Synergies in Intra- and Interpersonal Interlimb Rhythmic Coordination

David P. Black, Michael A. Riley, and Christopher K. McCord

The authors conducted two experiments that served as a test bed for applying the recently developed uncontrolled manifold (UCM) approach to rhythmic motor coordination, which has been extensively investigated from a coordination dynamics perspective. The results of two experiments, one investigating within-person and one investigating between-persons rhythmic movement coordination, identified synergistic behaviors in both of those types of coordination. Stronger synergies were identified for in-phase than antiphase coordination, at the endpoints of the movement cycles compared with the midpoints, for movement frequencies closer to the intrinsic frequency of the coordinated limbs, and for within-person coordination. Frequency detuning did not weaken the strength of interlimb rhythmic coordination synergies. The results suggest the synergistic behavior captured by the UCM analysis may be identifiable with the strength of coupling between the coordinated limbs. The UCM analysis appears to distinguish coordination parameters that affect coupling strength from parameters that weaken coordination attractors.

Key Words: uncontrolled manifold, synergy, interlimb rhythmic coordination, stability

Coordination refers to the organization of motor system degrees of freedom—how the degrees of freedom relate to and change with respect to one another. Bernstein (1967) posited that coordination is typically achieved by grouping degrees of freedom together to form softly coupled, functionally specific, low-dimensional units of control, termed synergies (see also Gelfand & Tsetlin, 1966; Turvey, 1990; Turvey, Shaw, & Mace, 1978). Interlimb rhythmic coordination (IRC), the synchronization of oscillatory movements of body segments at a common frequency and stable phase relation, is a fundamental type of coordination (Bernstein, 1996). Interlimb rhythmic coordination has been considered a paradigmatic example of a synergy (Kugler & Turvey, 1987) and has served as an empirical workhorse in efforts to understand coordination and synergies from the coordination dynamics perspective (Kelso, 1995; Kugler & Turvey, 1987; Turvey, 1990; Turvey & Carello, 1996).

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Recently the *uncontrolled manifold (UCM) method* has been developed as a means of detecting the presence and quantifying the strength of synergies (Latash, Danion, Scholz, Zatsiorsky, & Schöner, 2003; Latash, Scholz, Danion, & Schöner, 2001; Latash, Scholz, & Schöner, 2002; Scholz, Danion, Latash, & Schöner, 2002; Scholz & Schöner, 1999; Scholz, Schöner, & Latash, 2000; see related approaches by Cusumano & Cesari, 2006; Müller & Sternad, 2003, 2004; Todorov, 2004). The UCM approach, developed in the theoretical context of the relation between motor redundancy and motor variability, provides a new set of tools and concepts for understanding synergies. In the present study we applied the UCM method to rhythmic coordination of the hands of a single person (intrapersonal coordination) and two people (interpersonal coordination).

**Coordination and Synergies**

Seemingly implicit in the task of producing IRC patterns, such as 1:1 frequency-locked, in-phase movements of the hands, is the requirement to coordinate the hands’ angular displacements and velocities so as to ensure the achievement and maintenance of the coordination pattern. A change in the displacement or velocity of one hand could disrupt the coordination pattern, so it must be countered by a compensatory change elsewhere in the system (e.g., one hand must slow down if the other hand speeds up). Whereas it seems obvious that IRC involves synergistic behavior of this kind, there has been no direct test of this hypothesis during steady-state (i.e., unperturbed) coordination. The strongest evidence for synergistic behavior during IRC has been provided by studies that revealed compensation by some degrees of freedom after perturbing other degrees of freedom (Court, Bennett, Williams, & Davids, 2002; Post, Peper, & Beek, 2000; Post, Peper, Daffertshofer, & Beek, 2000; Scholz & Kelso, 1989; Scholz, Kelso, & Schöner, 1987; cf. Kelso, Tuller, & Fowler, 1982; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984).

An alternative to the synergy hypothesis is that synchronization of rhythmic movements could involve less actual coordination than is apparent: The two hands could be running off similar movement patterns relatively independently of one another, giving the appearance of coordination. Although the aforementioned perturbation studies and widely held intuitions about IRC seem to favor the synergy hypothesis over the latter hypothesis, it is nevertheless important to empirically evaluate whether synergistic behavior is present during steady-state rhythmic activity. We expected to confirm the synergy hypothesis and identify synergies for both intrapersonal and interpersonal tasks, consonant with the aforementioned perturbation studies and with widely held intuitions about IRC. Nevertheless, it is important to empirically evaluate whether synergistic behavior is present during steady-state rhythmic activity. Confirmation of synergistic behavior for interpersonal coordination would be important, as such a finding would raise fundamental questions about the ontological status of synergies as either neural or informational entities. Interpersonal synergies, which are visually rather than (primarily) proprioceptively mediated, were expected to be weaker than intrapersonal synergies. That prediction was based on research that identified weaker coupling strength for interpersonal relative to intrapersonal coordination (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; see also Mitra, Riley, Schmidt, & Turvey, 1998).
Our primary interest was not in whether the UCM method would identify synergies, however, but in identifying the effects of common IRC manipulations (phase mode, movement frequency, and frequency detuning) on the strength of interlimb synergies. As described in the next section, those variables and their empirical effects are well understood in the context of dynamical systems models of coordination, but how do they affect compensatory, synergistic behavior during IRC? How does synergy strength, as quantified in the UCM approach, map onto coordination dynamics parameters such as attractor strength?

**Dynamics of IRC**

Two measures are commonly used to quantify IRC. The spatiotemporal relation between the two rhythmically moving limbs is captured by relative phase (denoted $\phi$), which describes the difference in the limbs’ respective points in their movement cycles. The two intrinsically stable rhythmic movement patterns, in phase and antiphase, correspond respectively to $\phi = 0^\circ$ and $\phi = 180^\circ$. The stability of the movement pattern is commonly measured by the standard deviation of a series of $\phi$ values obtained during a trial, denoted $SD\phi$. Lower $SD\phi$ values indicate greater stability.

The dynamics of IRC are described by Equation 1 (Haken, Kelso, & Bunz, 1985 [HKB]; Schöner & Kelso, 1988):

$$\dot{\phi} = \Delta\omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q} \zeta_t (1)$$

The **HKB model**, as Equation 1 is termed, expresses that the time evolution of relative phase ($\dot{\phi}$) is a function of frequency detuning (differences between the limbs’ natural frequencies or *eigenfrequencies*, $\omega$; $\Delta\omega = \omega_L - \omega_R$, where the subscripts indicate left and right limbs, respectively), coupling between the limbs (the mutual influence of one oscillating limb on the other; $b/a$ is an overall index of coupling strength, although $a$ and $b$ are independent when $\Delta\omega \neq 0$), and the magnitude ($Q$) of stochastic noise ($\zeta_t$) stemming from underlying neuromuscular subsystems. The attractors (i.e., stable solutions) of Equation 1 are found at $\phi = 0^\circ$ and $180^\circ$, corresponding respectively to in phase and antiphase. Mean observed relative phase, $\phi_o$, is an empirical measure of attractor location. $SD\phi$ is an empirical reflection of the combined effects of attractor strength (which is proportional to the slope at a zero-crossing in a plot of $\phi$ vs $\phi$) and noise.

