linear positioning device placed on the table in front of them. In the individual sessions, only one of the participants was present, sitting either on the left or right side of the table.

Kinematic data of the participants' paddles and the ball was sampled at a frequency of 100 Hz and stored on an external disk. Before further analysis, the kinematic data was filtered with a low-pass second-order Butterworth filter with a cut-off frequency of 5 Hz run through twice in order to negate the phase shift.

3.3.3 Procedure

3.3.3.1 Individual session

In the first experimental session, participants performed the interception task individually. They had to intercept virtual white balls (2-cm diameter circles) depicted against a black background, moving downward across the screen at various angles and speeds, by making them bounce back upwards after contact with the white (3-cm wide and 0.8-cm high) paddle. Upon entering the experimental room, they were seated on either the right or left side of the table. They received a brief instruction about the task they had to perform: intercept as many balls as possible by moving the on-screen paddle laterally over the invisible horizontal interception axis. For a trial to start, participants had to move their paddle to the designated start position (21 cm to the left for a LP or the right for a RP of the center of the screen in the first session) marked by a 3-cm translucent red rectangle. If the center of the participant's paddle arrived within 0.3 cm of the center of the rectangle, the rectangle turned green indicating that the paddle was located at the right place. After the participant had remained in place for 2 s, the green rectangle disappeared, and after another second the ball appeared. Balls moved downward immediately with vertical speeds of 0.40 or 0.64 m/s, corresponding to movement durations for the ball to arrive at the interception axis of 1.6 and 1.0 seconds, respectively. Successful interception required that the paddle touched the ball when it crossed the interception axis. If so, the paddle turned green and the ball moved back up again. In trials where the participant did not reach the arrival position of the ball in time (i.e. unsuccessful trials), the paddle turned red and the ball continued moving downward. Two seconds after ball arrival at the interception axis (regardless of a successful or unsuccessful interception) the paddle turned to its original white color and the translucent red rectangle would appear again for the participant to start a new trial.

Balls moved downward following differently-oriented rectilinear trajectories. The design included five standard ball departure positions (Y = 64 cm) and five standard arrival positions (Y = 0 cm), both at X = −42, −21, 0, +21 and +42 cm (cf. Benerink et al., 2016). Combining the five departure positions with the five arrival positions gave rise to a total of 25 standard trajectories. On each trial a random distance between −10.5 cm and +10.5 cm was added to both the standard departure and arrival positions of the selected trajectory, shifting the entire trajectory to the left or right. This way, balls could appear and arrive anywhere between X = −52.5 cm and X = +52.5 cm (see Fig. 3.2A) while trajectory angles were kept the same. In a single block, all 25 trajectories appeared with two different vertical ball velocities for a total of 50 fully randomized trials per block.

The experimental session started off with ten practice trials. Participants were asked, besides intercepting a number of balls, to purposely miss one as well so as to experience all action possibilities, constraints and their outcomes. To motivate the participants the experiment was organized as a competition where all participants competed anonymously. All participants performed five blocks of trials, adding up to a total of 250 trials per participant in a first one-hour session.

3.3.3.2 Doubles session

For the doubles session, pairs were formed by combining a LP and a RP that had performed similarly in their individual sessions[3]. The eight pairs were randomly assigned to one of the two experimental groups. In both groups the initial position of the LP's paddle was fixed, at an eccentricity of either 30 cm (LP30 group) or 20 cm (LP20 group) to the left of the center of screen (see Fig. 3.2B and 3.2C, respectively). For both groups, the initial position of the RP's paddle varied randomly between an eccentricity of 30 cm or 20 cm to the right of the center of the interception axis.

In the doubles session, ball trajectories and instructions were similar to those of the individual session except that the participants' on-screen paddles were not allowed to touch one another, as doing so would lead both paddles to immediately disintegrate, thereby rendering interception impossible.

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[3] The score S used to match participants for the second session was calculated for each individual participant as S = (B3+B4+B5+Max)/4 where B3, B4, and B5 correspond to the percentage balls intercepted in blocks 3, 4, and 5 of the 5-block session and Max correspond to the largest percentage balls intercepted in any of the 5 blocks.

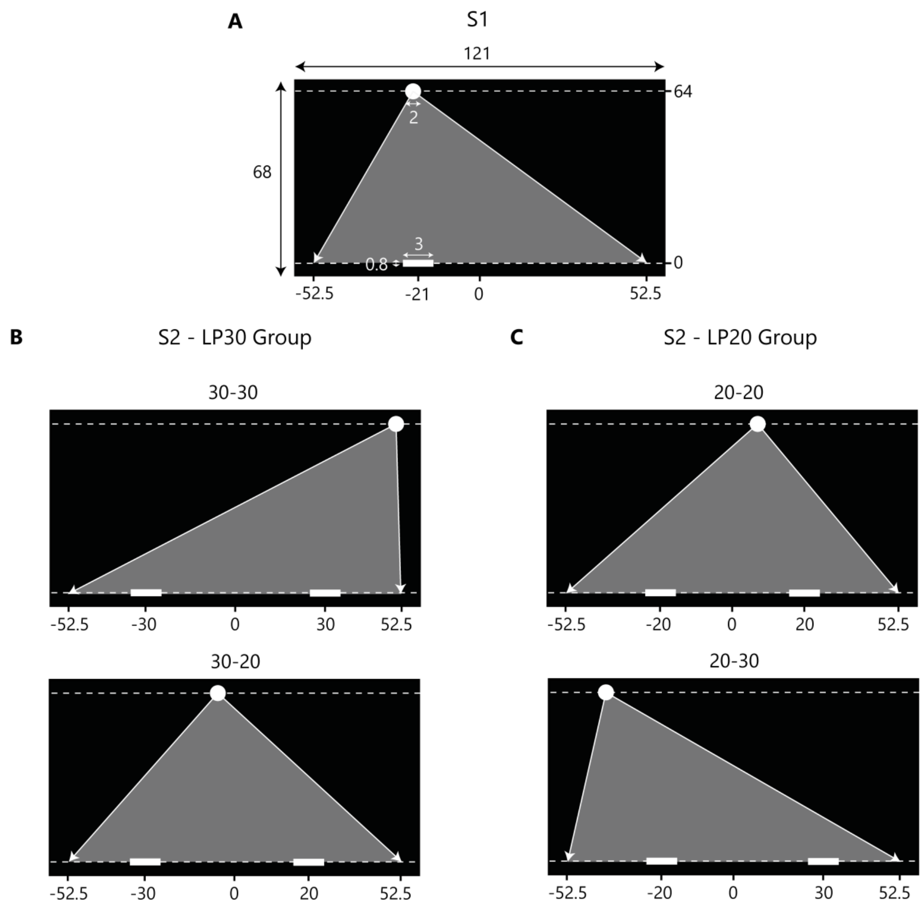

Figure 3.2 | Schematic overview of the set-up of the two consecutive experimental sessions for both the experimental conditions. Screen dimensions and other metrics are in cm. Note that the figures are not scaled to actual size. Balls appeared at the top of the screen (Y = 64) and moved downward towards the interceptions axis (Y = 0) at one of two constant vertical velocities. Grey triangles indicate the range of potential ball arrival positions for exemplary ball departure positions. (A) During the first session (S1) participants intercepted balls individually. The situation depicted here represents the initial conditions for a LP. (B) Schematic overview of the second session (S2) of the LP30 group, in which participants intercepted balls in dyads. Whereas LP was positioned at a fixed distance of 30 cm to the left of the center of the interception axis, the position of RP randomly varied between distances at an eccentricity of 30 cm (30-30 condition) or 20 cm (30-20 condition) to the right of the center of the interception axis. (C) Schematic overview of S2 of the LP20 group. LP was always positioned at a fixed distance of 20 cm to the left of the center of the interception axis. The position of RP randomly varied between distances at an eccentricity of 20 cm (20- 20 condition) or 30 cm (20-30 condition) to the right of the center of the interception axis.

As in the individual session, the doubles session started off with ten practice trials. Besides experiencing a few interceptions and at least one missed ball, participants were also asked to make contact with the other participant's paddle so as to see what would happen if they collided during a trial. Participants were explicitly instructed that the number of individual interceptions did not matter and that the team performance was the only thing that counted. All teams completed four blocks consisting of 50 symmetric and 50 a-symmetric trials that were presented in random order. This resulted in a total of 400 trials for each team in the doubles session with conditions 30-30 and 30-20 for the LP30 group and conditions 20-20 and 20-30 for the LP20 group. It took the teams about one-and-a-half hour to complete the doubles session.

3.3.4 Dependent measures

Along with the kinematic data, we registered trial characteristics like whether an individual intercepted the ball or not and, for the doubles session, the time and place of a collision, if any. With these characteristics, interception performance was calculated per block as the percentage of balls intercepted from the total number of balls presented in a block.

In order to quantify the division of interception domains, we computed logistic regression equations, with the ball's arrival position as predictor for who intercepted the ball, for each team in both conditions (cf. Benerink et al., 2016). Using a logit link function (Nelder & Wedderburn, 1972), logistic probability curves were derived for the balls intercepted by the LP and the RP for all teams in both conditions independently. From these logistic curves, we calculated the location of the boundary between interception domains and the magnitude of the associated overlap. The boundary location was defined as the point on the interception axis corresponding to the 50% point of the logistic curve, and the amount of overlap was defined as the distance along the interception axis between the 5% and 95% points of the curve (see Cox & Snell, 1989).

Movement initiation time was defined as the first moment a participant's paddle crossed a velocity threshold of 3.0 cm/s provided that the participant's movement amplitude reached at least 1 cm. Based on this criterion, we determined for every trial if LP and/or RP showed a movement initiation or not, and, if so, at what time.

Finally, from the ball and paddle positions we derived the time series of the angles β_{LP} and β_{RP}, each defined as the angle between the line connecting the ball center and the closest edge of the paddle and the interception axis (see Fig. 3.3). If present, zero crossings in the time series of the rate of change of both these angles were detected.

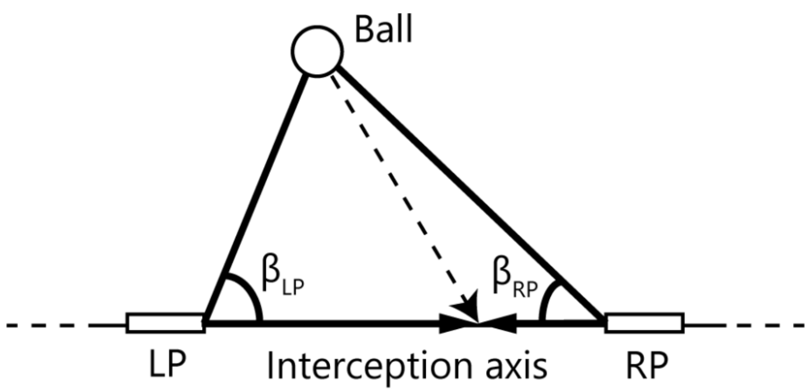

Figure 3.3 | Definition of the angles used to capture the relations between the paddles and the ball. LP and RP represent the paddles of the left and right participant, respectively. The paddles could move freely along the interception axis. βLP and βRP are the angles formed by the line connecting both paddles and the lines connecting each paddle with the ball. These angles change as a function of a) the displacement of the downward moving ball and b) displacements of the participants' paddles.

3.4 Results

3.4.1 Interception performance

As can be seen in Table 3.1, in the individual session (Session 1) participants attained interception performances between 75 and 91%, with an overall mean of 83.6 ± 4.6%. In the doubles session (Session 2) all teams performed quite well, almost always outperforming their individual session performances, in both the symmetrical (87.4 ± 6.3%) and asymmetrical (87.9 ± 4.3%) conditions.

Table 3.1 | Interception performance for the individual participants in Session 1 and for the teams in the different conditions of Session 2, for the LP30 and LP20 groups separately. Session 1 is the individual session. Session 2 is the doubles session. Reported performance (Perf.) is the percentage balls intercepted in each condition over all trials. The number of collisions (Coll.) is also reported for each team in the doubles session.

				Session 1	Session 2			
Group	Team	Side	Gender	Perf. (%)	Perf. (%)	Coll. (nb)	Perf. (%)	Coll. (nb)
					20-20		20-30	
LP30	1	LP	F	76,4	80,5	2	81	4
		RP	F	75,6				
	3	LP	M	84,4	95	0	91,5	2
		RP	M	88				
	5	LP	F	83,2	85,5	1	82	0
		RP	M	82,4				
	7	LP	M	83,6	91	1	92	2
		RP	F	85,2				
	Mean			*82,4*	*88*	*1*	*86,6*	*2*
					20-20		20-30	
LP20	2	LP	M	80,4	83	2	87	0
		RP	F	75,6				
	4	LP	M	88,8	91,5	3	92	0
		RP	M	91,2				
	6	LP	M	87,2	94	1	89,5	5
		RP	M	86,8				
	8	LP	F	84	78	0	88	6
		RP	F	84,4				
	Mean			*84,8*	*86,6*	*1,5*	*89,1*	*2,8*

Figures 3.4 and 3.5 provide graphical summaries, for the LP30 and LP20 groups separately, of the interception results in terms of which player intercepted which balls, thereby allowing inspection of the division of interception space by the two players of each team. The left panels summarize the results of the symmetrical conditions (Fig. 3.4A: 30-30 and Fig. 3.5A: 20-20) and the right panels the results of the asymmetrical conditions (Fig. 3.4B; 30-20 and

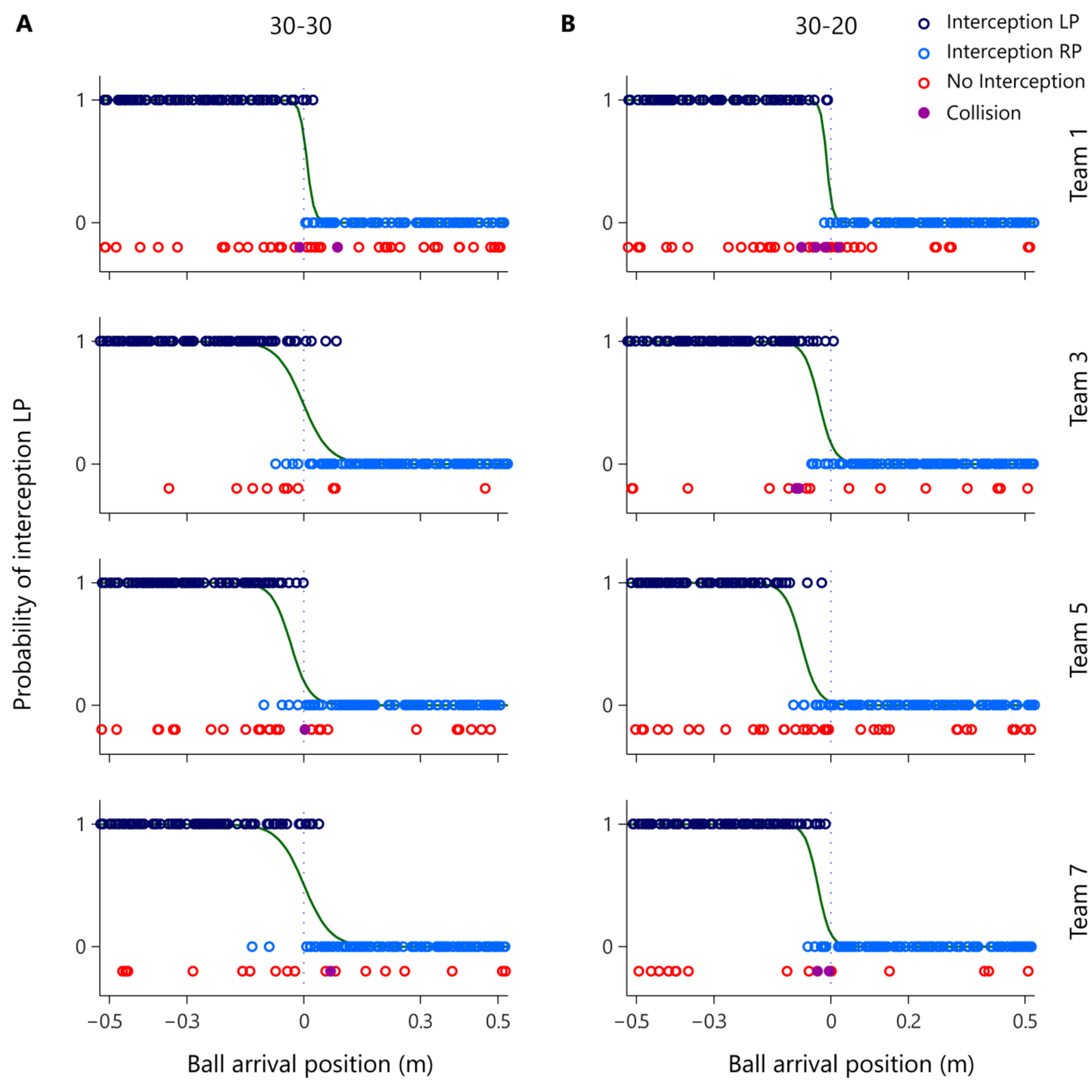

Figure 3.4 | Graphical summary of interception performance of the LP30 group as a function of ball arrival position for all four teams in both conditions (30-30 and 30-20) separately. Ball arrival positions for each successful trial are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of unsuccessful trials are indicated by red circles (misses) and purple dots (collisions). The green curves depict the logistic curves representing the probability that LP (P = 1) or RP (P = 0) will intercept the ball as a function of ball arrival position. The vertical dashed gray lines at ball arrival position 0 cm indicate the center of the interception axis. Initial positions of the participants are marked by a small tick at the abscissa in each subplot.

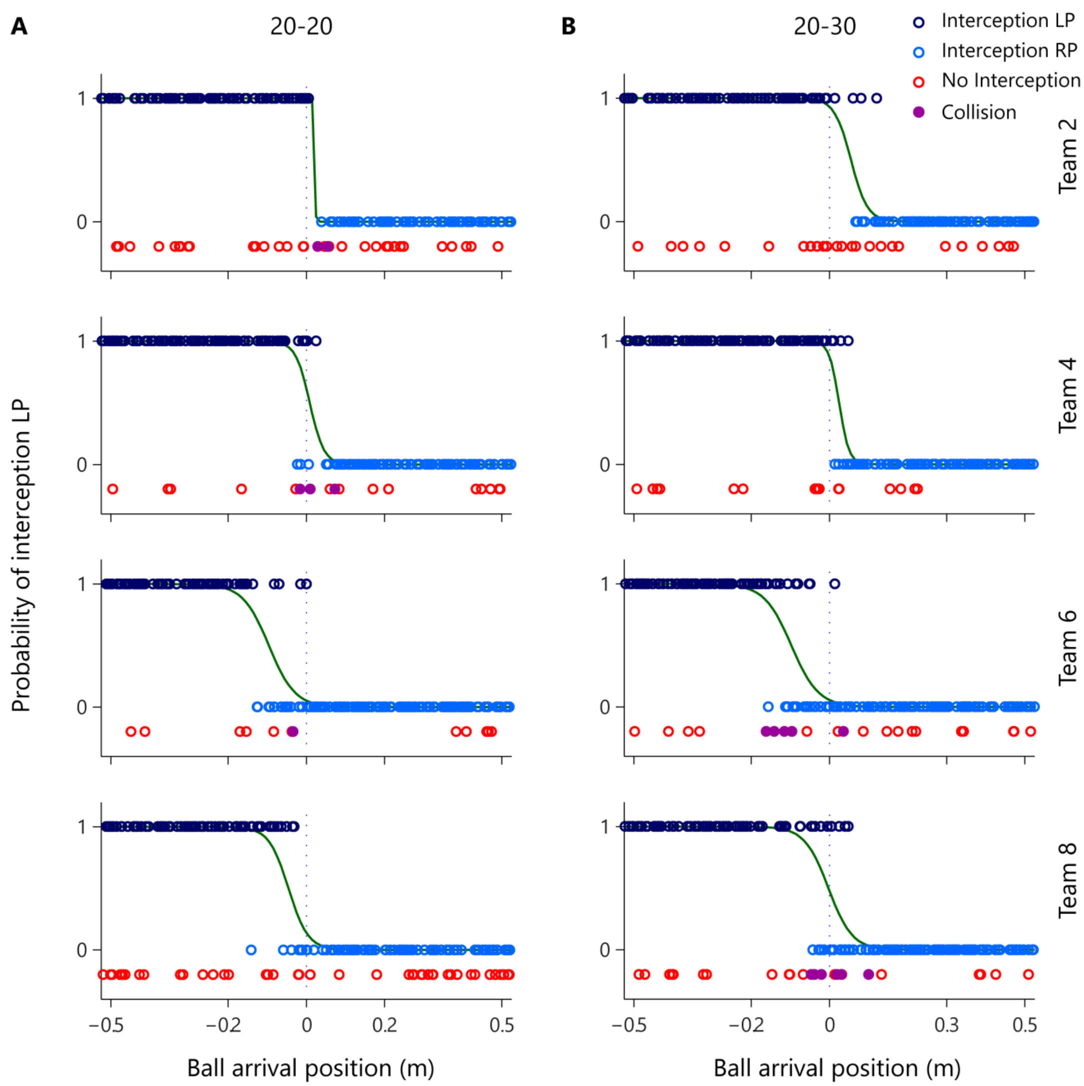

Figure 3.5 | Graphical summary of interception performance of the LP20 group as a function of ball arrival position for all four teams in both conditions (20-20 and 20-30) separately. Ball arrival positions for each successful trial are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of unsuccessful trials are indicated by red circles (misses) and purple dots (collisions). The green curves depict the logistic curves representing the probability that LP (P = 1) or RP (P = 0) will intercept the ball as a function of ball arrival position. The vertical dashed gray lines at ball arrival position 0 cm indicate the center of the interception axis. Initial positions of the participants are marked by a small tick at the abscissa in each subplot.

Fig. 3.5B: 20-30). In these figures, trial outcome is presented as a function of the ball's arrival position at the interception axis. Interceptions accomplished by the LP (dark blue circles) and by the RP (light blue circles) are presented on two different axes so as to allow visual discrimination of who intercepted balls where. Each panel also identifies the trials in which both participants failed to intercept the balls (red circles, referred to as misses) and the trials where the paddles of the participants collided (purple dots, referred to as collisions). Whereas the (rare) collisions mainly occurred around the center of the interception axis, misses were widely distributed along the interception axis (see red circles in Figs. 3.4 and 3.5). Overall, teams showed rather well-defined interception domains for both groups in both conditions, as well as non-negligible amounts of overlap between interception domains, defining regions where both participants intercepted some balls (cf. Benerink et al., 2016).

