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A Comparison of Intra- and Interpersonal Interlimb Coordination: Coordination Breakdowns and Coupling Strength

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Intra- and interpersonal interlimb coordination of pendulums swung from the wrist was investigated. For both kinds of coordination, the steady state and breakdown of bimanual rhythmic coordination as indexed by the time series of the relative phase angle ϕ were studied under the manipulation of coordination mode, frequency of oscillation, and the difference in the eigenfrequencies (preferred tempos) of the individual oscillating limbs. The properties observed for both intra- and interpersonal coordination were those predicted by a dynamical model of rhythmic coordination that considers the coordinated limbs coupled to be nonlinear oscillators. Using a regression method, the coupling strengths of the coupled system were recovered. As predicted by the dynamical model, the strength of the dynamic was generally greater for the in-phase than the anti-phase mode and decreased with increasing frequency. Further, the strength of the interpersonal interlimb coupling was weaker than that of intrapersonal interlimb coupling.

Much research over the past decade has demonstrated that stable patterns of interlimb coordination and their dissolution can be modeled by assuming that the nervous system and concomitant metabolic machinery manifest dynamical processes of self-organization (Haken, Kelso, & Bunz, 1985; Kelso, 1990; Kugler, Kelso, & Turvey, 1980; Kugler & Turvey, 1987; Turvey, 1990). The methodological tactic of this research has been to demonstrate that the patterns of rhythmic coordination observed in single (Feldman, 1980; Kay, Saltzman, & Kelso, 1991) and multilimb (Beek, 1989; Kelso & Jeka, 1992; Schmidt, Shaw, & Turvey, 1993) movements are just those expected if the neuromuscular systems involved are governed by the dynamics of nonlinear oscillators. Interestingly, research has also demonstrated that patterns of coordination similar to those found in within-person interlimb coordination occur in rhythmic movements optically coordinated across two people (Schmidt, Carello,

& Turvey, 1990; Schmidt & Turvey, 1994). These latter findings demonstrate the generality and abstract incorporeal nature of the organizing principles involved in biological rhythmic coordination: The same control processes seem to be at work regardless of whether the coordination involves one nervous system or two or whether the coupling medium is the optic array or neural tissue. In two experiments we further compared the coordination dynamics found in intra- and interpersonal interlimb rhythmic movements, particularly the strength of those dynamics and their patterns of coordination breakdown. We did this using a methodology that manipulated the frequency of oscillation and the dynamical similarity (i.e., the preferred frequency or eigenfrequency difference) of the rhythmic units being coordinated. We also present a new method of measuring the strength of the coupled oscillatory dynamic.

The research on the dynamics underlying interlimb rhythmic coordination has used the relative phase angle (ϕ) formed between the two oscillating limbs as a measure of interlimb coordination. The measurement of ϕ is useful because it provides a quantitative index of the qualitative space-time pattern between the rhythmic units: Given two limbs that are 1:1 frequency locked (i.e., oscillating at the same tempo), if they are at the same point in their cycle at the same time throughout the cycle or in-phase, ϕ is 0° , and if they are at the opposite points in their cycle at the same time throughout the cycle or in anti-phase, ϕ is 180° . Of interest is how this coordination index of the interlimb system is influenced by variables that affect the stability of the interlimb coordination. Using the terminology of *synergetics*, a general theory for investigating the self-organizing principles in complex systems, ϕ is an *order parameter* (i.e., it summarizes the spatiotemporal order of the rhythmic

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units) and the variables that influence it are *control parameters* (Haken, 1977/1983, 1983). The methods of synergetics allow researchers to mathematically model the changes in an order parameter's mean state and fluctuations that occur as a function of control parameter variations (i.e., to mathematically model the order parameter *dynamics*). Past researchers have investigated the dynamics of the interlimb order parameter ϕ under the influence of two control parameters: the frequency of oscillation of the coupled system and the difference between the eigenfrequencies (i.e., the uncoupled preferred frequencies) of two local rhythmic units $\Delta\omega$.

