Investigating Strategy Discovery and Coordination in a Novel Virtual Sheep Herding Game among Dyads

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Abstract

Previous research investigating the dynamical processes supporting coordinated joint action has typically used non-goal-directed tasks. The present study expands on this research by investigating the coordination that emerges among pairs in a complex, goal-directed task of herding virtual sheep to the center of a field. The results revealed that the majority of pairs converged on the same stable movement coordination strategy in order to complete the task. This strategy involved pairs moving in an in-phase or anti-phase oscillatory pattern around the sheep. By adopting this strategy pairs formed an interpersonal synergy. Interestingly, the strength of this synergy was modulated by the number of sheep being herded. More specifically, more dimensional compression was observed among pairs when herding the 7-sheep compared to herding 3 or 5 sheep. The implications of these results for understanding how task difficulty and mutually defined environmental co-regulation influenced the behavioral dynamics of coordinated joint-action are discussed.

Keywords: joint action; interpersonal synergies; coordination; strategy formation

Introduction

Joint action is generally defined as a "social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment." (Knoblich, Butterfill, & Sebanz, 2011). Examples of joint action include moving a couch with a friend, setting the table with your partner, playing a game of basketball, or deciding with classmates how to tackle an assigned group project.

Although a great deal of previous research has been directed towards understanding the top-down processes involved in successful joint-action, such as task monitoring and action prediction, (Sebanz, Knoblich, & Prinz, 2005; Welsh et al., 2007; Atmaca, Sebanz, & Knoblich, 2011), understanding the bottom-up behavioral dynamics of joint-action is equally important (Knoblich, Butterfill & Sebanz, 2011; Tollefsen & Dale, 2011). This includes determining how the physical, informational and environmental variables that define a task context and goal operate to structure and constrain the patterns of coordinated joint action behavior that are possible (Kelso, 1995; Saltzman & Kelso, 1997; Warren, 2006; Oullier et al., 2008; Schmidt & Richardson, 2008).

With regard to investing the behavioral dynamics of joint-action, a number of previous studies (Richardson et al., 2007; Schmidt, Carello, & Turvey, 1990; Schmidt et al., 1998; Schmidt & O'Brien, 1997) have demonstrated that the patterns of movement coordination that occur between the rhythmic limb or body movements of interacting individuals are equivalent to those observed for intrapersonal interlimb rhythmic movement coordination (Haken, Kelso, & Bunz, 1985) and can be predicted and modeled using a system of coupled oscillators (see Schmidt & Richardson for a review). This is true, irrespective of whether the rhythmic movement coordination that occurs between interacting individual is intentional or unintentional (Coey et al., 2011; Issartel, Marin, & Cadopi, 2007; Miles et al., 2011; Oullier et al., 2008; Richardson et al., 2007; Schmidt & O'Brien, 1997; van Ulzen et al., 2008).

One significant implication of the previous research examining the dynamics of interpersonal rhythmic coordination is that it suggests that the movements and actions of coordinating individuals form an *interpersonal synergy* (Riley et al., 2011). In movement science, a synergy refers to the reduction of multiple elements to form a single functional unit (Latash, 2008; Turvey, 1990). The motor system creates synergies to simplify the movement of various components and to promote stability (the elements are linked so they can compensate for one other if one is perturbed or fluctuates). For example, in human speech the elements (the speech articulators, i.e., lips, jaws, tongue, vocal tract) become tightly coordinated and are controlled as a single unit at the macro-scale. Thus, if one element of the speech system (e.g., the lower jaw) is perturbed during speech, others compensate in lock step (within as little as 20 msec delays) in order to assure the intended speech sound is achieved (Kelso et al., 1984).

A defining characteristic of a movement synergy is *dimensional compression* (DC) (Riley et al., 2011). DC refers to the reduction of the controlled movement degrees-of-freedom (*df*) or overall system dimensionality and results from a coupling of component *df* together, such that the movement of one motor *df* is connected to or dependent on the movement of others. The significance of DC is that it not only reduces motor system dimensionality, thereby simplifying control, but also improves a system's functional resistance to unexpected situational constraints or perturbations via the non-local component adaptations (Riley, et al., 2011; Romero et al., under review).