The left side of Table 3.2 presents the observed locations of boundaries and the amounts of overlap, as determined from the logistic functions fitted through the data of the successfully intercepted trials of each team in each condition (green curves in Figs. 3.4 and 3.5). Inspection of the mean locations of the boundaries revealed that, for the LP30 group, they were on average located 3.1 cm more to the left in the (asymmetrical) 30-20 condition than in the (symmetrical) 30-30 condition. For the LP20 group, the boundaries in the (asymmetrical) 20-30 condition were on average located 2.3 cm more to the right than in the (symmetrical) 20-20 condition. Taken together, these results indicated that in each group the boundary shifted in the direction of the middle between the two initial paddle position, with for the eight teams $Z = 2.38$, $p < 0.05$, providing evidence against the hypothesis of reliance on a boundary fixed at the center of the screen under all conditions. At the same time, the observed average shift of 2.7 cm was but around half the 5-cm shift expected if participants relied on a boundary in the middle between the initial paddle positions, thereby speaking against the latter hypothesis as well. Moreover, inspection of Table 3.2 (also see Fig. 3.9) revealed substantial variability in the location of the boundary across teams. Overall, it thus seems fair to conclude that both the hypothesis that teams relied on a boundary located at the midline of the screen or on a boundary positioned right in middle between the two paddles did not seem to hold in the present experiment.

Table 3.2 also revealed the variability in the amount of overlap of space covered by both players across all teams and conditions (also see Figs. 3.4 and 3.5). Whereas in the symmetrical 20-20 condition team 2 showed a very sharp boundary, with an overlap of only 0.6 cm, fuzzy boundaries with an overlap of more than 20 cm were seen in other teams and other conditions. Although the condition averages suggest that in both groups of participants (30-30/30-20 vs. 20-20/20-30) a larger interval between the initial paddle positions was accompanied by a larger overlap, the potential presence of such an effect in the present data was not sufficiently substantiated by a Wilcoxon signed rank test, Z = 1.82, $p = 0.069$.

Table 3.2 | Boundary locations and amounts of overlap for observed and simulated interception performance in the symmetrical (LP30: 30-30 and LP20: 20-20) and asymmetrical (LP30: 30-20 and LP20: 20-30) conditions for both experimental groups.

Group	Team	Observed				Simulated			
		Boundary (cm)		Overlap (cm)		Boundary (cm)		Overlap (cm)	
		30-30	*30-20*	*30-30*	*30-20*	*30-30*	*30-20*	*30-30*	*30-20*
LP30	1	0,8	-1,0	5,5	4,5	0,4	-1,8	9,9	19,7
	3	-0,2	-3,0	20,3	11,4	-0,8	-1,8	27,7	16,9
	5	-3,3	-7,5	14,4	12,7	-4,2	-9,4	24,7	22,2
	7	0,1	-3,3	20,2	9,4	-0,7	-2,7	27,6	10,7
	Mean	*-0,7*	*-3,7*	*15,1*	*9,5*	*-1,3*	*-4,0*	*22,5*	*17,4*
		Boundary (cm)		Overlap (cm)		Boundary (cm)		Overlap (cm)	
		20-20	*20-30*	*20-20*	*20-30*	*20-20*	*20-30*	*20-20*	*20-30*
LP20	2	2,2	5,5	0,6	12,7	4,7	5,5	7,8	12,7
	4	0,9	2,5	10,9	7,5	0,9	3,2	10,9	6,8
	6	-9,6	-9,7	20,0	20,8	-11,8	-10,3	20,0	24,9
	8	-4,6	-0,2	15,0	18,2	-5,3	-1,4	18,5	16,5
	Mean	*-2,8*	*-0,5*	*11,6*	*14,8*	*-2,9*	*-0,8*	*14,3*	*15,2*

Just as was the case in Benerink et al.'s (2016) study, in which teams were tested with the initial paddle positions of the present 30-30 condition, in a large proportion of the trials in which the ball would pass the interception axis at a position between the initial positions of both paddles, both players started to move. Figure 3.6 presents the distributions of observed movement initiations as a function of ball arrival position for each of the four conditions separately. In determining these distributions, all trials were assigned to one of the four

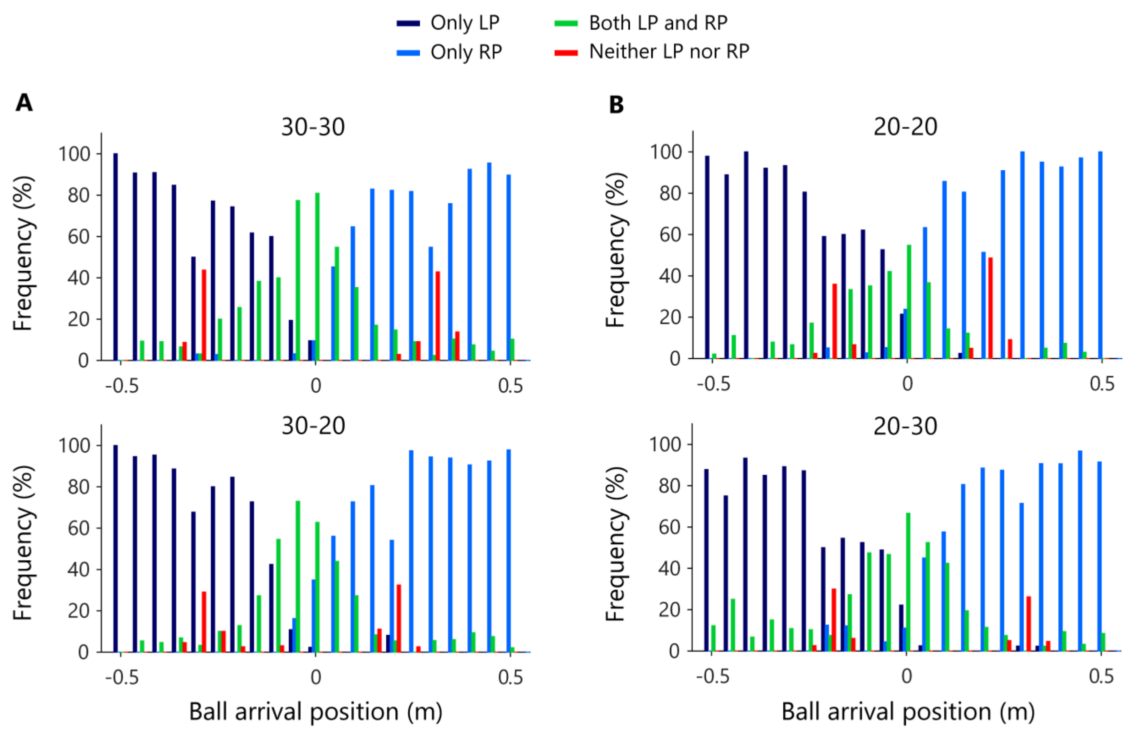

Figure 3.6 | Frequency distribution of the observed movement initiations of the LP and RP as a function of ball arrival position for the LP30 group (A) and the LP20 group (B). Each trial arriving in one of 21 (5-cm wide) bins was classified as showing initiation of only LP (dark blue), only RP (light blue), both LP and RP (green) or neither LP nor RP (red).

possible categories; an initiation of only RP (dark blue), an initiation of only LP (light blue), an initiation of both LP and RP (green) or no initiation (i.e. neither LP nor RP initiated any movement; red). Inspection of Figure 3.6 indicated rather comparable distributions for all four conditions[4]. The majority of initiations of only LP were associated with balls arriving on the left side of the interception axis whereas the majority of initiations of only RP were associated with balls arriving on the right side of the interception axis. Furthermore, the

[4] We note that, for each condition, the distribution included the 200 trials from all four teams concerned. The 5-cm spatial resolution used does not allow bringing out potential effects associated with the (on average subtle) boundary location shifts discussed above.

grand majority of trials without movement initiations corresponded to ball arrival positions near the initial positions of the participants' paddles. Finally, all teams demonstrated a considerable amount of trials with initiations of both participants (see Fig. 3.6). The distributions of these trials in which both players began to move their paddle (while only one of them intercepted the ball in the end) resembled Gaussian distributions with a peak around the center of the interception axis.

3.4.2 Applying the action-based decision model of Benerink et al. (2016)

Figures 3.7 (LP30 group) and 3.8 (LP20 group) present the results of a simulation deciding who will intercept the ball by attributing the interception to the first player to attain $d\beta/dt \geq 0$, as suggested by Benerink et al. (2016). The dark blue circles indicate the trials for which the LP both actually made the interception and was indeed the first to reach this criterion during the unfolding of the trial. Similarly, the light blue circles indicate the trials for which this was true for the RP. In addition to these correct final-recipient predictions, the pink circles denote the trials in which the participant who intercepted the ball was not the one who first reached $d\beta/dt \geq 0$, thereby identifying the trials with an incorrectly predicted outcome. As may be appreciated from Figures 3.7 and 3.8, the simple attribution of the interception to the player who first reached $d\beta/dt \geq 0$ almost perfectly captured the division of labor between the two players. Overall, 98.8 % of the intercepted trials were correctly attributed. Given this very high percentage of correct model predictions, it may come as no surprise that the locations of the boundaries and the amounts of overlap as computed from the simulation results mirrored those determined from the observed interceptions (Table 3.2, right side).

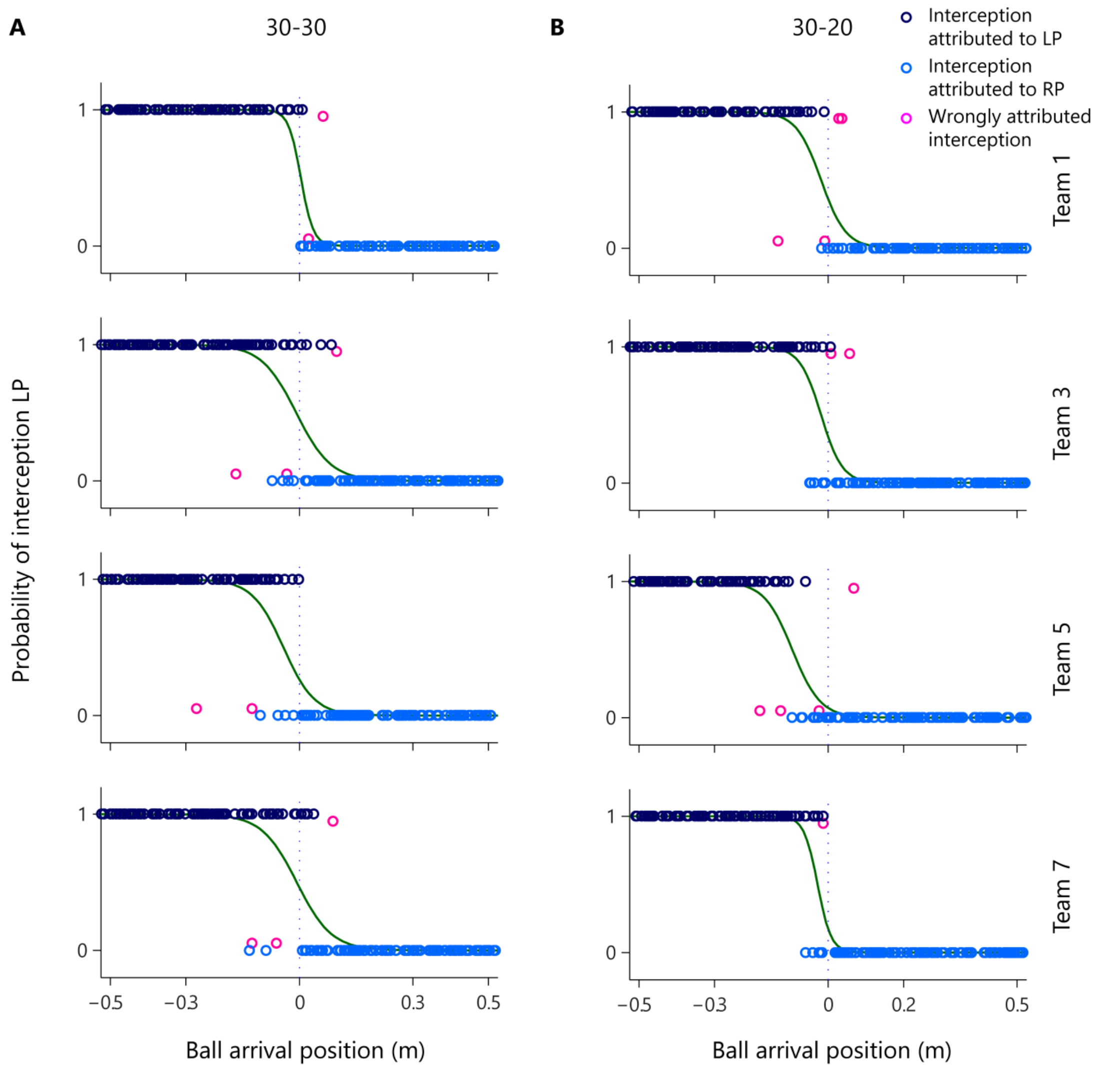

Figure 3.7 | Graphical summary of predicted interception performance of the LP30 group as a function of ball arrival position for all four teams in both conditions (30-30 and 30- 20) separately. The prediction of the participant to intercept the ball was based on first reaching $d\beta/dt \geq 0$. Ball arrival positions for correctly attributed interceptions are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of incorrectly attributed interceptions are indicated by pink circles, with a slight vertical offset. The green curves depict the logistic curves representing the probability that LP (P = 1) or RP (P = 0) were predicted to intercept the ball, as a function of ball arrival position. The vertical dashed gray lines at ball arrival position 0 cm indicate the center of the interception axis. Start positions of the participants are marked by a small tick at the abscissa in each subplot.

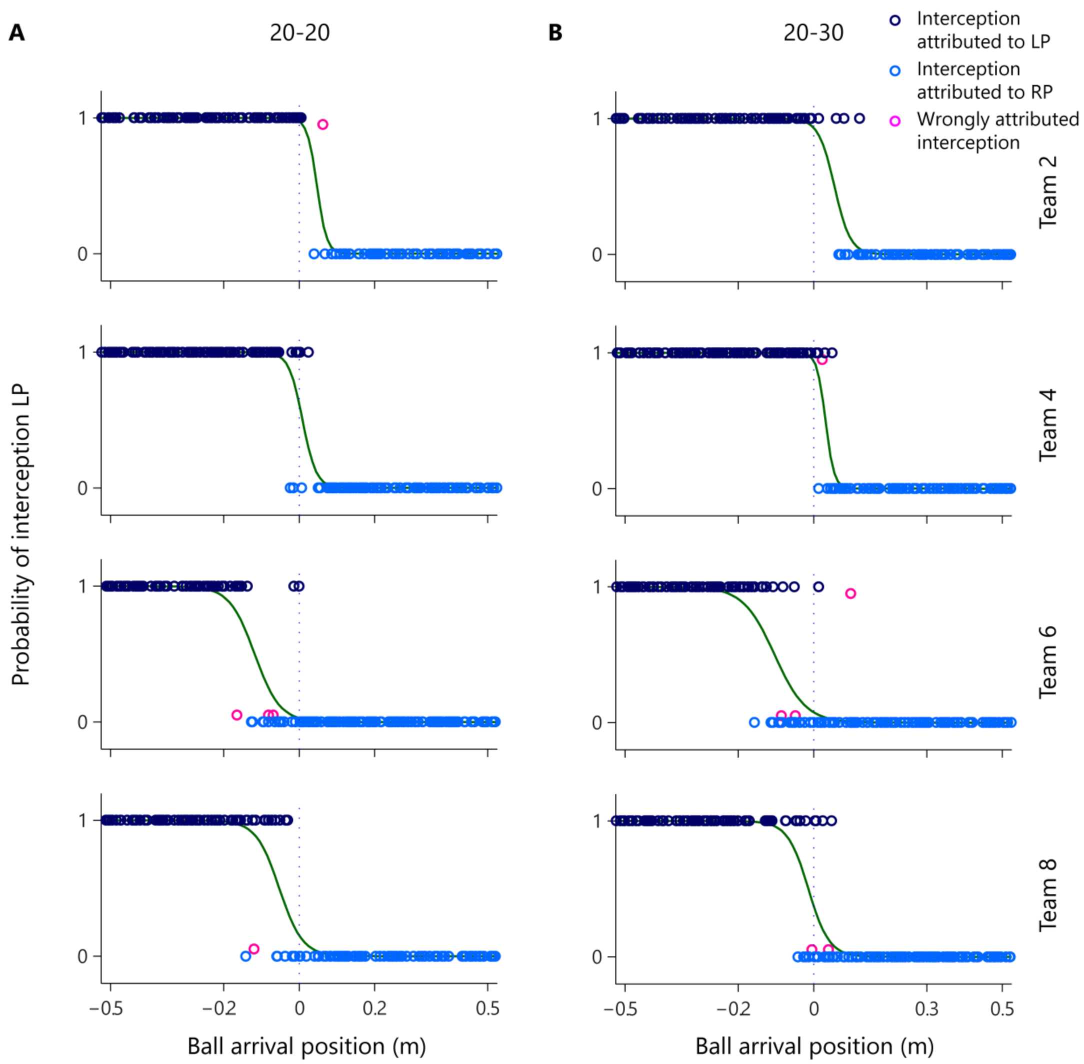

Figure 3.8 | Graphical summary of predicted interception performance of the LP20 group as a function of ball arrival position for all four teams in both conditions (20-20 and 20-30) separately. The prediction of the participant to intercept the ball was based on first reaching $d\beta/dt \geq 0$. Ball arrival positions for correctly attributed interceptions are indicated by dark blue (LP interception) and light blue (RP interception) circles. Ball arrival positions of incorrectly attributed interceptions are indicated by pink circles with a slight vertical offset. The green curves depict the logistic curves representing the probability that LP (P = 1) or RP (P = 0) will intercept the ball as a function of ball arrival position. The vertical dashed gray lines at ball arrival position 0 cm indicate the center of the interception axis. Start positions of the participants are marked by a small tick at the abscissa in each subplot.

Reinforcing this conclusion, Figure 3.9 illustrates the correspondence of the patterns as determined from observations and simulation. Particularly noteworthy in this figure is not only the variability over different teams in both the location of the boundary and the amount of overlap, but also how well the model captures all this variability. Strong correlations were indeed found between observed and simulated boundary locations (r = 0.98, $t(14)$ = 18.92, p < 0.001) and overlap magnitudes (r = 0.75, $t(14)$ = 4.22, p < 0.001).

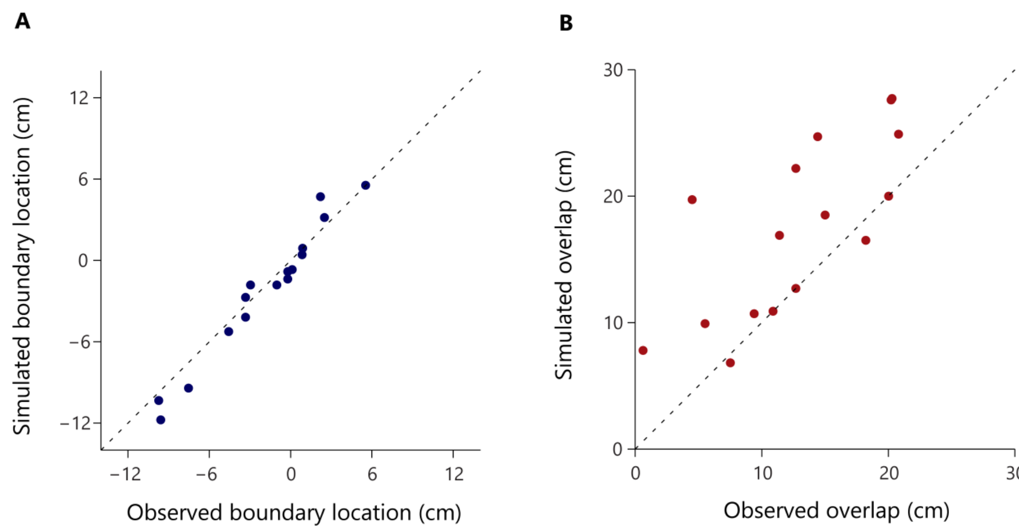

Figure 3.9 | Graphical representation of the relation between predicated and observed boundary locations (A) and amounts of overlap (B) for each team in each condition.

3.5 Discussion

In the present contribution, we studied the way division of interception space comes about from the contributions of two individuals cooperating on a doubles interception task. Following up on Benerink et al.'s, (2016) doubles-pong study, in which the initial positions of both paddles were systematically both located at the same distance from the vertical midline of the shared screen, we now varied these initial positions. One group of participants performed the task in the same configuration as used by Benerink et al. (the 30-30 condition), but also in a 30-20 condition, in which the right participant's initial paddle position was 10 cm closer to the horizontal screen center. Analogously, another group of participants were tested in a symmetrical 20-20 condition and an asymmetrical 20-30 condition. Importantly, for both groups, trials from asymmetrical conditions were randomly interleaved with trials from symmetrical conditions. Because no communication between the players was allowed, the joint interception task boiled down to one that required the two participants, on every trial, to decide among them who would perform the actual interception action and who would not, based only on information available from the movements of both paddles and the ball on their shared screen.

When considering the situation that the two players were facing, having to coordinate their movements in such a way that one of them intercepted the target while avoiding collisions between their paddles, one type of solution that they might have chosen would be to use an (tacitly agreed upon) boundary of the interception domains. The space to the left of this boundary would be for the left player to be covered, and the space to the right of this boundary would be for the right player. We considered two rules for the positioning of such a space-dividing boundary. In the first hypothesis, the boundary would coincide with the vertical midline of the screen. This seemed to be the boundary location experimentally observed for most teams in Benerink et al.'s (2016) study, in which the initial paddle positions were arranged symmetrically around the screen's vertical midline. Because, in the present study, the initial position of the left player remained the same during the entire experiment, settling on the vertical midline as a fixed boundary demarcating interception spaces for both players appeared to be a feasible option. However, it turned out that manipulating the initial position of the right players' paddles had a significant effect on the boundary location. That is to say, although the initial position of the right paddle changed randomly across trials, when comparing the symmetrical and asymmetrical configurations, the average location of the boundary differed a few centimeters.