The HKB model makes a number of specific predictions about the response of $\phi_o$ and $SD\phi$ to changes in the model’s parameters. All of those predictions have been confirmed for both intrapersonal (Bingham, Schmidt, Turvey, & Rosenblum, 1991; Rosenblum & Turvey, 1988; Schmidt, Beek, Treffner, & Turvey, 1991; Schmidt, Shaw, & Turvey, 1993; Schmidt & Turvey, 1994; Sternad, Amazeen, & Turvey, 1996; Sternad, Turvey, & Schmidt, 1992) and interpersonal coordination (Schmidt, Carello, & Turvey, 1990; Schmidt et al., 1993, 1994, 1998; Schmidt & O’Brien, 1997). Coupling strength ($b/a$) has been shown to relate inversely to movement frequency, $\omega_c$ (Haken et al., 1985; Schmidt et al., 1993; Sternard et al., 1992). The effect of increasing $\omega_c$ below the critical frequency at which phase transitions from antiphase to in phase occur (Kelso, 1984) is higher $SD\phi$. Frequency detuning (i.e., $\Delta\omega \neq 0$) shifts the attractors of Equation 1 away from $\phi = 0^\circ$ and $\phi = 180^\circ$ in a direction and magnitude determined, respectively, by the sign and absolute value of
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$\Delta \omega$. When $\Delta \omega \neq 0$, $\phi_o$ deviates from the intended $\phi$, with a greater shift for higher $\omega_c$. The strength of both attractors is decreased when $\Delta \omega \neq 0$, increasing the salience of underlying neuromotor noise and therefore resulting in an increase in $SD\phi$. All of these effects are magnified for antiphase relative to in-phase coordination.

The Uncontrolled Manifold Approach

The *uncontrolled manifold (UCM)* hypothesis assumes that solving a motor task is associated with stabilizing the value of one or more performance variables. When stabilizing a value of a performance variable, a subspace is created within a state space of elements (the degrees of freedom that participate in the particular task), such that within that subspace, the value of the performance variable remains constant. This subspace is the UCM. The set of solutions that does not lead to desired values of the performance variable (values that are not within the UCM) are restricted, whereas any of the abundant goal-related solutions (values within the UCM) that arise as a result of motor redundancy are allowed because they do not affect the value of the performance variable (Scholz et al., 2002).

The hypothesized stabilization of a performance variable is empirically evaluated by computing two quantities. Variance projected onto the UCM, denoted $Var_{\text{comp}}$, is an index of extent to which variability among the degrees of freedom is compensated to preserve the value of the performance variable. Variance orthogonal to the UCM ($Var_{\text{uncomp}}$) is an index of variability that is not compensated and thus causes values of the performance variable to deviate from the target value. If $Var_{\text{comp}}$ is greater than $Var_{\text{uncomp}}$, the hypothesized performance variable is selectively stabilized by compensation among the degrees of freedom—operationally, a synergy is said to exist. This is quantified by the ratio $Var_{\text{comp}}/Var_{\text{uncomp}}$. A ratio $> 1$ supports the existence of a synergy; a ratio $\leq 1$ does not support the existence of a synergy (or a different synergy exists—a different performance variable may be stabilized). The higher the ratio is, the greater the amount of compensated variability, which suggests a stronger synergy, depending on the magnitude of $Var_{\text{uncomp}}$ (because $Var_{\text{uncomp}}$ directly affects variability of the performance variable). In the present study, ratio served as the global dependent measure obtained from applying the UCM method. It is often informative to separately examine $Var_{\text{comp}}$ and $Var_{\text{uncomp}}$ in addition to examining ratio; in the present study, however, separate analyses of the two components of ratio did not aid in interpreting the results. In applying the UCM method, we treated $\phi_o$ as the performance variable, and the position and velocity of each hand as the component degrees of freedom.

Overview of Present Study and Predictions

The major contribution of this project was the opportunity to connect the UCM approach to the coordination dynamics approach by determining how ratio varied in response to manipulations of the parameters of Equation 1. In two experiments, participants oscillated hand-held pendulums with different intrinsic frequencies (detuned pendulums; $\Delta \omega \neq 0$) or with identical intrinsic frequencies (non-detuned pendulums; $\Delta \omega = 0$) at a frequency ($\omega_c$) higher than or equal to the eigenfrequency of the coupled wrist–pendulum system in either the in-phase or antiphase mode. Experiment 1 examined intrapersonal coordination and Experiment 2 examined
interpersonal coordination. We expected to replicate the well-known and previously described $\phi_o$ and $SD\phi$ effects in response to those manipulations.

Manipulation of the coordination parameters provided the opportunity to verify the assumption that performing intrapersonal and interpersonal rhythmic coordination tasks entails synergistic, compensatory behavior among the involved degrees of freedom. We predicted ratio > 1 in all conditions in both experiments, which would confirm the existence of synergies in steady-state rhythmic coordination. The manipulations additionally provided the opportunity to determine the effects of the coordination parameters on the strength of interlimb coordination synergies. In doing so we expected to discover how coordination dynamics parameters map to the UCM measure ratio as part of continuing efforts to develop new tools to disentangle the effects of attractor strength, coupling strength, and noise (Pellecchia, Shockley, & Turvey, 2005; Richardson, Schmidt, & Kay, 2007; Riley & Turvey, 2002; Shockley & Turvey, 2005, 2006).

We hypothesized that ratio might serve as a measure of coupling strength in IRC. Coupling is a likely mechanism for achieving the compensatory behavior characteristic of synergies. Without coupling of some form, synergistic behavior could not occur, although the appearance of coordination could arise if nearly identical yet independent movement patterns are executed concurrently by the two hands. If ratio is a reflection of coupling strength, it should be sensitive to manipulations of $\omega$, because $\omega$ has been tied to the coupling parameters $a$ and $b$ in the HKB model (Schmidt et al., 1993; Sternard et al., 1992). Differences in the stability of the in-phase and antiphase coordination modes do not, from the HKB perspective, fall out of differences in coupling strength, but there is empirical evidence suggesting weaker coupling for antiphase than in phase (Schmidt & Turvey, 1995), so ratio should be sensitive to phase mode as well. Similarly, research has identified stronger coupling for intrapersonal than interpersonal coordination (Schmidt et al., 1998), leading to the prediction of greater ratio for the former. Although frequency detuning does destabilize IRC, it does not do so by weakening coupling strength, so if ratio is a measure of coupling strength, it should be unaffected by $\Delta\omega$ manipulations. If instead ratio is a broader measure of coordination stability or a measure of attractor strength (to which coupling strength contributes, but which is not solely determined by coupling strength), ratio should decrease as $|\Delta\omega|$ increases.

