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Division of labor as an emergent phenomenon of social coordination: The example of playing doubles-pong

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Niek H. Benerink, Frank T.J.M. Zaal, Remy Casanova, Nathalie Bonnardel, Reinoud J. Bootsma. Division of labor as an emergent phenomenon of social coordination: The example of playing doubles-pong. Human Movement Science, 2018, 57, pp.134 - 148. 10.1016/j.humov.2017.11.012 . hal-01668074

HAL Id: hal-01668074

<https://amu.hal.science/hal-01668074v1>

Submitted on 19 Apr 2018

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Manuscript Details

Manuscript number	HMS_2017_373
Title	Division of labor as an emergent phenomenon of social coordination: the example of playing doubles-pong
Article type	Full length article

Abstract

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Keywords joint action; interception; social coordination; coupling; emergence

Taxonomy Group Processes, Interceptive Action

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Suggested reviewers Duarte Araujo, Michael Richardson

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- Teams of two players performed a doubles interception task
- Initial position of one player was varied over trials
- Initial player positions affected division of interception space within teams
- We tested predictive and emergent accounts of division of labor among individuals
- Division of labor emerged from social coordination via continuous visual coupling

**Division of labor as an emergent phenomenon of social coordination:
the example of playing doubles-pong**

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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 through vision of the shared screen was excluded. 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 that 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.

1. 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, Lamothe, Daffertshofer, Semin, & Beek, 2008). For instance, Richardson, Marsh, Isenhower, Goodman, and Schmidt (2007) showed that two individuals sitting side-by-side in rocking chairs unintentionally fall into either an in-phase or anti-phase 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, and 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, for both players 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.

2. Methods

2.1 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 dyad composed of participants with comparable scores on the individual session. The other subset of 12 participants took part in a separate study.

2.2 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. 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.

***** Figure 1 about here *****

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.

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.

2.3 Procedure

2.3.1 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 left (LP) or right (RP) 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. 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.

***** Figure 2 about here *****

2.3.2 Doubles session

For the doubles session, pairs were formed by combining a LP and a RP that had performed similarly in their individual sessions¹. 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. 2B and 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.

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

¹ 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.

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.

2.4 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). If present, zero crossings in the time series of the rate of change of both these angles were detected.

***** Figure 3 about here *****

3. Results

3.1 Interception performance

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

***** Table 1 about here *****

Figures 4 and 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. 4A: 30-30 and Fig. 5A: 20-20) and the right panels the results of the asymmetrical conditions (Fig. 4B: 30-20 and Fig. 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. 4 and 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).

***** Figures 4 and 5 about here *****

The left side of Table 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. 4 and 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 2 (also see Fig. 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 2 also revealed the variability in the amount of overlap of space covered by both players across all teams and conditions (also see Figs. 4 and 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 2 about here *****

***** Figures 6 about here *****

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 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 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 6 indicated rather comparable distributions for all four conditions². The majority of initiations of only LP were associated with balls arriving on the

² 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.

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 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. 6, green bars). 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.

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

Figures 7 (LP30 group) and 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 7 and 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 2, right side).

***** Figures 7 and 8 about here *****

Reinforcing this conclusion, Figure 9 illustrates the correspondence of the patterns as determined from observation 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 9 about here *****

4. 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 a (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 systematically differed.

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. 4 and 5 and Table 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. 4 and 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). 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 2 and Figs. 4 and 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 5, 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 moving³ 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

³ 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.

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, Richardson, Baron, & Schmidt, 2006; Passos et al., 2009; Richardson et al., 2007).

To conclude, this study shows that in a doubles interception task the division of interception space (i.e. who intercepts which balls) 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 each team member’s interceptive action 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 spatiotemporal capacity of performers in such a complex joint activity (e.g., Davids, Renshaw, & Glazier, 2005).

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6. Figure Captions

Figure 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 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 the individual sessions, only one of the participants was present, sitting either on the left or right side of the table.

Figure 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 interception 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.

Figure 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. β_{LP} and β_{RP} 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.

Figure 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 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 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.

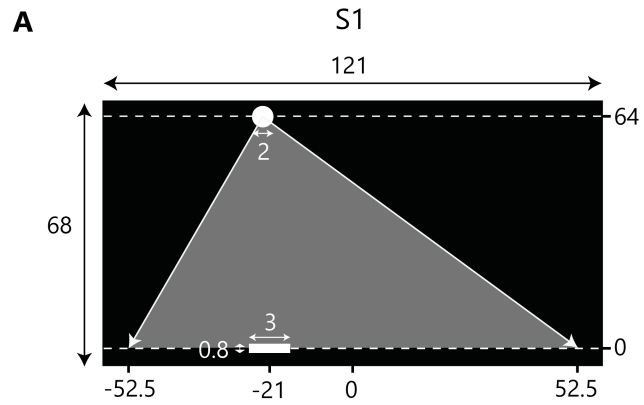
Figure 6: Frequency distribution of the observed movement initiations of the LP and RP as a function of ball arrival position for the LP30 group (A) and the LP20 group (B). Each trial arriving in one of 21 (5-cm wide) bins was classified as showing initiation of only LP (dark blue), only RP (light blue), both LP and RP (green) or neither LP nor RP (red).