A second hypothesis for the location of an implicit boundary that the players might use to partition interception space was to work with a boundary halfway the initial positions of both paddles. Given that the initial position of the right players' paddles could be different on every trial, this hypothesis implied that the boundary's location would also differ across trials. However, when we considered the boundaries determined from the empirical data, the pattern of results did not seem to fit this second hypothesis either. Although the boundary was, on average, close to the middle between the paddles in the 30-30 condition, this was not the case in the 20-20 condition. In addition, while the boundary was shifted in the expected direction when comparing the asymmetrical with the symmetrical conditions, the observed shift in boundary location was clearly less than expected. Furthermore, a closer inspection of the locations of the boundaries for the individual teams (see Figs. 3.4 and 3.5 and Table 3.2) revealed considerable variability across teams, making the interpretation of averages somewhat hazardous. All in all, it seems that the two hypotheses of mutually-shared rule-based boundaries that would determine the division of interception space did not seem to hold.

At a more general level, the idea that a player would decide that a particular ball is for him/her to intercept because it would arrive in his/her dedicated interception space has a number of consequences. First, as already pointed out, it requires that each player can perceive the ball's future arrival position at the interception axis with reasonable accuracy at an early stage of ball motion. Although this might be the case, control of interceptive actions does not seem to be based on early estimates of when the ball will be where (e.g., Bootsma et al., 2016; Fajen & Warren, 2007; Ledouit et al., 2013; Michaels, Jacobs, & Bongers, 2006; Peper et al., 1994). Second, it implies that overlap between interception domains should be considered as resulting from errors. Indeed, when a player moves into the partner's domain to intercept a ball, according to a shared-boundary hypothesis this player's assessment of the future ball arrival position must have been erroneous. Observing large overlap between interception domains would then be considered as a signature of poor team coordination. Yet, as in Benerink et al.'s earlier study, larger overlaps were not associated with lower performance; indeed, although not significant, Pearson correlations between amount of overlap and performance were positive rather than negative, with r = +0.68 for the LP30 group and r = +0.27 for the LP20 group. Moreover, as larger overlaps were not associated with more collisions either (see Figs. 3.4 and 3.5) the overall pattern of results observed (including team performances, locations of boundaries and amounts of overlap) did not fit with the logic behind the hypothesis of a boundary-based division of space.

An alternative to the prediction-based mode of coordination discussed above would be the use of prospective information enabling successful coordination. From the latter perspective, the coordination emerges from informational coupling based in the triangular relations between the movements of the players' paddles and the ball, as captured for the present purposes by the rates of change of the angles β_{LP} and β_{RP} (see Fig. 3.3). An account of the coordination patterns observed in the present joint interception task based on these angles turned out to be highly successful. Our action-based model of continuous interaction — expressing itself on each individual trial in the temporal co-evolution of the angles β_{LP} and β_{RP}, and attributing the interception to the player that first reached $d\beta/dt \geq 0$— was correct in an impressive majority (i.e., 98.8%) of all trials. Importantly, in doing so, this account recreated essentially all of the variability in the coordination patterns that we observed (see Table 3.2 and Figs. 3.4 and 3.5). Both the variability in the location of the boundary and in the amount of overlap across teams and conditions were captured by the model to a very high degree. The model even reproduced the idiosyncrasies of some teams' solutions for successful joint interception. Let us, for instance, consider team 6, a LP20 team that revealed a boundary location almost 10 cm to the left of the screen center in both the 20-20 and 20-30 conditions. As becomes clear from inspection of Figure 6, in this team the RP tended to intercept balls arriving quite close to the LP's initial paddle position, without such behavior negatively affecting team performance. Still, even for this non-typical team the model performed well, implying that the RP tended to produce expedient interception movements, that is, movements that rapidly lead to reaching $d\beta/dt \geq 0$.

Thus, an account in which both players start moving[5] when both $d\beta_{LP}/dt$ and $d\beta_{RP}/dt$ are negative, after which the player with the less expedient movement (i.e., still negative $d\beta/dt$) abandons the interception attempt when the player with the more expedient movement reaches $d\beta/dt \geq 0$ and continues the interceptive action, proved to be able to successfully characterize the observed joint-interception patterns, as they emerged for the different teams.

Paradoxically, in the light of the suggestions of the present study, we might ask ourselves the question to what extent the division of interception domains emerges from *joint* decision-making. Indeed, as our study shows that the decision to initiate or to abandon an interception attempt or not seems to be made at the level of the individual, based on the (spatiotemporal) characteristics of a team member's engagement with respect to the ball, the flexible division of interception domains appears to result from the coordination of decisions and actions made at the individual level rather than being the result of a mutually attended decision process. The coordinated pattern of behavior, that is, the 'joint' decision of 'who intercepts which ball', thus, emerges from the interactions between both team members, that are bound by constantly changing situational constraints (see also Araújo et al., 2006; Davids & Araújo, 2010; Fajen, Riley, & Turvey, 2009). From this perspective, a system of two individuals intercepting balls together might be perceived of as a self-organized collective with behaviors evolving over time with little direct external influence and sustained by information created by the interactions between the participants themselves (Marsh et al., 2006; Passos et al., 2009; Richardson, Marsh, Isenhower, et al., 2007).

[5] Note that for balls arriving at or beyond a partner's initial paddle position, the partner's $d\beta/dt$ is ≥ 0 from the beginning of the trial, indicating that no movement is required from the other player.

3.6 Conclusion

To conclude, this study shows that in a doubles interception task the division of interception space (i.e. who intercepts which balls where) is affected by the initial positions of both team members' paddles. Moreover, the decision to initiate or abandon an interception attempt seems to depend on (information about) the functionality of the team member's interceptive actions in relation to the ball. The results of our study support the view that (social) behavior is not stereotyped or rigid but rather flexible and emerging from local interactions between agents and between the agents and the environment (see e.g., Correia et al., 2012; Travassos et al., 2012; Warren, 2006). Although our study concerns a video-game-like task, we suggest that the experimental doubles-pong set-up, introduced by Benerink et al. (2016) and further explored here, does provide us with the opportunity to reveal some of the basic dynamics underlying real-life team behaviors, highlighting the spatio-temporal capacity of performers in such a complex joint activity (e.g., Davids, Renshaw, & Glazier, 2005).

4

ON THE EFFECT OF TEAM MEMBERS' SKILL DIFFERENCES ON THE DIVISION OF LABOR

Present chapter concerns a manipulation of the skill differences between members of a team. Results of previous chapters suggest that skill level and, particularly, differences between skill levels of members of a team are related to the way labor in a team is divided. This chapter will present the results of an experiment in which the interception task was performed by teams which were composed of participants with varying levels of skill.

Manuscript in preparation

4.1 Introduction

In many social interactions, each individual brings in a unique set of action capabilities to be used for successful or effective coordination. When unloading a dishwasher together, the taller person will likely be the one to take on the dishes that need to be placed on the upper shelf whereas the smaller individual will take on the dishes that have to be ranged at places within his or her reach (i.e., at lower heights). Similarly, a young adult probably carries most of the groceries when shopping with her grandmother. The differences in bodily dimensions and action capabilities, here, define how labor between both individuals is best divided. In sports collectives, such differences in capabilities often lead to the assignment of different roles to the different members of a collective. For instance, in rugby, the fastest and most agile players will be assigned a position in the back, as they are able to sweep the ball from one side of the field to the other while running at high speed, whereas the bigger, stronger and heavier players will be placed in the scrum (i.e., the forwards; e.g., see Meir, Newton, Curtis, Fardell, & Butler, 2001). This way, tasks are divided according to players' capacities and bodily dimensions. Another pertinent example of a division of labor is found in service reception in volleyball. In (sub)elite volleyball teams, typically, one of the players will only perform defensive actions in the back of the field. This so-called libero is used as a substitute for any back-row player having problems with reception of the serve. With the libero being specialized in serve reception and defensive skills, he or she typically takes on a large part of serve receptions compared to other players in the defense line. Division of labor (i.e., number of interceptions), hence, follows from a difference in skill level. Whereas the libero in volleyball has been assigned to intercept most of the serves, in many social situations division of labor does not follow from predefined roles. Instead, social behavior is the emergent result of labor of the individuals in interaction (cf. Benerink, Zaal, Casanova, Bonnardel, & Bootsma, 2016; Duarte et al., 2012; Richardson et al., 2015). Interesting then is if differences in action capabilities between individuals have a similar impact on division of labor when roles are not predefined. The present study investigates the effect of such skill differences on the division of labor in a cooperative joint-action task.

Important for successful cooperation in joint-action is information on what actions a co-actor can or cannot perform. Given that dyads were very successful in the doubles-pong task adopted in this study (and in this thesis), both individuals must have been able to perceive the possibilities for action, or affordances (Gibson, 1979), for themselves but also for their teammates (e.g., Davis, Riley, Shockley, & Cummins-Sebree, 2010; Fajen, Riley, & Turvey, 2009). Previous research has shown that individuals are able to perceive affordances for others. That is to say, they are able to perceive what action can be performed by another individual under a given set of environmental conditions (Fajen et al., 2009; Mark, 2007; Marsh & Meagher, 2016; Stoffregen, Gorday, Sheng, & Flynn, 1999). For instance, Richardson, Marsh, & Baron (2007) and Isenhower, Richardson, Carello, Baron, & Marsh (2010) showed that individuals are able to correctly perceive if an actor requires assistance when moving a (long) wooden plank or that the plank can be transported individually (either with one or two hands). The transition points from the need to use two hands rather than one, and from two persons rather than one, were similarly body-scaled (i.e., as a ratio of plank length and hand span or arm span, respectively). Not only can affordances be coined in body-scaled terms (e.g., Mark, 2007; Stoffregen et al., 1999; Warren, 1984), but possibilities for action can also be constrained by someone's action capabilities (Fajen et al., 2009). In baseball, for example, a ball is catchable provided that an outfielder can run fast enough. Successful cooperation between individuals in a team (for instance, between outfielders in baseball, or between the two individuals in the doubles-pong task) and thus an effective division of labor in any joint activity might depend on the perception of such action possibilities for the other, and perhaps for the team in general. Members of a team, hence, might adapt their actions to the perceived action capabilities for the other.

Recently, Benerink, Zaal, Casanova, Bonnardel and Boostma (2015, 2016), in their studies on the emergent division of labor in the doubles-pong interception task, suggested that participants of better skill were likely to cover a larger part of the common interception area than their weaker teammates. In their virtual interception task, inspired by serve reception in beach volleyball, Benerink and colleagues had teams of two participants manually intercept virtual balls. Both participants were seated next to each other without being able to see (any part of) the other and were facing a large television screen. Participants could move manually controlled on-screen paddles all along the horizontal interception axis (just above the bottom of the screen) to intercept the downward-moving balls. Critically, because of the constraint not to collide with one another and without the possibility of verbal communication, on every trial, the teams had to decide implicitly who would be the one to intercept the ball. Although all interceptions, technically, could have been performed by only one of the team members, all teams showed a systematic division of the interception area between both members of a team. Importantly, before participating in the doubles session, all participants performed two individual sessions, which were used to determine the skill level of each individual participant (operationalized as the percentage of balls intercepted). For the Benerink et al. (2016) study, this resulted in five of the six teams with roughly equally skilled team members, but also one team with larger skill differences between team members. Interesting for present purposes, the first five teams revealed equally distributed interception areas with a boundary located right in the middle between the initial paddle positions, whereas the latter team showed an atypical division of interception space, in which the better-skilled participant intercepted balls in a larger area, resulting in a boundary at a location closer towards the weaker team member (see Benerink et al., 2016 and Team 6 in Fig. 2.4 of this thesis). This suggested that the location of the boundary was also a function of action capabilities, with better participants taking responsibility for a larger interception area. A similar experiment, which was designed to study the effect of differences in paddle size (Benerink, Zaal, et al., 2015), including seven teams with varying differences between teammates' skill levels, revealed similar shifts in the observed location of the boundary. The shifts in boundaries were almost linearly related with the skill differences between the members of the team (Benerink, Zaal, et al. 2015). That is to say, with no skill differences between team members (and symmetric start positions around the vertical midline of the screen), the boundary was located close to vertical midline, and the larger the differences between individual skill levels, the more the boundary location shifted towards the weakest participant. The present contribution was designed to test if, indeed, skill differences between team members lead to such division of labor.

4.2 Methods

4.2.1 Participants

For the present experiment, a subset of 12 participants (8 men and 4 women, average age of 24.8 ± 1.2 years (M ± SD)) was selected from a mixed group of 28 right-handed (post)graduates from the University of Aix-Marseille (17 men and 11 women with an average age of 24.7 ± 2.2 years). All participants provided written consent before participating voluntarily in our study. The study was conducted according to University regulations and the Declaration of Helsinki.

All 28 participants first performed an individual session. This individual session was used to characterize their skill levels and to allow them to get accustomed to the experimental set-up. The subset of 12 participants that was selected for the present experiment, next performed the doubles-pong task, in two separate sessions, with a different partner in each session (see Table 4.1). Teams were composed of participants with varying differences in skill level, with skill level defined as the score obtained in the first individual session. The remaining 16 participants took part in a separate study (Benerink et al., 2017), described in *Chapter 3*.

4.2.2 Experimental set-up

The experimental set-up used to conduct present experiment was the same as used in the study of Benerink et al. (2016) and is described in detail in *Chapters 2* and *3*. The experiments were all performed in a darkened room that contained a large table with two adjacent seats at one end of the table and a large television screen (Samsung 55" LED ED55C, with a 1920 x 1080 pixels resolution) at the other end of the table positioned at 2 m from the participants' seats. The participants faced the screen at eye-height when seated. The experimental set-up for the session in which two participants performed the task together is presented in Figure 4.1. As can be seen in this figure, participants were separated by a curtain, hanging down from the ceiling, that effectively prevented the participants seeing (any part of) the other during the experiments. Additionally, participants wore headphones (3M Peltor Optime2) in order to withhold them from picking up (auditory) information about their partner's movements and to prevent any verbal communication between members of a team.

Figure 4.1 | Representation of the experimental set-up used in both doubles sessions. Participants were sitting side by side facing a large television screen. They were separated by a black curtain and wore headphones and earplugs so as to avoid overt communication between them. To intercept the balls moving downward across the screen, both participants could move an on-screen paddle along the (non-visible) interception axis by displacing a handheld knob on an in-house constructed linear positioning device placed on the table in front of them. In the individual session, only one of the participants was present, sitting either on the left or right side of the table.

For the interception of virtual balls moving downward on their shared screen, participants displaced their right hand laterally over an in-house constructed linear positioning device placed on the table in front of them, to individually control the movement of their on-screen paddle (For specifications of this positioning devise and the way the participant's hand movements are converted into on-screen paddle movements see *Chapter 2*). Both on-screen paddles moved along the same horizontal interception axis just above the bottom of the screen that extended horizontally (X-axis) from -60.5 cm to +60.5 cm and vertically (Y-axis) from -2 cm to +66 cm (see also Fig. 4.2). With their paddles, participants were able to move all along the full (121-cm) range of the interception axis without reaching the extremities of the

75-cm long device. Unless specified otherwise, positions and distances reported from here on correspond to distances on the screen, with the origin corresponding to the center of the horizontal interception axis (i.e., at the vertical midline of the screen).

Kinematic data of the participants' paddles and the ball was sampled at a frequency of 100 Hz and stored on an external disk. Before further analysis, the kinematic data was filtered with a low-pass second-order Butterworth filter with a cut-off frequency of 5 Hz run through twice in order to negate the phase shift.

4.2.3 Task & Procedure

The task of the participants performing in our experiment was to intercept virtual white balls (2-cm diameter circles) depicted against a black background, moving downward across the screen at various angles and speeds, by making them bounce back upwards after contact with their white (3-cm wide and 0.8-cm high) paddle. In the first experimental session, participants performed the interception task solo. Whereas this first individual session was important to characterize skill level of participants, in the present contribution we will only focus on both doubles sessions that followed on the first individual session. The task and procedure described next, therefore, will concern the experiments as performed on the doubles session. For more details about the individual session, see *Chapter 3*.

The goal of the doubles sessions was to examine the effect of skill differences between members of a team on the division of labor. To this end, pairs were formed by combining participants based on their score obtained in their individual sessions[6]. With a set of twelve participants this resulted in six dyads performing in each doubles session. Each participant was matched with a different partner for the second doubles session. Participants were matched in such a way that, over teams, the magnitude of skill differences ranged from small (almost no difference) to large (up to a difference of 16 % between individual interception scores corresponding to 40 more interceptions of the better skilled participant on the first

[6] The score used to match participants for the doubles sessions was calculated for each individual participant as the percentage balls intercepted in all blocks of the first 5-block session.

individual session; see also Table 4.1). Together, this resulted in twelve dyads with a range of skill differences between participants performing the interception task together, allowing to study if participants with better interception skills than their teammates take responsibility for a larger part of the interception space, and the participants with worse interception skills cover a smaller part.

Upon entering the experimental room, each member of a team was seated on either the right or left side of the table. If participants performed the first doubles sessions while being seated at the right side of the table (i.e., the right-playing participant; referred to as RP), they were seated at the left side of the table (i.e., the left-playing participant; referred to as LP) in the second doubles session. *Vice versa,* participants first seated at the left side of the table performed the second doubles session at the right side of the table. In both sessions participants were briefly instructed about the task they had to perform: Intercept as many balls as possible as a team by moving the on-screen paddles laterally over the invisible horizontal interception axis. Importantly, participants' on-screen paddles were not allowed to touch one another, as doing so would lead both paddles to immediately disintegrate, thereby rendering interception impossible (unless the collision occurred after interception had taken place).

For a trial to start, participants had to move their paddle to the designated start position (30 cm to the left of the center of the screen for a LP or to the right for a RP; see panel B of Fig. 4.2) marked by a 3-cm translucent red rectangle. If the center of the participant's paddle arrived within 0.3 cm of the center of the rectangle, the rectangle turned green indicating that the paddle was located at the right place. After both participants had remained in place for 2 s, the green rectangles disappeared, and after another second, the ball appeared. Balls moved downward immediately with vertical speeds of 0.40 m/s (slow ball speed) or 0.64 m/s (fast ball speed), corresponding to movement durations for the ball to arrive at the interception axis of 1.6 and 1.0 seconds, respectively. Successful interception required that one of the participants' paddles touched the ball before it crossed the interception axis. If so, both paddles turned green and the ball moved back up again. In trials in which none of the two participants reached the arrival position of the ball in time (i.e. unsuccessful trials), the paddles turned red and the ball continued moving downward. As mentioned before, if both participants' paddles touched before the ball reached the interception axis, both paddles disintegrated resulting in a failure to intercept the ball (i.e., unsuccessful interception). Trials in which such a collision occurred after ball interception were considered successful as the common goal of intercepting the ball was achieved. Two seconds after ball arrival at the interception axis (regardless of a successful or unsuccessful interception) the paddles turned to their original white color and the translucent red rectangles would appear again for the team to start a new trial.

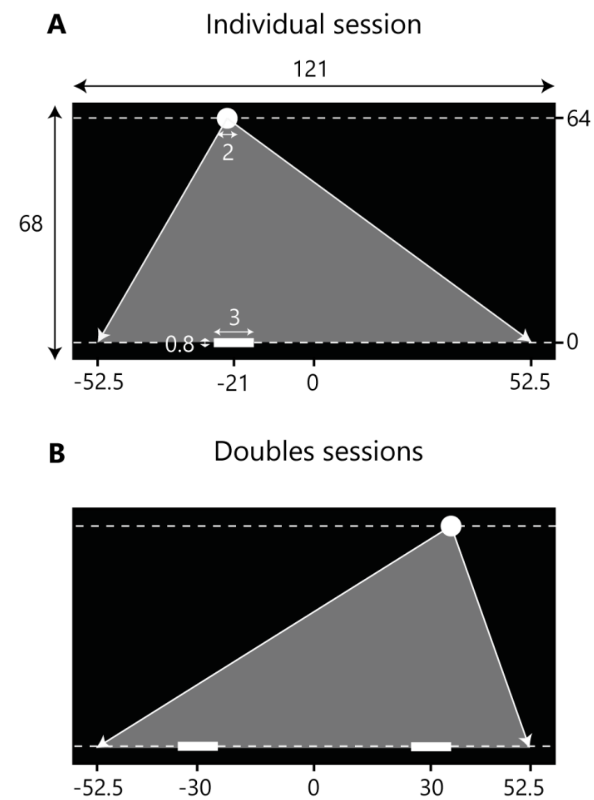

Figure 4.2 | Schematic overview of the set-up for both the individual and doubles sessions of the experiment. Screen dimensions and other metrics are in cm. Note that the figures are not scaled to actual size. Balls appeared at the top of the screen (Y = 64) and moved downward towards the interceptions axis (Y = 0) at one of two constant vertical velocities. Grey triangles indicate the range of potential ball arrival positions for exemplary ball departure positions. (A) During the first session participants intercepted balls individually. The situation depicted here represents the initial conditions for a LP. (B) Schematic overview of the doubles session in which both participants performed the interception task together. Participants' paddles were initially positioned at distances of 30 cm to the left (for the LP) or right (for the RP) of the center of the interception axis.

Balls moved downward following rectilinear trajectories and approached the interception axis under different angles. Similar to our previous studies (Benerink, Zaal, et al., 2015, 2016), the design included five standard ball departure positions (Y = 64 cm) and five standard arrival positions (Y = 0 cm), both at X = −42, −21, 0, +21 and +42 cm. Combining the five departure positions with the five arrival positions gave rise to a total of 25 standard trajectories. On each trial a random distance between −10.5 cm and +10.5 cm was added to both the standard departure and arrival positions of the selected trajectory, shifting the entire trajectory to the left or right. This way, balls could appear and arrive anywhere between X = −52.5 cm and X = +52.5 cm (see Fig. 4.2) while trajectory angles and lateral ball movements (LBM; i.e., the lateral distance between the ball departure and ball arrival position) were kept the same. Per block, all 25 trajectories appeared with two different vertical ball velocities resulting in a total of 50 fully randomized trials per block.

Both experimental sessions started off with ten practice trials. Participants were asked, besides intercepting a number of balls, to purposely miss one as well and to make contact with the other participant's paddle, so as to experience all action possibilities, constraints and their outcome. For the second doubles session, just ten practice trials were performed to let both participants get used to the set-up again. In both sessions, participants were explicitly instructed that the number of individual interceptions did not matter and that the team performance was the only thing that counted. On each doubles session, all teams completed four blocks consisting of 50 trials that were presented in random order. This resulted in a total of 200 trials for each team per doubles session which took the teams about an hour to complete.

