Can Joint Action be Synergistic?
Studying the Stabilization of Interpersonal Hand Coordination

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Abstract

The human perceptual-motor system is tightly coupled to the physical and informational dynamics of a task environment and these dynamics operate to constrain the high-dimensional order of the human movement system into low-dimensional, task-specific synergies. The aim of the current study was to determine whether synergistic processes constrain and organize the behavior of co-acting individuals. Participants sat next to each other and each used one arm to complete a pointer-to-target task. Using the uncontrolled manifold, the structure of joint-angle variance was examined to determine whether there was synergistic organization at the interpersonal or intrapersonal levels. The results revealed the motor actions performed were synergistically organized at both the interpersonal and intrapersonal levels. More importantly, the interpersonal synergy was found to be significantly stronger than the intrapersonal synergies. Accordingly, the results provide clear evidence that the action dynamics of co-acting individuals can become temporarily organized to form single synergistic two-person systems.

Keywords: joint-action, interpersonal coordination, motor synergies, motor control, uncontrolled manifold

Introduction

Individuals frequently perform social behavioral coordination in a robust and flexible manner, with seemingly little or no effort. Despite it being well known that performing social motor activities is a fundamental property of ongoing human behavior (e.g. Schmidt & Richardson, 2008) our scientific understanding of how co-actors are able to carry out joint motor acts remains lacking. One challenge to understanding how coordinated social motor behaviors are realized relates to the complexity of the human movement system. Determining how the human perceptual-motor system is able to organize and control its degrees-of-freedom (DoF)—the so called DoF problem (Bernstein, 1967)—is therefore an important question for cognitive scientists who study motor control and perception-action.

Contemporary theorists have argued that the DoF problem is greatly reduced when one considers that the human perceptual-motor system is tightly coupled to the physical and informational dynamics of a task environment and that these dynamics operate to constrain the high-dimensional order of the human movement system into low-dimensional, task-specific synergies (Turvey & Fonseca, 2009; Kelso, 2009). Here the term *synergy* is used to refer to a functional grouping of structural elements (neurons, muscles, limbs, individuals, etc.) that are temporarily constrained to act as a single coordinated unit. Evidence that the human movement system is organized synergistically has been demonstrated in a wide range of individual (i.e., non-social) motor tasks (e.g. Jacquier-Bret et al., 2009; Scholz et al., 2000). In each case, the movement DoF required for task performance are found to be temporarily coupled, such that the control or modulation of any one DoF functionally constrains and regulates the activity of the other DoFs, thereby reducing the dimensionality of the system as a whole.

Research demonstrating that rhythmic interpersonal coordination exhibits the same behavioral dynamics as intrapersonal, interlimb coordination (see Schmidt & Richardson, 2008; for a review) and that individuals appear to stabilize movement fluctuations during an interpersonal rhythmic movement task at a collective level (Black et al., 2007), has provided initial support for the *interpersonal synergy* hypothesis. More recently, Ramenzoni and colleagues (2011) provided evidence for interpersonal synergies by demonstrating that the behavioral control exhibited by a pair of individuals performing a continuous, interpersonal, postural targeting task also appears to be modulated in a collective or synergistic manner. More empirical work is still required to verify this hypothesis, however, especially with respect to goal-directed joint action tasks. Indeed, there have been no research studies that have investigated whether discrete joint-action movement tasks, such as when two individuals shake hands or pass an object, are synergistic.

Experimentally Investigating Synergies and the Uncontrolled Manifold

To be considered synergistic, a multi-limbed or multi-component action should exhibit two key characteristics: *dimensional compression* (DC) and *reciprocal compensation* (RC) (Riley et al., 2011). DC refers to the reduction of effective DoF or overall system dimensionality by coupling the relevant DoFs together, where the movement of one motor DoF is connected to or dependent on the movement of others. DC, coupled with the motor abundance characteristic of the human movement system (Latash, 2012) brings about RC, which refers to the processes that allow the system to adaptively react to movement noise or unexpected changes in the task environment—a change in one DoF will be compensated by activity of other DoF to preserve the overall movement goal. Together, these complementary processes reduce motor system dimensionality, thereby simplifying control, while ensuring the system's flexibility to resist and overcome unexpected situational constraints or perturbations via non-local component adaptations (Riley et al., 2011).