Figure 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.

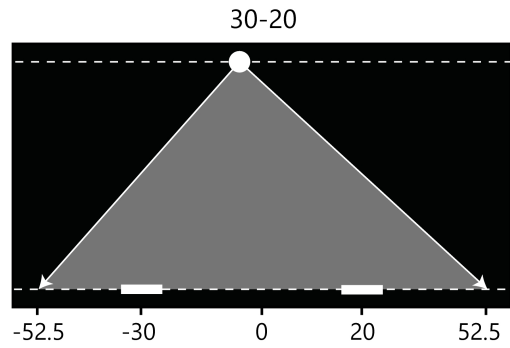
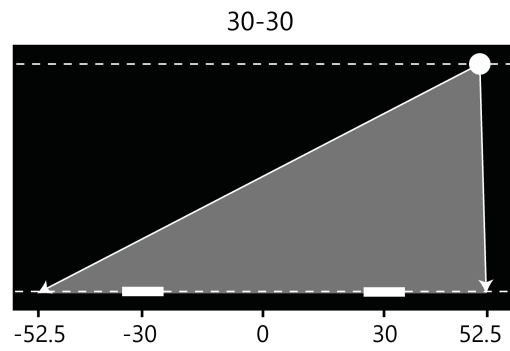
Figure 8: Graphical summary of predicted interception performance of the LP20 group as a function of ball arrival position for all four teams in both conditions (20-20 and 20-30) separately. The prediction of the participant to intercept the ball was based on first reaching $d\beta/dt \geq 0$. Ball arrival 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.

Figure 9: Graphical representation of the relation between predicated and observed boundary locations (A) and amounts of overlap (B) for each team in each condition.

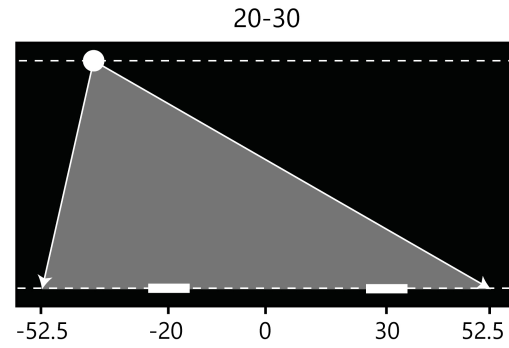
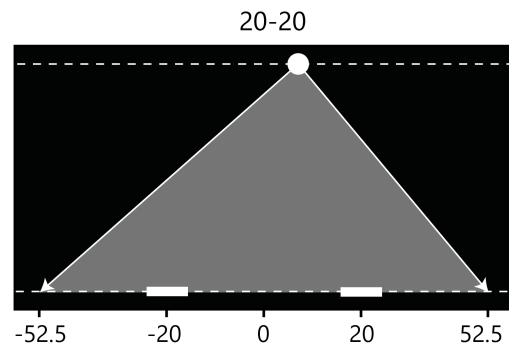