4.2.4 Analyses

Teams performed the doubles-pong task in one of two sessions (Sessions 2 or 3). Trials resulted either in a successful interception by the LP, the RP, or a miss. Furthermore, paddle movement could have resulted in a collision or not (in most cases, a collision also meant a miss, but in a small number of trials, a successful interception preceded a collision). The percentage of successful interceptions was taken to represent team performance, and skill level in the individual Session 1. Originally, skill-level difference was considered as a continuous variable (see Table 4.1). When developing the GLMER model (discussed later), this variable did not show up as a significant predictor. For this reason, we next considered a binary version of the variable, 'Better skilled', coding for which member of a team had demonstrated the better skill level (i.e., had performed best in the individual Session 1). Finally, the experimental design had factors of ball departure position (BDP), ball arrival position (BAP), lateral ball movement (LBM), and ball speed (slow vs. fast). Because BAP was a linear combination of BDP and LBM, only two of these factors (BAP and LBM) were considered in the GLMER model.

We developed two models to account for the observed patterns in the data. For both models, we considered the trials with successful interceptions. The first, statistical, model was developed with Generalized Linear Mixed Effects Regression (GLMER). Participants in the experiment performed multiple sessions, and multiple trials within each session. This type of repeated measures design, with a binary dependent variable and with nested data, can be modelled with a general linearized (mixed) model with a binomial distribution (GLMER). We developed the GLMER model using the R software package version 3.3.3 (R Core Team, 2017). The GLMER analysis was performed using the glmer function from the lme4 package (Bates, Maechler, Bolker, & Walker, 2015). All dependent variables were entered as fixed effects into the model, with the exception of the factor of team, which was considered as a random effect. Furthermore, all continuous variables were centered before including them into the model.

We started out with a null model, which included only the effect of BAP on result. Then, predictors were added to the model in a stepwise forward manner. In order to avoid possible multicollinearity predictors were not included in the model simultaneously if they showed high correlation ($\rho > 0.7$). Predictors were included in the model if they turned out to be significant ($\alpha < .05$) and also led to a decrease of the Akaike Information Criterion (AIC) of more than 2. This procedure was performed until no further improvement of the model could be achieved.

The second model was the action-based angular-velocity (AV) model, introduced in Benerink et al. (2016). For this model, we computed time series of angles β_{LP} and β_{RP}, defined as the angles between the line connecting the ball center and the closest edge of the left and right paddle, respectively, and the interception axis (see Fig. 4.3). Angular velocities were computed for both the left and the right paddle, and the paddle whose angular velocity first reached a positive value was taken as the paddle that was predicted to be used for the successful interception (for details, see *Chapters 2* and *3*).

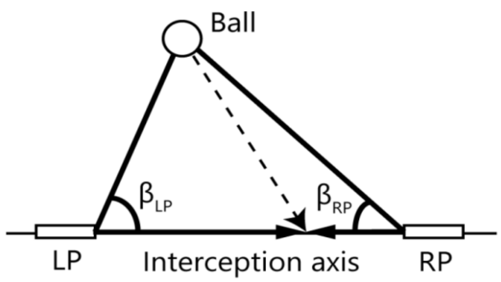

Figure 4.3 | Definition of the angles used to capture the relations between the paddles and the ball. LP and RP represent the paddles of the left and right participant, respectively. βLP and βRP are the angles formed by the line connecting both paddles and the lines connecting each paddle with the ball. These angles change as a function of the displacement of the downward moving ball and the displacements of the participants' paddles.

4.3 Results

As mentioned before, the teams were formed from a set of twelve participants. In both sessions, six different teams were created from this participant pool. The characteristics of all teams can be found in Table 4.1. All teams, to a greater or lesser extent, showed differences between skill levels of team members with half of the teams showing a negative difference indicating that the skill level of the LP was better, whereas in the other half the skill level of the RP was better.

Table 4.1 | Team compositions and interception performance for the individual participants in Session 1 and for the teams in both doubles sessions. Reported performance (Perf.) is the percentage balls intercepted in each session over all trials. Skill difference is the difference between the performance of both team members on Session 1.

		Session 1				Doubles sessions	
	Team	LP	Perf. LP (%)	RP	Perf. RP (%)	Skill difference	Perf. Team (%)
Session 2	9	14	86.4	6	95.2	8.8	94.0
	10	4	79.2	7	88.0	8.8	88.5
	11	27	94.4	1	84.0	-10.4	86.5
	12	17	87.2	26	82.8	-4.4	84.5
	13	24	80.0	22	90.0	10.0	89.5
	14	3	86.8	8	78.8	-8.0	85.5
Session mean						*|8.4|*	*88.1 ± 3.1*
Session 3	15	7	88.0	14	86.4	-1.6	92.0
	16	6	95.2	4	79.2	-16.0	87.5
	17	26	82.8	27	94.4	11.6	90.0
	18	1	84.0	17	87.2	3.2	85.0
	19	8	78.8	24	80.0	1.2	76.0
	20	22	90.0	3	86.8	-3.2	88.5
Session mean						*|6.1|*	*86.5 ± 5.2*
Total mean						*|7.3|*	*87.3 ± 4.3*

Teams managed to intercept the ball in 87.3 % of all trials (n = 2400). Collision between team members occurred in 1.8 % of all trials (this meant no successful interception in 1.3 % of all trials, and a collision after a successful interception occurred in 0.5 % of all trials), whereas the ball was simply missed in 11.5 % of all trials. For the current study, only the successful trials of the twelve teams were analyzed. Performance of the teams was defined as the percentage of balls that was successfully intercepted by the team. These scores can be found in Table 4.1.

Table 4.2 | Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) for final model[b]

Model variables						
Random effects	*Variance*	*Standard Deviation*			*95 % CI Lower*	*95 % CI Upper*
Team[a]	1.680	1.296			0.584	2.593
Fixed effects	*Estimate (β)*	*Standard Error*	*p-value*		*95 % CI Lower*	*95 % CI Upper*
(Intercept)	-1.886	0.876	0.031	*	-3.418	0.416
BAP	75.745	14.055	< 0.001	***	25.409	93.422
Speed (2)	0.846	0.752	0.261		-1.087	2.611
LBM	-13.961	2.733	< 0.001	***	-17.555	-4.588
Better skilled (right better)	1.244	0.872	0.154		-0.777	2.830
Session (3)	2.339	0.984	0.017	*	0.104	4.039
BAP*Speed (2)	37.869	10.846	< 0.001	***	-4.438	55.413
LBM*Better skilled (right better)	3.509	1.293	0.007	**	0.127	5.935
BAP*Session (3)	-29.518	14.844	0.045	*	-52.716	17.732
LBM*Session (3)	6.535	2.644	0.013	*	-1.878	10.766
Speed2*Session (3)	-2.194	0.969	0.024	*	-4.129	0.342

[a]n=12; [b]Model formula: result ~ BAP * speed + LBM * score_LR + session * (BAP + LBM + speed) + (1 | team)
Significance codes: *** <0.001; ** <0.01; * <0.05

The main manipulation of the present experiment concerned the differences between team members in their proficiency in the task, as assessed by their performance on the first individual session (Session 1). Table 4.1 shows the team compositions for Sessions 2 and 3, as well as the differences between the team members' skill levels. Absolute score differences ranged from 1.2 % to 16.0 %, with an average of 7.3 %.

Generalized Linear Mixed Effects Regression (GLMER) was used to analyze the data. The analysis led to a final model that included significant fixed effects of ball arrival position (BAP), lateral ball movement (LBM), and session. The model also included significant interaction effects of BAP × speed and LBM × 'Better skilled'. A random effect for team was also included in the model, allowing the intercept of the curve to differ for each team. The results of the final model are shown in Table 4.2. The GLMER-model correctly predicted the outcome in 98.4 % of the trials (see also Fig. 4.11).

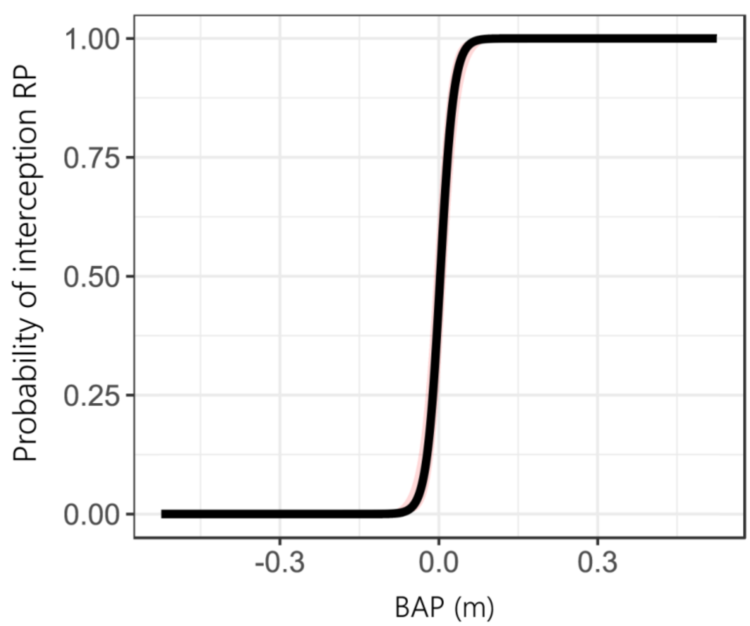

Figure 4.4 | Partial effect of BAP on interception probability of an interception by the RP.
95 % confidence bands are indicated in light red.

As can be seen in Figure 4.4, the odds for interception by the RP increase when BAP increases. That is to say, when the future arrival position of the ball is located more toward the right side of the screen, the interception is more likely to be performed by the participant whose paddle is initially positioned on the right side.

Figure 4.5 shows how the effect of BAP is moderated by speed. The probability curve is more gradual for balls with lower vertical speed than for balls moving down at higher speed. This means that the amount of overlap between interception areas is bigger for balls moving at lower speed. The effect of BAP is also moderated by session (see Fig. 4.6). The probability curve is slightly more gradual for trials in Session 3 (i.e. the second session performed in teams), indicating a bigger overlap between interception areas in this session. Furthermore, the probability curve is shifted more leftward in Session 3 compared to Session 2 pointing out that the RP was likely to cover a larger portion of the ball's arrival positions in the second doubles session.

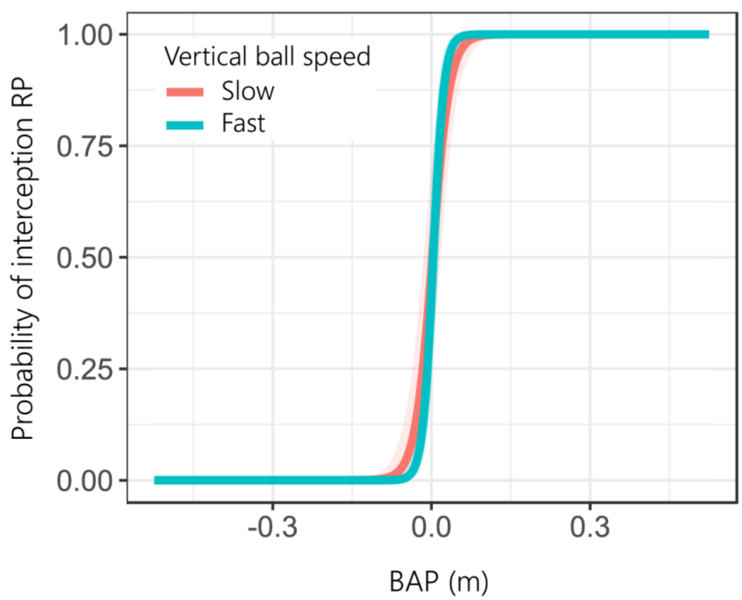

Figure 4.5 | The partial effect of BAP on the probability of an interception by the RP, moderated by the speed of the ball. The red curve represents the effects for trials in which balls move downward at the slow vertical ball speed. The blue curve represents the effects for trials in which balls move downward at the faster vertical ball speed. 95 % confidence bands are

shown for both curves in lighter color.

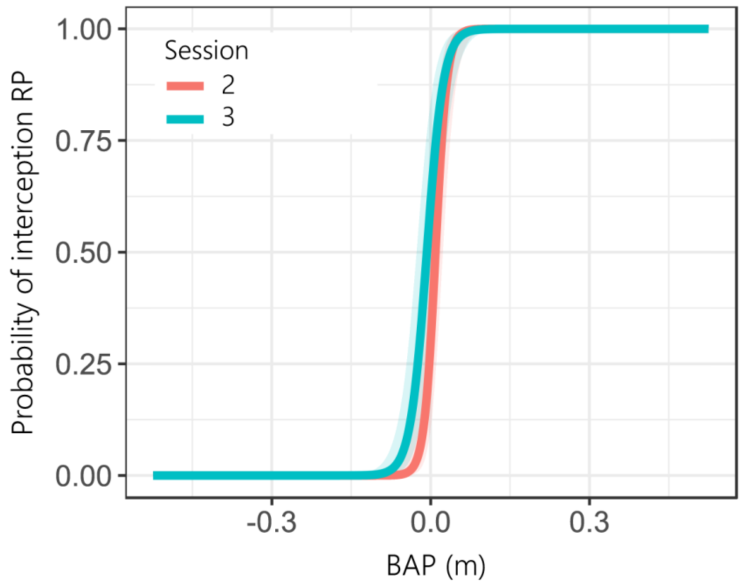

Figure 4.6 | The partial effect of BAP on the probability of an interception by the RP, moderated by session. The red curve represents the effects in Session 2 and the blue curve represents the effects in Session 3. 95 % confidence bands are shown for both curves in lighter color.

As can be seen in Figure 4.7, the odds of interception by the RP increase as LBM decreases. Note that this effect of LBM is a partial effect, which means that other variables like BAP are assumed to have their mean value. The odds of interception by the RP are highest when lateral ball movement is negative (i.e. when the ball moves in a leftward direction). This does not necessarily mean that all leftward moving balls are more likely to be intercepted by the participant located on the right. Because the mean value of BAP coincides with the vertical midline of the screen (which coincides with the location exactly halfway both participants' initial paddle positions), the effect plays out most prominently around this position.

The effect of LBM on the interception probability is moderated by the side on which the better skilled participant is located (see Fig. 4.8). The interception boundary –defined by the 0.50 interception probability point– instead of being located in the middle, shifts toward the side of the better-skilled participant. This indicates that this participant has a broader range of LBM in which he or she is most likely to be the interceptor, allowing this participant to intercept more balls.

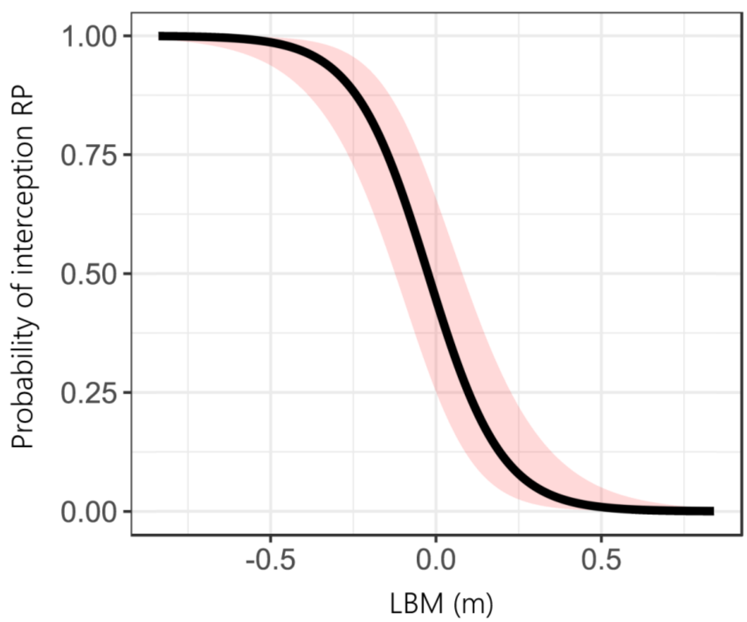

Figure 4.7 | Partial effect of LBM on the probability of an interception by the RP. 95 % confidence bands are indicated in light red.

The effect of LBM on the interception probability is also moderated by session. Figure 4.9 shows that the probability curve is more gradual in Session 3 compared to Session 2. This, again, indicates that the amount of overlap between interception areas was bigger in the second doubles session. Also, the interception boundaries (i.e. the point with 0.5 interception probability) in both Session 2 and 3, instead of being located in the middle, are shifted to the left and to the right, respectively. This indicates that in Session 2, the RP covered a smaller portion of the possible LBM's whereas in Session 3 the RP covered a larger portion of the possible LBMs. As said before, this effect is mainly important for balls arriving at a location around the center of the interception axis.

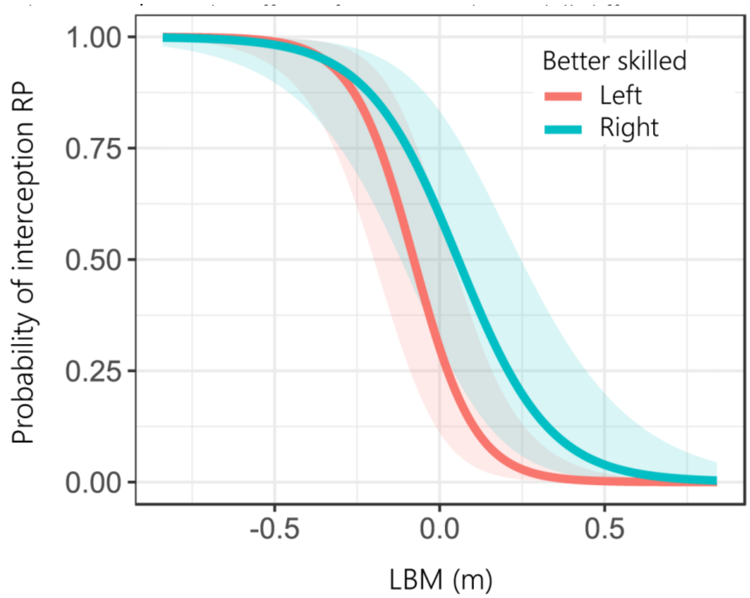

Figure 4.8 | The partial effect of LBM on the probability of an interception by the RP depending on the position of the better skilled participant. The red curve represents the effect of a better skilled LP on the probability of an interception of RP. The blue curve represents the effect of a better skilled RP on the probability of an interception of RP. 95 % confidence bands are shown for both curves in lighter color.

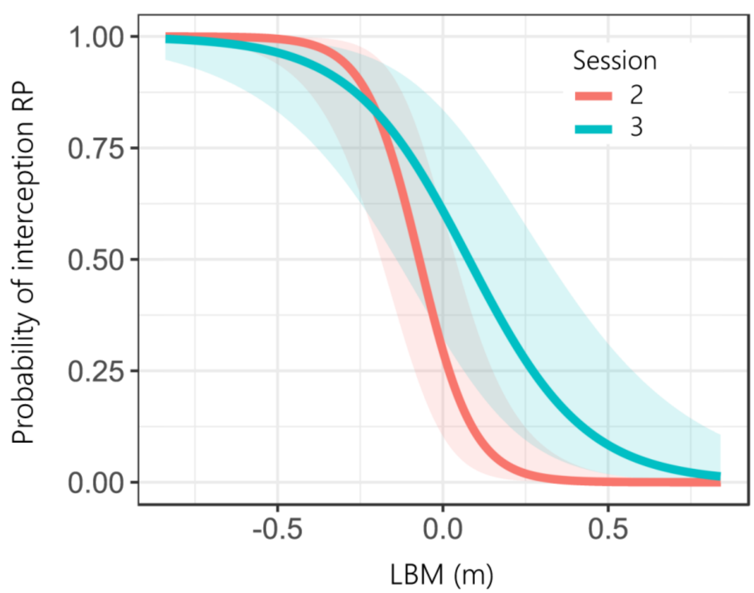

Figure 4.9 | The partial effect of LBM on the probability of interception by the right player, moderated by session. The red curve represents the effects of the second session (2) and the blue curve represents the effects observed in the third session (3). 95 % confidence bands are shown for both curves in lighter color.

Finally, the factor of session significantly contributed to the GLMER model. The effect of session indicates that the odds of interception by the RP increased with session point out that the RP was more likely to intercept the ball in Session 3 compared to Session 2. Besides, the factors of LBM, BAP and speed appeared to be moderated by session as well, indicating that the effects of LBM, BAP and speed on the probability of an interception of RP differed over both experimental sessions.

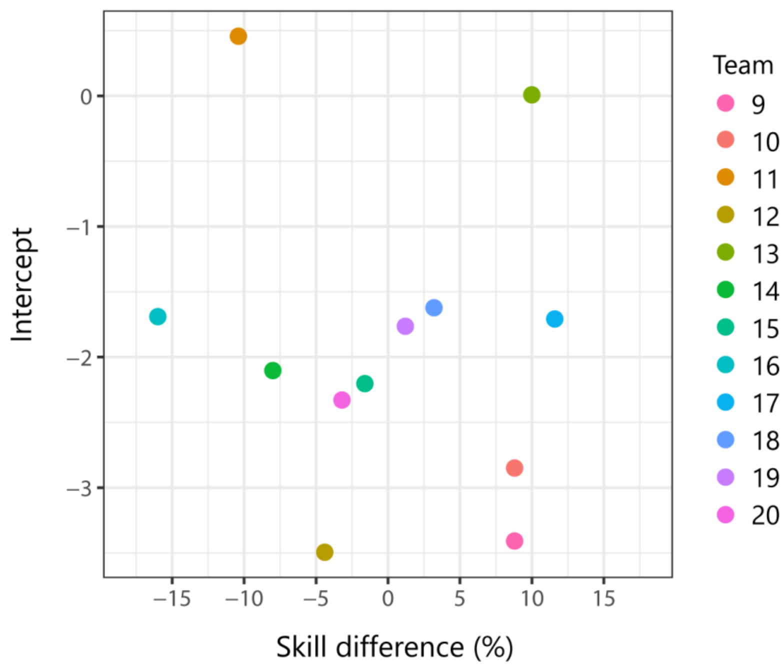

Figure 4.10 | The random intercepts from the GLMER model plotted as a function of skill differences between members of a team (as the % of intercepted balls in the first individual session). Each team is represented by a different colored dot.

The initial reason to perform the present analysis was the hypothesis that differences in skill level between team members intercepting balls together would affect the location of the boundary between the interception areas that each participant covered. Figure 4.10 shows the random intercepts from the GLMER model for each team, plotted as a function of the skill differences between members of a team. The finding that no coherent pattern can be seen in this figure, in combination with the fact that skill difference (included in the analysis as the variable 'Better skilled') did not show up as a main predictor in the GLMER model, makes that we are forced to conclude that the present experiment did not provide support for the hypothesized relation between skill differences and the location of the boundary separating interception domains.