The uncontrolled manifold (UCM) method was first introduced by Scholz and Schöner (1999), and enables one to analyze data and test hypotheses about RC and DC. This method is widely used, theory-neutral and useful in simple tasks in which successful completion can be clearly measured. An excellent example of how this can be achieved was provided by Domkin and colleagues (2002) who devised an experimental task in which a single participant bent both his/her arms from a lateral, outstretched position to the forward frontal position such that a pointer located on the right hand was connected with a target located on the left hand. They asked their participants to repeat this movement several times and looked at the effects of repetitive performance by comparing the configuration of the joint angles at the beginning of the experiment to that at the end. They were particularly interested in whether the control employed to ensure the meeting of the pointer and target was manifested at each arm separately, or if the two arms were controlled together as a synergy.

To determine whether task control was organized at the unimanual or bimanual level, Domkin et al. (2002) employed the UCM method. Successful completion of the task employed by Domkin et al. is achieved by bringing the tip of the pointer to the intended target. For such tasks, a task space of all possible end-effector positions can be created in which a sub-space or manifold (typically a line or a plane) within the task space specifies all of the joint-angle configurations (i.e., between elbows, wrists, shoulders) that result in successful task completion (Scholz & Schöner, 1999). Variation along this manifold results in task completion and is referred to as compensatory or uncontrolled (i.e., tolerated) variation. Variation that is perpendicular or orthogonal to the manifold is considered uncompensated since it corresponds to variation that negatively affects the ability to bring the pointer to the target in a given trial. A synergy is thought to be present when the ratio of uncontrolled variation to orthogonal variation is above one.

By determining the ratio of uncontrolled to orthogonal variation, the UCM method can therefore be used to index DC and RC in a potentially synergistic action. RC is represented in the UCM method through the sub-space of successful completion of the task along which uncontrolled variation falls. When comparing different DoF configuration hypotheses at different organizational levels (i.e. interpersonal vs. intrapersonal) against each other DC can be measured. If the interpersonal joint configuration is the strongest synergy identified via the ratio of uncontrolled to orthogonal variation, then this would show the presence of DC at an interpersonal level.

By employing the UCM method to measure RC and DC across 315 trials completed over four days, Domkin et al. (2002) were able to test three competing hypotheses: The target and pointer position are stabilized by a joint interaction of both arms; the target position is stabilized by controlling the joints in the left arm; or the pointer is stabilized by controlling the joints in the right arm. They found that a bimanual synergy was formed in order to complete the task effectively, and that this bimanual synergy was stronger than each of the unimanual synergies. In other words, the two-arm-system was controlled as a unitary system and worked as a whole to bring about successful completion of the task.

Current Study

The objective of this study was to use the UCM method to directly examine whether synergistic processes constrain and organize behavior in a simple, discrete, joint-action task. Given the qualitative similarity to the simple joint-action of shaking hands with another person, a two-participant version of a Domkin et al. (2002) target-pointing task was employed, in which pairs of participants sat next to each other and each person used one arm to complete the two-dimensional pointer-to-target task together (see Figure 1). By determining the UCM ratio of compensated-to-uncompensated variation at the interpersonal *and* intrapersonal arm-system levels, the study centered on testing the hypothesis (H1) that successful task completion is stabilized by the collective and non-additive interaction of each participant's arm (i.e., participants form an interpersonal synergy) against the hypotheses (H2 & H3) that successful task completion is stabilized by participants individually and independently controlling the joints in their respective arm (i.e. intrapersonal left and intrapersonal right) in a coordinated, yet additive manner (i.e., the coordinated interpersonal action is not a synergy).