Method

Participants

Eleven female and one male University of Cincinnati undergraduates participated in this experiment to fulfill a course requirement. They ranged in age from 18 to 36 years ($M = 20.42, SD = 5.12$). All participants were right-handed according to a positive laterality quotient on the Edinburgh Handedness Inventory (Oldfield, 1971). Participants had no history of neurological or musculoskeletal disorders or injuries. Participants signed an informed consent document approved by the local institutional review board.
Materials and Apparatus

Participants sat in a special-purpose wooden chair (88.2 cm high × 83.2 cm wide at the back of the chair) with oversized armrests (38.1 cm long × 19.1 cm wide). The chair permitted support of the forearms while allowing for unrestricted oscillations of the hand-held pendulums about the wrist. The wide armrests ensured that the pendulums would not contact the chair legs. The seat of the chair was 47 cm from the floor.

Kinematic data were collected using a Polhemus FasTrak (Polhemus Corporation, Colchester, VT) and 6D Research System software (Skill Technologies, Inc., Phoenix, AZ) running on a PC. Sensors were attached with Velcro to the top of each pendulum. Data were collected at 60 Hz, filtered with a low-pass Butterworth filter (cutoff frequency of 6.0 Hz), and stored on the PC’s hard drive.

The pendulums were wooden rods of 1.2 cm in diameter attached to 12.7-cm-long cylindrical wooden handles of 2.3 cm in diameter. Three sets of pendulums were used for this experiment. Table 1 lists the physical properties of the pendulums.

For Set A, both pendulums had a length of 65.5 cm. A 75-g plastic cylinder (radius = 2.50 cm, radius of central hole into which the rod was inserted = 0.70 cm, length = 1.50 cm) was attached at the end opposite the handle for both pendulums. For Set B, one pendulum had a length of 50 cm with a 50-g cylinder (radius = 2.50 cm, inner radius = 0.70 cm, length = 1.50 cm) attached at the end distal to the handle. The other pendulum had a length of 65.5 cm with a 75-g cylinder attached at the distal end. Set C was the same as Set B except the pendulums were held in the opposite hands.

The eigenfrequency, $\omega$, of an individual wrist–pendulum system can be estimated according to $\omega = (g/L_s)^{1/2}$ (Kugler & Turvey, 1987), where $L_s$ is the rotational inertia of the pendulum and $g$ is the gravitational constant. Table 2 lists $\omega$ and $\Delta\omega$ for the sets of wrist–pendulum systems.

<table>
<thead>
<tr>
<th>Set A</th>
<th>Rod Length</th>
<th>Rod Mass</th>
<th>Handle Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.50 cm</td>
<td>45.76 g</td>
<td>32.50 g</td>
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<tr>
<td>65.50 cm</td>
<td>45.76 g</td>
<td>32.50 g</td>
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<tr>
<td>Set B</td>
<td>65.50 cm</td>
<td>45.76 g</td>
<td>35.50 g</td>
</tr>
<tr>
<td>50.00 cm</td>
<td>32.70 g</td>
<td>27.20 g</td>
<td></td>
</tr>
<tr>
<td>Set C</td>
<td>50.00 cm</td>
<td>32.70 g</td>
<td>27.20 g</td>
</tr>
<tr>
<td>65.50 cm</td>
<td>45.76 g</td>
<td>35.50 g</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 Eigenfrequencies of the Pendulums

<table>
<thead>
<tr>
<th></th>
<th>( \omega_L )</th>
<th>( \omega_R )</th>
<th>( \Delta \omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set A</td>
<td>0.71 Hz</td>
<td>0.71 Hz</td>
<td>0 Hz</td>
</tr>
<tr>
<td>Set B</td>
<td>0.71 Hz</td>
<td>0.86 Hz</td>
<td>-0.15 Hz</td>
</tr>
<tr>
<td>Set C</td>
<td>0.86 Hz</td>
<td>0.71 Hz</td>
<td>0.15 Hz</td>
</tr>
</tbody>
</table>

Procedure

Each participant sat in the chair and was asked to place the arms so that the wrists were flush with the end of the armrest. The arms were secured to the armrests using a Velcro band to ensure participants did not lift their arms while oscillating the pendulums about the wrist. The participants were asked to look straight ahead and swing the pendulums about the wrists in the parasagittal plane at a self-chosen, comfortable amplitude, and at a frequency prescribed by an auditory metronome. The task was to coordinate oscillations of the pendulums in an in-phase \( (\phi = 0^\circ) \) or antiphase \( (\phi = 180^\circ) \), 1:1 frequency-locked pattern, in synchrony with the metronome frequency. The participants were asked to hold the pendulums tightly to ensure that motion occurred only about the wrists. Participants were instructed when performing in-phase coordination to have the pendulums reach the maximum forward position, that is, the position of maximum radial deviation, when the metronome tone sounded. During the antiphase conditions, participants were instructed to achieve maximum radial deviation with the right pendulum and maximum ulnar deviation (i.e., pendulum in the maximum backward condition) with the left pendulum when the tone sounded. After the instructions were given, participants were allowed to practice oscillating the pendulums in all conditions. Practice ceased when the participant and experimenter were confident in the participant’s ability to perform in-phase and antiphase coordination in synchrony with the metronome, and generally lasted about 5 min. Kinematic data collection began on each trial when participants achieved the required coordination pattern and verbally indicated readiness.

There were three trials per condition for a total of 36 trials. The order of conditions was randomized. Each trial lasted 20 s. Three factors were manipulated: intended phase mode (in phase or antiphase), detuning \( (\Delta \omega) \), and movement frequency \( (\omega_c) \). Those three factors were factorially combined. The three sets of pendulums (see Table 2) were used to create the three levels of detuning: no detuning \( (\Delta \omega = 0 \text{ Hz}) \) and two directions of the same magnitude of detuning \( (\Delta \omega = \pm 0.15 \text{ Hz}) \). The metronome was set at either the coupled wrist–pendulum system’s eigenfrequency \( (\omega_c) \) or slightly higher than the eigenfrequency \( (\omega_{x_c}) \). For
the non-detuned pendulum set, $\omega = 0.71$ Hz and $\omega > c = 0.84$ Hz. For the detuned pendulum sets, $\omega_c = 0.78$ Hz and $\omega > c = 0.94$ Hz.

Data Analysis and Reduction
The kinematic data were subjected to software analyses to compute the primary dependent measures. Data reduction and analysis routines were executed in Matlab.