The GLMER model that we developed shows how a set of many variables can be used to statistically predict the chances of the LP or RP realizing the interception. Figure 4.11 shows the predicted outcome of all trials according to the GLMER-model as compared to the measured outcome of all trials for each team separately. As an alternative, we also considered the action-based angular-velocity (AV) model, introduced by Benerink et al. (2016). This model correctly predicts the outcome in 97.9 % of the trials. Similar to Figure 4.11, Figure 4.12 shows the measured and the predicted outcomes of the trials for each of the twelve teams separately, as predicted by the AV-model. Comparing the predicted trial outcomes with the GLMER model and the AV-model shows that these models generate different predictions in 67 trials (3.2 % of trials).

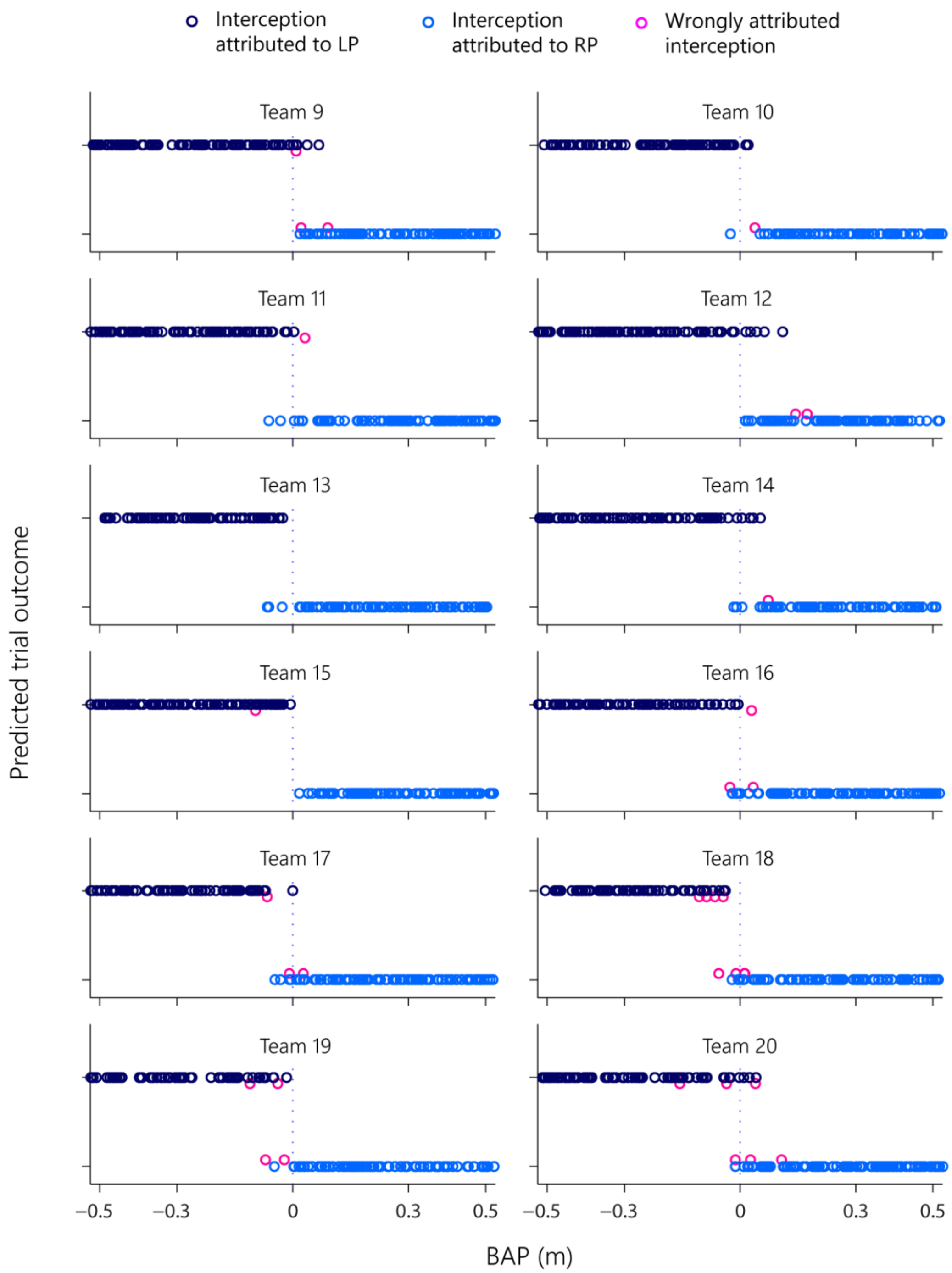

Figure 4.11 | Graphical summary of predicted interception performance based on the GLMER model. Interception performance is plotted as a function of ball arrival position for all twelve teams (9-20) in both doubles sessions. Correctly attributed interceptions are indicated by dark blue (LP interception) and light blue (RP interception) circles. Incorrectly attributed interceptions are indicated by pink circles with a slight vertical offset. The vertical dashed gray lines at ball arrival position 0 m indicate the center of the interception axis.

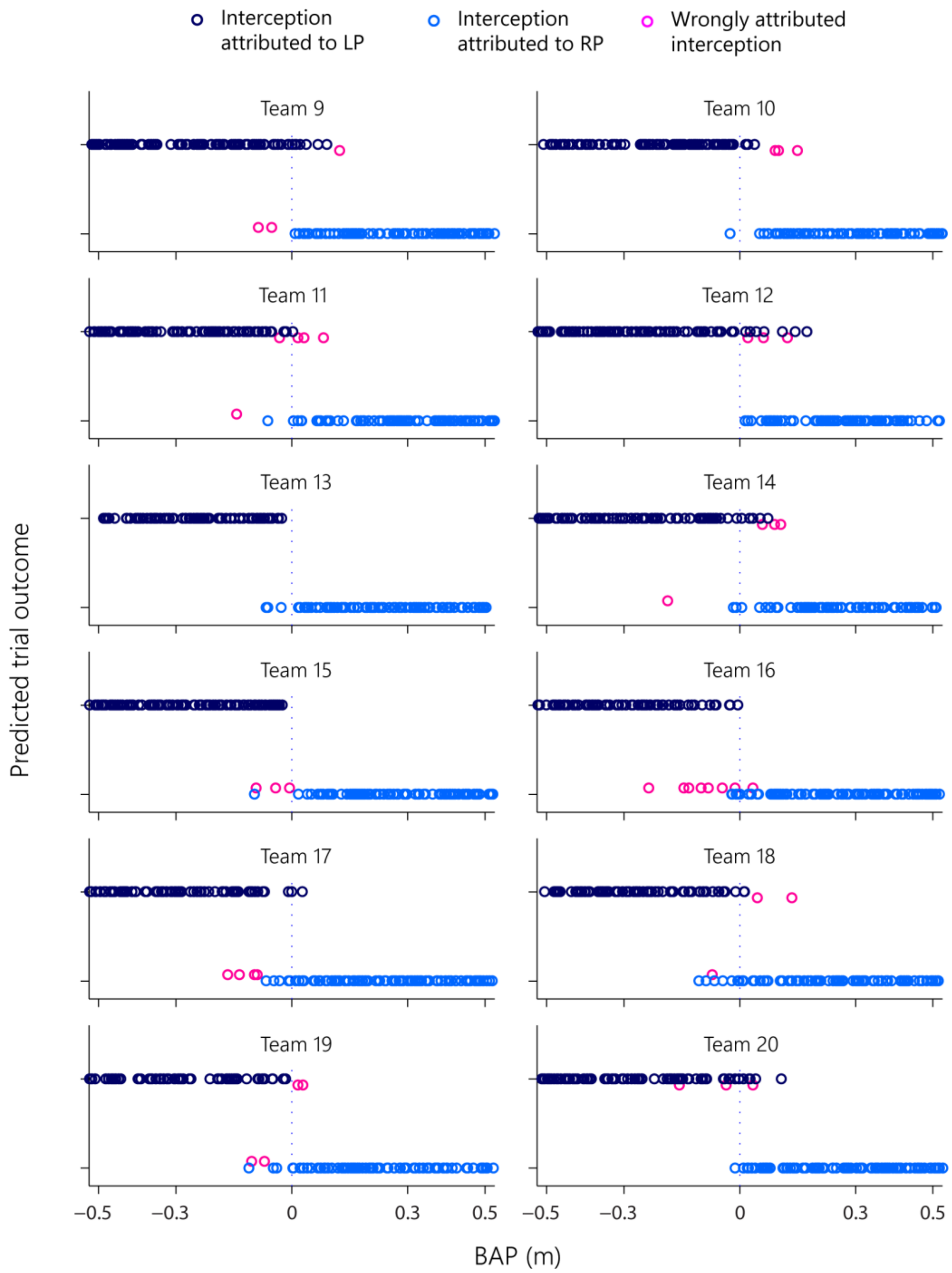

Figure 4.12 | Graphical summary of predicted interception performance based on the AV-model. Interception performance is plotted as a function of ball arrival position for all twelve teams in both doubles sessions. Correctly attributed interceptions are indicated by dark blue (LP interception) and light blue (RP interception) circles. Incorrectly attributed interceptions are indicated by pink circles with a slight vertical offset. The vertical dashed gray lines at ball arrival position 0 m indicate the center of the interception axis.

4.4 Discussion

In the present contribution, we investigated the performance of teams on a doubles-pong task, in which the task of both participants was to make sure that virtual balls moving downward from the top of their shared screen would not reach the bottom of the screen. Both participants could manually control their own on-screen paddle, and apart from trying to have the ball bounce back up again by either one of the paddles, the paddles should also not collide. Members of a team thus had to decide on every trial who would intercept the ball. The study was designed to demonstrate a relation between the difference in individual proficiency between two team members and the location of the boundary separating interception areas covered by each participant. Suggested by earlier studies (Benerink, Zaal, et al., 2015, 2016), we expected to see the boundary locations move in the direction of the participant who had scored lowest in the individual session. The results of the present experiment did not provide overwhelming support for this hypothesis.

The continuous factor of the difference between skill levels of the two teammates appeared to be a non-significant variable in the GLMER model. The alternative, binary factor representing the side the best skilled participant was positioned did not reveal any significant effects either other than being part of a significant interaction with lateral ball movement (LBM). The hypothesized effect of skill differences on the location of the boundary between interception areas was thus not clearly supported. Furthermore, when considering the random intercepts—the random effect of the factor of team on the location of the boundary—the lack of a clear relation between the values of these intercepts and the skill differences between team members also did not point at the expected relation (see Fig. 4.10). It seems fair to conclude that other factors related with the teams than simply their skill difference (as assessed by their performance on a first individual session) affect the boundary locations between interception domains and, hence, division of labor between team members.

As expected, and in line with our previous studies (Benerink, Zaal, et al., 2015, 2016, 2017), ball arrival position (BAP) was a very strong predictor in the GLMER model. However, whereas in previous studies we only considered this variable, and on a team-by-team basis, the GLMER model developed in the present study included factors such as vertical ball speed and lateral ball movement (LBM). For instance, the model demonstrated that boundaries were sharper (i.e., less overlap between interception domains) when balls approached at the higher speed. Session appeared another factor influencing division of labor. Not only as main predictor but also in interaction with BAP, LBM and speed, session significantly affected division of labor between team members, pointing out that in the second doubles session RP typically intercepted more balls. Running two doubles sessions, however, was done for practical purposes instead of being another manipulation to study the effect of skill differences on a team's division of labor. Interpreting the observed effects of session, therefore, is somewhat precarious as they might be attributed to various factors like, for instance, a learning effect.

The most interesting and, perhaps, most surprising factor was LBM. Apparently, not only where the ball crossed the interception axis, but also how it arrived there affected the way that interception space was divided up between the two members of a team. The effect of the factor LBM is equivalent to an angle-of-approach effect, a prominent effect in the literature on the online control of interception (e.g., Bootsma, Ledouit, Casanova, and Zaal, 2016; Ledouit, Casanova, Zaal, and Bootsma, 2013; Peper, Bootsma, Mestre, and Bakker, 1994). For straight-line ball trajectories, the angle-of-approach effect can be used to infer that people do not control interception by predicting the interception point. Another interpretation of the same effect is that, when using prospective information, people do not rely on exactly first-order information (see Bootsma et al., 2016). Both interpretations are interesting for present purposes. The first perspective would suggest that also in the doubles-pong task under study here (and in this thesis), observed boundaries are not the result of knowing where a ball will end up and deciding among the two team members to whose domain this interception position belongs. When accepting that the information used in the present task is related with the information used to control lateral interception, an account of explicitly using tacitly agreed-on boundaries becomes implausible (see also *Chapter 3*). The location of the boundaries more probably is related with information for interception that is prospective in nature.

As mentioned before, a second interpretation of demonstrating an angle-of-approach effect is that the prospective information used for lateral interception is not exactly first-order. This interpretation is directly relevant in the context of the angular-velocity (AV) model that we presented as an alternative to the statistical GLMER model. Taking the GLMER model to illustrate the complexity of the predictions of BAP (required to attribute approaching balls to either side of an explicit boundary), needing to factor in ball speed, lateral ball movement, the alternative is that the boundary emerges from the interactions between both participants through the dynamics of the system of two paddles and the ball (cf. Benerink, Zaal, et al., 2015, 2016, 2017). The AV model was developed around the rate of change of the angles β between the lines connecting paddles with ball and the interception axis. In spite of its simplicity—the paddle whose rate of change of angle β first reached a positive value is predicted to be the paddle to actualize the interception—the AV model performed equally well as the GLMER model in predicting the observed patterns. Note, however, that the AV model is a first-order model. When future studies will be able to better characterize the close-to-first order information used in lateral interception (i.e. individual interception), the possibility of translating these future steps in understanding individual interception to the present case of joint interception might help to bring the explanatory power of the AV model even closer to 100 %. That is to say, admittedly, the AV model is a first, but already very successful, approximation of the informational coupling that plays out into the emergent patterns observed in this, and previous studies. A next step in modelling the dynamics of the doubles-pong task might well benefit from considering prospective information of an order slightly under one.

In conclusion, the present study was designed to demonstrate the effects of skill differences between the two participants of our doubles-pong task on their division of interception space. Our results did not speak in the direction of such an effect. However, we were able to identify a fair number of variables that together would predict the participant to make the interception. Variables included ball arrival position, the lateral movement of the ball during its approach (equivalent to an angle of approach), and ball speed. We suggest that an account of the division of interception space based on a tacitly agreed boundary would have to assume that all these factors can be used for predicting the future arrival position of the ball. The alternative model that we introduced in Benerink et al. (2016), in which the boundary emerges from the dynamics of the visually coupled paddles and ball, performed just as well as the statistical GLMER model. Although we do not wish to rule out any effects of differences in action capabilities of team members, the present study, again, underscored the success of an account of emergent behavioral patterns.

5

GENERAL DISCUSSION

In this thesis we sought to find out how a dyad (jointly) decides who performs an interceptive action where and when and, thus, how they decide on a division of labor in a cooperative joint interception task. Modeled after serve reception in beach volleyball, the virtual doubles interception task used in this thesis was taken to represent a variety of daily life social encounters in which cooperation follows from the joint responsibility to attain a common goal and the constraint not to collide with each other. The aim was to provide an answer to the question whether coordination in such social interactions necessarily follows from (tacit) agreements or that it might be an emerging property of the interactions between cooperating individuals. The introduction of the doubles pong task allowed us to get answers to questions regarding how members of a team[7] decide who will perform a particular action (i.e., the interception) and who will not. Moreover, the experimental set up provided a way to manipulate and study –in a controlled way– the relations between cooperating individuals and their environment resulting in suggestions about the information individuals use to decide on and the factors influencing this decision. This way, this thesis provides evidence that the observed division of labor in a doubles interception task is the emergent result of the ball-related interactions between team members instead of being the result of (tacit) agreements about who intercepts what ball where.

This last chapter will briefly recapitulate the situation of interest and the experimental paradigm introduced in this thesis. It will provide an overview of the main findings of this thesis which, thereafter, will be discussed in the context of joint decision making and social coordination in general. Furthermore, this chapter will elaborate on the methodological contributions and limitations of studying joint decision making in a virtual joint interception task as used in our doubles pong studies. Finally, some suggestions for future research will be provided before getting to the concluding remarks.

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[7] Over the course of this general discussion I will use both the terms dyad and team to refer to a grouping of two individuals cooperating on a task. The term 'dyad' will be mainly used for references to a more general grouping of two individuals, whereas 'team' will particularly be used to refer to the composition of two participants performing together in our doubles interception task. Participants that constitute a team, hence, will be referred to as team members.

5.1 Summary of the studies and the main findings

In this thesis, different experiments were conducted to find out how labor between team members is divided in a virtual doubles interception task. Because of the constraint not to collide, the interception task required the teams to decide, on every trial, who would be the one to actualize the interception and who would not. Using a manually controlled on-screen paddle, participants could move freely along their shared horizontal interception axis to intercept the downward moving ball or to get out of the way to let their partner intercept the ball. Critically, verbal communication was not allowed, implying that any division of labor between team members was based on visual information from ball and paddle movements only. Division of labor thus followed either from close spatiotemporal coordination of both team members' actions or from tacit agreements about a separation of interception domains, possibly predicated upon situational geometry (e.g., the center of the screen or a location halfway both participants' initial paddle positions). The experimental set-up allowed to measure interception performance, to identify the places where the left and right participant intercepted balls and to point out the places where balls where missed or collisions occurred. Moreover, the set-up provided a way to obtain kinematics of the participants' paddles and the ball over time allowing for a thorough analysis of the interactions between participants and the ball. This way, we could establish if and how individuals use information about their partners' (interceptive) actions and the ball's movement when deciding to intercept a ball or not. Whereas in a first experiment both members of the teams were initially positioned at the middle of their screen half and matched with a partner based on a comparable level of skill, later studies allowed to manipulate initial positions and team compositions in order to find out how such factors influenced the division of labor between team members, that is, the decision of who intercepted what balls where.

The way the experiments were set up resulted in a large amount of data and new insights into joint action coordination of which only the most pertinent are presented in this thesis. To start, performance on the task was overall quite good, both in the solo and doubles sessions, as shown by the high percentages of trials in which the ball was successfully intercepted. At the same time, observed differences between individual interception scores allowed for the discrimination between more or less skilled participants. These differences in skill level allowed us for the doubles sessions to form teams with participants of comparable skill levels (*Chapter 2* and *3*) or, conversely, of differences between skill levels (*Chapter 4*). In all of the doubles sessions, nonetheless, the number of collisions was remarkably low, showing that members of a team, whether highly skilled or not, quite successfully coordinated their actions with one another. Moreover, in all of the doubles sessions reported in this thesis (*Chapters 2, 3* and *4*), teams showed a clear division of labor in that both team members intercepted balls in separate interception domains. Indeed, without overt communication or the possibility to divide labor upfront, the participant with his or her paddle initially positioned left from the center of the screen (LP) typically intercepted the majority of balls arriving on the left half of the interception axis, whereas the participant with his or her paddle initially positioned right from the center of the screen (RP) typically intercepted the majority of balls arriving on the right, resulting in an (experimentally defined) boundary separating both team members' interception domains. Importantly, boundaries were rather fuzzy instead of clear-cut as there was some overlap between the interception domains of both participants, indicating that in a (small) area (i.e., the overlap) both participants intercepted some balls. Moreover, boundary locations and the amount of overlap between interception domains and, hence the division of labor, showed to be different when compared over teams in the same condition (i.e., between-team differences) and, importantly, also within teams over different conditions (i.e., within-team differences).

5.1.1 Between-team differences in division of labor

Although our first observations in *Chapter 2* revealed comparable distributions of interception domains for five out of six teams with boundaries around the center of the screen, suggesting that a division of labor might have resided in situational geometry[8], later

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[8] Cognitive approaches to human functioning locate the organization of human (inter)action in underlying plans, often specified *a priori* through some form of direct communication (see e.g., Sebanz et al., 2006; Sebanz & Knoblich, 2009). With possibilities for overt communication being precluded in our studies, action plans here could have followed from social conventions and common sense – specifying a typical action for both team members in a typical situation– to equally divide labor upfront (Schank & Abelson, 1977). Such a division of interception domains would then imply a reference point

studies (*Chapter 3* and *4*) pointed out that division of labor was rather flexible and varied (to a considerable extent) over teams. Indeed, when compared over teams, boundary locations and the amount of overlap between interception domains proved to be quite variable. This thesis allowed to test (some of) the factors suggested to influence the decision of who will intercept a ball where, and, therewith, contributed to understanding the origins of the observed differences in the teams' division of labor.

First, results of *Chapter 2* pointed out that (differences in) skill level might have influenced a team's division of labor. *Chapter 2* showed that in teams with equally skilled participants, interception domains were equally divided, with a boundary located at the geometrically defined center of the screen. Furthermore, it revealed that the one dyad with larger skill differences between participants showed a different division of labor, in that the better skilled participant intercepted more balls and covered a larger area, manifested in a shift of the boundary location of almost 5 cm towards the weaker participant. These results, together with observations from a comparable study of Benerink, Zaal, Casanova, Bonnardel and Bootsma (2015), in which seven teams performed the same doubles-pong task while paddle size was being manipulated, suggested that skill level of both team members was linearly related to boundary locations separating interception domains.

Observations in *Chapter 3* and manipulations of the skill levels of team members in *Chapter 4,* nevertheless, did not confirm these observations. *Chapter 3*, for one, revealed that boundary locations varied widely over teams even though skill levels of team members were comparable and *Chapter 4*, thereafter, showed as well that boundary locations varied over teams. The latter result, however, did not seem to be an immediate result of skill differences between members of a team but more an effect of situational constraints and other trial characteristics. Indeed, in an analysis towards a probability model to statistically predict a team's division of labor, *Chapter 4* revealed several factors that need to be integrated for a successful attribution of the interception to the left or right playing participant. Whereas skill differences between team members, here, delivered a minimal contribution to the model –as a

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visible for both team members, like the center of the screen or the location halfway both participants' initial paddle positions and, thus, would have been located in situational geometry.

significant interaction effect with lateral ball movement– the analysis revealed that factors like the arrival position of the ball, the angle of approach of the ball, the duration of the trial (i.e., vertical ball speed), the session in which the teams performed and several between-factor interactions all significantly affected the probability of an interception by the left or right participant. This way, the analysis showed there are many factors contributing to a team's division of labor of which the effect of individual skill differences within a team was only marginal.