Dynamic Modeling of Interlimb Rhythmic Coordination: Frequency Scaling

The starting point for the dynamical modeling of interlimb coordination is the observation that there are two naturally occurring interlimb relative phase patterns, the in-phase and anti-phase, and that these two modes are differentially stable. In a frequency scaling paradigm, in which participants rhythmically oscillated their index fingers in phase or in antiphase as the frequency of oscillation was increased, Kelso (1984) reported breakdowns in anti-phase followed by transitions to in-phase at high frequencies. The similarity between these interlimb coordination properties and those of coupled oscillator systems led to the proposal of a coupled oscillator model of rhythmic interlimb coordination. Haken et al. (1985) demonstrated how two physical limit cycle oscillators interacting across a low-energy coupling medium could exhibit the ϕ behavior observed in interlimb coordination and derived the following model of the ϕ dynamics:

$$\dot{\phi} = -a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q} \xi, \quad (1)$$

where $\dot{\phi}$ is the rate of change of the relative phase angle formed between the two oscillators, a and b are coefficients whose magnitudes govern the strength of the between-oscillator coupling and ξ is a Gaussian white noise process dictating a stochastic force of strength Q (Haken et al., 1985; Schöner, Haken, & Kelso, 1986). Equation 1 models the two interlimb coordination modes because it has stable solutions (i.e., where $\dot{\phi} = 0$) at $\phi = 0^\circ$ and $\phi = 180^\circ$ and displays a breakdown of the anti-phase mode as the frequency is increased. Importantly, this model predicts additional phenomena that should be observed immediately before the transition from anti-phase to in-phase: enhancement of fluctuations and critical slowing down (Schöner et al., 1986). The top panel of Figure 1 shows how manipulations of frequency affect changes in the stable states of Equation 1. The predicted phenomena (i.e., enhancement of fluctuations and critical slowing down) were subsequently observed in empirical studies (Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987), hence, substantiating a dynamical interpretation of interlimb coordination.

Following these investigations, similar methods were used to investigate the effect of frequency scaling on the breakdown of between-person interlimb coordination. When two individuals were asked to visually coordinate the

Figure 1. Depictions of the dynamical model under frequency scaling and frequency detuning. The top panel shows a plot of Equation 1 for three values of b/a ($a = 3.14$ rad/s and $b = 3.14, 1.57$, and 0.785 rad/s, respectively). The stable solutions where $\dot{\phi} = 0$ indicate *point attractors* at 0 and π rad (i.e., 0° and 180°). Furthermore, if one assumes that the ratio b/a decreases as frequency increases, then Equation 1 models the breakdown of anti-phase. The middle panel shows a plot of Equation 2 for three values of $\Delta\omega$. The manipulation of $\Delta\omega$ adds a constant to the $\dot{\phi}$ function, indirectly changes the slope of ϕ at the stable points (i.e., moves the function along the y-axis), and thereby manipulates the attractor strength. Scaling $\Delta\omega$ to large values (relative to a and b) will cause the stable solutions, first at $\phi = 180^\circ$ and then at $\phi = 0^\circ$, to disappear. The bottom panel shows the potential function (V) solution for Equation 2 near $\phi = \pi$ for four values of $\Delta\omega$. (Note that the potential V magnitudes have been normalized in the bottom panel and that $a = 3.14$ rad/s and $b = 3.14$ rad/s for the middle and bottom panels.)

oscillation of their lower legs either in phase or in anti-phase, Schmidt et al. (1990) found that increases in frequency produced breakdowns of anti-phase and a transition to in-phase at higher frequencies. If the two people began their movements in anti-phase without watching each other, the transition between modes did not occur. The phase transition depended on the visual information linkage. As evidence that this change of interpersonal coordinative state is dynamical, enhancement of fluctuations occurred immediately before the transition. The researchers successfully used Equation 1 to model their findings. The important implication of this study is that rhythmic coordination in biological movement systems abides by general dynamical principles that are indifferent to the physical details of the coupling.

Direct comparisons could not be made between intra- and interpersonal coordination dynamics (e.g., comparisons of the strength of the coupling) because the limbs being oscillated were different in the two cases (index fingers vs. lower legs). One of the goals of the present research was to directly compare the breakdown of coordination in within- and between-person rhythmic coordination using the same experimental task in both cases. To make a direct comparison, a method that measures the strength of the dynamic is needed. Although the strength of the dynamic can be inferred from the magnitude of the fluctuations observed (Kelso et al., 1986) or a measure of the coupled system's response to a perturbation (i.e., its relaxation time, θ_{rel} ; see Scholz et al., 1987), a more explicit way is to estimate the coupling strengths a and b of Equation 1. Such a method can be implemented when the symmetry of the local oscillator dynamics is broken, that is, when the eigenfrequency difference between the individual rhythmic units is manipulated under frequency detuning.

Dynamic Modeling of Interlimb Rhythmic Coordination: Frequency Detuning

The dynamical modeling of interlimb coordination thus far presented has assumed that the individual rhythmic units being coordinated were dynamically identical. That is, it is assumed that they have the same oscillatory components (i.e., stiffness, damping, escapement) and therefore the same frequency of oscillation when they oscillate uncoupled (i.e., the same eigenfrequency). The limbs to be coordinated do not often fulfill this criterion. For example, when limbs of the upper and lower body that differ in their inertial properties are coordinated (Kelso & Jeka, 1992), they differ in their eigenfrequency. An index of *frequency detuning* is the arithmetic difference between the oscillators' eigenfrequencies, $\Delta\omega = \omega_1 - \omega_2$ (see Sternad, Collins, & Turvey, 1995, for an alternative formulation).

