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Effects of Complementary Control on the Coordination Dynamics of Joint-Action

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Abstract

Previous research has revealed that the behavioral dynamics of joint-action can naturally emerge from the physical and informational constraints that define a shared task-goal. The emergence of complementary actions or functional differences in control also appear to be a natural part of such behavior, and are often an inherent aspect of robust and highly flexible joint-action performance. The aim of the current study was to explore these latter aspects of joint-action behavior. More specifically, we examined the interpersonal coordination and control that emerged between two individuals performing a virtual labyrinth ball-control game. Key manipulations involved whether control was symmetrical (i.e. both individuals had full control of the board tilt), asymmetrical (i.e. one with control of the *x*-axis of tilt and the other with control of the *y*-axis of tilt), or unbalanced (i.e. one joystick had full control of the *y*-axis of tilt, but only ½ the gain control of the *x*-axis of tilt, and vice versa). Data on a solo individual two-handed version of the task was also collected for comparison purposes. Our results revealed that the patterns of synergistic coordination that emerged were the same for pairs and individuals, and that both pairs and individuals maintain task success by mutually adapting the coordination and control dynamics across the different task manipulations.

Key words: interpersonal coordination; joint-action; recurrence analysis; motor-control.

Introduction

Social movement coordination is a fundamental part of everyday interaction, from navigating a crowded sidewalk, to playing a game of pat-a-cake, to clearing a dinner table with friends and family. It should come as no surprise, therefore, that a great deal of previous research has demonstrated how individuals are able to expertly coordinate their movements and actions with those of other individuals (for reviews see Bekkering et al., 2009; Sebanz & Knoblich, 2009; Marsh, Richardson & Schmidt, 2009; Schmidt & Richardson, 2008; Shockley & Riley, 2015).

Previous research on joint-action and social movement coordination has predominately focused on the incidental or non-goal directed movement coordination that spontaneously occurs between co-present or interacting individuals (e.g., the spontaneous entrainment that occurs between two people sitting side-by-side in rocking chairs or the full body coordination that occurs during conversation; e.g., Richardson, et al., 2007; Shockley, Santana & Fowler, 2003; Schmidt, Nie, Franco, & Richardson., 2014). However, many everyday joint action tasks involve goal directed activities that require that co-actors explicitly co-control external events or environmental objects (e.g., moving a table or passing a football). In many instances, these tasks also involve complementary actions or movement control and are characterized by a strong level of mutual adaptation, anticipation and reciprocal compensation (Knoblich & Jordan, 2003; Richardson, Harrison, Kallen, Walton, Eiler, & Schmidt, in press; Vesper & Richardson, 2014). In these instances, the coordinated behavior of co-actors can be considered synergistic (Turvey & Fonseca, 2009; Riley, Richardson, Shockley, & Ramenzoni, 2011).

The term synergy refers to a functional grouping of structural elements that are temporarily constrained to act as a single coordinated unit (Kelso, 2009; Turvey & Fonseca, 2009). Historically, the term synergy has been used to refer to flexible and adaptive intrapersonal systems of coordination and control (i.e., the interlimb coordination that occurs between an individual's two hands when carrying an object). However, there is now a growing body of evidence indicating that the behavioral coordination that occurs during many joint-action tasks meets the technical definition of a synergy (Riley, et al., 2011; Romero, Kallen, Riley, & Richardson, in press), such that the coordinated movements of co-acting individuals should be understood to be a single unified behavioral system.

The goal of the current study was to further explore the synergistic nature of joint-action behavior and, in particular, the degree to which the coordinated control of co-acting individuals naturally and spontaneously adapts to changing task constraints. To do this, individual participants and pairs of cooperating participants were required to play a virtual labyrinth ball-control game, in which the rotation of the virtual table was controlled using two joysticks. The aim of the game was to use the two joysticks to move a virtual marble from a start location to a target location while avoiding a set of obstacles. Unbeknownst to the participants, the degree to which the two joysticks controlled the *x*- (left-right) and/or *y*- (forward-back) axes of table rotation was manipulated. Of particular interest was the degree to which individuals and pairs spontaneously and mutually adapted to these changes in table control and, moreover, whether the same synergistic reorganization was observed for individuals and pairs.