Although the synergistic property of DC has been observed across a range of joint action tasks (e.g., Black, Riley & McCord, 2007; Ramenzoni et al., 2011; Riley et al., 2011; Romero et al., under review), most of this research has relied on either non-goal-directed, or minimally goal-directed tasks. For instances, two individuals rhythmically coordinating wrist-pendulums (Black et al., 2007) or one individual moving a stick through a hoop held by a partner (Ramenzoni et al., 2011). Thus, a more generalized understanding of the role of synergistic coordination in everyday goal-directed joint-action remains limited. Accordingly, the goal of the present study was to expand this sub-field of joint-action research by investigating the coordination dynamics that occur for a more complex goal-directed joint-action task. To do this, we designed a simple video-game that resembled sheep herding. The goal of the game was for pairs of participants to work together to contain virtual sheep (i.e. small, 'wool'-covered balls) within the center of a virtual field presented on a large tabletop display (see Figure 1a). The sheep were repelled away from virtual dogs (grey boxes) that the players' controlled using hand held motion tracking sensors.

The task was inspired by a single player game employed by Dotov, Nie and Chemero (2010), in which subjects used a mouse to control an on-screen cursor that repelled objects as the cursor approached them. The goal was to move the objects to a specific location on a screen. (see also Nie, Dotov, and Chemero, 2011.) An important finding was that the patterns of fluctuations of participant hand movements followed a pattern characteristic of synergistically organized systems (Anderson, Richardson & Chemero, 2012; Van Orden et al., 2003). We sought to investigate whether the behavior of two individuals coordinating together to complete a comparable game would also become synergistic. Accordingly, the aims of the current study were to determine the successful coordination patterns or strategies that emerged and then quantify the degree to which these strategies resulted in DC. The number of sheep (3, 5 or 7) pairs had to corral was manipulated in order to determine whether task difficulty (i.e., the number of sheep) facilitated the discovery of synergistic stable task solutions.

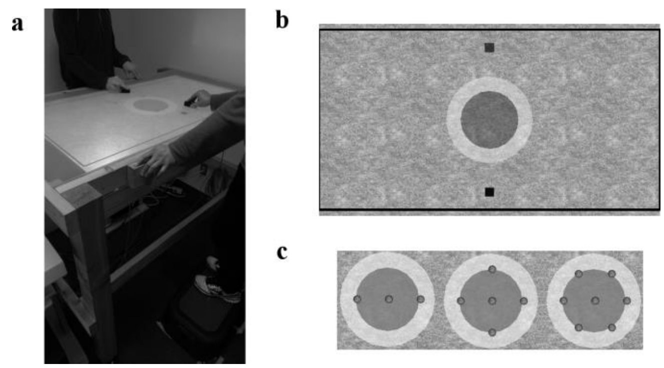

Figure 1: Illustration of (a) sheep herding room, (b) visual display of playing field with sheep dogs represented as squares, (c) initial sheep configuration for the 3, 5 and 7-sheep between-subject conditions.

Method

Participants

Forty-five right-handed undergraduate student pairs from the University of Cincinnati participated in the experiment. Pairs were randomly assigned to one of three between-subject conditions, which determined how many sheep they needed to herd (3, 5, or 7 sheep). Participants received research credit as compensation for participating in the experiment.

Apparatus

A visual depiction of the sheep herding game is pictured in Figure 1b. The game takes place in a top-down view of a 1.17m by 0.62m fenced grass field. Players were allowed to move within the fenced area, with handheld Polhemus motion tracking sensors moving grey boxes (hereafter referred to as sheepdogs) that that sheep were repelled away from. The players' goal was to contain the balls (hereafter referred to as sheep), to the center of a dark gray circle measuring 19.2 cm in diameter. Each trial lasted one minute and participants were given the goal of keeping all the sheep inside the dark gray circle for 70% of the last 45 seconds of the trial (the first 15 seconds served as time to set up and corral the sheep). If pairs made it past the 70% threshold eight times, the experiment ended. Otherwise, pairs continued to play until the end of the 45 minute experimental period.

At the start of a trial, the sheep appeared in the center of the field (see Figure 1c). The sheep moved randomly but reacted dynamically to the player's sheepdog location if the sheepdog was within 10 cm of the sheep. When a player's sheepdog was within the sheep's threatened region, the sheep would move directly away from the player at a speed proportional to the inversed distance squared between the sheep and the player. If one of the sheep managed to hit the perimeter fence or if all sheep escaped the outer white circle measuring 29 cm in diameter surrounding the dark grey circle, then the trial ended without a score. Pairs received visual feedback regarding their performance at the end of each trial (i.e., what percentage of time they managed to keep the sheep within the target area).