Kelso, DelColle, and Schöner (1990; Kelso & Jeka, 1992) used the following variation of Equation 1 to understand the effects of eigenfrequency difference— $\Delta\omega$ —manipulations:

$$\dot{\phi} = \Delta\omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q} \xi. \quad (2)$$

Equation 2 makes predictions about the effect of $\Delta\omega$ on steady state interlimb coordination. The middle of Figure 1

shows how manipulations of $\Delta\omega$ affect changes in the stable states of Equation 2. However, to demonstrate the predictions more clearly, it is helpful to represent the states of Equation 2 as the position of a particle in the landscape of a potential function, V . Assuming that $\dot{\phi} = -dV(\phi)/d\phi$ and eliminating the noise term, the integration of Equation 2 produces the following potential function (Fuchs & Kelso, 1994):

$$V = -\Delta\omega\phi - a \cos(\phi) - b \cos(2\phi). \quad (3)$$

Of interest are the changes that occur in the basins of attraction around $\phi = 0^\circ$ and $\phi = 180^\circ$ as frequency detuning ($\Delta\omega$) is increased. The basin of attraction at $\phi = 180^\circ$ for four values of $\Delta\omega$ are displayed in the bottom panel of Figure 1. Similar but less dramatic changes occur at $\phi = 0$. Two properties should be noted. First, frequency detuning causes *attractor or fixed-point drift*: The potential minimum moves away from its original position at 180° until it disappears when $\Delta\omega$ becomes relatively large. Underlying its disappearance is the second property: Frequency detuning causes a *distortion of the basin of attraction* (i.e., one side remains steep while the other side flattens until the potential minimum no longer exists). Importantly, the model predicts that the fixed-point drift and basin deformation are less acute for the attractor at $\phi = 0^\circ$ than $\phi = 180^\circ$.

To verify that these model properties exist in interlimb coordination, a methodology is needed that parametrically manipulates frequency detuning. In an experimental paradigm in which an individual oscillates hand-held pendulums from the wrist joint (Kugler & Turvey, 1987), the eigenfrequencies of the two wrist-pendulum systems can be independently manipulated by changing the inertial properties of the pendulums. Investigations using this paradigm have found evidence for fixed-point drift: As $\Delta\omega$ was manipulated away from 0 (increasing frequency detuning), mean ϕ was found to deviate linearly from 0° and 180° as predicted (see Schmidt & Turvey, 1995, for a review). This research has also found evidence for the distortion of the basin of attraction with frequency detuning. The flattening of the basin of attraction indicates a decrease in the strength of the attractor and causes an increase in the observed variability of ϕ (see Schmidt & Turvey, 1995).

Studies of the effect of frequency detuning on interlimb coordination have also found evidence for the differential strength of the two phase modes as predicted by the dynamical model. The anti-phase variability of ϕ was found to be greater than the in-phase variability (Schmidt et al., 1993; Treffner & Turvey, 1995; Turvey, Rosenblum, Schmidt, & Kugler, 1986). Note, however, that only a few studies have produced evidence for the model prediction that fixed-point drift is greater for the anti-phase than the in-phase mode of coordination (Sternad et al., 1995; Treffner & Turvey, 1995). The difficulty in verifying this prediction seems to be one of statistical power (Treffner & Turvey, 1995).

Between-person coordination investigations of frequency attest to the generality of Equation 2 as a model for interlimb coordination (Schmidt, 1988; Schmidt & Turvey, 1994). To manipulate frequency detuning, the wrist-pendulum paradigm was adapted to a between-person situation such that

two people sitting side by side had to visually coordinate pendulums swung in their outer hands in the anti-phase mode. The interpersonal wrist-pendulum coordination displayed the same properties as interpersonal coordination: As $\Delta\omega$ was manipulated away from zero, mean ϕ was found to deviate from 180° and fluctuations in ϕ were found to increase. In brief, the effects of scaling $\Delta\omega$ seem to be the same regardless of whether the coordination of the limbs is within a person or between two people (Schmidt & Turvey, 1994).