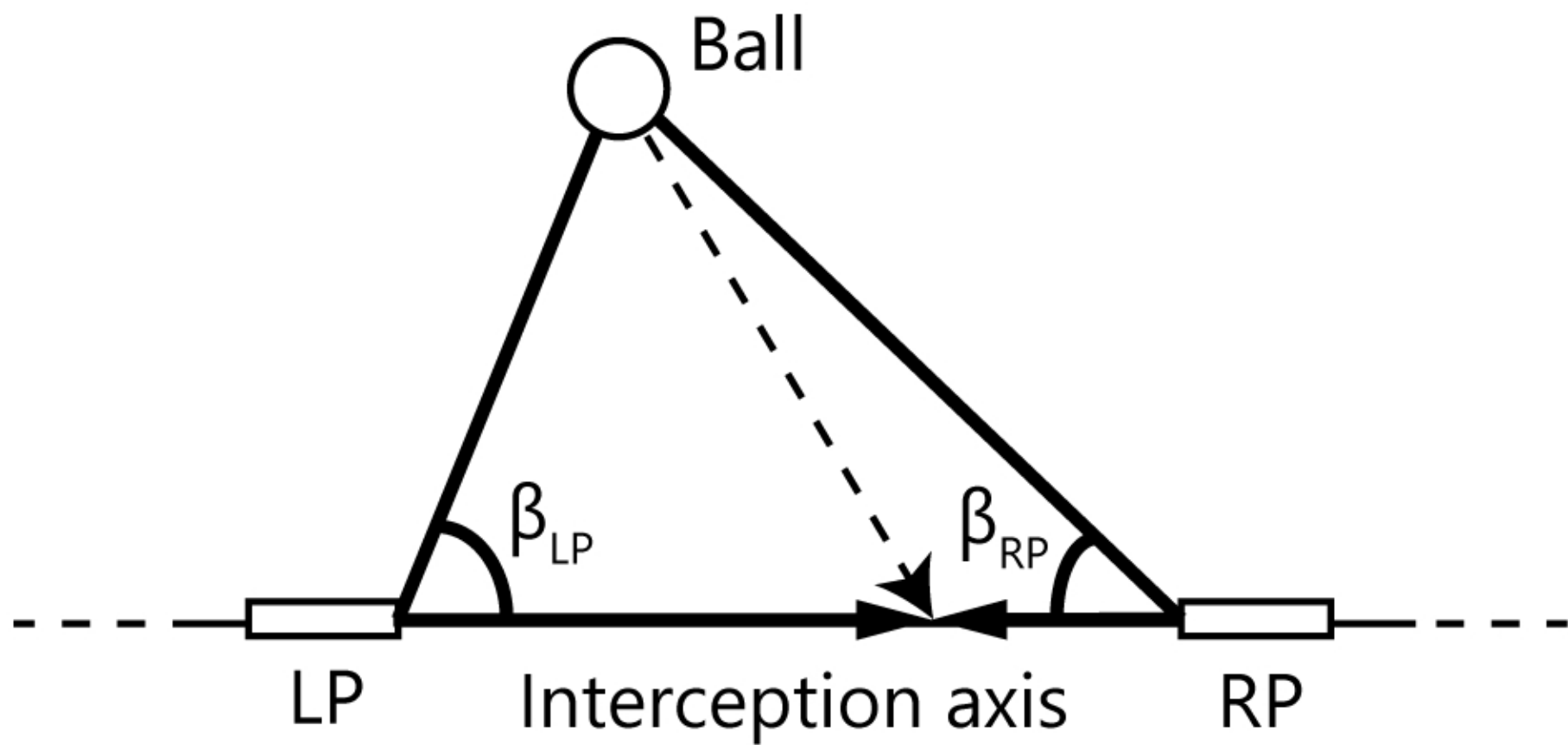


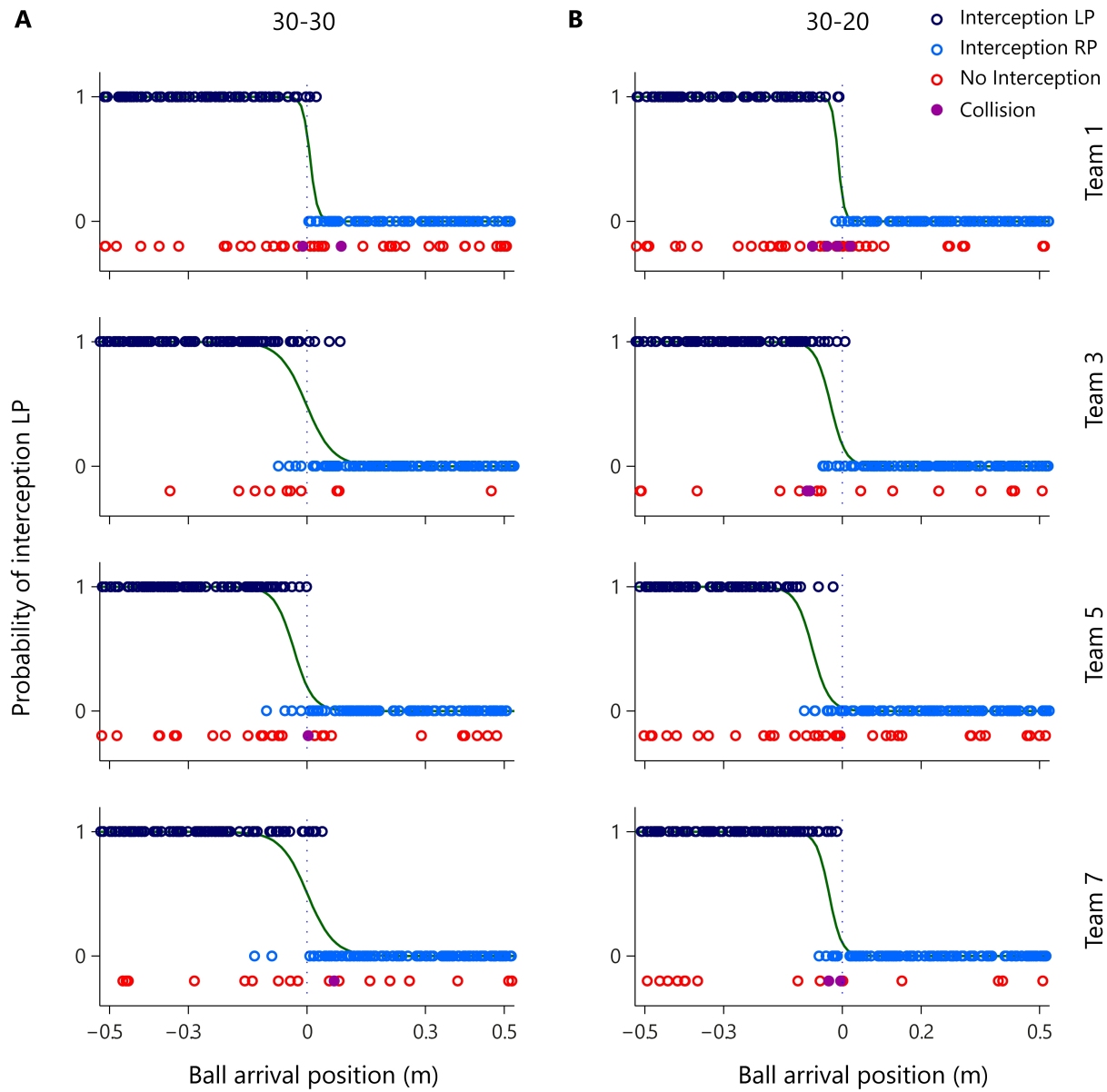