Method

Participants

Thirty students (15 pairs) from the University of Cincinnati were recruited to participate in the experiment. Participants were both male (N = 13) and female (N = 17) and ranged in age from 19 to 34 years. All participants were right-handed, had healthy motor function, and had normal or corrected-to-normal vision. Participants were matched within pairs by height.

Apparatus

Participant pairs sat in rigid chairs that were constructed in the laboratory to accommodate adjustable shoulder straps. The chairs were positioned side-by-side in front of a 74 cm high table. The participant seated to the left (participant 1) held a plastic semi-circle (11.1 cm in diameter) in her/his left hand, which was referred to as the target. The target was taped to the participant's left index finger and thumb. The participant located to the right (participant 2) held a pointer on her/his right hand. This pointer was a 23 cm long wooden stick that was taped to her/his right index finger.

An optical, marker-based Optotrak Certus motion-tracking system (Northern Digital Inc.) was employed to track the 3D position of arm joints. Markers were placed on the standard bony landmarks that correspond to participants' shoulder (the acromion), elbow (lateral epicondyle), and wrist (between the radius and ulnar bones) (Domkin et al., 2002, p. 14). Additionally, markers were placed at the tip of the pointer and the center of the target. Finally, a marker was placed between the two chairs at the level of the participants' shoulders so that the position of all other markers could be re-scaled for analysis (see below for more details). Position data for each marker was recorded at a frequency of 100 Hz and filtered using a second order Butterworth IIR filter with a cutoff of 10 Hz.

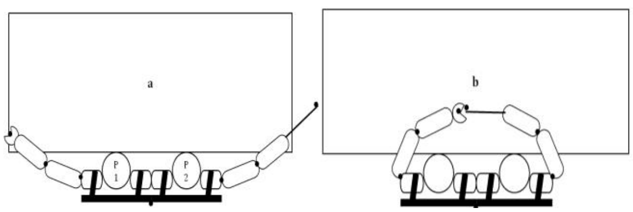

Figure 1. Bird's-eye view of the experimental set-up with participant 1 sitting on the left side using his or her left arm to hold the target and participant 2 using his or her right hand to hold the pointer at (a) the initial and (b) objective position. Black dots represent markers placed on the participants and on the back of the chairs.

Procedure

Upon entering the experimental room, participants were asked to sit side-by-side in the chairs and their shoulders were strapped securely in place. The table was then placed in front of them and the motion tracking markers were attached to each participant. The participants were informed that the objective of their task was to bring the pointer to the center of the target as fast and as accurately as possible. They were informed that the straps were placed on their shoulder to prevent the use of their torso during the movement. Additionally, they were instructed to perform the task movement parallel to the table (so as to prevent movement in the vertical plane). Participants were instructed to open their arms until they were flush with the end of the table (thereby enabling full arm extension) and to wait for a verbal command to perform the movement quickly and accurately. They were then allowed to practice the movement two times, so the experimenter could verify that they were in fact limiting their movements to the sagittal and coronal planes (see Figure 1).

Pairs completed 300 trials across two separate sessions, with both sessions performed within the span of a single week. For the first session, pairs completed two sequences of 100 trials each, with a pause of at least 5 minutes between each sequence. They were also allowed breaks every 25 trials if they deemed it necessary. For the second session, pairs completed another 100 trials. Although position data were collected for every trial, in replication of Domkin et al. (2002) only the first and last 15 successfully completed trials were used for analysis. More specifically, the first 15 successfully completed trials from the first 30 trials of the first 100 trial sequence (pre-test) and last 15 successfully completed trials within the last 30 trials of the third 100 trial sequence (post-test) were used in the analyses[1].

Measures

The same measures and UCM model calculations employed by Domkin and colleagues (2002) were used for the current analyses[2].