Measuring Interlimb Coupling Strength

A benefit of using an experimental paradigm that allows the parametric manipulation of $\Delta\omega$ is that it allows one to obtain estimates of the regime's coupling coefficients. That is, the strength of the coupling dynamic can be inferred from the observed patterning of fixed-point drift induced by the frequency detuning. The procedure involved relies on the relation of observables specified in the dynamical model without the noise term $\sqrt{Q}\xi$. Equation 2 specifies that interlimb phasing is stable when $\dot{\phi} = 0$. Under this condition, an equality exists between $\Delta\omega$ and $a \sin(\phi)$ and $2b \sin(2\phi)$. Because the experimenter manipulates $\Delta\omega$ and measures ϕ during stable interlimb coordination of wrist pendulums, a multiple regression involving these two quantities (in particular, $\sin[\phi]$ and $\sin[2\phi]$ on $\Delta\omega$) yields estimates of a and b in the multiple regression coefficients. Estimating these coefficients for different coordination (e.g., frequency) conditions allows one to estimate the coupling strength for the conditions and, ultimately, the topology of the attractor layout.

The results of such a regression analysis on previous data have not always yielded statistically reliable estimation of the coupling coefficients (Schmidt & Turvey, 1995). Underlying this fact may be the methodological problem that the measurement of fixed-point drift (mean ϕ) is necessarily circumscribed to small intervals around 0 and 180° and that the two terms, $\sin(\phi)$ and $\sin(2\phi)$, are not independent for the range of ϕ less than $[0, 360]$ (see Fuchs & Kelso, 1994). It has been suggested, however, that the measurement of coupling strength can still be made if a local model of ϕ —a simplification of Equation 2 that models only one phase mode at a time—is used in the regression analysis (Schmidt & Turvey, 1995). Such a local model is

$$\dot{\phi} = \Delta\omega - K \sin(\phi), \quad (4)$$

where K is the coupling strength of the coupled regime (Cohen, Holmes, & Rand, 1982). Whether this regime produces in-phase or anti-phase behavior depends on the sign of the coupling term K : A negative K has a stable solution near 180° , whereas a positive K has one near zero. Similar to Equation 2, the manipulation of $\Delta\omega$ causes fixed-point drift and distortion of the basin of attraction. Consequently, estimates of the coupling strength (K) can be obtained with a regression analysis of $\sin(\phi)$ on $\Delta\omega$. This analysis has been used to estimate the strength of the dynamic underlying wrist-pendulum coordination (Schmidt, Christianson, Carello, & Baron, 1994; Schmidt et al., 1993).

These analyses have not only yielded significant estimates of K but they have also shown, as predicted by Equation 2, that K decreases as frequency increases (Schmidt & Turvey, 1995). They also have provided prima facie evidence that the K for anti-phase is smaller than the K for in-phase. Note, however, that a formal equivalence exists between the coefficients a and b in the global model (Equation 2) and the K s for in-phase and anti-phase in the local model (Equation 4), namely, $a = (K_0 - K_{180})/2$ and $b = (K_0 + K_{180})/8$ (A. Fuchs, personal communication, March 30, 1994). Consequently, assuming that one measures K for the in-phase and anti-phase in the same coordination condition, one can use the local model regression method to recover the topology of the entire attractor layout for that coordination condition.

Focus of This Research: The Measurement of Coupling Strength During Frequency Scaling

In this research, the frequency scaling and frequency detuning manipulations were combined to evaluate the change in the strength of the coupling dynamic (and hence the change of the attractor layout) in both intrapersonal (Experiment 1) and interpersonal (Experiment 2) interlimb systems. Because the same manipulations and movements were studied in both experiments, a direct comparison of the dynamics underlying these two kinds of interlimb coordination could be made. Intuitively, because of the nonkinetic basis of visual coupling, one may expect the between-person dynamical regime established by linking two central nervous systems (CNSs) across the optic array to be weaker than the dynamical regime established across the CNS of a single person. On the other hand, there is a long history of considering the CNS an informational medium. Following Kugler and Turvey (1987), the movement control structures established in the CNS can be thought of as temporary, softly assembled informational systems. Hence, the coupling medium of the CNS in within-person coordination is arguably an informational, rather than a mechanical, linkage between the two limbs. Given the proposed informational basis of both the intra- and interpersonal interlimb couplings, the two kinds of coordination could be of equal strength if the information involved is equally informative in the two cases. In our experiments we wanted to evaluate the relative strengths of the two coordination dynamics by measuring their stability (i.e., number of coordination breakdowns and magnitude of fluctuations) and using the aforementioned regression technique to estimate the magnitudes of the coupling coefficients.