B S2 - LP30 Group

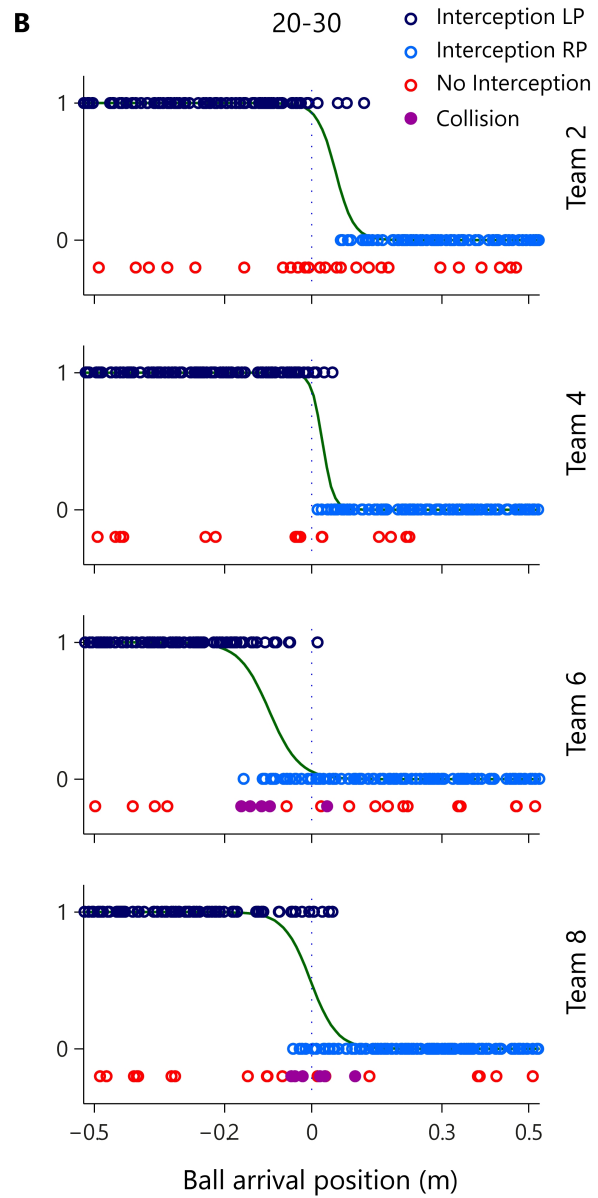
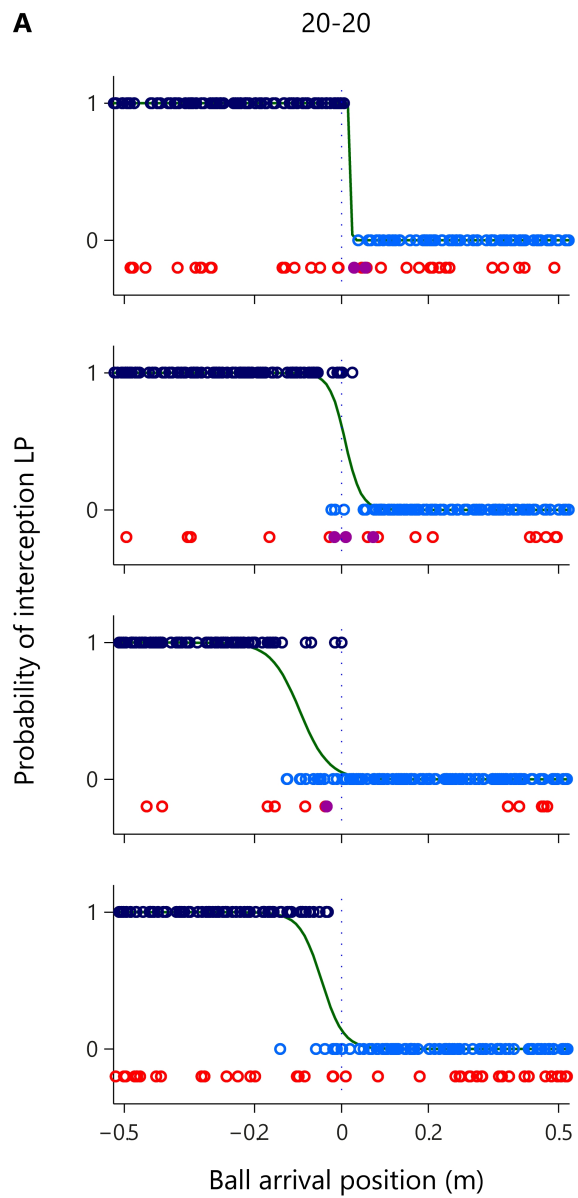