Relative Phase and Standard Deviation of Relative Phase. Interlimb rhythmic coordination performance was quantified using within-trial mean continuous relative phase, $\phi_o = \theta_L - \theta_R$ (the difference in the left and right limbs’ respective phase angles, $\theta$). The term $\phi_o$ represents the mean difference in the limbs’ respective points in their movement cycles. The within-trial standard deviation of continuous relative phase, $SD\phi$, was also calculated. These are standard measures of IRC (e.g., Turvey & Carello, 1996). The former gives the location of coordination steady states (i.e., it describes the spatiotemporal pattern of coordination of the two hand-held pendulums), whereas the latter is a measure of coordination variability.

To compute those measures, Matlab routines were executed to compute the time series of the individual hand phase angles $\theta_L$ and $\theta_R$ from the recorded pendulum displacement time series. The times of maximum radial and ulnar deviations were determined by a peak-picking algorithm. From the peak radial deviation times, the frequency of oscillation for each cycle was computed as

$$f_j = 1/\text{(time of peak radial deviation } j+1 - \text{time of peak radial deviation } j)$$ (1)

and the mean frequency of oscillation for each trial $f_o$ was calculated from these cycle frequencies. For each sample, the phase angle time series of hand $i$, $\theta^i$, was calculated for the displacement time series. The phase angle of hand $i$ at sample $j$, $\theta^i_j$ was calculated as

$$\theta^i_j = \text{arctan} \left( \frac{v_j}{f_o \Delta x_j} \right)$$ (2)

where $v_j$ is the velocity, $f_o$ is the mean frequency, and $\Delta x_j = x_j - x^o$, is the displacement from the mean position of hand $i$ for the trial. To account for the differences in the measurement units of the component variables, velocity was divided by mean angular frequency. The relative phase for sample $j$ is $\phi(X) = \theta^L_j - \theta^R_j$, where $X = (x_R, x_L, v_R/f_o, v_L/f_o)$.

Mean $\phi_o$ and $SD\phi$ were calculated for each trial and then averaged over trials within conditions to yield one value of $\phi_o$ and one value of $SD\phi$ per condition per participant. The deviation of observed relative phase from the intended phase $\psi(X) = \phi(X) - \phi_o$ was calculated and used in subsequent statistical analyses to avoid trivial statistical differences that would be found between in-phase and antiphase coordination modes.

UCM Analysis. The goal of the UCM analysis is to partition the variability of the component variables with respect to a particular task-level variable, in this case $\phi_o$, into two components, $\text{Var}_{\text{comp}}$ and $\text{Var}_{\text{uncomp}}$. The UCM calculations were performed at three locations in the movement cycle, corresponding to when the pendulum in
the right hand reached maximum radial deviation (termed \textit{max}), maximum ulnar deviation (termed \textit{min} to contrast with max, because the pendulum was at the opposite extreme position in this case), or the midpoint between those position extremes (termed \textit{mid}). Because our geometrical model is nonlinear, a linear approximation of the model was achieved by computing the Jacobian, a matrix of partial derivatives that correspond to changes in the task-level variable with respect to each of the position and normalized velocity values (the grand means of the respective latter two quantities were used in these calculations). The null space of the Jacobian, \( e_i \), was computed to provide basis vectors spanning the linearized UCM. There were \( n - d \) basis vectors, where \( n \) represents the number of dimensions in the component space (4) and \( d \) represents the number of dimensions of the task variable (1). At each location (max, mid, or min), the deviation from the grand mean for position and normalized velocity at the respective location was computed to obtain a deviation matrix, \( \theta - \bar{\theta} \). This deviation matrix was then projected onto the null space:

\[
\Theta_{\parallel} = \sum_{i=1}^{n-d} (e_i^T \cdot (\theta - \bar{\theta}))e_i
\]

(3)

\( \Theta_{\parallel} \) represents scalar values that correspond to how much deviation leaves the value of the task variable unchanged. The perpendicular complement of the null space was defined as

\[
\Theta_{\perp} = (\theta - \bar{\theta}) - \Theta_{\parallel}
\]

(4)

The amount of variability per degree of freedom within the uncontrolled manifold is

\[
Var_{\text{comp}} = (n - d)^{-1} \cdot N_{\text{Tries}}^{-1} \cdot \sum \Theta_{\parallel}^2
\]

(5)

The amount of variability per degree of freedom perpendicular to the uncontrolled manifold is

\[
Var_{\text{uncomp}} = d^{-1} \cdot N_{\text{Tries}}^{-1} \cdot \sum \Theta_{\perp}^2
\]

(6)

The primary dependent variable used in subsequent analyses is

\[
\text{Ratio} = \frac{Var_{\text{comp}}}{Var_{\text{uncomp}}}
\]

(7)

\section*{Results}

\subsection*{Frequency Analyses}

Bonferroni-corrected \( t \) tests revealed that the left- and right-hand oscillation frequencies did not differ significantly in any condition \((p > .05)\), indicating that participants produced 1:1 frequency-locked movements. Paired \( t \) tests comparing the intended (i.e., metronome-specified) and observed frequencies revealed no differences for the \( \omega_c \) conditions \((p > .05)\), indicating participants accurately matched the metronome, but during \( \omega > \omega_c \) conditions, participants were slightly slower than the metronome, \( t(11) = 3.72, p < .01 \), for the 0.84 Hz condition (observed mean frequency = 0.83 Hz), and \( t(11) = -5.52, p < .01 \), for the 0.94 Hz condition (observed mean frequency = 0.93 Hz). Participants oscillated the pendulums faster in the high-frequency than in the low-frequency conditions, \( t(11) = -36.91, p < .001 \) (\( \omega_c \)) and \( t(11) = -30.00 \),
Mean Relative Phase and Standard Deviation of Relative Phase

The results for $\phi_o - \psi$ and $SD\phi$ were consistent with HKB predictions and with previous empirical findings (see Table 3 for a summary of the analyses). There was a phase shift in the direction of $\Delta\omega$. There was greater variability for antiphase than in-phase coordination and when $\Delta\omega \neq 0$. However, no $\omega_c$ effect was found for either $\phi_o$ or $SD\phi$. The $\omega_c$ manipulation may not have been large enough to substantially destabilize the coordination pattern.

UCM Analysis: Ratio

Mean ratio values exceeded unity in all conditions, indicating the relative phase was selectively stabilized and that synergistic behavior was present. In order to evaluate how the experimental manipulations affected the strength of the synergy, a Location $\times$ Phase $\times$ $\Delta\omega \times \omega_c$ repeated-measures ANOVA was conducted on the ratio data. Location had three levels, max, mid, and min, corresponding to the points in the movement cycle at which the UCM calculations were performed, as described earlier.

**Location.** ANOVA revealed a significant main effect of location, $F(2, 22) = 17.15$, $p < .001$, $\eta^2_p = 0.82$. Bonferroni-Dunn post hoc comparisons revealed significant differences between the min vs. mid ($p < .001$) and max vs. min ($p < .01$) locations. The greatest ratio value was found for the min condition (mean ratio = 2.97).