In addition to comparing intra- and interpersonal coordination, we combined frequency scaling and frequency detuning manipulations, which allowed us to demonstrate the continuity between coordination breakdowns and coordination stable states. Previous researchers have investigated the steady state predictions of Equation 2 using frequency detuning and between-trials frequency scaling (e.g., Amazeen, Schmidt, & Turvey, 1995; Schmidt et al., 1993), whereas other researchers have investigated the breakdown predictions of Equation 2 using frequency scaling (e.g., Kelso et al., 1986; Schmidt et al., 1990). We, however, combined frequency detuning and within-trials frequency scaling to

investigate both coordination breakdowns and coordination stable states. Because estimating the coupling coefficients relies on the frequency detuning methodology, using it with frequency scaling allowed us to explicitly determine the role that coupling strength would play in coordination breakdown.

Experiment 1

Method

Participants. Two male and 3 female students served as participants in partial fulfillment of a course requirement. All 5 students were right-handed and free of perceptual-motor disabilities.

Materials. The pendulums consisted of an aluminum rod 1 cm in diameter attached to a wooden hand grip 2.5 cm in diameter and 12 cm in length. Steel cylinders were attached to the end of the aluminum rod by screws built into the weight. Four such pendulums with a 0.03-kg mass attached were used. The rod lengths were 0.20, 0.20, 0.36, and 0.50 m for Pendulums A through D, respectively. The total mass of the rod, weight, and hand grip for the three different pendulums was 0.15, 0.20, and 0.25 kg. The effective mass and length of a single wrist-pendulum system were taken to be the equivalent simple pendulum mass and length of a compound pendulum consisting of the attached mass, the rod, and the hand of the participant. These magnitudes were calculated using an algorithm analogous to that reported by Kugler and Turvey (1987). The characteristic frequencies or eigenfrequencies (ω_i) of these simple equivalent pendulums considered as gravitational pendulums were calculated from these simple pendulum lengths (see Schmidt et al., 1993). These ω_i values averaged across the 5 participants are shown in Table 1.

Each participant was asked to coordinate the oscillation of five pairs of pendulums during the experiment: The two shortest together, the longest in the right hand with each of the two shorter ones in the left hand, and the longest in the left hand with each of the two shorter in the right hand. The design of these coupled wrist-pendulum systems and the differences in the eigenfrequencies $\Delta\omega$ ($=\omega_{\text{left}} - \omega_{\text{right}}$) averaged across the 5 participants are shown in Table 1. The range of $\Delta\omega$ values used was smaller than in previous studies (e.g., Schmidt, Beek, Treffner, & Turvey, 1991; Schmidt et al., 1993). This circumscribed range was due to the fact that the pendulums were required to be light enough to be oscillated at a reasonably high frequency of oscillation (2 Hz) without strain. Pilot testing indicated that the long pendulum swung at 2 Hz was near the limit of stable single pendulum oscillation.

Wrist-pendulum movement trajectories were collected using a 3-space sonic digitizer (Science Accessories Corporation, Stratford, CT). A 1-m² plywood board with movement acquisition microphones in each corner was on the floor in front of the

Figure 2. Side view of the experimental apparatus used in Experiment 1.

participant. Because the movement acquisition apparatus was sonic, the microphone surface was shielded from auditory reflections off hard surfaces by enclosing it within 0.5-m-high foam padded walls. This created an enclosure in which the pendulums were swung. A stool was placed at the center of one side of the enclosure. Armrests to the right and left of the participant were attached to the sides of the enclosure to support the arms. The pendulums could then be oscillated parallel to the sagittal plane about an axis in the wrist as depicted in Figure 2. Further details about the use of sonic digitizer can be found in Schmidt et al. (1993).

A metronome tape consisting of an auditory pulse was used for scaling the frequency of oscillation. Each trial on the tape included eight different frequency "plateaus." The frequencies ranged from 0.6 to 2.0 Hz in 0.2-Hz steps. Each frequency plateau lasted 5 s. The 0.6-Hz frequency plateau was repeated at the beginning of the trial to ensure that the participant had enough time to become entrained to the auditory pulse.

Procedure and design. For a given trial, the participants were asked to coordinate one of the five pendulum pairs (see Table 1) either in in-phase or in anti-phase at the frequency of oscillation prescribed by the metronome. Because the frequency plateaus lasted 5 s, the participants had to increase their frequency every 5 s. The participants were instructed to place their forearm squarely on the armrests, gaze straight ahead without looking at the pendulums, and swing the pendulums smoothly in the sagittal plane. They were further instructed to hold the pendulums firmly in the hands so that as much of the rotation of the pendulum as possible was created about the wrist joint rather than the finger joints. Participants were allowed to practice the task in both phase modes and at different frequencies for a number of the pendulum combinations before the experiment began. They were told that it may be hard for them to maintain the specified coordination pattern in some of the conditions and were instructed to try to return to the original phase mode and frequency if the specified coordination pattern was lost. This task instruction differed from that used in some of the previous coordination breakdown studies (see Kelso, 1990, for a review) in which the participant was instructed not to intervene if a breakdown was imminent and to remain in whatever coordination pattern that was the most stable. We did this to avoid the criticism that the participants were succumbing to task demands and intentionally forcing a change in coordination in particular conditions.