Method

Participants

Twenty-seven students at the University of Cincinnati participated in the experiment. All participants were over 18 years of age. Nine participants were randomly assigned to the individual condition and eighteen participants were randomly assigned to the joint (pair/two person) condition.

Task and Materials

Participants in both the individual and joint action conditions were instructed to tilt a virtual game board using two joysticks in order to move a virtual marble from a start location to a green target location. The goal of the game was to move the marble from the start location to the target location as quickly and efficiently as possible without hitting (i) the barrier positioned around the edge of the game board or (ii) any of the 10 obstacles (small vertically oriented cylindrical pegs) positioned at various locations around the game board. Once the target was successfully reached, a new target would appear at a new location on the virtual board (see Figure 1. left), with each game (trial) involving 20 target locations. During the course of a single game the location of the 10 obstacle pegs (i.e., the obstacle map) remained fixed, however, these locations changed across games (see below for more details).

Figure 1. (*left*) An example of the task stimulus. The marble is in the top left corner and the current target is in the middle-right region of the display. The obstacle pegs are represented by the brown dots position throughout the map. (*middle*) An example of a single participant individually controlling the game board with both joysticks. (*right*) An example of two participants controlling the game board together, with each member of the pair using only one joystick.

Individuals and pairs completed the task under three different control conditions: symmetrical control, asymmetrical control, and unbalanced control. In the symmetrical condition, both joysticks had control of both the *x* and *y* rotation axes of the virtual game board with equal gain. In the asymmetrical condition, one joystick controlled the game board's *y*-axis of table rotation (with no influence/control over the game board's *x*-axis), while the second joystick controlled the game board's *x*-axis of table rotation (but had no control over the game board's *y*-axis). In the unbalanced condition, one joystick had full control of the *y*-axis of table rotation, but only 50%-gain control of the *x*-axis of table rotation, while the second joystick had full control of the *x*-axis of table rotation, but only 50%-gain control of the *y*-axis of table rotation. Note that 50%-gain control refers to the fact that the mapping between the movements of board rotation was ½ of that of the joystick that had full (i.e., 100%-gain) control. Joystick movement was recorded at 30Hz.

In the individual condition, participants controlled the two joysticks using their right and left hands respectively (see Figure 1. center). In the joint action condition each member of a pair controlled only one joystick (see Figure 1. right). To be consistent with the individual control condition one participant in a pair controlled the 'right' joystick with their right hand, while the other participant controlled the 'left' joystick with their left hand. For the remainder of this paper we refer to the two joysticks as the right-hand (RH) and left-hand (LH) joysticks respectively. Each member of a joint action pair was randomly assigned to the LH and RH joystick, with joystick assignment kept constant across all trials and sessions.

Procedure

Both individuals and pairs performed three separate game sessions, one session for each control condition (order of control condition was counterbalanced across individuals and pairs. In each session, participants performed four practice games before performing two test games (each game consisting of 20 target locations). Different obstacle maps were employed for each practice game. For the test games, however, the same obstacle maps were used across participants and sessions for comparison purposes.

Results & Discussion

Only data from the two test games (trials) was analyzed to determine the effects of the different control conditions and the comparative task performance of individuals and pairs. For each of the analyses presented below, data was averaged across the two test games.

Inter-Target Movement Time. The mean and *SD* of the inter-target movement time was relatively consistent across all conditions for both individuals and pairs (Fig. 2). This was confirmed using 2 (group: individual, joint) × 3 (condition: symmetric, asymmetric, unbalanced) mixed design analyses of variance (ANOVA), which only revealed a significant and marginally significant main effect of condition for the mean, $F(2, 30) = 6.08$, $p < .01$, $\eta_p^2 = .29$, and *SD*, $F(2, 30) = 3.09$, $p < .06$, $\eta_p^2 = .17$, of inter-target movement time, respectively (all other *F*s < 1.0). With regard to the significant main effect of condition for mean inter-target movement time, a post hoc *t*-test revealed that this was due to the modest difference between the asymmetric and unbalanced conditions ($p < .025$). No other differences were found to be significant (all $p > .10$). In these and all subsequently reported post hoc analyses, a Bonferroni correction was applied to control Type-I error rates.