C S2 - LP20 Group

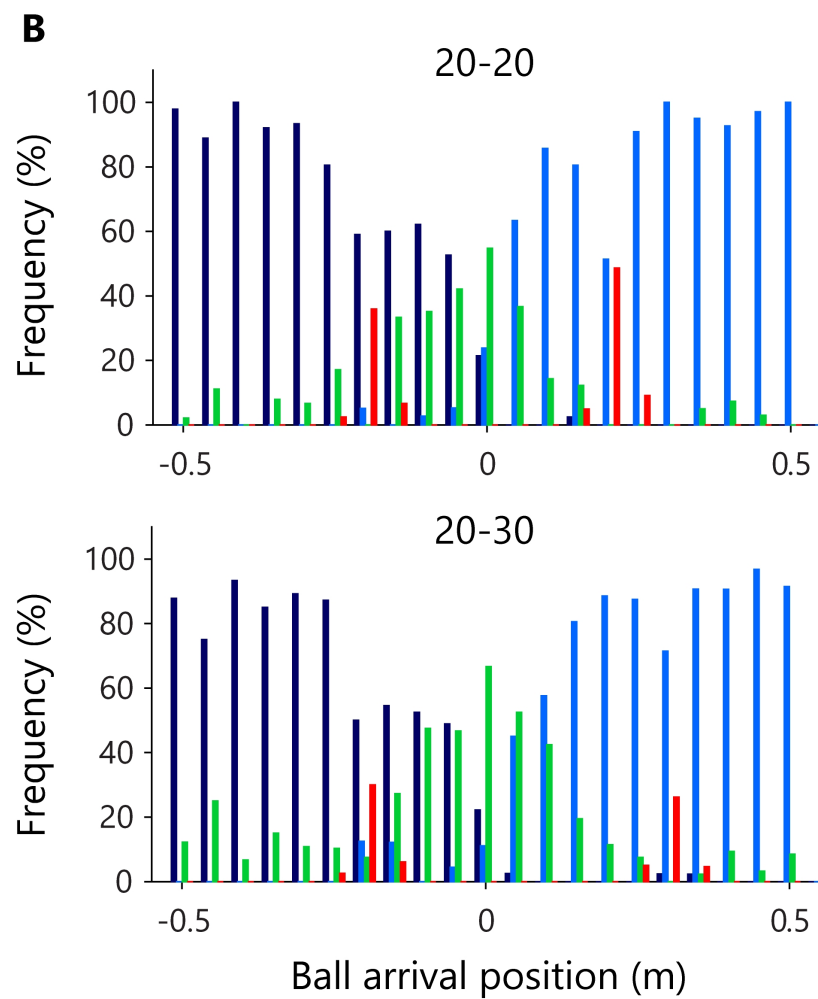
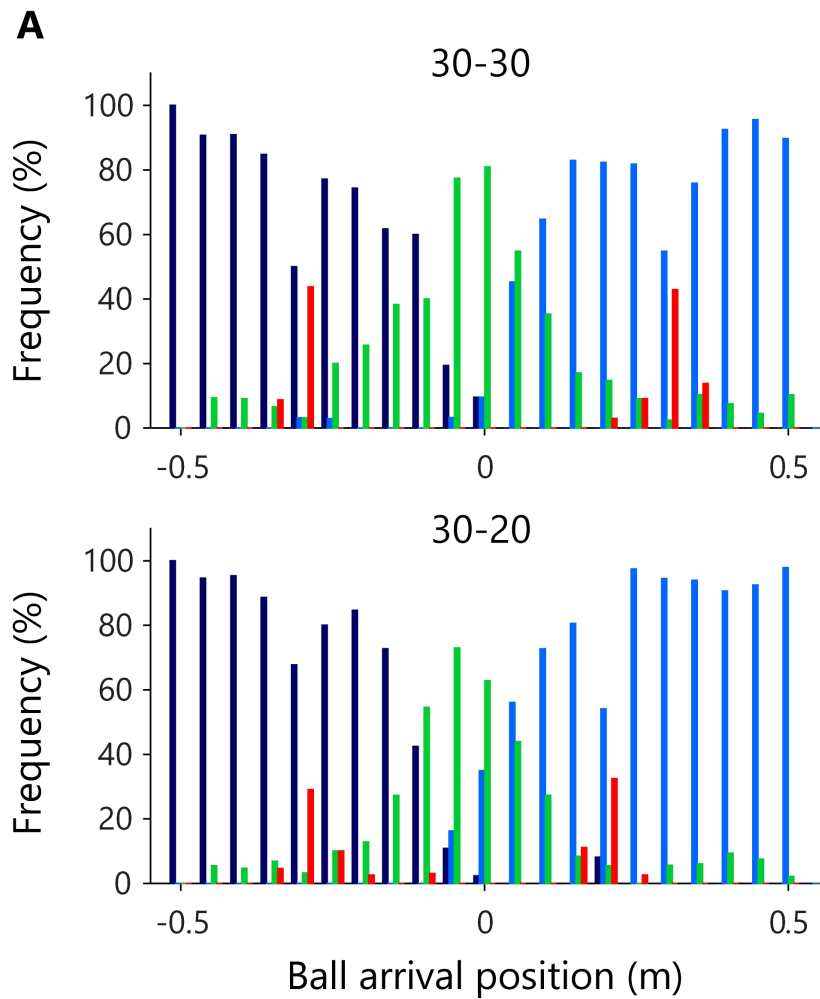