5.1.2 Within-team differences in division of labor

Besides the observed differences between teams, labor appeared to be divided differently and changing within teams as well. Indeed, with a manipulation of the initial positions, *Chapter 3* showed that interception domains changed within teams as a result of (the distance between) the participants' start positions. With the RPs randomly alternating their initial position between two alternative locations (resulting in a symmetric and a-symmetric condition around the vertical midline of the screen), results revealed that the LPs systematically intercepted balls further from their initial position if their partner was positioned further away as shown by systematic shifts of boundary locations when compared over conditions. Moreover, overlap between interception domains appeared to increase as well when participants were located further apart, reinforcing the findings that interception domains (i.e., the range in which a participant intercepts balls) are flexible and, among other things, depend on a dyad's initial positions.

5.1.3 Temporal evolution of the division of labor

Whereas division of labor between team members in the end seemed rather clear, a look at the frequency of trials in which both team members initiated an interceptive action (*Chapters 2* and *3)* revealed that the division of space was not a matter of fact at the beginning of the trials. Indeed, although trials with future ball arrival positions close to or behind the participants' initial paddle positions (i.e., left of the LP's paddle or right of the RP's paddle) typically showed a movement initiation of only one of the participants, implying that the other participant knew he or she did not have to intercept that ball, trials with ball arrival positions around the center of the interception axis showed a high prevalence of initiations of both team members. In about 22 % of all trials both team members initiated a movement, implying that one of them had to abandon his or her interception attempt to avoid a collision and let their partner intercept the ball. Consequently, in at least almost a quarter of all trials the decision of who had to intercept the ball must have been made on-the-fly.

In *Chapter 2* we used the rate of change of angle β (i.e., $d\beta/dt$) –the angle formed by the interception axis and a line connecting the inside of the participant's paddle and the center of the ball– to capture the time-evolving paddle-ball relations for both participants. When participants started moving their paddles they actively changed its relation with the ball, which is functionally captured by a change in $d\beta_L/dt$ for the LP and $d\beta_R/dt$ for the RP. Plotted in the ($d\beta_L/dt$, $d\beta_R/dt$) state space, the $d\beta/dt$ allowed to scrutinize the evolution of the behavior of both participants' paddles with respect to the ball over time. This way, *Chapter 2* not only revealed that the first to reach a positive rate of change of angle β (i.e., $d\beta/dt \geq 0$) was likely the one that ended up intercepting the ball, but also that the state space showed the gradual separation of both groups (i.e., an interception of the LP or RP) over the course of a trial, indicating that the decision of who intercepts the ball emerged over the trials. A simulation of the interception performance based on a simple action-based decision criterion stating that 'the first participant to attain $d\beta/dt \geq 0$ will intercept the ball' revealed that in the grand majority of trials the interception was thereby indeed assigned to the participant actually intercepting the ball. In *Chapter 3* and *4*, this same criterion was applied to the data and, in a similar fashion, recreated to a large extent the variability in the observed coordination patterns. That is to say, the simulation revealed both the variability in the location of the boundaries and the amount of overlap as observed over teams, therewith reproducing even the most peculiar team solutions to divide labor for a successful team performance. In the next section I will discuss how aforementioned findings might be accounted for from different perspectives on division of labor in social interactions.

5.2 On division of labor

In the introduction I already mentioned that there are different ways of looking at the problem of division of labor in a doubles interception task. One of those ways of looking at the problem at hand is that both individuals decide, among the two of them, who performs the interceptive action and who should get out of the way. Such a decision-making perspective considers the observed coordination (i.e., division of labor) as the result of a decision-making operation between the individuals. Based on a shared understanding of interception areas and the ability to predict the arrival position of the ball, both participants would be able to decide who should perform the interception and who should not. Alternatively, a social coordination perspective considers coordination as an emergent property of the interactions of both individuals over time. Instead of (mental) decision making operations, such a perspective emphasizes the lawful relations that exist between interacting individuals that give rise to coordinated patterns of movement. In this perspective division of labor emerges from the mutual influence of the interactions between individuals with respect to their environment.

Whereas most observations described in this thesis provide converging evidence for a division of labor as being an emergent property of two individuals cooperating in an interception task, some of the results were rather ambiguous and could also be taken to reflect a decision-making perspective to joint-action. In what follows I will, therefore, elaborate on how the observed results may relate to both aforementioned perspectives. Consequently, I hope we might agree that considering division of labor as an emergent property of ongoing triangular interactions between both individuals and the ball is a more parsimonious way to account for the observed patterned interception behavior than is a shared-knowledge based decision-making account of the joint action studied.

5.2.1 Decision-making perspective

From a decision-making perspective to joint action the question is how both individuals decide who performs what action where. For a successful performance on our doubles interception task the question thus becomes: how do both team members decide on a proper action so one of them can intercept the ball while collisions between paddles are avoided? Following a cognitive approach to joint-action coordination, considering this decision process as something between both individuals implies a certain amount of shared knowledge about the task that participants use to decide on (e.g., Bicho et al., 2011). As explained in the general introduction, shared knowledge is taken to be all of the knowledge that is held in common between both individuals, like a joint-action goal and a specification of tasks to be performed, and, therefore, is argued to be a prerequisite for successful joint action coordination (e.g., Eccles & Tenenbaum, 2004; Sebanz & Knoblich, 2009; Vesper et al., 2017). For the doubles interception task at hand, this implies that both individuals should have a shared understanding of a (preferably identical) division of labor specifying the domains in which both participants should intercept their balls. Whereas shared knowledge and a division of labor typically follow from communication between individuals acting together (e.g., a team captain specifying a game plan upfront; see e.g., Eccles, 2010; Eccles & Tenenbaum, 2004; Reimer et al., 2006), in the present experiments possibilities for overt communication were precluded to study how joint actions are coordinated based on visual information only. Shared knowledge about a division of interception space, here, only could have followed from pre-existing knowledge and unspoken assumptions (i.e., common sense) about the behavior a co-actor is likely to perform (e.g., Cannon-Bowers & Bowers, 2006; Espinosa, Lerch, & Kraut, 2002; Schank & Abelson, 1977).

If we assume that both team members indeed had a shared understanding of a (boundary-based) division of interception space, knowledge about the future arrival position of the ball would be sufficient for both team members to decide whether the LP or RP had to intercept the downward moving ball. Although debatable, several studies on manual interception have suggested that individuals might indeed be able to (early) predict arrival positions of ball trajectories (e.g., Arzamarski, Harrison, Hajnal, & Michaels, 2007; La Scaleia, Zago, & Lacquaniti, 2015; but see e.g., Bootsma, Ledouit, Casanova, & Zaal, 2016; Ledouit, Casanova, Zaal, & Bootsma, 2013). Under this assumption, the task of both team members is to accumulate enough information to allow for an exact prediction of the arrival position of the ball which, subsequently, can be used to decide who should intercept that ball and who should wait according to their boundary-based division of space. As a result, such a boundary-based division of labor should be reflected in a team's interception performance in that interception domains are expected to be clearly divided with a boundary separating interception domains located in situational geometry (e.g., center of the screen) and, possibly, some collisions representing erroneous predictions of the ball arrival position and subsequent interception attempts of both participants.

At first sight, the observations reported in *Chapter 2* to a certain extent matched aforementioned expectations concerning the interception performance as resulting from a shared-space boundary-based division of interception domains. Indeed, as five out of six teams revealed a boundary at or close to the vertical midline of the screen and all teams showed a low number of collisions, the decision of who had to intercept balls where seemed remarkably clear, indicating that interception domains were symmetrically divided by the vertical midline of the screen or the middle in both initial positions (which happened to be the same location). These results revealed that also without communicating humans are perfectly able to divide labor when cooperating on a dynamic joint activity. Nevertheless, the extent to which the observed division of labor and the decision to intercept a ball or not follow from a tacitly agreed-upon division of space was rather questionable as pointed out by further analyses of the data in *Chapter 2* and later performed experiments in *Chapter 3* and *4*.

The first and foremost indication hereof was the finding that all teams (*Chapter 2*, *3* and *4*) revealed a certain amount of overlap between interception domains instead of the space division being clear-cut. That is to say, boundaries between interception domains of the two team members were never absolute but were rather fuzzy, implying that there was a certain area on the interception axis where both participants intercepted some balls. From a boundary-based division-of-space hypothesis, such excursions into the interception domain of the other might be taken to represent incorrect predictions of ball arrival positions and hence erroneous decisions to intercept that ball. Nevertheless, if the decision to intercept a ball or not only depended on future ball arrival positions and boundary-based interception domains, I would have expected to see more collisions with increasing magnitude of the excursions into a partner's domain. Instead, collisions mainly occurred close to the boundary separating both interception domains. Moreover, the 'intrusions' into their partner's interception space did not necessarily result in more collisions or a lower interception performance. On the contrary, the majority of observed excursions were found to result in successful interceptions and dyads with larger overlap between interception domains did not show lower interception scores than dyads with smaller overlap. Whereas such successful excursions into a partner's interception domain might be explained as coincidental errors in decisions of a team member, the high prevalence of successful interceptions outside their respective interception domains suggests that the decision to intercept a ball or not is neither dependent on coincidence nor a consequence of mutually-shared boundary-based interception domains.

A second indication of the inadequacy of a geometry-based division-of-space hypothesis was the observation that boundary locations between interception domains varied largely over teams and, notably, shifted within teams when conditions changed. The findings of *Chapter 3* hereto were important as they revealed that with a change in the initial position of the RP's paddle, the boundary between interception domains shifted accordingly. That is not to say that boundaries shifted as far as being located exactly halfway both initial paddle positions. No, instead of an average shift of 5 cm required for a geometry-based boundary located exactly halfway both initial paddle positions, boundaries shifted on average around half that distance, indicating that they were not based on any geometrically defined point of reference. Moreover, *Chapter 3* and *4* showed that in all of the symmetrical conditions –in which both team members' paddles were initially located at similar distances from the vertical midline of the screen– boundary locations could vary widely amongst dyads as a result of, among other things, participants' idiosyncrasies[9]. These results confirmed that a division of space was not based on geometrically-defined boundaries and, more generally, they suggested that a boundary-based division of space resulting from tacit agreement was highly unlikely.

A third and last observation typically seen over studies was less of a proof against boundary-based interception domains but, together with aforementioned findings, more a reason to, generally, question the use of a decision-making perspective as an account for joint-action coordination in our doubles interception task. As frequency counts of the initiation of interceptive movements of both participants revealed that overlap between interception domains was not only spatial but also temporal, the experiments showed that a division of labor was not that clear at the start of a trial either. Indeed, a look at the frequency of trials with movement initiation by both participants revealed that in almost a quarter of all trials (with a higher prevalence around the center of the interception axis) both participants

[9] Whereas all teams showed a clear division of interception domains, some of the teams decided on a somewhat peculiar division of space. For instance, in team 6 from *Chapter 2* it was the RP that successfully intercepted balls arriving right next to the initial paddle position of LP. Although the LP easily could have intercepted these balls, the LP let the RP's paddle move far leftward to intercept balls near its initial position resulting in an emergent boundary at a distance of more than 10 cm to the left of the center of the screen. Such a division of interception domains is referred to as idiosyncratic as it deviated from the norm while interception performance of both individual members as well as the team performance was quite good.

initiated a movement implying that, at least in those trials, the decision as to who was to intercept the ball was made on-the-fly rather than being clear from the beginning.

Proponents of a shared knowledge-based account for joint action might argue that in these trials it took the individuals longer to gather enough information for making a precise prediction of the arrival position of the ball. At the same time, the imposed time-constraints required the participant to initiate a movement before decision completion as, otherwise, the interception would not have been possible altogether. Hence, being uncertain about the arrival position of the ball, both participants would start moving while continuously integrating information to decide to continue or abandon the interception attempt (see e.g., paragraph 1.2.1.1 in the introduction or Cisek, 2007; Lepora & Pezzulo, 2015 for a more detailed explanation of the continous integration of sensory input used for decisions in dynamic situations). Nevertheless, as aforementioned findings point out, the decision to intercept a ball or not does not appear to reside in a boundary-based division of space; the question is what information participants do use to decide to intercept the ball or not. Considering the flexible division of interception space and the low number of collisions, it seems likely that they use information about (the functionality of) their teammate's interceptive movements. With that in mind, an account based on the integration of sensory information about the trial characteristics (see also *Chapter 4*) and actions of their team member, hence, might not be the most parsimonious way to explain observed patterned interception behavior.

Indeed, to enable the close spatiotemporal coordination observed in our studies, an information-processing approach to real-time social interactions requires participants to make predictions about the (consequences of the) behavior of their partner (e.g., Bekkering et al., 2009; Bicho et al., 2011; Pezzulo & Dindo, 2011; Sebanz & Knoblich, 2009; Vesper et al., 2010). These predictions, hence, might be used to decide to continue an interception attempt or not. However, in dynamic situations like our doubles interception task that requires fast on-the-fly adaptations of one's behavior, shared representations are supposed to contain knowledge about the interactive roles of both participants as well, as knowledge about the individual action plans of both the self and another is not sufficient to let both participants simultaneously act together (cf. Marsh et al., 2009). Although it is unclear how such interactive roles are neurally represented, clear is that such an account would imply a large computational load (cf. Marsh et al., 2009; Schmidt et al., 2011) and that the proposed decision-making perspective would lose its straight-forward appeal, that is, its simple nature of assigning the interception to the left or right playing participant based on the to-be-covered space left or right of a tacitly agreed-upon boundary. An account for decision making in joint actions based on shared representations, hence, might prove limited when accounting for *in-situ* coordination of multiple actors acting together on a doubles interception task.

Taken together, aforementioned findings provide converging evidence that observed division of interception space does not follow from any type of mutually-shared boundary-based interception domains. Indeed, an account for observed division of labor that confines the decision to intercept a ball or not to a predicted ball arrival position left or right of a (tacitly) agreed-upon boundary has proven limited. The decision of who intercepts a ball where appears to be founded in between-participant interactions rather than in situational geometry. Consequently, a decision-making perspective, taken to represent a cognitive approach to joint-action coordination, might not be the most satisfactory approach to account for observed joint decision behavior in our doubles interception task. Rather than focusing on internal cognitive structures, observed coordinated patterns of behavior might be better accounted for with a focus on the social unit at the level of the interactions between individuals with respect to their environment (Marsh et al., 2006, 2009; Richardson et al., 2010; Schmidt et al., 2011; Warren, 2006).

5.2.2 Social coordination perspective

In a dynamics-based social coordination approach to joint action, the emphasis lies on the self-organizing nature of a system of two co-acting individuals. Instead of looking for an explanation for behavioral control in neurophysiological areas, a dynamical approach to human behavior provides a way to describe the lawful principles that govern the causal unfolding of social interactions (Kelso, 1995). From this point of view, a collective is not directed by something or someone, but is self-organized in that interactions at a microscopic scale lead to the emergence of patterned behavior at a more macroscopic scale (Kelso, 1995; Kugler & Turvey, 1987). In our doubles interception task this means that, under a given set of constraints, interactions between informationally coupled individuals should give rise to coordinated patterns of behavior at the level of the collective (e.g., Marsh et al., 2006;

Richardson et al., 2010; Riley, Richardson, Shockley, & Ramenzoni, 2011; Warren, 2006). With the activity of one individual in a system being constrained by (i.e., dependent on) the activity of the other individuals in that system, the interaction itself is critical for an account of the observed behavior (Coey et al., 2012). Taking a social coordination perspective to the problem at hand, hence, emphasizes the interactions between both cooperating team members and their direct environment (i.e., the moving ball) in an account of dynamic patterns and behavioral regularities at the level of the collective (Marsh et al., 2006, 2009; Richardson et al., 2010). In the present thesis, I tried to demonstrate (or at least convincingly argue) that also in more goal-directed and discrete joint actions like our doubles pong task, stable behavioral patterns emerge from a process of self-organization between cooperating individuals.

Portraying a dyad intercepting balls together as self-organizing and an emergent functional unit requires a few assumptions to be met. First, patterns and behavioral regularities need to be observed at the collective level recurring under various circumstances. Such regularities are first indications that behavior between dyad members might be lawfully constrained and is attracted to certain stable behavioral states. Second, it is necessary to establish if the observed behavioral patterns result from a mutual influence between a system's components, that is, a coupling between individuals. Whereas this is obvious in, for instance, a situation in which individuals carry a sofa together and hence are physically coupled to each other, it is less clear in situations that rely on an informational coupling between individuals like is the case in the doubles interception task under study. With behavioral regularities and a necessary coupling between dyad members identified, a last step would be the simulation of a system's dynamics to shed light on the structural relations that give rise to the successful coordinated and robust behavior. Simulating a system's behavior would allow to make testable predictions and validate hypotheses in order to uncover the fundamental processes that shape and constrain cooperative actions in a doubles interception task.

Findings reported in this thesis provide converging evidence that a team intercepting balls together might indeed be perceived as self-organizing with the observed joint interception patterns being the emergent result of the ball-related interactions between both team members. A first indication hereof was the observation that teams revealed characteristic patterns of a division of space between both team members in all of the experiments reported in this thesis. That is, all teams showed a clear division of interception domains with a certain amount of overlap, showing similar stable behavioral solutions to the task requirements to intercept as many balls possible as a team without colliding with each other. Hypothetically, many other solutions exist: for instance, both participants could have decided to alternate the interception of balls arriving at locations in between both initial paddle positions or they could have opted for a division of labor in which these balls were intercepted by only one of the participants. Yet, all teams ended up intercepting balls in (which afterwards turned out to be) clearly demarcated interception domains. Whereas the first observations reported in *Chapter 2* could not eliminate the possibility that labor was divided based on tacit agreements, later studies indicated that observed patterns of division of labor were the emergent result of the team members' interdependent interceptive actions. To summarize, *Chapter 3* revealed that with a change in initial position of the RPs, the LPs systematically intercepted more balls when the RPs were initially positioned further away. In addition, *Chapter 2, 3* and *4* revealed that boundary locations between interception domains varied considerably over teams, showing that, together with the low number of collisions, a division of space, among other things, must have followed from perceived actions of a team mate. Furthermore, and perhaps most important, our findings indicated that participants seemed to use information about the expediency of their partner's interceptive movements to decide to abandon their interception attempt or not. An expedient movement, for present purposes, was characterized as attaining $d\beta/dt \geq 0$, as, by physical law, a positive rate of change of angle β implies that the participant's paddle, when continuing at current movement speed, will arrive ahead of the ball at the future arrival position at the interception axis and that this participant, thus, is engaged in an expedient movement for a successful ball interception. Interestingly, *Chapter 2* and *3* revealed that being the first to engage in an expedient movement was closely related to being the one to intercept the ball, implying that in all trials in which both participants initiated a movement the other necessarily abandoned his or her interception attempt. Abandoning an interceptive action, this way, seemed closely tied to the expediency of a partner's actions (see also section 5.2.3 and 5.3 of this discussion for a more detailed explanation about how the expediency of one team member could be informative for the other).

Together with the conclusions formulated in the previous section that a division of space was not based on situational geometry or tacitly agreed-upon boundaries, above-mentioned findings suggest that members of a team used information about their partner's position and (expediency of their) interceptive actions to decide to go and intercept a ball or not. This way, our studies support the view that (social) behavior is not stereotyped or rigid but rather flexible and emerging from local interactions between (informationally-coupled) agents and between the agents and the environment (see e.g., Correia et al., 2012; Travassos et al., 2012; Warren, 2006). Below I will explain in more detail how the observed joint interception patterns can be understood as resulting from continuous and dynamic interactions between team members in relation to the ball, therewith providing an action-based account for the observed coordination in teams performing our doubles interception task.

5.2.3 Action-based account for joint interception behavior

Besides patterned interception behavior (*Chapter 2*) and a coupling between team members (*Chapter 3*), the experiments described in this thesis also provided the first suggestions for an action-based account for the observed joint decision behavior. Following the findings in *Chapter 2* that joint interception behavior seemed principle-based (i.e., the first to attain a positive rate of change of the angle β will be the one to intercept the ball) we proposed a simple action-based criterion based on the rate of change of the angle β (also referred to as angular velocity; AV), which allowed us to test some of our predictions regarding the outcome of a trial (i.e., who would be the one to intercept the ball) as being the emergent result of the interactive behavior of participants during the trials. Here, I will explain in more detail how our action-based criterion possibly serves as an account for the emergent division of labor and the on-the-fly decision process, therewith, showing its possible value for unravelling the organizational principles underlying the division of labor in a doubles interception task.

Whereas $d\beta/dt$ was first introduced in *Chapter 2* to visualize the temporal co-evolution of the interceptive movements of both participants' paddles, this key-variable appeared to be highly related to the interception outcome, as the first participant to obtain a positive angular rate of change was in a grand majority of the trials the one that intercepted the ball. Bearing in mind that a positive angular rate of change of β means that a paddle is (currently) to arrive at the interception location ahead of the ball, these findings pointed out that the first to engage in an expedient interceptive action was likely the one to intercept the ball. Hence, from the point of view of the non-intercepting participant, this might have been the information used about (the expediency of) their partner's interceptive actions in their decision to abandon their interception attempt or not. Indeed, if a participant was to perceive that its partner's paddle was engaged in an expedient interceptive action he or she could safely decide to abandon his or her own attempt as a successful interception (attempt) was to follow. This way, dβ/dt appeared to be more than just one of many possible variables relating to the ongoing triangular interactions between both participants' paddles and the ball.

Although some researchers might argue that the temporal evolution of dβ/dt and, particularly, the event of obtaining a positive angular rate of change is a mere post-hoc description of the situation and a prerequisite for a successful task performance, simulating the outcome of each intercepted trial as done in *Chapter 2* and *3* pointed out that the close relation between obtaining a positive angular rate of change and intercepting the ball has more to it than just being a coincidental reflection of the task demands. First, applying the action-based AV criterion that attributes the interception to the participant first attaining $d\beta/dt \geq 0$ not only correctly predicted the outcome in an overwhelming majority of the trials (± 98 %), but it also provided first evidence that also the timing thereof seemed related to the abandoning of the interceptive action by the non-intercepting participant (as exemplified by peak velocity values; see *Chapter 2*). Indeed, in 85 % of all trials, the non-intercepting participant reached peak velocity after their partner obtained $d\beta/dt \geq 0$, indicating that (the observation of) the event of a partner attaining $d\beta/dt \geq 0$ might have led the non-intercepting participant to decrease their velocity in order to avoid colliding. Important here is that even in almost 84 % of the early abandoned interceptive actions (exemplified by trials with lower peak velocity values than might have been expected in typical interceptive actions for ball arriving at a comparable location; *see Chapter 2*) followed after a partner (early in the trial) engaged in an expedient interceptive action. Second, simulations of the interception outcome in *Chapter 3* showed that also under different circumstances (i.e., symmetric and asymmetric initial paddle positions) the same principle-based behavior allowed for the qualitative aspects of the observed joint interception patterns to be reproduced, that is, the clearly demarcated interception domains together with the observed shift in boundary locations and the changing amount of overlap between interception domains. Even though simulated overlap tended to be somewhat larger than observed overlap, this finding shows the ability of an information-based coupling to explain the observed phenomena. Last, even the idiosyncrasies of some teams regarding their way of dividing labor were reproduced, showing that a team's decision who will intercept the ball –even though sometimes peculiar– might be understood as emerging from the ball-related between-participant interactions.