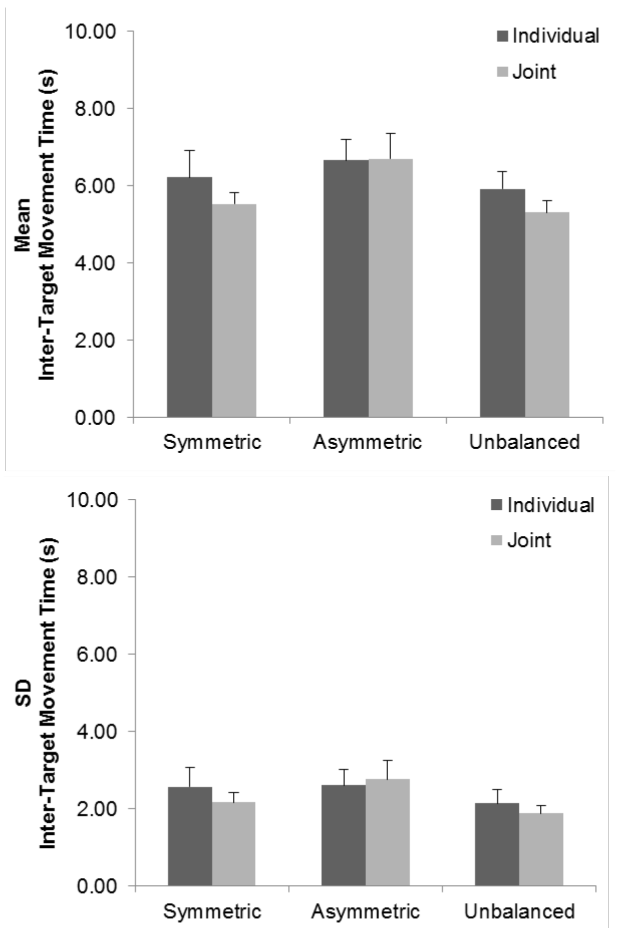

Figure 2. Mean (*upper graph*) and *SD* (*lower graph*) of inter-target movement time (in seconds) for individual and joint (pair) joystick control as a function of condition.

Peg and Wall Collisions. Individuals collided with more pegs and the game board boundary (wall) than pairs, suggesting that individual action was slightly worse overall compared to pairs (Fig. 3). However, a 2 (group: individual, joint) × 3 (condition: symmetric, asymmetric, unbalanced) mixed design ANOVA did not result in a significant effect of group, $F(1, 15) = 3.06$, $p = .10$, $\eta_p^2 = .17$.

Joystick Movement. To determine whether the symmetry manipulations of joystick axis control influenced the manner by which participants moved and controlled the joystick, the difference between x and y mean change in position over the course of a trial was calculated (calculated as the x_{mean} - y_{mean} of the joystick positional time-series). In short*, this measure indexes the difference in amount of movement between the x and y dimensions of a joystick.* Thus, positive values correspond to a greater magnitude of positional movement in the x dimension of joystick control; zero corresponds to equal amounts of positional movement in the x and y dimension of joystick control; and negative values corresponded to greater positional movement in the y dimension of joystick control.

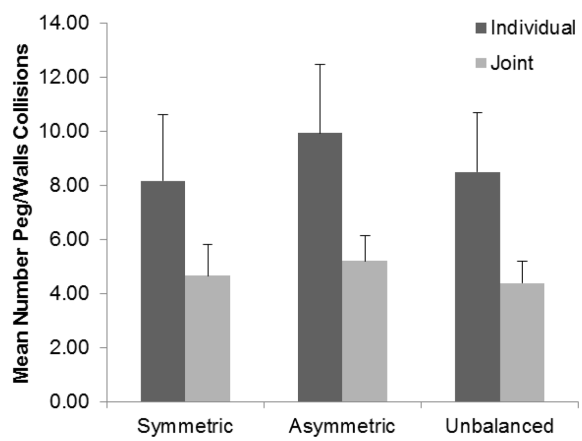

Figure 3. Mean number of pegs and walls hit for individual and joint (pair) joystick control as a function of condition.