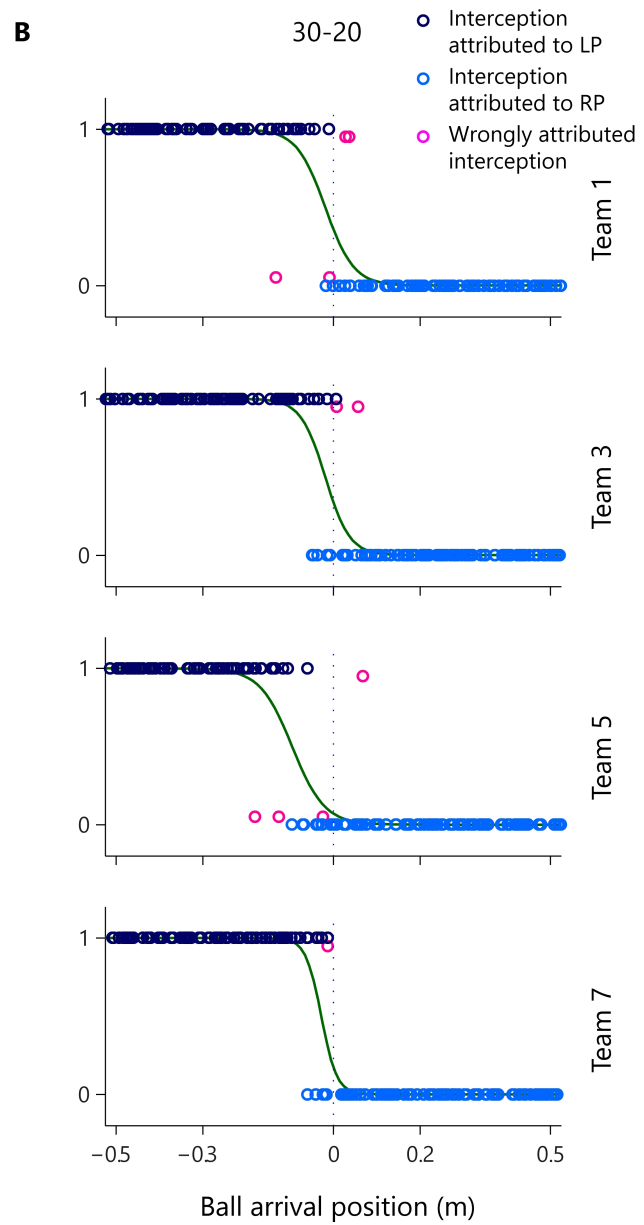
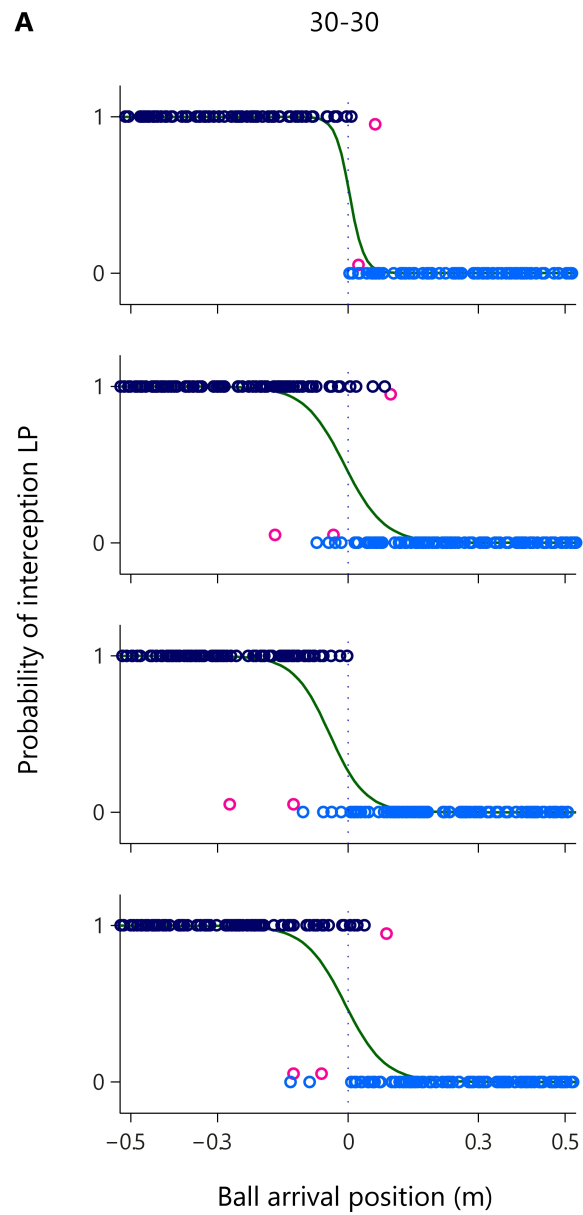