Table 1
Design of the Coupled Wrist-Pendulum Systems
and the Average Values of ω_{left} , ω_{right} , and $\Delta\omega$ (in Hertz)
for Experiment 1

System	Combination	ω_{left}	ω_{right}	$\Delta\omega$
1	A-D	1.057	0.760	0.297
2	A-C	1.057	0.866	0.191
3	A-B	1.057	1.057	0.0
4	C-B	0.866	1.057	-0.191
5	D-B	0.760	1.057	-0.297

The design of the experiment was a $2 \times 5 \times 8$ factorial with within-subjects variables of phase mode, pendulum combination ($\Delta\omega$), and frequency of oscillation. The analyses of variance (ANOVAs) reported here were of this design unless otherwise noted. Each participant performed three 45-s trials per condition for a total of 30 trials. The order of phase mode and pendulum system conditions was randomized within three blocks of 10 trials.

Data reduction. The acquired angular excursions of the wrist-pendulum systems were subjected to software analyses to determine the time series of the relative phase angle ϕ between the two wrist-pendulum systems. The phase angle of each wrist-pendulum system (θ_i) was calculated for each sample (90/s). The phase angle of wrist pendulum i at sample j (θ_{ij}) was calculated as

$$\theta_{ij} = \arctan(\dot{x}_{ij}^* / \Delta x_{ij}), \quad (5)$$

where $\dot{x}_{ij}^*$ is the velocity of the time series of wrist pendulum i at sample j divided by the mean angular frequency for the trial and Δx_{ij} is the excursion time series at sample j minus the average excursion for the trial. The normalization used in this equation was based on the assumption that the angular excursions are close to sinusoidal in form. Past research suggests that this assumption is true. The relative phase angle (ϕ_i) between the two coupled wrist-pendulum systems was calculated for each sample as $\theta_{\text{left}j} - \theta_{\text{right}j}$.

The ϕ time series allowed an evaluation of the stability of phase locking across the different conditions. This evaluation was accomplished by calculating the mean ϕ and standard deviation of ϕ (ϕ SD) for each frequency plateau. To eliminate transient relative phase caused by the frequency increases, 0.5 s at the beginning and end of the plateau were not included in these estimates of ϕ . Using visual inspection of the ϕ time series, individual frequency plateaus were identified as *stable* if ϕ was steady about a constant mean value for the entire plateau and *unstable* if ϕ was not. Unstable plateaus were further categorized as *transitional* if ϕ changed from a value indicative of the one phase mode to that of the other phase suggestive of a phase transition (Kelso et al., 1986; Schmidt et al., 1990) or if the phase was constantly changing its value suggestive of phase wrapping (Kelso & Jeka, 1992); *errors* if the change was indicative of a momentary loss of control (e.g., a large change in ϕ with an immediate return to stability); or *other mode* if ϕ remained steady for at least 1 s near a ϕ indicative of the other possible phase mode (180° for in-phase and 0° for anti-phase). The first two unstable categories were defined with respect to the style of change involved in the instability, whereas the other mode category specified a newfound stability, albeit different from intended. The percentages of stable and unstable plateaus were calculated for each condition to evaluate the effect of the independent variables on the breakdown of coordination. This categorization scheme was further used to identify the stable ϕ data needed to evaluate the model predicted patternings of mean ϕ and ϕ fluctuations.

Results

Breakdowns of intended phase mode. Of the 1,200 frequency plateaus performed by the 5 participants, 27 (~2%) were categorized as unstable. These results indicate that across the conditions, the coordination was stable. An ANOVA performed on the percentage of unstable plateaus revealed only a trend for frequency, $F(7, 28) = 2.13$, $p = .07$. As the frequency of oscillation increased, the percentage of unstable plateaus increased from 0% to 6%. Of the 27 unstable plateaus, 23 were errors and 4 were transitional. No

other mode plateaus were found. The error plateaus observed were best characterized as momentary losses of control followed by an immediate return to stability. The transitional plateaus were more substantive, seemingly dynamical breakdowns in phase locking: The steady state was permanently lost. Example times series depicting these kinds of coordination breakdowns as well as an other mode breakdown are displayed in Figure 3. Interestingly, all four of the transitional breakdowns occurred in the conditions that Equation 2 predicts to be the least stable (i.e., the anti-phase mode) at the highest frequencies and the largest $\Delta\omega$ s (± 0.30), suggesting that the patterning of coordination breakdowns is consistent with the dynamical model of interlimb coordination even though only a few dynamical breakdowns occurred.