Whereas aforementioned simulations almost perfectly predicted the outcome of trials all along the interception axis, we mainly focused on the trials with ball arrival positions in between initial paddle positions. Because in this area the ball could have been intercepted by both team members and revealed a high frequency of trials with an initiation of both team members, these trials embodied the on-the-fly decision process at the heart of this thesis. Before initiating any movement and with the ball starting to move downward across the screen, all these trials were characterized by a negative $d\beta/dt$ for both participants from the start. As participants began moving their paddles they actively altered their paddle-ball relation resulting in increasing values of $d\beta/dt$ for both participants. These trials thus allowed us to simulate trial outcome as the first to attain $d\beta/dt \geq 0$ after which the participant that was engaged in a less expedient interceptive action could have abandoned his or her attempt. Note that in a considerable amount of the trials both participants attained $d\beta/dt \geq 0$ and thus both were, at some point in time, engaged in an expedient interceptive action (see the top-right quadrant of panel D of Figure 2.8). If at this stage both team members were to continue their interception attempt, a collision would inevitably occur. Yet, our simulations pointed out that, here as well, the first to engage in a functional interceptive action was the one to successfully intercept the ball. The (apparent) engagement in an expedient interceptive movement of the non-intercepting participant should undoubtedly be taken to reflect the visuomotor delay between perceiving the partner reaching $d\beta/dt \geq 0$ and subsequently decelerating and abandoning their interceptive action. In all, the simulations revealed that for trials in which both team members initiated a movement, the decision to abandon an interception attempt or not depended on the temporal evolution of the expediency of a partner's actions captured in $d\beta/dt \geq 0$.

Interestingly, observations from the other three-quarters of the trials could be accounted for in a similar fashion. Consider for instance balls arriving at or beyond a partner's initial paddle position, that is, left of the LP's paddle and right of the RP's paddle. In these trials, the decision for an interception by LP or RP is rather clear, as the other team member is not able to arrive at the future arrival position of the ball without colliding. Accordingly, a large majority of these trials were characterized by a movement of only the intercepting participant, implying that there was information available for the non-intercepting participant that their partner's paddle was in place to intercept the ball. Interestingly, the intercepting participant's paddle-ball relation dβ/dt was ≥ 0 from the beginning of the trial. Simulations with our action-based AV criterion, hence, correctly (although directly at the start of the trials) attributed the interception to the participant actually intercepting the ball. These findings suggest that the information used when deciding not to initiate an interceptive action might be similar to the information related to the abandoning of an interception attempt (i.e., dβ/dt ≥ 0). A non-initiation, hence, might be conceived of as an early abandoned interception attempt, highlighting the use of the same information when deciding to initiate an interception attempt or not and to abandon one. This way, our action-based AV criterion provides a simple but parsimonious account for multiple characteristics observed in the joint interception patterns.

5.2.3.1 Action-based versus computational account

The simple but all-encompassing nature of our action-based account for observed division of labor becomes more evident when considering the factors that need to be taken into account for a successful prediction of trial outcome. With a statistical regression analysis to study which factors (i.e., trial characteristics) affect the probability of an interception by LP or RP, *Chapter 4* revealed that for a successful prediction of trial outcomes factors like ball arrival position, ball speed, lateral ball movement (i.e., lateral distance between ball departure and arrival position), the session in which teams performed and several interaction effects between those factors all should be considered. Taking all these factors into account, the analysis allowed for a successful prediction of trial outcomes in over 98 % of all trials, comparable to the amount of correctly predicted trial outcomes with our action-based simulation. However, whereas our action-based criterion provides an account for decision behavior as it unfolds over dyads during trials, the statistical analysis only highlights which combination of factors increases the possibility of an interception by the left or right playing participant. This way, the statistical analysis represents a more computational approach to observed decision behavior and seems limited as an alternative account for observed decision behavior. Indeed, it would imply that both team members are able to perceive, among other things, the exact ball arrival position, ball speed and lateral ball movement early during the trial and are able to integrate these factors as 'building blocks' to come to a decision of an interception by the left or right playing participant. Considering that all this happens within one second, such an explanation of observed decision behavior would entail a high cognitive load, not to mention the difficulties a dyad might have to come to the same decision from calculations in two separate brains. The way of analyzing interception behavior as done in *Chapter 4* thus might be informative for researchers as it highlights the significant factors influencing the collective decision-making behavior, but as an account for observed decision behavior it is limited.

For a more parsimonious explanation of observed behavior our action-based AV model seems better suited. This account stands out for its simplicity and effectiveness of coupling information to behavior as it showed that the abandoning of interceptive actions seems coupled to perception of functionality of a partner's actions. This way, it provides an interesting suggestion for future studies to reveal the informational basis underlying joint-action coordination in a doubles interception task. Taken together, the two ways of simulating a team's division of labor that appeared in this thesis contribute significantly to reveal some of the fundamental aspects of a division of labor in a doubles interception task, however, as an account for observed joint decision behavior our action-based criterion seems far more appealing.

5.2.4 Concluding remarks for an interaction-based account for a division of labor

In all, the findings presented in this thesis provide converging evidence that observed patterns of joint interception emerge from the interactions between members of a team instead of being based on the existence of tacitly agreed-upon boundary-based interception domains. The quantification of ball-related local interactions with our action-based criterion revealed that the decision to intercept a ball or not seemed to be principle-based. Indeed, in order to avoid collisions and allow for a successful interception of the ball, all that both team members have to do is act in such a way that when one team member's paddle attains a specific relation with the ball (i.e., a positive rate of change of angle β) and, thus, is engaged in an expedient interception attempt, the other should get out of the way. This way, there is no need to know when and where the ball will arrive; neither does one have to predict the actions of their team member to successfully coordinate the interceptive actions of both team members and achieve an optimal team performance. Like observed in other studies on social coordination in humans (e.g., Kiefer et al., 2017; Passos et al., 2011) as well as in animal groups (e.g., Couzin & Krause, 2003; Couzin, Krause, Franks, & Levin, 2005), aforementioned rule-based behavior emphasizes the self-organizing nature of a team intercepting balls together, bounded by their mutual goal and the constraint not to collide. These findings highlight the pertinence of an interaction-based account for the observed action coordination (i.e., division of labor) in dynamic joint activities.

5.3 On information specifying the expediency of interceptive movements

From the perspective of an ecological approach, perceiving the expediency of an interceptive movement might be understood as resulting from the use of prospective information. As briefly mentioned in the introduction, prospective information is (time-evolving) information about the state of a particular (i.e., pertinent) relationship with the environment that is lawfully related to the current future (Bootsma, 2009). Establishing and subsequently maintaining such a particular relationship with the environment thus guarantees the future outcome of an action, such as intercepting a moving target (e.g., Chapman, 1968; Peper, Bootsma, Mestre, & Bakker, 1994; Turvey, 1992). By continuously attending to such information, specifying the state of the agent-environment system and thereby indicating what the agent must do so as to ensure the desired outcome of a certain action (e.g., interception), it is able to control its actions prospectively in an on-line fashion (Turvey, 1992; Turvey & Shaw, 1995). In this framework, studies into locomotor interception of targets moving along straight trajectories have shown that the rate of change of the target's bearing angle (i.e., the optical angle subtended at the point of observation by the target's angular position with respect to an exocentric reference direction; see also Bootsma et al., 2016), informs an agent on the adequacy of its actions when attempting to intercept a target. By physical law, a constant bearing angle (i.e., an angular rate of change of zero) specifies that an agent continuing to move at the present speed in the present direction will reach the interception location at the same time the target arrives there. The control strategy based on reaching and maintaining this state (of constant bearing angle) by nulling the rate of change of the bearing angle has been experimentally addressed in situations where the agent is constrained to move at constant speed and must therefore control the direction of locomotion (e.g., Fajen & Warren, 2007) and in situations where the agent is constrained to move along a fixed direction and must therefore control the speed of locomotion (e.g., Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999; Lenoir, Musch, Thiery, & Savelsbergh, 2002; Bastin, Craig, & Montagne, 2006; Chardenon, Montagne, Laurent, & Bootsma, 2004, 2005; Chardenon, Montagne, Buekers, & Laurent, 2002). While these studies invariably concluded that the results were compatible with a control strategy based on nulling the rate of change – that is, the velocity– in target bearing angle, this conclusion was recently challenged by Bootsma et al. (2016)

Indeed, results obtained in a lateral (i.e., direction-constrained) locomotor interception task militated against the use of an interception strategy solely based on information about the target bearing angle velocity. In an attempt to bridge the gap with studies on lateral manual interception (e.g., Arzamarski et al., 2007; Bootsma, Fayt, Zaal, & Laurent, 1997; Jacobs & Michaels, 2006; Ledouit et al., 2013; Michaels, Jacobs, & Bongers, 2006; Montagne, Laurent, Durey, & Bootsma, 1999; Peper et al., 1994), Bootsma et al. (2016) demonstrated that participants (goalkeepers moving along the goal line to intercept incoming balls) showed characteristic movement patterns that could not be accounted for by a strategy based exclusively on optical velocity (i.e., the rate of change of the bearing angle). Results revealed that interceptive movements of participants were systematically influenced by ball trajectory characteristics in that, for ball movements along straight trajectories, balls departing from different locations but converging onto the same location at the interception axis resulted in systematically different players' positions at 1 s for ball arrival, pointing out that movement kinematics differed over conditions where the ball reached the same interception location after the same flight duration but started from a different position. These findings revealed the presence of a so-called angle-of-approach[10] effect and, hence, that information about the

[10] In short, the angle-of-approach effect (Ledouit et al., 2013) describes the phenomenon observed in lateral interception that for balls following different straight trajectories starting from the same distance from the interception axis converging onto the same interception location after the same movement duration evoke different, trajectory-dependent movement kinematics. This effect, first observed by Peper et al. (1994), militates against an interception strategy based on predicted arrival position of the ball as these were invariant over trajectories. Instead, the observation of an angle-of-approach effect is evidence for a prospective control strategy underlying the interceptive actions, based

optical position of the moving target was used as well in the control strategy for intercepting a moving target.

The presence of an angle of approach effect in both a manual lateral interception task (in which participants intercepted balls in a plane of motion perpendicular to a participant's line of sight; see also Ledouit et al., 2013) and a locomotor lateral interception task (in which participants intercepted balls moving in the transverse plane; see Bootsma et al., 2016) suggests that an unique prospective control strategy might be underlying different types of human interceptive action. Controlling (and perceiving the expediency of) interceptive actions, hence, would be based on the use of (prospective) information about the state of the agent-target relation, but this state would not be fully captured by the rate of change (first-order derivative) of a pertinent optical angle. Since a discussion of the alternative proposed by Bootsma et al. (2016) of the use of information of fractional order is well beyond the scope of the present thesis, for the present purposes it is sufficient to bear in mind that control of interceptive actions cannot be adequately captured (but is approximated) by the use of first-order (i.e., rate of change related) information.

5.3.1 Perceiving the functionality of interceptive movements of others

In this thesis we introduced an interception task in which each individual participant was required to cooperate with another, who could intercept the ball as well. Because of the constraint not to collide, members of a team needed to decide on every trial who was going to intercept the ball. Interestingly, our observations showed that the decision to abandon an interception attempt or not was related to the state of a partner's angular paddle-ball relation captured by $d\beta/dt$. These observations raise the question whether participants might be able to use the same information as used in the control of their own interceptive actions (i.e., some type of combination of the optical position and velocity) to perceive the expediency of the interceptive actions of others possibly specifying the need to abandon an interception attempt.

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on the idea that the body or hand-position is continuously attracted towards an informationally-specified future arrival position of the moving object (Ledouit et al., 2013).

Although our results do not allow me to answer aforementioned question affirmatively, our observations do point out that information about the state of the optical angle β is possibly involved in the emergence of a division of labor between individuals cooperating on a doubles interception task. A first indication hereof was seen in our simulated attribution of trial outcomes (i.e., who will intercept the ball) based on the criterion of the first participant attaining $d\beta/dt \geq 0$. These findings showed that in the grand majority of trials the first to engage in an expedient interceptive action (i.e., $d\beta/dt \geq 0$) was indeed the one to actually intercept the ball. Consequently, in the trials where both participants initiated a movement, our simulation correctly predicted that the other abandoned his or her interception attempt. In the light of the foregoing, the decision to abandon an interception attempt might have followed on the perception of a partner being on its way to intercept the ball. Like in control of one's own interceptive actions, an optical velocity might be used to perceive the functionality of movements of others as well. Interesting therefore is that, although initially introduced to simply capture the time-evolving paddle-ball kinematics[11], the angle β and its rate of change (i.e., $d\beta/dt$) are actually optically accessible for both participants and, therefore, information available for participants to use in the control of their (interceptive) action coordination. The decision to abandon an interception attempt, hence, might have followed from detecting the relative motion between a partner's paddle and ball by using $d\beta/dt$ information about the current state of the partner's paddle-ball relation, specifying the instantaneous functionality of the partner's interceptive action. Considering that in order to avoid collision (that would impede successful interception) continued movement of both paddles towards the future arrival position of the ball is to be proscribed, acting according to the simple behavioral rule that the first to engage in an expedient interceptive action should continue its interception attempt, hence, seems a stable solution to the problem at hand corresponding with our observations.

[11] The rate of change of angle β (i.e., $d\beta/dt$) was chosen to capture the time-evolving paddle-ball relations of each participant, because it allows focusing on the relation between movements of the paddle and ball in a way that is independent of ball speed or distance to be covered by the participant. It is, moreover, outcome related as $d\beta/dt = 0$ specifies an upcoming interception and, hence, provides a way to capture the functionality with which a participant engages in his or her interceptive action.

Second, the presence of an angle-of-approach effect in the individual participants' interception behaviors was found to affect the division of labor between members of a team. The analysis performed in *Chapter 4* showed that lateral ball displacement (i.e., the lateral distance between ball departure and arrival positions, corresponding to the ball's angle of approach) significantly affected the observed division of labor over teams. This means that, especially in the area on the interception axis where both members of a team intercepted some balls (i.e., the overlap area), for balls following different trajectories and arriving at a similar location on the interception axis, the decision of a team for an interception by the LP or RP appears to depend, among other things, on the angle of approach of the ball.

All in all, these findings suggest that, like the interception itself, the decision of who intercepts a ball where (i.e., the division of labor) possibly follows from the use of prospective information related to the state of angle β with respect to the ball for oneself and, perhaps, also for one's partner. Placed within the framework of continuous control (e.g., Bootsma et al., 1997) and considering the findings of Bootsma et al., (2016), the whole action sequence of intercepting a ball –from not moving, via starting to move at a particular moment and moving in a particular way, to perceiving the expediency of a partner's interceptive action and subsequently abandoning of an interception attempt– might thus be understood using the same logic. Nevertheless, although available, the use of such information is, for now, still uncertain. Demonstrating that the observed behavior fits with the use of an informational invariant is not sufficient to conclude that the invariant actually modulates an individual's actions (cf. Lenoir et al., 1999; Michaels & Beek, 1995). More research is therefore needed to elucidate the informational basis of (manual) interception strategies and the possibility of perceiving the expediency of an interceptive action for oneself and, importantly, also for the other.

5.4 How should we conceive two individuals acting together?

The act of intercepting balls as a team, as a paradigmatic example for various social collision-avoidance tasks, is a rather particular example of social coordination as it is a cooperative activity in which an action of only one of both individuals involved is sufficient to succeed. Like two pedestrians approaching one another head-on are able to continue their stroll with one of them changing his or her course of action, only one participant will intercept the ball in our doubles interception task. An interesting question, hence, is how we should go about conceiving two individuals intercepting balls together. That is to say, how do the patterned interactions described in this thesis relate to behavioral organization in other social interactions? Taking as a starting point our suggestion that observed characteristic joint interception patterns emerge from information-based local interactions between dyad members and the ball, our studies support the view that (social) behavior is not stereotyped or rigid but in fact flexible, not necessarily depending on external influences and sustained by informational interactions between the participants themselves (Marsh et al., 2006; Passos et al., 2009; Richardson, Marsh, Isenhower, et al., 2007). The finding of these self-organizing principles underlying movement coordination, hence, point out that a dyad intercepting balls together might be conceived of as a single system with dynamics of its own (Marsh et al., 2006, 2009; Richardson et al., 2010).

5.4.1 Social synergy

Several studies on self-organizing collective behaviors have coined the term 'social synergy' to describe the emergence of such a new social unit (e.g., Marsh et al., 2006). A social synergy, or interpersonal coordinative structure, has been described as a functional grouping of individuals that are temporally and functionally constrained to act as a single unit. Like in intrapersonal synergies (e.g., motor synergies; see e.g., Latash, Scholz, & Schöner, 2007), characterizing interactions between individuals as synergistic helps identifying and predicting how stable functional spatiotemporal interpersonal movement patterns emerge out of a wealth of movement solutions possible.

As mentioned in the introduction, following a dynamical systems perspective a paradigmatic example of a synergy is found in studies on (interpersonal) rhythmic coordination. Whether coordinated at the intrapersonal or the interpersonal level, rhythmically moving limbs exhibit the same coordination phenomena (predicted by the well-known HKB model; see Haken, Kelso, & Bunz, 1985), such as the existence of more than one stable coordination mode, transitions between coordination modes at critical values of an a-specific control parameter (e.g., oscillation frequency in rhythmical activities) and increased variability within a given coordination mode (signifying loss of stability) when approaching a transition region. Based on these findings, various researchers have argued that interpersonal coordination in joint action might reflect the activity of a synergy, supported by a visual coupling, operating at interpersonal level (Marsh et al., 2009; Richardson et al., 2010; Riley et al., 2011; Schmidt & Richardson, 2008). This may explain that many recent studies performed on joint action coordination focused on the presence of such coordinative structures in a variety of social interactions, such as observed in continuous rhythmic activities (Black, Riley, & Mccord, 2007; Mottet et al., 2001; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; See also Schmidt & Richardson, 2008 for a review), in a rhythmic collision-avoidance task (Richardson et al., 2015), in interpersonal reciprocal and discrete precision aiming tasks (Ramenzoni, Davis, Riley, Shockley, & Baker, 2011; Romero, Kallen, Riley, & Richardson, 2015) and in team sport activities (Araújo & Davids, 2016; Passos, Araujo, Travassos, Vilar, & Duarte, 2014). Together, the findings reported in these studies suggest that in a variety of social activities our interactions might indeed be characterized as synergistic and, hence, that social coordination follows from principles of self-organization instead of being the result of blueprints of coordinated activity (e.g., predefined divisions of labor) or the execution of similar, hierarchically induced, motor programs mediated by shared motor representations (Pacherie & Dokic, 2006; Sebanz, Bekkering, et al., 2006; Sebanz et al., 2005).

Because findings in this thesis point out that coordinated behavior in a doubles interception task (i.e., division of labor) is neither predefined nor requires any references to shared motor representations, this brings up the question whether a dyad intercepting balls should be considered a social synergy as well. Considering the organization of collective behaviors as synergistic requires characteristics of a (social) synergy to be observed between elements comprising a system. Although there are different perspectives on what the relevant properties of a synergy are (see e.g., Latash, 2008; Riley et al., 2011), typically, the interactions between elements of a synergy are characterized by dimensional compression (DC) and reciprocal compensation (RC). DC implies that the dimension of the behavior of a system is lower than that of the constituent elements. This means that relevant elements of a system are coupled together by constraints imposed to reduce overall dimensionality of the system. Rather than changing independently, coupled elements of a system, hence, change together (Riley et al., 2011). With DC in place, RC refers to how the movements of one element of the system adapt to changes in the other. That is to say, with a perturbation of one element, another element can be used to compensate for the perturbations in order to stabilize task performance at the level of the collective (Riley et al., 2011; Romero et al., 2015). To speak of a synergistic organization, movement variance at the level of the collective, hence, should be lower than the sum of variances of each of the constituent elements separately (Black et al., 2007; Riley et al., 2011; see also the study of Mottet et al., 2001, for a demonstration of RC in a dyadic pointer-to-target task). Together with a specific contribution of each element to a group task (Latash, 2008), DC and RC, make it possible to modulate the behavior of a system for a successful action or task performance by controlling only one of them or by controlling a higher-order collective parameter (Black et al., 2007; Riley et al., 2011) and, hence, to ensure a system's flexibility to cope with unexpected events and perturbations on the system.

Do observations from our studies relate to the aforementioned characteristics of a social synergy? First, our observations did point out that participants depended on each other when intercepting balls together. Individuals and, more particularly, their on-screen paddles were coupled to each other because of their mutual goal and, importantly, the constraints to move along the same horizontal interception axis without colliding with a partner's paddle. Because of the constraint not to collide team members could not exhibit all of their potential behaviors (i.e., move along the entire interception axis) and, thus, depended on their partner to achieve their common goal of intercepting as many balls as possible. This way, the constraint not to collide led to the emergence of the characteristic division of labor[12], highlighting the unique

[12] Interestingly, findings from a non-reported additional experimental condition of this thesis' first experimental study showed that in the absence of the constraint to avoid colliding, division of labor over teams became much more variable. Indeed, as in that condition participants intercepted balls together while moving their paddles along (vertically) separated interception axes, the task did not include the possibility of collision between the two paddles. Results revealed large differences in the division of labor over teams. For instance, one team showed that the team member moving along the upper interception axis (with player assignment to the upper or lower interception axis varying randomly over trials) was in the large majority of trials the one to intercept the ball. Another team decided to form a larger interception platform by partially aligning both paddles in the vicinity of the future arrival position of the ball. Overall, the observation of different types of team organization in this unconstrained condition reveals the importance of constraints for the coupling between individuals and the emergence of patterned behavior at the level of a collective.

contribution of both team members intercepting balls in largely separated interception domains.