Kinematic variables. The kinematic measures detailed below were calculated as preliminary measures, both to assess whether the shoulder straps had the intended consequence of reducing the movement of the torso and as preparation for the UCM calculations. Movement time was based on the calculated initiation and termination time. The initiation time was calculated as the moment where the velocity of the target and pointer sensors exceeded 10% of the maximum velocity over the whole trial. The movement termination time was determined as the point at which the velocity fell below 10% of its maximum. Both initiation and termination times were calculated for both arms and when these times were different the earliest initiation time and the latest termination time were adopted as respective trial beginning and end markers. All measures reported below were calculated with respect to these movement period markers.

The final movement position was considered to be 100 ms after the termination time of the movement (Domkin et al., 2002). It was at this final movement position that the constant and variable errors were calculated as a function of the target and pointer positions in the *x* (coronal) and *y* (saggital) planes. Constant errors were calculated for each plane separately and were determined as the spatial separation between the pointer and target at the final movement position. These measures quantified successful completion and variability of placement at the termination of the movement. The variable error, on the other hand, was the *SD* of the constant error in individual trials with respect to the mean position of the pointer sensor in each plane. This measure provided a measure of variability at the meeting point in each trial compared to the other trials.

The two-dimensional (x,y) meeting point position (where the pointer and the target sensors actually met in the final movement position) was also examined within the movement plane. Since there was inherent variance in how participants performed the task from trial-to-trial (even when they completed it successfully), it was necessary to assess how scattered the meeting point was within the movement plane. The variability of this meeting point was

[1] Trials where sensors were lost due to occlusion problems had to be discarded. Due to these technological issues the pre-test block for two of the pairs consisted of 11 trials instead of 15.

[2] Prior to conducting the current study, a single-person pilot experiment (N=5) was conducted using the same procedure and methodology presented here. The results of this pilot study replicated those of Domkin et al.

calculated as the difference in planar distance of the meeting points in the individual trials from the averaged planar distance across the 15 trials of the respective trial block. This provided a measure of variance of this meeting point for both the initial and final trial blocks.

The average shoulder displacement of participants was only 1.59 cm. This is consistent with the 1 cm displacement found by Domkin et al. (2002) and indicates that the shoulder straps on the chairs did stop participants from using their torsos much during the task. Thus, only the three arm joints (shoulder, elbow and wrist) for each participant needed to be considered. The contribution of each joint to the movement was first determined by calculating the range of motion of each joint. This range of motion was calculated as the difference between the biggest and the smallest joint angle during each movement (i.e., between the initial and final movement markers defined above). As was the case in Domkin et al.'s study, these joint angles were calculated using the approximations of arm segment lengths, obtained by calculating the Euclidian distance between the markers at the joints.

Total joint variance of joint configuration. Since trials varied in duration, angular trajectories were time-normalized using a cubic spline interpolation within the pre- and the post-test blocks. The movement time in each trial was divided into ten even time bins. This normalization made direct comparison between trials possible.

The mean joint configuration was then computed for each time bin and also across the whole trial. This measure indexed how much each joint moved and contributed to the overall completion of different parts of the trial. Furthermore, the joint variance was the variable considered to be stabilized in the formation of the synergy and was therefore the main variable used for the UCM analysis detailed below. Finally, the deviation of the mean configuration of each time bin ($\Delta k(t)$) from the mean for the whole trial was calculated. This deviation was then divided by the number of trials in the block (i.e., 15) and the number of degrees of freedom available (six when considering both arms simultaneously and three when considering each arm separately), to obtain the total variance per DoF of joint configuration (V_{TOT}) for each trial. V_{TOT} quantifies the degree of variability present in each trial when compared to the other trials in the block. Since it is dependent on the DoF used, it can be calculated at both the interpersonal (H1) and intrapersonal (H2 & H3) levels.

Control hypotheses and task variables. Following Domkin et al. (2002), three stabilization hypotheses were tested. The first hypothesis (H1) to be tested was whether the necessary joint stabilization needed to complete the task was distributed across both arms (interpersonal or bimanual hypothesis). In contrast, the second hypothesis (H2) was that the control focused on stabilizing the target and, therefore, that the joint configuration of the left arm of Participant 1 was central to task performance (intrapersonal or unimanual left). The third hypothesis (H3) was that the right arm pointer (Participant 2) stabilization was the focus of control (intrapersonal or unimanual right).