Procedure

Following consent, each participant in the pair stood on either side of an elevated table which displayed the sheep herding video game from a video projector below the table onto a frosted glass top. Participants used Polhemus motion sensors with their right hand in order to control their sheepdogs. Participants were told to keep the Polhemus sensors on the table the entire time. The video game was calibrated so that the sheepdog moved directly underneath the motion sensor placed on the table. The rules of the game were described to the participants and participants were also told that they were not allowed to talk to their partner.

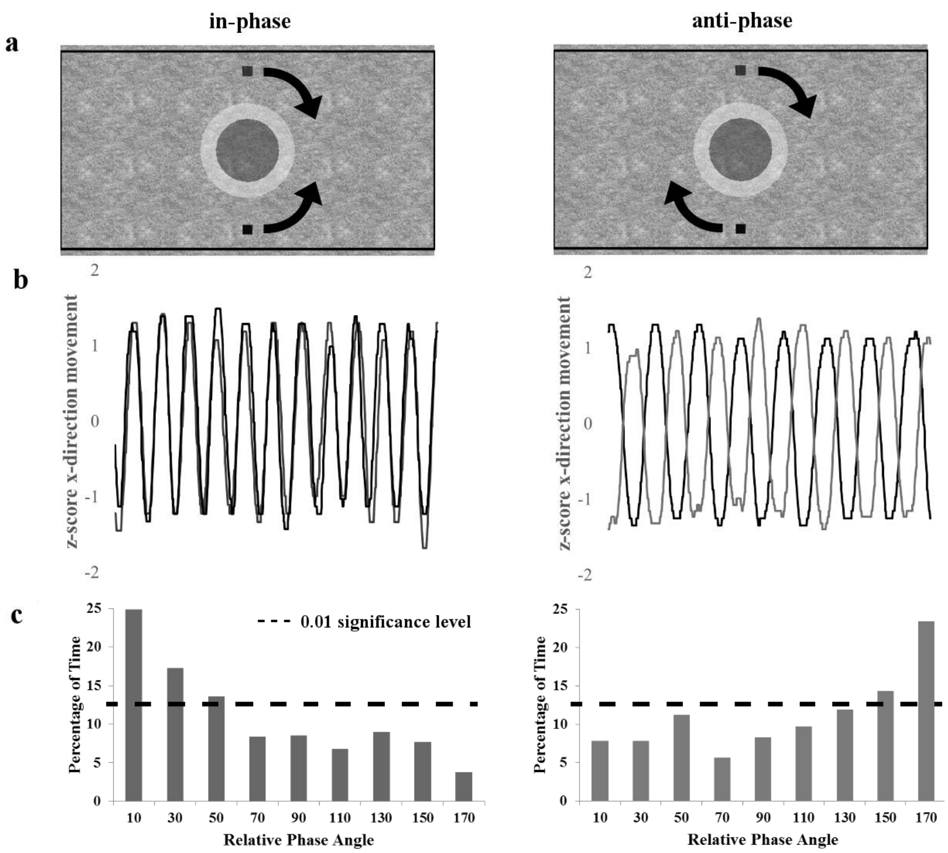

Figure 2: Illustration of (a) in-phase and anti-phase behavior, (b) representative time-series data of the last 15 seconds from two different pairs, (c) example of relative phase frequency distributions of significantly in-phase and anti-phase movement from experiment.

Table 1: Average Proportion of Trials that Exhibit Specific Phase Behavior (Standard Error Listed in Parentheses)

	In-Phase	Anti-Phase	Both-Phase	No-Phase
3-Sheep	45.45% (10.18%)	29.55% (9.12%)	7.95% (5.66%)	17.05% (6.37%)
5-Sheep	41.67% (8.95%)	30.56% (8.07%)	5.56% (9.72%)	22.22% (4.66%)
7-Sheep	55.56% (9.08%)	13.89% (9.80%)	9.72% (2.20%)	20.83% (6.51%)
Total Average	**47.41% (5.21%)**	**25.00% (4.95%)**	**7.76% (2.28%)**	**19.83% (3.26%)**

Results

Data from the last 45 seconds of each successful trial (containing the sheep at least 70% for that time) were analyzed. Of the 45 pairs who participated, one was dropped from the study because a fire alarm went off during the experimental session. Thirty-one of the remaining 44 pairs (70.45%) were able to successfully complete the sheep herding game before the end of 45 minute experimental period. All but two of the 31 pairs (eleven [78.57%], nine [60%] and nine [60%] in the three, five and seven-sheep conditions, respectively) settled on a specific strategy that involved performing either a semi-circular in-phase or anti-phase oscillatory pattern of behavior (see Figure 2a). Figure 2b, shows time series of two representative examples of trials illustrating these in-phase and anti-phase movement strategies. The remaining two pairs who successfully completed the task both resorted to a strategy that involved one partner moving in a circular motion rapidly along the perimeter of the grey circle region where the sheep had to be contained. This strategy was qualitatively unlike what the majority of pairs completed, and only involved the actions of one participant, while the other would stand idly for the majority of time. Because this latter strategy was different from the strategy formed by a majority of pairs, and because their behavior involved individual, and not joint action, these two pairs were also excluded from analyses.