**Phase Mode.** There was a significant main effect of phase mode, $F(1, 11) = 49.74$, $\eta^2_p = 0.82$, $p < .001$, which indicated that participants stabilized relative phase more when the coordination mode was in phase (mean = 3.78) than antiphase (mean = 1.64). There was also a significant Location $\times$ Phase mode interaction, $F(2, 22) = 4.69$, $p < .05$, $\eta^2_p = 0.30$ (see Figure 1). Simple-effects analyses revealed that the interaction was driven by greater ratio values in the min condition during in phase compared to antiphase, $F(1, 11) = 20.30$, $\eta^2_p = 0.25$, $p < .001$. 

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>$F$</th>
<th>$\eta^2_p$</th>
<th>$SD\phi$</th>
<th>$\eta^2_p$</th>
</tr>
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<tr>
<td><strong>Within subjects</strong></td>
<td>0</td>
<td></td>
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<tr>
<td>Phase Mode</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\Delta\omega$</td>
<td>2</td>
<td>178.29**</td>
<td>0.94</td>
<td>12.54***</td>
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<tr>
<td>Phase Mode $\times$</td>
<td></td>
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<tr>
<td>$\Delta\omega$</td>
<td>2</td>
<td></td>
<td></td>
<td>7.95**</td>
<td>0.42</td>
</tr>
</tbody>
</table>

* $p < .05$ ** $p < .01$ *** $p < .001$ Not significant
Movement Frequency. The ANOVA revealed a significant $\omega$ main effect, $F(1, 11) = 20.72, p < .001, \eta_p^2 = 0.65$. There was a significant decrease in ratio for $\omega_{c}$ compared with $\omega_{c}$ (mean difference = 0.608).

Location $\times$ $\Delta\omega \times \omega$ Interaction. A significant three-way interaction involving Location, $\Delta\omega$, and $\omega$ was found, $F(4, 44) = 3.64, p < .05, \eta_p^2 = 0.25$ (see Figure 2). Simple effects analyses, reported in detail in the next two paragraphs, revealed the interaction was driven by the following effects. Ratio was significantly greater at the end points of the movement cycle (max and min locations) compared with the midpoint in the putatively less stable $\omega_{c}$ condition, but there was no location effect in the putatively more stable $\omega_{c}$ condition. In addition, there were significantly larger ratio values at the max and min locations than at the mid location for all $\Delta\omega$ conditions. For $\Delta\omega = 0.15$ Hz in the $\omega_{c}$ condition, there was a substantial increase in ratio relative to the other conditions.

Simple effects analyses of location at each level of movement frequency were first performed. A significant location effect was found in the $\omega_{c}$ condition, $F(2, 22) = 38.02, \eta_p^2 = 0.32, p < .001$. Bonferroni–Dunn post hoc tests revealed significantly greater ratio values in the max and min locations relative to the mid location (both $p < .01$).

Simple-effects analyses at each level of $\Delta\omega$ were then performed, and revealed a significant effect of location for all levels of $\Delta\omega$, $F(2, 22) = 17.60, \eta_p^2 = 0.19, p < .001$ ($\Delta\omega = -0.15$ Hz), $F(2, 22) = 6.48, \eta_p^2 = 0.19, p < .01$ ($\Delta\omega = 0$ Hz), and $F(2, 22) = 9.97, \eta_p^2 = 0.27, p < .001$ ($\Delta\omega = 0.15$ Hz). Bonferroni–Dunn tests revealed significant differences between the max and mid locations and between the min and mid locations for $\Delta\omega = -0.15$ Hz and for $\Delta\omega = 0$ Hz ($p < .001$). Only a significant difference between the min and mid locations was observed when $\Delta\omega = 0.15$ Hz. In addition, a significant $\omega_{c}$ effect was revealed for $\Delta\omega = 0$ Hz, $F(1, 11) = 16.29, \eta_p^2 = 0.10, p < .001$, and for $\Delta\omega = 0.15$ Hz, $F(1, 11) = 14.73, \eta_p^2 = 0.15, p < .01$, but not for $\Delta\omega = -0.15$ Hz.

Figure 1 — Mean ratio as a function of phase mode and location in Experiment 1.
Discussion

As expected, mean ratio values were greater than 1 in all conditions, implying that even when the coordination pattern was less stable as a result of manipulating $\Delta \omega$, $\omega_c$, and intended phase mode, the two limbs remained a functionally coupled unit (i.e., a synergy). However, those manipulations did have effects on the strength of the IRC synergy. The pattern of results suggests that the UCM measure ratio might be sensitive to changes in coupling strength. Another important finding was that synergy strength was not constant across the movement cycle.
Ratio as a Measure of Coupling Strength

The results of manipulating the HKB parameters were largely supportive of the hypothesis that ratio indexes coupling strength. The most direct support for the hypothesis was that ratio decreased as $\omega_c$ increased. That manipulation had no effect on $\phi$, or $SD\phi$, which suggests ratio may be a very sensitive measure that can detect decreases in synergy strength before the effects are felt by a change in attractor location or an increase in relative phase variability. Ratio was greater for in-phase than antiphase coordination, in accordance with empirical measures of coupling strength for those two coordination modes reported by Schmidt and Turvey (1995). Detuning did produce the typically observed phase shift and increase in $SD\phi$, but did not uniformly affect ratio. The only effect on ratio involving detuning was the three-way interaction, which in large part was driven by increases in ratio when the right pendulum had a lower eigenfrequency. The detuning results are important for two reasons. First, because the mechanism by which detuning disrupts IRC is not by decreasing coupling strength, the finding that ratio did not decrease during conditions involving detuning is consistent with the possibility that ratio indexes coupling strength. Second, because within the HKB framework detuning has a straightforward interpretation as a means of decreasing attractor strength and stability, the insensitivity of ratio to detuning suggests that not all means of destabilizing coordination involve a weakening of the synergistic behavior among the degrees of freedom that are being coordinated. Further research and modeling will be required to understand paths to coordination destabilization that do not involve a reduction in the degree to which the degrees of freedom compensate for fluctuations in the coordination pattern.