A 2 (group: individual, joint) × 2 (Joystick: LH, RH) × 3 (condition: symmetric, asymmetric, unbalanced) mixed ANOVA performed on this measure resulted in a significant main effect of joystick, $F(1, 15) = 26.55$, $p < .01$, $\eta_p^2 = .64$, and a significant two way interaction between joystick and condition, $F(2, 30) = 14.53$, $p < .01$, $\eta_p^2 = .49$. There were no other significant effects, including no effects for group, indicating that the differences in movement change between the x and y dimensions of joystick control were comparable for individuals and pairs. As can be seen from an inspection of Figure 4, results revealed that the amount of movement change exhibited in the x and y joystick axes were consistent with the control manipulations. This was most notable in the asymmetric condition, in which participants tended to exhibit more joystick movement with regard to the dimension that actually influenced the rotation of the table. Not surprisingly, this difference was present but much less pronounced in the unbalanced condition and non-existent in the symmetric condition.

To further verify this result, a simple effects analysis of condition was performed for both RH and LH joysticks. For the RH joystick, although this analysis revealed a significant effect of condition, $F(2, 32) = 3.46$, $p < .05$, $\eta_p^2 = .18$, with more *y*-axis control in the asymmetric and unbalanced condition compared to the symmetric condition (as expected), post hoc *t*-tests revealed that these differences were not statistically significant (all $p > .12$). For the LH joystick, the simple effects analysis also resulted in a significant effect of condition, $F(2, 32) = 15.10$, $p < .01$, $\eta_p^2 = .49$. Furthermore, a post hoc *t*-test revealed that the *x-y* movement change in the asymmetric condition was significantly different from that observed in both the symmetric and unbalanced conditions (both $p < .01$). There was no difference between the symmetric and unbalanced conditions ($p > .5$). Finally, for the LH joystick, the *x-y* movement change for the symmetric, asymmetric and unbalanced conditions were all found to be significantly different from zero (all $t(16) > 3.64$, $p < .01$). In contrast, for the RH joystick, the *x-y* movement change for all three conditions were not significantly different from zero (all $t(16) < 3.32$, $p > .11$).

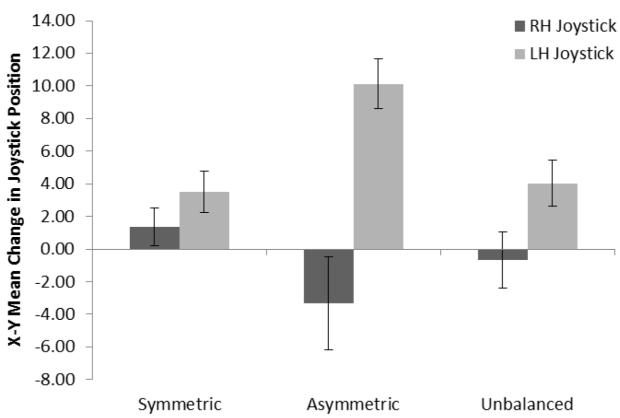

Figure 4. Mean *x-y* change or amount of positional movement control as a function of joystick and condition.

Cross-Recurrence Quantification Analysis (CRQA). The coordination that occurred between the LH and RH joystick movements was indexed using cross-recurrence analysis. CRQA is a nonlinear time-series analysis that determines the degree of recurrent structure between two time-series in reconstructed phase space. The advantage of CRQA over linear forms of bivariate time-series analysis (e.g., cross correlation, relative phase analysis) is the fact that it does not require any a priori assumptions about data structure or stationarity. Accordingly, it has previously been employed to index the occurrence and stability of interpersonal movement coordination across a number of joint-action settings (e.g., Shockley et al., 2003; Richardson & Dale, 2005; Richardson, et al., 2005).

CRQA provides a set of dependent metric, each characterizing a different aspect of the dynamics that underlie the recurrent structure of two time-series. Of most relevance to the current study are the CRQA metrics %REC and MaxLine. In short, %REC captures the amount of recurrent activity that occurs between the two time-series or, with regard to the current task, the degree of movement similarity. Maxline corresponds to the longest line or sequence of recurrent states and in this context, can be thought to index the overall strength of the coordination that occurs between two behavioral time-series (see Richardson, et al., 2007, 2008 for more details).