The stable patterns of coordination that occurred for the 29 pairs retained for analysis was evaluated by calculating the distribution of relative phase angles formed between the lateral (left-to-right) movements of the participants along the game field. These distributions included the percentage of relative phase angles (calculated using the Hilbert transform) that occurred within nine 20° regions of relative phase between 0° and 180°. In-phase and anti-phase coordination are indicated by a concentration of relative phase angles near 0◦ and 180◦, respectively. To determine whether participants engaged in in-phase or anti-phase oscillatory behavior for a significant proportion of a trial, 1000 random relative phase distributions of the same sample length to the experimental data were created and organized into these bins. The 990th largest value for each bin represented our 0.01 significance level, which was found to be 12.69% of the total sample length (Varlet & Richardson, 2015). Each trial was then checked to determine whether the in-phase bin (0-20°) and/or the anti-phase (160-180°) bins were above the 12.69% cutoff (see Figure 2c for emblematic examples of each). Table 1, provides a summary of the proportion of trials averaged across pairs that were statistically classified as either in-phase or anti-phase, or exhibit a significant degree of both in-phase and anti-phase coordination within a trial or no stable phase relationship. An increase in in-phase behavior emerges for the 7-sheep condition, with an accompanying decrease in anti-phase behavior when comparing trials from the first half of successful trials (1-4) with the second half (5-8). However, this trend is not significant (Figure 3).

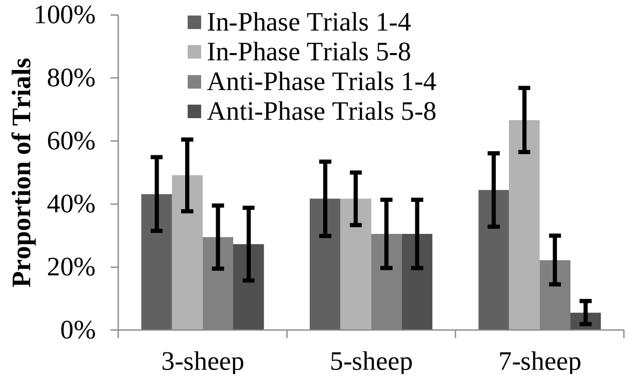

Figure 3. Strategy (in-phase vs. anti-phase) comparison between first and second half of successful trials.

A principle component analysis (PCA) was also conducted on the players' movements to determine the degree to which the coordinated behavior of pairs was synergistic—the degree of DC—and whether the number of sheep that needed to be herded had an effect on the strength of interpersonal synergy formed. PCA is a widely used statistical technique that identifies covariation within high-dimensional datasets and in order to remap the data (taking the covariation into account) into a space whose axes (principal components) represent the dataset's primary dimensions of variation (Daffertshofer et al., 2004; Forner-Cordero et al., 2005). Those dimensions, termed the principal components, can be abstract and need not (and typically do not) relate directly to the original measurement dimensions. If the original variables are in fact correlated, PCA yields a dimension reduction—fewer principal components are required to account for most of the variance in the dataset than the number of original variables (i.e., provides a measure of DC). Finally, note that for PCA only successful trials were analyzed. That is, only those trials in which pairs reached the 70% herding threshold were analyzed.

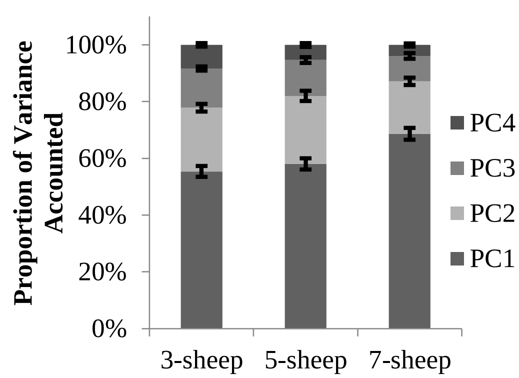

Figure 4. Principle component analysis (PCA) of the pair's controller movement (variables 1 to 4) for the three between-subject conditions.