V_{TOT} was partitioned into the variance that occurred along the uncontrolled manifold (V_{UCM}) subspace—which is considered to be compensated variance—and the variance occurring orthogonal (V_{ORT}) to this subspace—which is considered uncompensated. The V_{UCM} and V_{ORT} were calculated for each time bin of each trial in the pre- and post-test blocks for each pair for each hypothesis level. Finally, the ratio of V_{UCM} to V_{ORT} was calculated for each hypothesis (by averaging V_{UCM} and V_{ORT} across pairs and time bins). If the variance along the UCM was found to be higher than that found along the orthogonal task-space dimensions (numbers higher than 1 in the ratio), the organization of the movement DoF would be considered synergistic. Accordingly, if this ratio is higher in H1 compared to H2 and H3 analyses, then the interpersonal movement system would not only be considered synergistic, but would be the strongest synergy and the one that best characterizes the organization of the task-directed movement system. In other words, the stabilization necessary to complete the task would be found to be dependent on the movements of both participants (as one single interpersonal synergistic system) as opposed to the separate stabilization of each arm (two synergistic [arm] systems interacting).

Results

Due to equipment malfunction and marker occlusion issues, data from two pairs could not be analyzed. Thus, the following analysis and results include data from only thirteen of the fifteen pairs recruited (i.e., $N = 13$).

Movement Kinematics

A paired samples one-tailed t-test comparison revealed an expected significant decrease in mean movement time from pre-test to post-test ($M_{pre\text{-}test} = 1.36$ sec; $M_{post\text{-}test} = 1.20$ sec; $t(12) = 1.91$, $p = .04$).

Paired samples t-test analyses of the constant errors in the final position in the x and y plane and as a function of test block revealed no significant differences for these dependent measures (all $t(12) < 1.71$, $p > .11$). The variable error of this meeting point as a function of test was also calculated, but there was no significant difference between pre- and post-test, $t(12) = 1.78$, $p = .19$, indicating that the meeting point was achieved successfully for all trials and remained relatively constant across pairs and test blocks.

With respect to range of joint angles, even though Domkin et al. (2002) found differences of joint range by arm, indicating a handedness effect, this was not the case in the current results. Repeated measures 2 (side: left vs. right) × 2 (test: pre vs. post) ANOVAs for each major joint showed only a significant main effect of test for the shoulder range of motion, which was significantly reduced with practice. All other main effects and interactions were not significant (all $F(1,8) < 3.58$, $p > .08$), which suggests that participants contributed equally during the actualization of the movement across all trials and sessions.

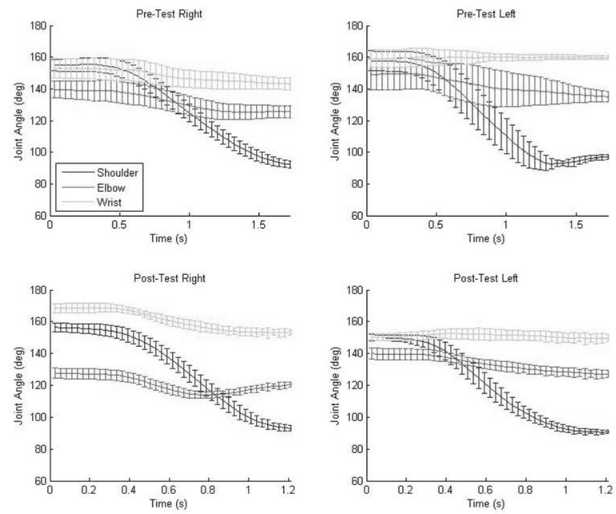

Figure 2. Mean joint angle configuration time series of the pre- (top) and post-test (bottom row) blocks by arm in a representative pair. The error bars depict standard deviation. The x-axis depicts the mean time it took to complete the trial.