Location Effects

Higher ratio values were observed at the end points of the movement cycle compared with the midpoint, suggesting that coupling between the limbs may not be uniform across the movement cycle. There are several (perhaps not exclusive) possible explanations of this result that require further research to distinguish. One possibility is that the degree of coordination achieved may be more perceptually salient at the endpoints of the movement cycle (although there is evidence that relative phase perception is not based on discrete samples of movement cycle end point; Bingham, 2004). This could be related to the phenomenon of anchoring (Beek, 1989; Byblow, Carson, & Goodman, 1994; Carson, 1995; Fink, Foo, Jirsa, & Kelso, 2000), although phase portraits of the data from this experiment did not upon inspection yield any qualitative evidence for anchoring. An alternative to the perceptual saliency hypothesis is that for biomechanical reasons, it may be easier to execute corrective adjustments when the pendulum velocities are approaching zero at the end points of the movement rather than when the pendulums reach peak velocity (and hence have greater momentum) at the midpoint of the movement cycle. Another possible explanation is that this result could reflect the fact that at the end point of movement cycles wrist angles can effectively vary in only one direction, whereas at the midpoint of the movement cycle wrist angles can effectively vary in two directions.
There was also an overall tendency for ratio to be higher at the min location than at the max location. This result could reflect biomechanical constraints. In the present experiment, the forearm was positioned on the armrest of the chair in a position intermediate between pronation and supination. Bringing the pendulum into max location involved radial deviation and bringing the pendulum into the min location involved ulnar deviation. With the forearm supported in the chair and intermediate between pronation and supination, full ulnar deviation can be achieved passively largely by allowing the wrist and pendulum to fall under the influence of gravity. In contrast, full radial deviation requires active force generation to achieve. The relatively higher passive stability and the reduced need to generate active forces during ulnar deviation (corresponding to the min location) may reduce the extent to which uncompensated variance arises from noisy muscular contractions required to actively generate force, although biomechanical studies of oscillations of hand-held pendula are necessary to determine whether this interpretation might be correct.

**Location × Δω × ω Interaction**

The Location × Δω × ω interaction was not straightforward to interpret. The interaction was largely driven by greater ratio values for the min location when Δω = 0.15 Hz. Although it remains unclear why Δω = 0.15 Hz would have a different influence on ratio than Δω = −0.15 Hz (which involved an equal degree of detuning, but in the opposite direction), it is possible that the result suggests a subtle handedness effect. The interaction suggests that participants (all of whom were right-handed) were able to better regulate φ when the pendulum held in the right hand had a lower eigenfrequency (i.e., was the longer of the two pendulums). The greater rotational inertia and hence greater stability of the longer pendulum may have afforded the right-handed participants the chance to produce greater compensated variability when the longer pendulum was in the right hand and at the min location. In order to evaluate this possible explanation additional experiments are needed, including left-handed in addition to right-handed participants. It would be expected that for left-handed participants there would be greater stabilization of φ when Δω = −0.15 Hz.

**Experiment 2**

In Experiment 2 an interpersonal coordination task was employed. Pairs of participants visually coordinated pendulum oscillations to produce in-phase or antiphase coordination patterns. Participants each oscillated a hand-held pendulum in one hand and coordinated its motion with that of a pendulum oscillated by the other participant. Because the interpersonal task required adding hand as an experimental factor (participants used their right hand on half the trials, and the left hand on the other half), we did not manipulate ω in this experiment to simplify the design and reduce the number of trials.
Method

Participants

Seventeen female and eleven male University of Cincinnati undergraduates participated in this experiment to fulfill a course requirement. They ranged in age from 18 to 32 years \( (M = 19.71, SD = 2.82) \). All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). Participants had no history of neurological or musculoskeletal disorders or injuries.

Materials and Apparatus

The materials and apparatus remained the same from Experiment 1, except that two special chairs were required for Experiment 2.

Procedure

The procedure of Experiment 2 was similar to Experiment 1 except two participants coordinated pendulum movements with each other. Participants were seated in two chairs that faced the same direction and were separated by 73 cm. Each participant was instructed to watch the other participant’s pendulum during the entire trial (an experimenter verified that this always occurred). The pacing metronome was set at the movement frequency of the coupled wrist–pendulum system, which was 0.70 Hz for the non-detuned pendulums and 0.78 Hz for the detuned pendulums. For in-phase coordination, participants were instructed to have the pendulum tips in the maximum forward position (maximum radial deviation) when the metronome tone sounded. For antiphase coordination, the participant who held the pendulum in the right hand was instructed to achieve the maximum radial deviation and the participant who held the left pendulum was instructed to achieve the maximum ulnar deviation when the tone sounded. After the instructions were given, the participants were allowed to practice all conditions. On a given trial, kinematic data collection began when participants achieved the required coordination pattern and both verbally indicated their readiness.

There were 3 trials per condition for a total of 36 trials. Each trial lasted 20 s. Two factors were manipulated and factorially combined: intended phase mode and detuning. A hand factor was added to account for any possible differences that might have occurred owing to hand preference because participants used their preferred hand on half the trials and the nonpreferred hand on the other half. The experiment was split into two blocks, each containing 18 trials. In the first block, one of the participants was randomly chosen to oscillate the pendulum with the right hand and the other participant used the left hand. In the second block, the participants switched seats and used the opposite hand. Each block contained an equal number of trials in each phase mode and detuning condition. The order of conditions within blocks was randomized.
Results

Frequency Analyses

Bonferroni-corrected $t$ tests revealed the left-hand and right-hand frequencies were not significantly different ($p > .05$) for either frequency condition. The participant pairs produced 1:1 frequency locking. Paired $t$ tests revealed no differences between metronome-specified and observed movement frequencies ($p > .05$), indicating that participants accurately matched the metronome.

Mean Relative Phase and Standard Deviation of Relative Phase

The $\phi_o - \psi$ and $SD\phi$ results (see Table 4 for a summary of the analyses) were consistent with HKB predictions and with previous empirical findings (Schmidt et al., 1990, 1994, 1998). There was a phase shift in the direction of $\Delta\omega$, and $SD\phi$ was greater during antiphase than in-phase coordination and when $\Delta\omega \neq 0$.

UCM Analysis: Ratio

As was the case in Experiment 1, ratio exceeded unity in all conditions, indicating the presence of synergistic behavior and the selective stabilization of relative phase in interpersonal coordination.

**Location.** A Location × Phase Mode × $\Delta\omega$ × Hand repeated-measures ANOVA revealed a significant location main effect, $F(2, 26) = 5.02, \ p < .05, \ \eta^2_p = .07$. There were greater ratio values at the end points of the movement cycle (means for the max, mid, and min locations were 2.33, 1.44, and 2.21, respectively), with Bonferroni–Dunn post hoc tests indicating a significant difference between the min and mid locations ($p < .01$) and the max and mid locations ($p < .01$). Also a significant Location × $\Delta\omega$ interaction was found, $F(4, 52) = 2.73, \ p < .05, \ \eta^2_p = 0.17$ (see Figure 3), with simple-effects analyses revealing the interaction was driven by greater ratio values in the min location when $\Delta\omega = 0.15$ Hz, $F(2, 52) = 7.38, \ \eta^2_p = 0.11, \ p < .01$.

**Phase Mode.** A significant phase mode main effect was found, $F(2, 26) = 8.26, \ p < .05, \ \eta^2_p = 0.39$, indicating a stronger synergy during in-phase (mean ratio = 2.31) than antiphase (mean ratio = 1.68) coordination.