Despite the coupling and mutual influence between two individuals intercepting balls together, the identification of both RC and DC is less clear. Indeed, the way our experiments were set up does not allow for a direct evaluation of the so-called interpersonal synergy hypothesis (Riley et al., 2011). Although observed division of labor shows signs of RC between team members in that for team members that were initially located further away (and thus had to cover a larger distance to intercept balls arriving at the same position; see *Chapter 3*), the other team members compensated in a certain way for the perturbation of their team members' initial position as they intercepted more balls in a larger area, no analysis was performed to measure how variance at team level might have been related to movement variances at the level of both individuals that constitute the dyads. Neither could DC be identified as no pertinent measures were used to address the overall dimensionality of the system.

Besides, present observations did not allow us to identify an order parameter (i.e., a collective variable describing the state of a system) that appeared to be stabilized at collective level. That is not to say that a stable order parameter does not exist, however. Future studies should point out if, for instance, minimal spatial or temporal distance between paddles might be stabilized at a particular value so as to avoid colliding and assure the possibility for a successful interceptive action. Taken together, unlike what has been done in precision-aiming tasks (Mottet et al., 2001; Romero et al., 2015), in the present studies we were not able to clearly point out signs of both characteristics of a synergistic organization (i.e., DC and RC) underlying behavioral organization over teams. For now, it thus remains to be seen to what extent a dyad intercepting balls might in fact be considered a single synergistic two-person system.

5.4.2 Self-organizing collective

Rather than describing dyads in our study as social synergies, observed patterned interception behavior might be better accounted for as a self-organizing collective in the broadest sense of the term. That is to say, a dyad should be conceived of as a collective with coordinated behaviors at global level that emerge from the local interactions between the two dyad members and the ball. The collective is self-organized in the sense that it shows coordinated patterns of behavior between individuals with little direct external influence and without a 'self' inside the collective responsible for the (emergent) division of labor (Kelso, 2000). This way, observed behavioral organization in our doubles interception task bears similarities to observed spatiotemporal pattern formation in other biological systems like a flock of birds (e.g., Vicsek & Zafeiris, 2012), a school of fish (e.g., Couzin & Krause, 2003), a small pedestrian group (Kiefer et al., 2017) or a sports collective (e.g., Bourbousson, Sève, & McGarry, 2010; Passos et al., 2011). Pattern formation and coordinated behavior here seems to follow from simple behavioral interaction rules, pointing out that behavior is self-organized at collective level and emerging from local interactions and a mutual influence between the systems' elements.

By conceiving two individuals intercepting balls together as a self-organizing collective we emphasize the observed principle-based behavior at individual level and uphold our suggestions that social coordination in a doubles interception task and, therewith, division of labor is best studied at the level of the collective, that is, at the level of interactions between individuals and their environment. Indeed, our studies point out that for a complete and parsimonious account of observed coordinated behavior one should consider the system of the two paddles and the ball as a whole and focus on the way the spatiotemporal relations between those elements develop over time. This way, our studies may provide building blocks for future studies that dive deeper into accounting for the (perhaps synergistic) organization of joint interception behavior and, social coordination in general in situations in which our actions are coupled by a mutual goal and the constraint not to collide.

5.5 Assessing our new experimental paradigm

Research into joint action coordination is still rather scant, which is somewhat surprising considering the omnipresence of social interactions we engage in on a daily basis. Although interest for studies into social coordination considerably increased over the past 20 years (e.g., Marsh et al., 2006; Richardson et al., 2010; Rizzolatti & Craighero, 2004; Schmidt et al., 1998; Schmidt & Richardson, 2008; Sebanz et al., 2006; Sebanz & Knoblich, 2009), much remains unknown about the way we arrive at the tight spatiotemporal coordination necessary for a successful performance of our actions with those of others. In this thesis we developed a new experimental set-up to study joint decision behavior in a discrete goal-directed joint activity. As many of our social interactions in daily life involve a decision about what behavior to perform, or in some cases, what behavior *not* to perform in order to avoid colliding and achieve a common goal, joint decision-making is an integral part of our day-to-day joint action coordination. Consider for instance the awkward dances we sometimes perform when trying to avoid another pedestrian that is approaching head on. Such a situation typically requires a joint decision of both individuals in order to walk past each other either on the left or right hand side. Another paradigmatic example is found in serve reception in beach volleyball. Serve reception in beach volleyball requires cooperation between both team members whereas *in fine* only one will actualize the interception. A team, hence, is forced to make a decision as to who will intercept the ball and who will wait in order to avoid colliding. Aforementioned situations bring to the front the question how a decision comes about in such short time. All the more since possibilities for communication are often limited (or absent altogether), do such decisions necessary follow from a predefined division of tasks or are they made on-the-fly and, hence, the emergent result of the interactions between individuals? To what extent are the observed decisions 'joint' decisions and a coordinated team effort or should they, in fact, better be considered a mere aggregation of decisions made at individual level?

In order to answer the aforementioned questions, this thesis was dedicated to study how two individuals decide who is going to perform a certain action and who is not (i.e., how they decide on a division of labor) in a doubles interception task. In doing so, we developed a new experimental paradigm in which a two people cooperate on a goal-directed discrete movement task, while being forced to make a decision about who is going to perform a certain action on a certain occasion and who is not. As studying social interactions in dynamic real-life situations is technically still challenging and, moreover, does not allow for the necessary experimental control, we decided to first take a step back and study joint interception behavior in a video game-like interception task. Our doubles pong task allowed us to study how two people intercepting balls together decide on a division of labor. This way, it provided the first answers to some of the most basic questions as to how labor between individuals is divided and what information they use when deciding to intercept a ball or not. Our analyses led us to argue that an interaction-based explanation provided the most parsimonious account of observed division of labor and, furthermore, that participants seemed to use information about the expediency of their partner's interceptive actions when deciding to intercept a ball or not. At the same time, the abundance of results obtained over the different experiments reported gave rise to many new questions of which only few could be addressed in this thesis, highlighting the richness of the experimental paradigm introduced.

In this last section I will briefly discuss the advantages and disadvantages of studying social coordination (i.e., division of labor) and, more specifically, joint decision behavior in a set-up like our doubles interception task. In doing so, I hope to show that taking a step back to study decision making and social coordination in an (admittedly simplified but well-designed) experimental set-up provides a way to thoroughly investigate the basic principles underlying joint action coordination. Subsequently, I will elaborate on how ideas developed in this thesis might be generalizable to coordination in other (more natural) social contexts and, hence, how this thesis might contribute to a better understanding of joint action coordination and a division of labor in social situations. Finally, I will provide some suggestions about possibilities for improving the study of social coordination in a doubles interception task and round off with some suggestions for interesting directions of future studies that seem a logical next step to unravel the principles underlying the coordination of our goal-directed activities with others.

5.5.1 Methodological contributions of 'Playing pong together'

The introduction of our experimental paradigm opened up new ways of studying social coordination and, more particularly, the act of joint decision-making in discrete and goal-directed joint activities. First, by taking a step back and studying the joint activity of intercepting balls in a simplified experimental setting, the set-up allowed the necessary experimental control. Indeed, from the size, speed and trajectory of the ball, via the size and initial positions of the participants' paddles, to the information available for both members of a team (e.g., visuals on-screen and auditory information through communication or a partner's interceptive hand movement along our in-house constructed device), all could be regulated by the experimenter to create equal circumstances for all participating dyads and manipulate situational and informational constraints in a controlled way. This way, our doubles pong task provides a means to investigate, in a systematic fashion, how coordination (i.e., division of labor) comes about from the contribution of both cooperating individuals.

Second, the experimental set-up allows for an easy and thorough manipulation of the task and its constraints to investigate how different situational factors and constraints lead to a (possibly) different division of labor. Indeed, the task itself is easily manipulated because of its virtual (on-screen) character and, additionally, it provides the possibility for the experimenters to impose different roles or constraints on one or both members of a team. Our manipulation of the participants' initial positions, thereto, provided a simple but effective example. Moreover, with some of the basic principles underlying joint decision-making being identified in our first experiment in which teams played doubles pong in its most elementary form (i.e, only basic visual information available on a shared screen with equally divided arrival positions of the ball and without any communication before or during the task), future studies could attempt to focus more on the interaction process typically observed in trials where the ball is to be intercepted in the area between both initial paddle positions.

Third, the adaptation of this video game-like task allowed for a thorough analysis of participants' interactions and their decision behavior. Indeed, because on-screen paddle and ball movements were both directly digitally sampled (instead of being globally videotaped and subsequently digitized, e.g., Passos et al., 2011; or coordination being rated by experimenters, e.g., Blickensderfer et al., 2010) the experimental set-up provides a way to easily and reliably capture the (unidimensional) paddle kinematics to study the time-evolving triangular interactions between both participants and the ball. This way, the set-up allows studying how movements of participants might be structurally related to occurrent (on-screen) information. That is to say, it provides a way to study the perception-action coupling between two individuals intercepting balls together. This aspect indeed allowed us to make some suggestions about the way information about a partner's interceptive action is used when deciding to intercept a ball or not.

Last, not only does the task allow for a wide variety of manipulations of constraints, the experimental set-up itself can be easily extended as well. In order to reveal information pick-up, for instance, experimenters might provide both team members with an eye-tracking device to study their gaze behavior (see e.g., Dicks, Button, & Davids, 2010). This would allow testing whether participants indeed focus on their partner's interceptive actions (i.e., a partner's paddle-ball relation) when deciding to abandon their own interception attempt. The experimental paradigm thus opens up a wealth of possibilities for the study into joint decision-making and social coordination in general, emanating from the simple but versatile nature of the task.

In all, the experimental set-up introduced in this thesis is unique in the sense that it combines the more observational studies on social interaction in natural (sports) contexts (Araújo et al., 2006; Araújo, Diniz, Passos, & Davids, 2013; Bourbousson et al., 2010a, 2010b; Hristovski et al., 2006; Passos et al., 2011) with the possibility for manipulating task constraints as observed in various dyadic rhythmical coordination studies performed in controlled experimental environments (Mottet et al., 2001; Richardson et al., 2015; Richardson, Marsh, Isenhower, et al., 2007; Schmidt et al., 1998, 1990; Schmidt & Turvey, 1994). This way, it allowed us to study how the free interplay between individuals and the ball resulted in stable behavioral solutions at team level and, hence, how they divided labor to achieve a common goal of intercepting as many balls as possible under a given set of informational and physical constraints. Whereas, studies on cooperation in goal-directed joint actions typically require a complementary action of both individuals to complete a given task (Ramenzoni et al., 2011; Richardson et al., 2015; Romero et al., 2015), present cooperative activity is different as the two individuals cannot perform the full interceptive action together and, hence, a decision between individuals is required as to who will ultimately perform the action and who will not. Besides, instead of looking for neurological structures underlying social interaction and decision behavior (although an adapted set-up might allow measuring neural activity when combined with e.g. fMRI; Newman-Norlund, Bosga, Meulenbroek, & Bekkering, 2008), it provides a way to study how in-situ coordination (i.e., division of labor) emerges from the time-evolving interactions between individuals with no need for communication or predefined roles. This way, our task, like for example the dyadic plank carrying task (Isenhower et al., 2010; Richardson, Marsh, & Baron, 2007), is representative for its particular category of goal-directed social interactions and might contribute to a better understanding of the social interactions we encounter on a daily basis.

5.5.2 Generalizations

In this thesis we decided to take a step back and study social coordination and decision-making in a video game-like experimental set-up. With some of the basic principles being identified, it is interesting to consider if and how (some of) our results might be generalizable to more real-life settings. Indeed, observing the emergence of a division of labor in a virtual doubles interception task is one thing, but might observed coordinated patterns of movement in our daily life also be an emergent property of the interactions between individuals?

First, and perhaps most obvious, let us consider how our findings might relate to the exemplary situation our task was modeled after; the serve reception in beach volleyball. Our findings indicated that the decision to intercept a ball or not emerged from the ongoing triangular interactions between team members and the ball and, more particularly, that this decision possibly followed from perceiving the expediency (captured by rate of change of angle β) with which a partner engaged in its interceptive action. In volleyball this would imply that a player is able to evaluate the expediency with which a partner is engaged in the reception of the serve (besides perceiving their own spatiotemporal relation with the ball; see Lenoir, Vansteenkiste, Vermeulen, & de Clercq, 2005). Unfortunately, the interceptive actions participants performed in our doubles-pong where constrained alongside a uni-dimensional interception axis and, therefore, our findings are not directly generalizable to the 2D movements and spatiotemporal relations with the ball of players performing in an actual volleyball play. However, considering that the decision process during a volleyball only takes about one second (i.e., the mean time it takes from serve start to reception of the ball in top level volleyball; see Benerink, Bootsma, & Zaal, 2015), an account that places the origin of the decision to initiate and abandon an interception attempt or not in the spatiotemporal relation of a partner and the ball would provide a parsimonious explanation of the complex problem that is decision-making in volleyball serve reception. Instead of focusing on predefined interception domains ('does it arrive in your interception domain or mine?'), looking at the way you and a partner engage in the interception allows for a more functional division of labor whatever the arrival position of the ball. Nevertheless, although the information about the angular ball velocity might be optically available and appears to be involved in the reception of a serve in volleyball (see Lenoir et al., 2005), experiments revealing the use of such information to evaluate the interceptive actions of others have yet to be contrived.

More generally, in sports or other social interactions we encounter on a daily basis, our findings might be taken to represent decision behavior for a certain action that follows from the perception of the functionality with which a co-actor is engaged in its action. Such functionality might be specified by the rate of a change of an optical angle subtended by a line connecting the observer with a co-actor and another line connecting the observer with a point of reference related to a common goal (i.e., an object, another person or, in case of the bearing angle, a distant point near the horizon). Consider for instance a situation in which two colleagues are both walking towards a door to exit a conference room. Successful cooperation, here, signifies that both colleagues can leave the room without colliding before or in the doorway. If both colleagues were able to perceive that the rate of change of the optical angle subtended by a line connecting both individuals and a line connecting the individual and the door opening remains zero, by physical law, this would specify a, here unwanted, relation (i.e., a upcoming collision) with that person denying the desired future action. Purposefully changing the angular velocity (making it positive or negative) by a change in walking speed or direction of, at least, one of the colleagues would allow them to continue leaving the room without colliding in the doorway. This way, perceiving (no) change in the optical angle of a co-actor specifies if one is to arrive before (opening angle), at the same time (constant angle) or after (closing angle) the other and, thus, if any action is needed in order to avoid colliding. Without communicating or abiding to a pre-defined order of crossing the doorway, such an on-line account for the emergence of coordination from the interactions between individuals with respect to a common goal, would provide a parsimonious way to describe observed emergent cooperative behavior. Aforementioned generalizations and ideas, nonetheless, have to be considered with care. Future (empirical) studies should point out in how far we are actually able to perceive the functionality of the actions of another and, hence, how our observations might relate to observed coordination in real-life social settings.

5.5.3 Improvements for studying interpersonal coordination in an experimental set-up

Whereas our experimental set-up opened up new possibilities for studies into social coordination, there are some aspects of the experiments that might be improved in future studies. For instance, future studies could focus on the way the study design might be improved to decrease overall time spent on the experiments or to increase data output of the doubles session. The one-hour doubles sessions of *Chapter 2* and *4* resulted in 200 analyzable trials per team of which almost a quarter was characterized by a double initiation (with a high prevalence of trials with ball arrival positions around the center of the interception axis) and, hence, allowed for an analysis of the team members' interactions. Although over teams and over studies this resulted in a fair amount of trials to study the triangular interactions between team members and the ball, considering the time needed –two hour, including a first individual one-hour session of which the data has been marginally used in the analysis– the amount of useful data collected might be improved. A higher prevalence of balls arriving around the center of the screen, for instance, would allow the duration of the experiment to be shortened or the number of interesting trials for an analysis of the social interactions to be increased. Of course, manipulating the frequency distribution of ball arrival position might affect some aspects of the participants' behavior, which, by the way, would also be interesting in and of itself.

Second, future studies might pay more attention to (behavioral) characteristics of the individuals that compose a team. This way, one might be able to show how an individual's character or movement kinematics (e.g., fast and short or slow and longer interceptive movements) affects its role within a team and, thus, how it influences a team's division of labor. Also, it might be interesting to study how social motives such as social awkwardness shape the coordinative actions between members of a team. That is to say, members of a team might tend to act according to social norms by sharing the interception of balls equally instead of going after all balls possible and push away a partner's paddle (although some teams did not seem to care). Studying such constructs may provide a more complete picture of the way a dyad decides who intercepts ball where and improve our understanding of social coordination in general.

When trying to generalize the findings of our experimental set-up to more natural real-life settings, our set-up, for now, might (seem to) be kind of limited. Indeed, our observations may not directly apply to all aspects of decision making as, for instance, observed in serve reception during a beach volleyball match. As proponents of a more naturalistic approach to decision making might argue there are many more situational factors (e.g., sand and sun) that might play a role in the decision to intercept a ball or not than just the simple paddle and ball movements on a screen. Nevertheless, I for one believe that an experimental set-up like our doubles pong task does provide the experimental control necessary to reveal some first basic principles underlying joint decision behavior that, thereafter, can be tested in more natural situations. Therefore, the introduction of this experimental paradigm, I suggest, holds great promise for future studies into decision making and social coordination.

5.5.4 Future research

Interesting directions for further research abound. Whereas in present series of experiments we revealed some of the basic principles underlying coordinated behavior on a doubles interception task, future studies should evaluate whether these principles hold under different situational constraints as well. Besides some of the interesting suggestion for future studies provided in the sections before, below I provide two suggestions for future studies that follow directly on findings reported in this thesis.

A first important direction for future research to address is the way communication might play a role in division of labor. In this thesis we decided to preclude verbal communication between members of a team so that the decision to intercept a ball or not would come down to one based on visual information only. Interestingly, results showed that verbal communication, upfront or *in-situ*, was not necessary for a successful joint performance on our doubles interception task (although a priori considered essential by proponents of a shared-knowledge based account on social coordination; Clark, 1996; Eccles, 2010; Eccles & Tenenbaum, 2004; Ward & Eccles, 2006). Nevertheless, we did not study how coordination between members of a team would play out if they had been able to communicate a division of labor in advance or announce their decision to intercept the ball during the trials. Future studies should address the effect of communication on the coordination between team members and evaluate whether team performance and division of labor is changed (for better or for worse) when such communication is allowed. Similarly, it might be interesting to study how the ongoing triangular interactions between team members and the ball are affected in a condition in which teams are explicitly instructed to divide interception space around a specific point of reference.

A second idea for future studies would be to not only focus on successful cooperation, but also on trials in which cooperation and, hence, the interception was not successful. Indeed, in present studies we only used successful trials to test our action-based criterion. Obviously this was done as otherwise no outcome could be related to the first to engage in an expedient interceptive action. However, now we have seen that our criterion successfully accounts for the outcome in the large majority of successful trials, it might be interesting to look into the way team members coordinated their actions in the non-successful trials as well. Indeed, such an analysis might provide insights if failure on the task was the result of bad cooperation or just the failure at individual level to intercept the ball. Bad cooperation would imply that the team members did not adhere to the criterion 'the first to attain $d\beta/dt \geq 0$ will be the one to intercept the ball' which subsequently might have led to missing the ball. To study the failure of team members to adhere to the action-based criterion in non-successful trials one might think of taking the participant's paddle closest to the arrival position of the ball when it crossed the interception axis (taken to be the one that made the best interception attempt) and study if it was also the one to first arrive at a positive angular change (i.e., indicating that it was 'entitled' to intercept the ball but failed in its interceptive action) or not (i.e., indicating that it should not have continued its interception attempt in the first place and, hence, that it led to uncertainty about who was to intercept the ball). This way, the experimental work not only allows gaining insight into the coordination principles underlying a successful division of labor, but also into situations in which unsuccessful coordination follows from failure to adhere to the same principles.

Conclusion

In this thesis we sought to find out how two individuals cooperating on a doubles interception task decide who should intercept which ball where, that is, how they decide on a division of labor. To this end, we developed a new experimental paradigm to study how division of labor comes about between two individuals cooperating on a video game-like interception task. In the series of experiments presented in this thesis, verbal communication between participants was precluded and participants were to avoid contact between the on-screen paddles (with which they could intercept the balls moving downward across the screen). As a result, the visually informed decision about who was to intercept the ball and who was not constituted an important aspect of the task. Our results provided converging evidence that the remarkably clear division of interception domains (i.e., of the space domain along the interception axis where each participant intercepted balls) emerged from the time-evolving interactions between participants' interceptive behaviors with respect to their partner's dynamic paddle-ball relation. An action-based account of joint decision making that attributes the interception to the first participant to engage in an expedient interceptive action successfully predicted trial outcomes in the large majority of trials of all teams participating in the different experimental sessions. Also considering that all teams showed some degree of overlap between interception domains and that the division of labor depended on the team members' initial paddle positions, the decision to intercept a ball or not seemed to reside in the ongoing triangular interactions between both team members and the ball rather than being based on (tacitly agreed upon) predefined interception domains. Moreover, our work indicated that an alternative in which both team members relied on individual predictions of locations of ball arrival (with respect to a tacitly agreed-upon boundary between individual interception domains) would not only give rise to a high cognitive load but would also not be able to explain the full range of behavioral characteristics observed. Overall, our studies pointed out that a parsimonious account of joint decision making and the coordinated behavior observed on our doubles interception task required that one should consider the system of the two paddles and the ball as whole and focus on the way the spatiotemporal relations between those elements develop over time. In order to generalize our findings, future studies need to address whether similar coordination phenomena, emerging from the interactions between individuals with respect to their environment, may indeed be observed in other controlled laboratory tasks and, importantly, in real-life social interactions as well.

In sum, the introduction of our experimental 'Playing PONG together' paradigm opened up a wealth of possibilities for the study of joint decision making and social coordination in goal-directed joint actions. It allowed us to answer some of the first and most basic questions regarding the way division of labor between two cooperating team members comes about from the interactions between them. Many questions, of course, remain. Like a wise man once said 'The more you know, the more you know you don't know' (Aristotle). Nevertheless, I, for one, believe that with the experiments and analyses presented we have made a valuable contribution to science and I hope that this thesis may serve as a stepping stone for future studies into joint decision making and, more generally, social coordination in goal-directed joint actions to unveil more of the principles underlying our remarkable ability of action coordination in a social context.

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