Joint-Angle Variance

Figure 2 provides a prototypical example of the mean joint angle trajectory exhibited by the arms of participants during pre- and post-test trials. The standard deviation, depicted in the error bars, shows a general decrease in the overall variance from pre- to post-test. To test whether this decrease was significant we analyzed, the total variance per DoF (V_{TOT}), depicted in Figure 3left, averaged across pairs and time bins. Since the interpersonal V_{TOT} is the result of the addition between the value of the two intrapersonal hypotheses, a 2 (side: left vs. right) × 2 (test: pre vs. post) ANOVA was conducted. As expected, this analysis resulted in a significant main effect of test, $F(1, 12) = 14.83$, $p < .01$, $\eta_p^2 = .55$, with V_{TOT} being significantly lower in the post-test ($M = 0.005$) compared to the pre-test ($M = 0.01$). That is, participants showed significantly less variability in the post-test than the pre-test trials (i.e., their task performance improved with time). No other significant effects were obtained for the analysis of V_{TOT} (all $p > .51$).

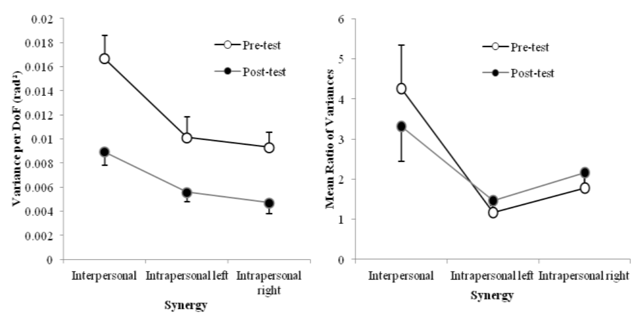

Figure 3. (left) Total variance per degree of freedom (V_{TOT}) averaged across the pairs and time bins presented by synergy and (right) mean ratio of UCM variance to ORT variance by hypothesis and test. Error bars represent standard error of the mean.

Figure 4 shows the mean V_{UCM} and V_{ORT} for both pre- and post-test for each stabilization hypothesis across the ten normalized time bins. All possible synergy configurations—intrapersonal (arm) and interpersonal synergy configurations—show higher V_{UCM} than V_{ORT}, both for pre- and post-test, indicating that the system at either level can be considered to be synergistically organized. Consistent with the V_{TOT} results reported above, the UCM and ORT variance for all level configurations (i.e., interpersonal, left-arm-participant, right-arm participant) also decreased from pre- to post-test.

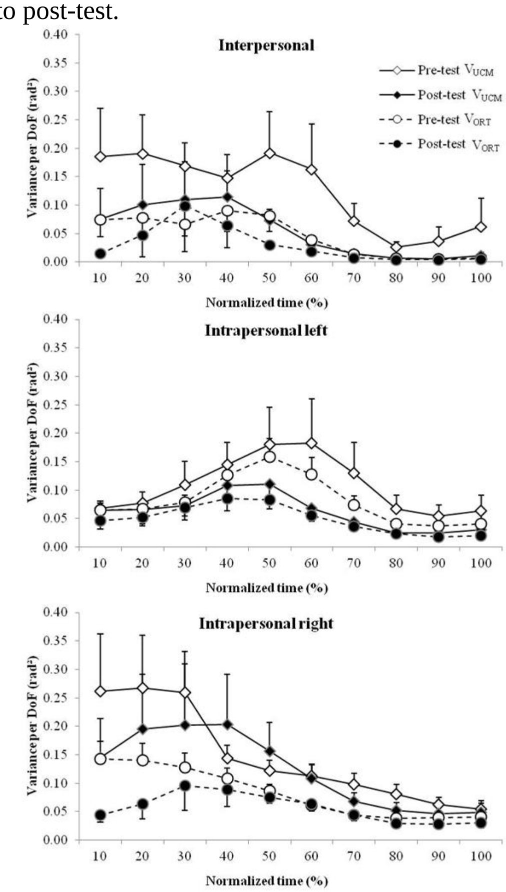

Figure 4. V_{UCM} (represented by diamonds) and V_{ORT} (represented by circles) averaged across pairs by time bins for the three control configurations (interpersonal at the top, intrapersonal left in the middle and intrapersonal right at the bottom). The variances are also separated by test (pre-test being the unfilled and post-test being the filled symbols). Error bars represent standard error of the mean.