**Location × Phase Mode × $\Delta\omega$ Interaction.** There was a significant three-way interaction between Location, Phase Mode, and $\Delta\omega$, $F(4, 52) = 3.70, \ p < .01, \ \eta^2_p = 0.22$ (Figure 4). Simple-effects analyses, reported in detail in the following paragraph, indicated the three-way interaction was driven largely by the fact that during in-phase coordination there were consistently higher ratio values in the min location and when $\Delta\omega = 0.15$ Hz.
Table 4  Results for Relative Phase and Standard Deviation of Relative Phase for Experiment 2

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>$F$</th>
<th>$\psi - \phi_o$</th>
<th>$\eta_p^2$</th>
<th>$\psi - \phi_o$</th>
<th>$SD$</th>
<th>$\phi_o$</th>
<th>$\eta_p^2$</th>
<th>$SD$</th>
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<tr>
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<td>0.55</td>
<td>21.29***</td>
<td>0.62</td>
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<tr>
<td>$\Delta\omega$</td>
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<td>59.18***</td>
<td>0.82</td>
<td>9.23***</td>
<td>0.51</td>
<td></td>
<td></td>
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<tr>
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<td>5.67**</td>
<td>0.30</td>
<td></td>
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<td></td>
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<tr>
<td>Phase Mode x $\Delta\omega$</td>
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<td></td>
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<tr>
<td>Phase Mode x Handedness</td>
<td>1</td>
<td>5.67**</td>
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<td>$\Delta\omega$ x Handedness</td>
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<tr>
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* $p < .05$  ** $p < .01$  *** $p < .001$  Not significant
Figure 3 — Mean ratio as a function of location and $\Delta \omega$ in Experiment 2.

Figure 4 — Mean ratio as a function of location and $\Delta \omega$ in the antiphase and in-phase conditions in Experiment 2.
Simple-effects analyses revealed a significant effect of location when $\Delta\omega = 0.15$ Hz, $F(2, 26) = 7.38$, $\eta_p^2 = 0.21$, $p < .01$, with Bonferroni–Dunn tests indicated greater ratio values at the min compared with the mid location, $p < .001$. There was a significant Location $\times$ Phase Mode interaction when $\Delta\omega = 0.15$ Hz, $F(2, 26) = 7.00$, $\eta_p^2 = 0.15$, $p < .01$, which additional follow-up tests revealed was due to a significant effect of location during in-phase coordination, $F(2, 26) = 7.65$, $\eta_p^2 = 0.27$, $p < .01$ (Bonferroni–Dunn post hoc tests revealed significantly greater ratio values for the min location than the mid location and for the max location than the min location, both $p < .01$). For the min location, simple-effects analysis indicated significant effects of phase mode and $\Delta\omega$, $F(1, 13) = 10.03$, $\eta_p^2 = 0.17$, $p < .01$, and $F(2, 26) = 5.61$, $\eta_p^2 = 0.10$, $p < .01$, respectively. Ratio was significantly greater during in-phase than antiphase coordination ($p < .01$) and significantly greater for $\Delta\omega = 0.15$ Hz than for $\Delta\omega = -0.15$ Hz ($p < .01$). Finally, the simple-effects analysis revealed a significant Location $\times$ $\Delta\omega$ interaction during in-phase coordination, $F(4, 52) = 3.93$, $\eta_p^2 = 0.19$, $p < .01$. At the min location, ratio was significantly greater for $\Delta\omega = 0.15$ Hz than for $\Delta\omega = -0.15$ Hz ($p < .01$).

**Discussion**

Experiment 2 identified synergies in interpersonal coordination. As in Experiment 1, the mean ratio values fell above 1 in all conditions, indicating that relative phase was selectively stabilized when two people used visual information to coordinate the oscillations of the pendulums. As was also the case in Experiment 1, ratio values were greater for in-phase than antiphase coordination, and greater at the end points of the movement cycle than at the midpoint.

These results provide support for arguments that the control processes that govern intrapersonal coordination are abstract and similar to the processes that govern interpersonal coordination (Schmidt et al., 1990, 1993, 1994, 1998; Schmidt & O’Brien, 1997; Schmidt & Turvey, 1994; see also Kelso, 1995). Findings from research on interpersonal coordination raise an important question about the fundamental nature of synergies: Are synergies “hard-wired” structures that exist within the neuromuscular system of one person, or are they more abstract, informational entities? The present results suggest the latter. A previously offered definition of synergies conceives them as timed sequences of control signals sent to groups of muscles in order to form functional linkages between motor elements (Latash, 1993, 1998). Such a definition, which was offered in the context of intrapersonal coordination, does not prohibit abstraction to the case of interpersonal coordination. The presence of a synergy, in the UCM approach, means that the elements of a system are linked together in such a way as to promote the stabilization of a macroscopic, task-relevant performance variable. The medium of the link between the elements can presumably take many forms. The elements may be linked through proprioceptive feedback within a single person’s nervous system or by visual information in the performer’s environment. Latash’s definition of synergies could easily be generalized to include interpersonal synergies by simply broadening the conception of “control signals” to include optical information.
Schmidt et al. (1998) observed that coupling strength during interpersonal coordination was weaker than during intrapersonal rhythmic coordination. Assuming (based on the results of Experiment 1) there is a direct relation between coupling strength and the strength of a synergy, we predicted that a weaker synergy would exist in interpersonal compared with intrapersonal coordination. An omnibus ANOVA to directly compare ratio values across experiments was prohibited because different designs were used in Experiments 1 and 2. However, ratio values in Experiment 1 (mean ratio = 2.72) were higher than in Experiment 2 (mean ratio = 1.93), and higher in every condition in Experiment 1 than in Experiment 2, consistent with the claim that intrapersonal synergies are stronger than interpersonal synergies. Thus, the informational linkage connecting the degrees of freedom participating in a synergy is not inconsequential with regard to the strength of the synergistic behavior and, thus, the comparative stability of the behavior. Degrees of freedom that are directly, neurally coupled may be more strongly constrained to act as a synergistic unit than are optically coupled elements. Nevertheless, the flexibility of the CNS, witnessed by instantiating very similar processes in intrapersonal and interpersonal coordination tasks, is remarkable. The differences between intrapersonal and interpersonal coordination seem to be only a matter of degree, and a small degree at that—the difference between mean ratio values in Experiments 1 and 2 (0.79) was smaller than the difference in ratio values obtained across coordination modes in Experiment 1 (mean difference = 2.14).

The three-way interaction observed in Experiment 2 was similar in form to the interaction observed in Experiment 1 (for both experiments \( \Delta \omega \) and location were involved in the interaction, but the third factor was phase mode in Experiment 2 and \( \omega_c \) in Experiment 1). In both cases, the interaction involved much higher ratio values when \( \Delta \omega = 0.15 \text{ Hz} \) in the min location. As in the case of the interaction in Experiment 1, the meaning of the interaction in the present experiment was unclear, but the similarity of the overall pattern of results across the experiments suggests that the Experiment 1 result was not spurious. Handedness may again have been involved. All participants were right-handed, but on a given trial, one participant was required to use the left hand. The interaction was driven by an increase in ratio when the participant using the right hand held the longer, heavier pendulum.