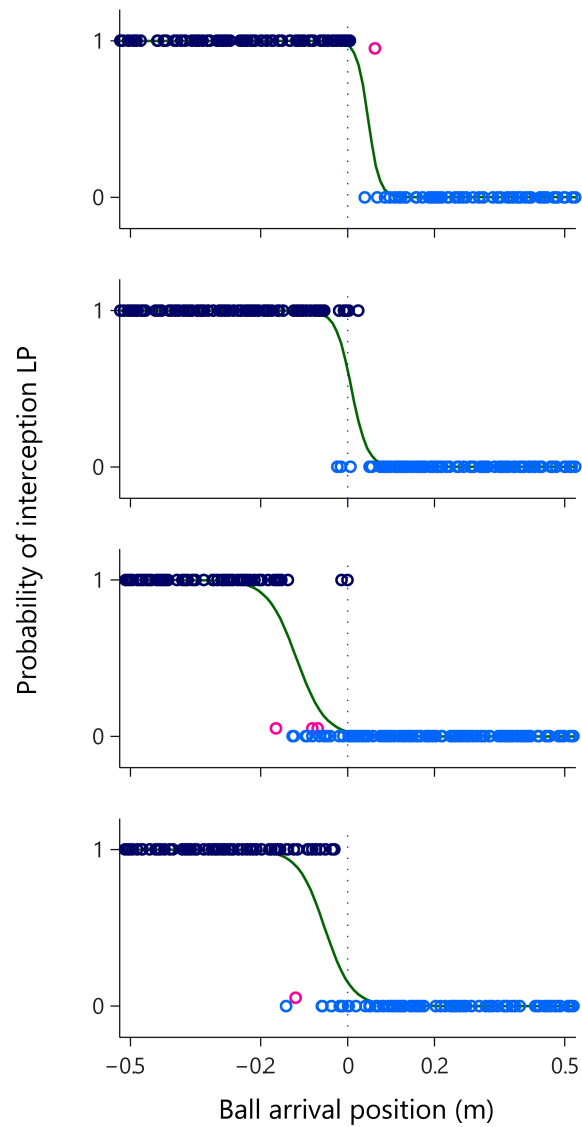
- Only LP
- Only RP
- Both LP and RP
- Neither LP nor RP