The PCA results are shown in Figure 4. A one-way between-subject ANOVA, with the number of sheep being the independent variable, was conducted on the first principle component to determine whether the number of sheep had an effect on the proportion of variance that the first principal component accounted for (i.e., degree of DC). There was a significant main effect on level, $F(2,26) = 12.18$, $p < 0.001$, $\eta 2 = 0.48$, such that the first principle component explained significantly more variance in the 7-sheep condition than both the 3-sheep ($p < 0.001$) and 5-sheep ($p = 0.001$) conditions. There was no significant difference between the 3-sheep and 5-sheep condition ($p = 0.34$).

Discussion

The goal of the present experiment was to determine: (a) whether pairs could work together to successfully complete the sheep herding game; (b) what coordination strategies would be employed to complete the task; and (c) how task difficulty (i.e., number of sheep) would influence the patterning and DC of these coordination strategies.

The results revealed that most pairs quickly learned to work together to herd the sheep successfully. Moreover, 93.5% of the 31 pairs who were able to complete the game successfully discovered the same coordination strategies, categorized by in-phase or anti-phase pattern of movement. That is, pairs converged on the same two stable states of coordination known to constrain rhythmic intra- and inter-personal coordination in general (Kelso, 1995; Schmidt & Richardson, 2008) and predicted by the dynamics of coupled nonlinear oscillators (Haken et al., 1985). Pairs also exhibited significantly more in-phase coordination than anti-phase coordination, which is consistent with previous rhythmic coordination research that has consistently found a relative difference in the inherent stability of in-phase and anti-phase coordination—in-phase coordination is known to be more stable than anti-phase coordination (Kelso, 1995; Schmidt & Richardson, 2008).

With regard to task difficulty, pairs exhibited more in-phase patterns of movement coordination in the 7-sheep condition compared to the 5 and 3 sheep conditions (see Table 1). This suggests that decreasing the number of sheep increased the number of perturbations affecting the pair's movement dynamics and, thus, resulted in a more intermittent pattern of in-phase and anti-phase coordination, as well as a greater number of transitions between anti-phase and in-phase coordination. As discussed in more detail below, this appears to be due to a smaller amount of sheep co-regulation in the 3- and 5-sheep conditions compared to the 7-sheep condition. The more robust in-phase coordination observed in the 7-sheep condition was also associated with the greatest amount of DC as measured by PCA. Recall that dimensional compression, or a reduction in the number of principle components required to explain movement variance, provides a measure of synergy strength. Therefore, finding that a significantly greater amount of variance was captured by the first principle component (and second principle component) for the 7-sheep condition compared to the 3 and 5 sheep conditions therefore implies that the behavioral coordination of pairs in the 7-sheep condition was not only more stable, but also more synergistic.

As noted above, the reason for this latter finding appears to be due to the fact that the more tightly coupled and controlled a pair's movements were the greater the degree of co-sheep-regulation. An artifact of the sheep's' random movement behavior was that collisions among sheep caused their movement to be slower and more collectively predictable. Thus, a more tightly coupled and robust in-phase pattern of movement resulted in a higher probability of one sheep hitting another sheep, particularly in the 7-sheep condition compared to the other conditions. Indeed, for the 7-sheep condition a more tightly coupled and robust in-phase pattern of movement coordination more often resulted in a single slow-moving clump of sheep compared to the 3 and 5 sheep conditions (although a degree of clumping did occur in the other conditions). In this sense, the increased DC observed in the 7-sheep condition not only produced a greater amount of sheep-to-sheep regulation, but was also a product of this greater sheep-to-sheep regulation. Indeed, the clumping behavior seems necessary for the observed strategy to emerge. Thus, one would expect that removing the ability for the sheep to collide with one another (by having them pass through each other), or to adjust the speed of the sheep to be similar between conditions, will decrease coupling strength (by making the task too difficult in the first case, and too easy in the second).

One intriguing possibility is that the co-regulation that occurred between the sheep in the 7-sheep condition provided an environmental scaffold that supported discovering the oscillatory strategy employed by participants. If true, future research could explore whether individuals discovered the stable in-phase and anti-phase patterns of movement coordination that lead to task success more quickly the greater the number of sheep. It is important to appreciate that although no verbal communication was allowed, in a few instances a participant would exaggerate their oscillatory movements in what seemed to be an attempt to communicate with their partner. In instances where this occurred, their partners did not immediately alter their behavior in response to these motions. However, this non-verbal communication would seem to suggest interpersonal differences in the perception of stable action possibilities. How and why some individuals perceived the task solution before others is therefore another interesting question that could be explored in future research.

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