Mean ϕ . Because the model-based predictions of fixed-point drift and ϕ fluctuations hold only for the steady state relative phase values, only stable ϕ frequency plateaus were used for the analysis of mean ϕ and ϕ SD. To compare the two phase modes, we normalized the mean ϕ to index the mean deviation from the intended mode (i.e., $\phi - 0$ or $\phi - 180^\circ$). An ANOVA performed on these magnitudes revealed a significant main effect of pendulum combination, $F(4, 16) = 40.83$, $p < .001$, and a significant Pendulum Combination $\times$ Frequency interaction, $F(28, 112) = 15.94$, $p < .001$. The main effect indicated a drifting of mean ϕ from 0° or 180° as $\Delta\omega$ deviated from 0 (fixed-point drift), and the interaction indicated an exaggeration of this drift with the frequency of oscillation. The interaction is displayed in Figure 4. The ANOVA also yielded a significant Phase Mode $\times$ Frequency interaction, $F(7, 28) = 2.64$, $p < .05$, which indicates that high frequencies affected the two phase modes differently (i.e., for in-phase the mean ϕ was positive, whereas for anti-phase the mean ϕ was negative). The importance of this effect was undermined by a subsequent simple effects analysis, which showed no significant differences between the phase modes at the higher frequencies.

The Pendulum Combination $\times$ Frequency interaction replicates the previous findings (e.g., Schmidt et al., 1993; Sternad, Turvey, & Schmidt, 1992) that indicate that fixed-point drift is exaggerated by increasing frequency of oscillation. However, our results also extend past findings by demonstrating that these effects occur for within-trials increases in and across a wider range of frequencies. Equation 2 predicts fixed-point drift with decreasing symmetry of the component oscillator's dynamics as indexed by $|\Delta\omega|$ (see the middle of Figure 1) and an exaggeration of it with increasing frequency because the coupled oscillator regime is weakened as the frequency of oscillation is increased (see the top of Figure 1). The dynamical model also predicts, however, that the fixed-point drift should be greater in the anti-phase than in the in-phase mode. Such a fact would have been evidenced by an interaction between $\Delta\omega$ and phase mode. Although this interaction was not significant, more fixed-point drift was evidenced by a greater absolute mean ϕ for anti-phase (4.8°) than in-phase (3.5°) at the two highest frequencies. Several previous studies (Schmidt et al., 1993; Sternad et al., 1992; Turvey et

Figure 3. Time series of ϕ representative of the three kinds of unstable trials observed: error, transitional, and other mode. The asterisks indicate the beginning of each breakdown. The tick marks at the top of the graphs indicate 5-s intervals. Note that the error plot was from Experiment 1, whereas the transitional and other mode plots were from Experiment 2.

al., 1986) also did not show statistically significant support for this prediction. The studies that did (Treffner & Turvey, 1995; Sternad et al., 1995) used many more observations, thus increasing the power of the analysis. It may be the case that the difference in fixed-point drift for the phase modes may be too small to be statistically resolvable without such power. Alternatively, it may be that the anti-phase mode for this interlimb system is nearly as stable as the in-phase mode for this range of $\Delta\omega$, as suggested by the few coordination breakdowns observed.

ϕ SD. A more fine-grained view of the stability of ϕ than the number of breakdowns can be gained by an examination of ϕ fluctuations. An ANOVA performed on ϕ SD revealed significant main effects of phase mode, $F(1, 4) =$

10.22, $p < .05$, pendulum combination, $F(4, 16) = 8.48$, $p < .001$, and frequency, $F(7, 28) = 21.85$, $p < .001$. These effects indicated that ϕ fluctuations were greater for anti-phase than in-phase (17.2° vs. 15.2°), changed as a U-shaped function of $\Delta\omega$ (17.9° , 15.2° , 14.1° , 16.3° , and 17.7°), and generally increased with frequency (15.5° , 14.6° , 14.0° , 14.6° , 15.0° , 16.7° , 18.7° , and 20.8°). However, in the latter effect, a significant decrease in ϕ SD was observed from the first to the third frequency condition ($p < .05$) before the general increase. Also significant was the Phase Mode $\times$ Pendulum Combination interaction, $F(28, 112) = 4.15$, $p < .05$, which is shown in Figure 5. Post hoc t tests indicated that ϕ SD increased on both sides of $\Delta\omega = 0$ for the in-phase mode but only on the negative side of $\Delta\omega = 0$ for the

Figure 4. Deviation of mean ϕ from intended phase as a function of frequency scaling and frequency detuning ($\Delta\omega$) in Experiment 1.

anti-phase mode. These results suggest that the nonsignificance between the phase modes for positive $\Delta\omega$ s was a consequence of a suppression of anti-phase mode fluctuations for these $\Delta\omega$ conditions.