**General Discussion**

Consistent with the assumption that during bimanual rhythmic coordination the two hands act as a synergy (Kelso, 1995; Kugler & Turvey, 1987; Turvey & Carello, 1996), mean ratio values were greater than 1 in all conditions across both experiments, indicating a functionally coupled unit (i.e., a synergy) was formed between the wrists of a single person (Experiment 1) and of two people (Experiment 2) during steady-state IRC. Synergies were established for both in-phase and antiphase movement patterns, and synergistic behavior was evident despite the destabilizing effects of detuning and increasing the coupled movement frequency.

Although none of the manipulations of standard coordination parameters resulted in the dissolution of the interlimb rhythmic synergy, some of them did
affect the strength of the synergy. Ratio was sensitive to some, but not all, of the parameters that play a role in determining the stability of IRC. Ratio was lower during antiphase coordination. In Experiment 1, ratio was lower for $\omega_c$. Ratio was also lower for interpersonal coordination in Experiment 2 than for intrapersonal coordination in Experiment 1. Ratio did not decrease during detuned conditions in either experiment.

**Ratio as an Index of Coupling Strength**

The pattern of results suggests that the UCM measure ratio is sensitive to coupling strength. Coupling strength (usually indexed by the ratio $b/a$, although for $\Delta \omega \neq 0$ $a$ and $b$ are independent) and the detuning parameter ($\Delta \omega$) are the components that determine attractor strength in the HKB framework (Amazeen, Amazeen, & Turvey, 1998). $SD\phi$ is influenced by the effects of both of those parameters—$\Delta \omega \neq 0$ and increasing movement frequency both lead to higher $SD\phi$—but that measure cannot differentiate whether coordination stability is compromised by decreased coupling strength or by a weakening of the attractor induced by some factor other than decreased coupling strength. The present study indicates that ratio is differentially sensitive to the influence of coupling strength. In Experiment 1, ratio significantly decreased with an increase in $\omega_c$, which has been experimentally tied to the coupling strength parameters $a$ and $b$ (Haken et al., 1985; Schmidt et al., 1993; Sternard et al., 1992). Ratio did not decrease during detuned conditions in either experiment. Moreover, $\Delta \omega$ effects were present only in the three-way interactions that were driven by increases in ratio in some detuned conditions. The ratio results were, in addition, consistent with empirical estimates of coupling strength (using regression techniques) that have revealed lower coupling strength for antiphase coordination (Schmidt & Turvey, 1995) and for interpersonal coordination (Schmidt et al., 1998), conditions both associated with lower ratio values in the present study.

**Location Effects**

Another important finding was that the amount of variability that is structured along the UCM was not uniform across the movement cycle. The effects of location observed in both experiments provided evidence that the strength of the interlimb rhythmic synergy may vary within the movement cycle, which could indicate that the coupling between limbs varies systematically across the cycle rather than remaining constant. This finding recalls the debate regarding the nature of periodic fluctuations of relative phase revealed by spectral analysis and the possibility that higher-order coupling terms could reproduce that finding (Fuchs & Kelso, 1994; Schmidt & Turvey, 1995). The UCM method could perhaps be fruitfully brought to bear in a reexamination of the issues on which that debate centered.

**Interpersonal Synergies**

As discussed earlier, the results of Experiment 2 suggest a conception of synergies as abstract, informational mechanisms for coupling the activity of degrees of freedom. The control signals (Latash, 1993, 1998) must be thought of as informational variables that specify how the degrees of freedom need to interact in order
Synergies in Rhythmic Behavior

...to preserve a desired value (or range of values) of the performance variable. Those variables can be instantiated in a variety of sensory media, including not only the field of interconnected, excitable haptic receptors spanning an actor’s body (Kugler & Turvey, 1987), but also the optic array. Thinking of synergies as informational entities should spur closer examination of the role of perception in IRC, a point emphasized by Bingham (2004) in a discussion of research on the visual perception of relative phase and relative phase variability (Bingham, Schmidt, & Zaal, 1998; Bingham, Zaal, Shull, & Collins, 2001; Zaal, Bingham, & Schmidt, 2000).

Conclusion

It could be argued that the existence of stable relative phase modes already provides evidence for synergies in IRC, and furthermore that $SD\phi$ is a measure of the strength of the synergy. However, $\phi$ is mute regarding whether synergistic, compensatory behavior occurs—it simply expresses the spatiotemporal differences between the motion of two limbs. There is no specific value of $\phi$ that identifies the existence of a synergy, and a phase shift does not necessarily indicate a weakened synergy. Also, as was revealed in this study, fluctuations of $\phi$ (i.e., $SD\phi$) are not necessarily indicative of a weaker synergy (i.e., a decrease in the UCM measure ratio). Detuning led to both a phase shift (i.e., a change in attractor location) and increased $SD\phi$, but not to a decrease in ratio.

$SD\phi$ cannot index synergistic behavior because it does not distinguish compensatory variability that contributes to maintaining an intended value of the performance variable from variability that impairs the maintenance of that value of the performance variable, and because it does not map to variability of the component degrees of freedom. High amounts of velocity and positional variability could occur in the absence of changes in $\phi$ (i.e., compensatory variability), resulting in low $SD\phi$ but higher ratio values. Black, Smith, Wu, and Ulrich (submitted) found that children with Down syndrome (DS) exhibited higher levels of variability in the position of the center of mass (COM; the task-level variable), but they also exploited more $Var_{comp}$ and exhibited similar amounts of $Var_{uncomp}$ compared with children with typical development (i.e., children with DS yielded higher ratio values than their peers with typical development). They argued that children with DS cope with increased variability of the position of the COM caused by their inherent physical and cognitive limitations by exploiting the variability that leads to successful performance of the task and constraining the variability that would truly hinder performance (i.e., taking advantage of a larger workspace of solutions).

By emphasizing functional roles for variability, the UCM approach and the present study contribute to the developing understanding of movement variability (Davids, Bennett, & Newell, 2006; Newell & Slifkin, 1998; Riley & Turvey, 2002; Slifkin & Newell, 1998; Van Emmerick & van Wegen, 2000, 2002). Although dynamical theories of movement coordination admit a functional role of variability in allowing for behavioral flexibility (Kelso, 1995), they have typically also equated variability with a loss of stability (e.g., Kelso, Scholz, & Schöner, 1986). The UCM perspective also emphasizes a functional role of variability with regard to the structuring of variability to preserve a desired value of a performance variable by allowing for reciprocal compensation among degrees of freedom, but does not...
equate variability with a loss of stability because increased variability along the UCM actually contributes to maintaining stability. It seems the UCM and dynamical systems approaches, both conceptually and methodologically, may serve as useful complements in efforts to understand movement coordination.

Acknowledgments

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