To assess the relative strength of the interpersonal synergy and the two intrapersonal synergies, the ratio of UCM variance over ORT variance (average across pairs and time bins) was calculated for each possible synergy configuration. As can be seen in Figure 3right, all the V_{UCM} to V_{ORT} ratios obtained were higher than one, indicating that the DoF used for this task were synergistically organized at all levels (interpersonal and intrapersonal). More importantly, a 2 (test) × 3 (hypothesis: bimanual, left and right) ANOVA showed a significant main effect of synergy configuration, $F(2, 24) = 7.13$, $p = .01$, $\eta_p^2 = .37$, with LSD post-hoc analyses revealing that the interpersonal synergy was significantly stronger ($M = 3.79$) than the intrapersonal left (M = 1.32; p = .01) and also significantly stronger than the intrapersonal right (M = 1.97; p = .04). No other OMNIBUS effects were significant (all p > .20).

Discussion

As expected, task performance improved over the course of the study, as demonstrated by the reduction of V_{TOT} observed from the pre- to the post-test blocks. The significant decrease in mean movement time also pointed to an increase in task efficiency. Since a certain level of variance is expected and even considered beneficial for motor task completion (Bernstein, 1967; Black et al., 2007), of greater relevance to the three hypotheses being examined here was the nature of the variance (compensated vs. uncompensated). Therefore, a V_{UCM} to V_{ORT} ratio was calculated for each of the three stabilization hypotheses (with a variance ratio higher than one representing synergistic organization at that level). The ratio of variance analysis revealed two key findings.

The first finding was that the behavior was synergistic at both the interpersonal and intrapersonal levels from the start of the study (pre-test) and remained synergistic until the end (post-test). This finding corroborates previous evidence indicating that synergistic organization is prototypical of human perceptual-motor behavior in general (e.g. Domkin et al., 2002; Jacquier-Bret et al., 2009; Scholz & Schöner, 1999; Scholz et al., 2000). Moreover, it validates the hypothesis that co-actors can spontaneously form a two-person synergistic system in order to carry out a joint action task. Related to the latter point, the second key finding was that the strongest synergistic organization observed in the task was at the interpersonal level. This finding suggests that the movements of co-acting individuals were temporarily constrained and organized to form a single synergistic two-person system (Riley et al., 2011).

The findings of the current project extend our previous knowledge of interpersonal synergies in several ways. First, the current study provides the first definitive evidence that interpersonal synergistic organization can characterize discrete joint action tasks (Black et al., 2007). Second, by using UCM the results of the current study show that joint-action behavior can possess *both* of the key characteristics of synergistic behavior—RC and DC. While the use of PCA had previously demonstrated DC across participants in a supra-postural targeting task (Ramenzoni et al., 2011) it failed to test the presence of RC. The presence of these two key characteristics in the organization of DoF in a discrete joint motor task therefore provides definitive support for the emergence of interpersonal synergies.

Finding that the action dynamics of individuals performing a joint-action task can become temporarily organized to form a single synergistic two-person system implies that social interactions in general may need to be investigated from a synergistic perspective. In other words, future research should be directed towards identifying the reciprocal and functionally defined couplings that constructively constrain the DoFs of co-actors. Distinguishing such synergistic processes will likely impact our understanding of other joint-action and social motor coordination phenomena (e.g. interpersonal passing behaviors, team sports), as well as the dynamics of social action and interaction in general.

Acknowledgment: This research was supported by the National Institutes of Health (R01GM105045).

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