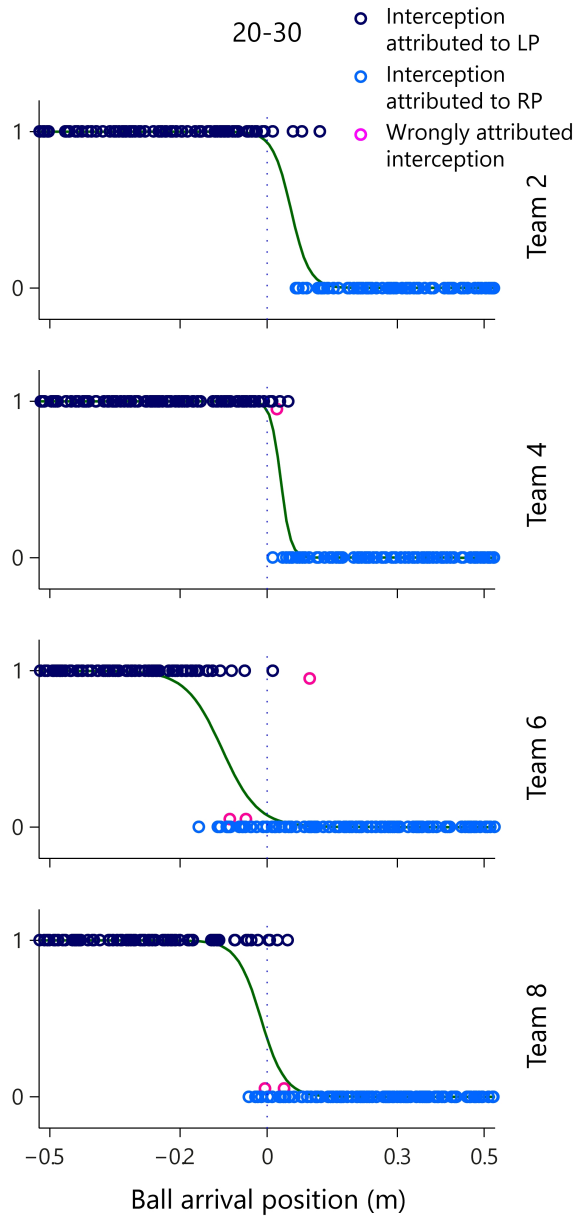


A

20-20

**B**

20-30



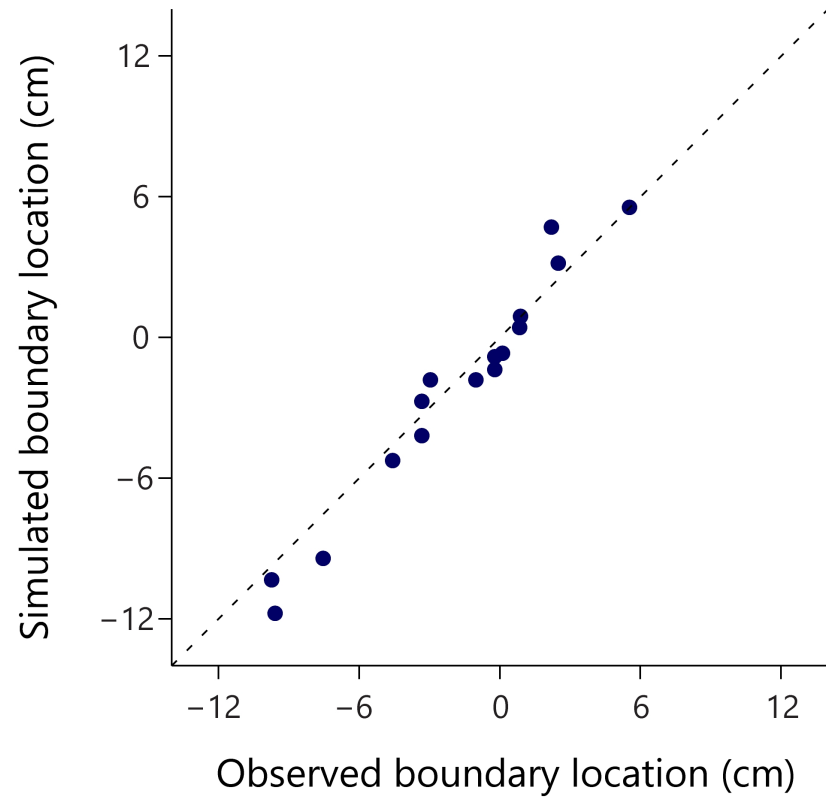
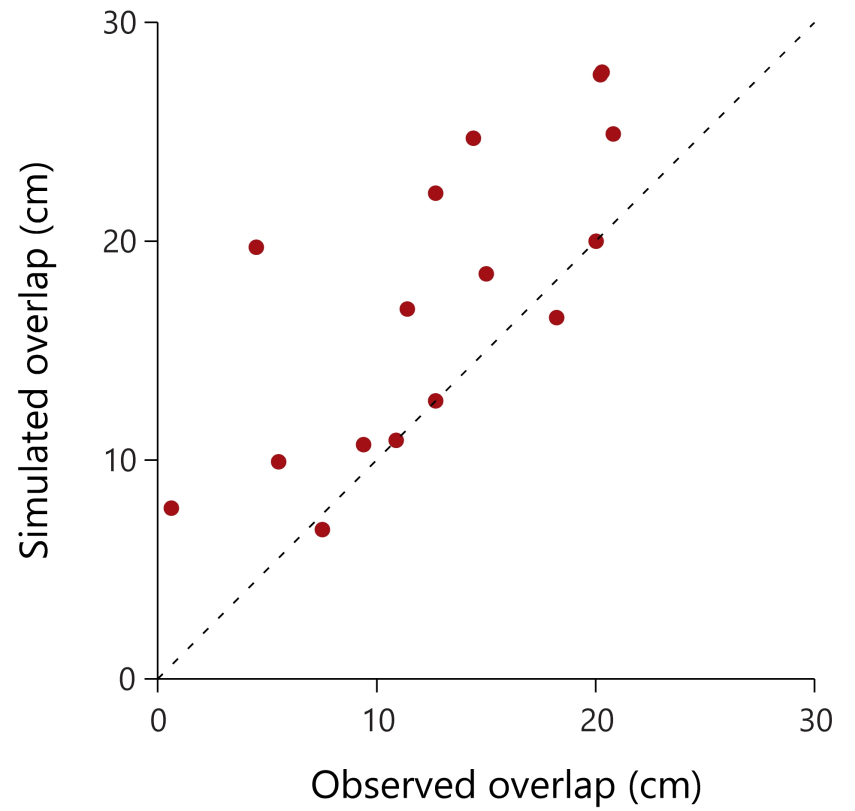
A**B**

Table 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 (Pref.) 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.

Group	Team	Side	Gender	Session 1		Session 2			
				Perf. (%)	Perf. (%)	Coll. (nb)	Perf. (%)	Coll. (nb)	
LP30	1	LP	F	76.4	80.5	2	81.0	4	
		RP	F	75.6					
	3	LP	M	84.4	95.0	0	91.5	2	
		RP	M	88.0					
	5	LP	F	83.2	85.5	1	82.0	0	
		RP	M	82.4					
	7	LP	M	83.6	91.0	1	92.0	2	
		RP	F	85.2					
	<i>Mean</i>				82.4	88	1	86.6	2
	LP20	2	LP	M	80.4	83.0	2	87.0	0
RP			F	75.6					
4		LP	M	88.8	91.5	3	92.0	0	
		RP	M	91.2					
6		LP	M	87.2	94.0	1	89.5	5	
		RP	M	86.8					
8		LP	F	84.0	78.0	0	88.0	6	
		RP	F	84.4					
<i>Mean</i>				84.8	86.6	1.5	89.5	2.8	

Table 2. Boundary locations and amounts of overlap for observed and simulated interception performance in the symmetrical (LP30: 30-30 and LP20: 20-30) 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
	<i>Mean</i>	<i>-0.7</i>	<i>-3.7</i>	<i>15.1</i>	<i>9.5</i>	<i>-1.3</i>	<i>-4.0</i>	<i>22.5</i>	<i>17.4</i>
LP20		Boundary (cm)		Overlap (cm)		Boundary (cm)		Overlap (cm)	
		20-20	20-30	20-20	20-30	20-20	20-30	20-20	20-30
	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
	<i>Mean</i>	<i>-2.8</i>	<i>-0.5</i>	<i>11.6</i>	<i>14.8</i>	<i>-2.9</i>	<i>-0.8</i>	<i>14.3</i>	<i>15.2</i>