Here, we compared the *x*-axis movements of the RH joystick to the *x*-axis movements of the LH joystick and *y*-axis movements of the RH joystick to the *y*-axis movements of the LH joystick. The CRQA parameters employed were as follows: time-lag = 20 samples; embedding dimension = 6; radius = 10 percent of the maximum distance between points (see e.g., Marwan 2008; Webber & Zbilut 2004; for more details about these parameters and how they are chosen). All time-series data was *z*-score normalized prior to performing CRQA.

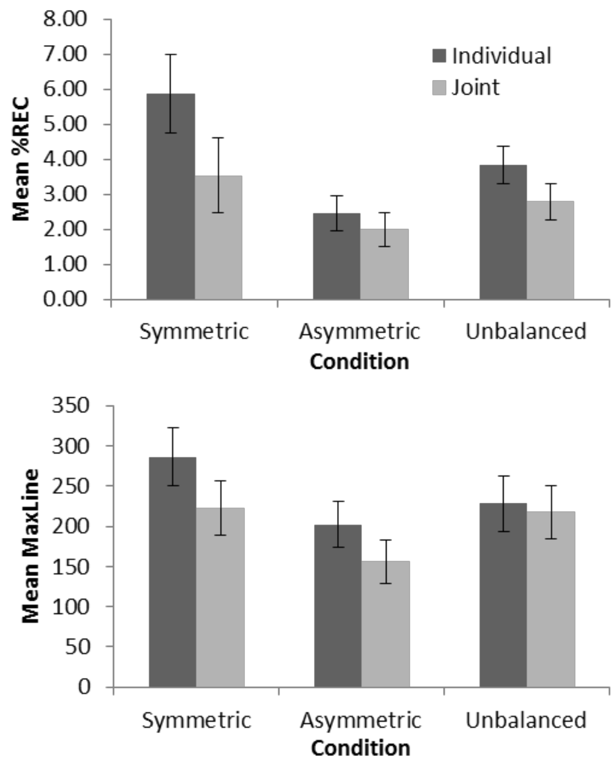

Figure 5. Mean %REC (*upper graph)* and mean MaxLine (*lower graph*) for individual and joint (pair) joystick movement averaged over the X and Y direction as a function of condition

A preliminary analysis of the resulting %REC and Maxline values revealed a similar pattern of results for the *x*-axis and *y*-axis comparisons. Accordingly, the %REC and MaxLine data were averaged across the two movement planes (i.e., *x*-to-*x* and *y*-to-*y*) prior to statistical analysis. Both %REC and MaxLine were then analyzed using a 2 (control: individual, joint) × 3 (condition: symmetric, asymmetric, unbalanced) mixed design ANOVA.

For %REC, this analysis revealed a significant main effect of condition, $F(2, 30) = 8.492$, $p < .01$, $\eta_p^2 = .36$, with post hoc *t*-tests finding significantly less recurrence in the asymmetric condition (M = 2.22, SD = 1.42) compared to both the symmetric (M = 4.70, SD = 3.31, p < .01) and the unbalanced conditions (M = 3.31, SD = 1.58; p < .01; see Figure 5). There were no other significant effects (all p > .14).

For MaxLine, the ANOVA also revealed a main effect for condition, $F(2, 30) = 5.83$, $p = .01$, $\eta_p^2 = .28$. Post hoc t-tests revealed that this was due to mean MaxLine being significantly longer in the symmetric condition (M = 254.63, SD = 102.97) compared to the asymmetric condition (M = 178.98, SD = 81.33, p < .01; see Figure 5). The unbalanced condition (M = 222.82, SD = 95.55) was only marginally different from the symmetric and asymmetric conditions (both p < .1).

Conclusion

The current study examined the effects of control symmetry on the movement coordination and performance dynamics exhibited by *individuals* and *pairs* completing a virtual labyrinth type ball moving game, with the task goal of moving a virtual marble from a start location to a target location while avoiding obstacles. For both individuals and pairs, the rotation of the virtual table board was controlled using two joysticks, so that three different control manipulations were included: a *symmetrical control condition*, where both joysticks had control of both the x and y rotation axes of the virtual game board with equal gain; an *asymmetric control condition*, where one joystick controlled the game board's y-axis of table rotation, while the second joystick controlled the game board's x-axis of table rotation; and an *unbalanced control condition*, where one joystick had full control of the y-axis of table rotation, but only 50%-gain control of the x-axis of table rotation, while the second joystick had full control of the x-axis of table rotation, but only 50%-gain control of the y-axis of table rotation.

Overall, the results revealed that the control dynamics of individuals and pairs was more or less equivalent and that pairs performed as well, if not slightly better, than individuals with regard to task errors (i.e., obstacle collisions). In other words, joint control did not seem to reduce task performance compared to individual performance, nor did it result in different patterns of inter-joystick control. This suggests that individual and joint task success was defined by the same behavioral dynamics and that both individuals and pairs were able to converge upon these dynamics during practice (also see Knoblich & Jordan, 2003; Schmidt & Richardson, 2008). Although the firm constraints inherent to the task surely narrowed the possible behavioral space that individuals and pairs could adopt to achieve task success, this does not change the fact that the apparent similitude of individual and joint-action performance provides evidence that the interpersonal coordination exhibited by pairs was as synergistic and mutually responsive as the interlimb coordination exhibited by individuals.

The synergistic and mutually adaptive organization of the behavioral control exhibited by pairs and individuals was apparent from the differences in the inter-joystick movement dynamics that occurred for the different control conditions. The most notable differences arose when comparing the asymmetric condition to the symmetric and unbalanced conditions. In general, participants tended to move their joysticks more in the directional axis/axes that the corresponding hand had control over, even though they were not informed of the difference in control. This was most pronounced in the asymmetric condition in which each joystick had complete control of only one of the two rotation axes. As expected, for this condition both individuals and pairs spontaneously organized the directional magnitude of joystick control in response to the differential control. A similar, yet less pronounced differential organization was observed for unbalanced condition.

It is worth noting that a funnel debriefing was conducted at the end of the experiment and only 1 pair suspected that the symmetry of joystick control was being manipulated across sessions. In contrast, most individuals indicated that they either suspected or came to realize that the symmetry of joystick control was being manipulated over the course of the experiment. This implies that knowledge of differential control is not necessarily required for individuals to converge upon complementary task solutions during joint-action behavior. Indeed, the fact that in the current task pairs and individuals performed in a similar manner and were similarly affected by the control manipulations, indicates that being aware (or not aware) of the task constraints played little to no role in shaping the coordination and control strategies adopted. Rather, individual and team performance appeared to be determined by the physical and informational properties of the task and task context. In other words, task success for both individuals and pairs was constrained by the same behavioral dynamics (Warren, 2006), with these dynamics defining the set of task control laws that were independent of whether the effectors employed were from a single nervous systems or two visually coupled nervous systems.

Finally, CRQA was employed to examine the stability of the inter-hand coordination exhibited by individuals and pairs across the different control conditions, with the asymmetric condition resulting in weaker coordination (i.e., lower Maxline) and less recurrent movement dynamics (%REC) compared to the symmetric and unbalanced conditions. This is consistent with the movement control exerted on the LH and RH joysticks being more independent (i.e. less coupled), and is yet further evidence that individuals and pairs were sensitive (unintentionally in the case of pairs) to the asymmetry of control and spontaneously adapted their behavioral coordination accordingly. Although not significant, the overall lower %REC and Maxline scores for pairs compared to individuals is also likely to be a result of the weaker inter-hand coupling for pairs compared to individuals. An interesting possibility for future research is whether this reduced inter-hand coupling is the reason why pairs exhibited fewer errors and obstacle collisions compared to individuals (although not significantly fewer errors). Indeed, it is possible that for some tasks a weaker and less tightly coupled control system may actually result in more robust and adaptive control dynamics than a stronger and more tightly coupled control system, and hence lead to greater task success (e.g., Strang, Funke, Dukes, & Middendorf, 2014). If true, joint-action control may in some instances be preferable over individual control.

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