These ϕ SD results replicate previous findings (Kelso & Jeka, 1992; Schmidt et al., 1993; Treffner & Turvey, 1995; Turvey et al., 1986) but also demonstrate that these effects occur for within-trials increases of frequencies and across a wider range of frequencies than has been previously observed. The general trends are predicted by the dynamical model in Equation 2. The shallower slopes around 180° than around 0° in the top of Figure 1 indicated a slower relaxation time to this fixed point and consequently indicated greater fluctuations for the anti-phase mode. This result indicates

Figure 5. Standard deviation of ϕ as a function of frequency detuning ($\Delta\omega$) and phase mode in Experiment 1.

that the anti-phase mode was indeed weaker for this interlimb system even though fixed-point drift and the number of breakdowns was not significantly greater for anti-phase. The ϕ SD increased as $\Delta\omega$ deviated from zero because the breaking of symmetry of the rhythmic units caused the basin of attractions to become more shallow (see the bottom of Figure 1). Also, on average, the ϕ SD increased with the frequency of oscillation indicating a decrease in the strength of the coupling dynamic with increasing frequency.

The fact that ϕ SDs were higher at the initial frequency suggested that the coupling dynamic may not be strongest at the lowest frequencies. It seemed that the middle frequencies (e.g., 1.0 Hz), which were near the eigenfrequencies of the wrist pendulums, were more stable. Indeed, the phenomenological experience of the participants was that swinging the pendulums slowly was more difficult than at a moderate tempo. Finally, the interaction between phase mode and $\Delta\omega$, although not predicted by the dynamical model, was consistent with work on handedness asymmetry constraints in bimanual rhythmic movements (Treffner & Turvey, 1995). Little difference between the phase modes was observed when $\Delta\omega$ was positive—when the left-hand pendulum had a greater eigenfrequency than the right. To create a common tempo in this condition, the right pendulum must speed up relative to its preferred tempo while the left slows down. Recent work suggests that these frequency changes are more natural for right-handed participants than other $\Delta\omega$ conditions and consequently may suppress the variability for the more difficult anti-phase condition.

Measuring the coupling strength of intrapersonal coordination. Using the method described in the introduction, the change of mean ϕ with $\Delta\omega$ can be used to estimate the strength of the coupling dynamic. A regression analysis was performed at each frequency in which $\sin(\phi)$ was regressed on $\Delta\omega$ to estimate the local model (Equation 4) coupling strength K . As necessitated by the local model, in-phase and anti-phase data were analyzed separately. The results in Table 2 show that all K s were statistically significant. Note that, as required, they were positive for in-phase and negative for anti-phase. Furthermore, the strength of the coupling in general decreased as the frequency increased, $r(7) = -.93$, $p < .001$, although, as suggested by the ϕ SD

Table 2
Regression Evaluation of Coupling Term K in Equation 4 in Experiment 1

Frequency	In-phase			Anti-phase		
	r^2	K	n	r^2	K	n
0.6	.13	0.76***	75	.18	-0.69***	75
0.8	.61	0.87***	74	.60	-0.79***	75
1.0	.70	0.58***	73	.76	-0.68***	74
1.2	.73	0.53***	74	.71	-0.58***	74
1.4	.79	0.50***	74	.75	-0.57***	75
1.6	.79	0.47***	72	.72	-0.50***	72
1.8	.80	0.43***	72	.79	-0.44***	73
2.0	.76	0.38***	70	.74	-0.41***	71

*** $p < .001$.

analysis, the lowest frequency did not have the strongest dynamic. The low r^2 s for this condition may be a consequence of the difficulty the participants had in maintaining the coordination at the lowest frequency. No significant difference was found between the in-phase and anti-phase K magnitudes ($p > .05$). This result indicates that anti-phase and in-phase modes were not different in their coupling strengths, a finding anticipated by the nonsignificance of phase mode in the number of coordination breakdowns and fixed-point drift analyses. It is interesting to note that the ϕ SD results provided antithetical evidence that the anti-phase mode was weaker than the in-phase mode. This difference in outcomes could have been caused by relative sensitivity of the fluctuation and mean phase measures to differences in strength. In short, fluctuations are a more fine-grained measure of stability than the mean state's location.

The change of the global attractor layout can be derived by calculating Equation 2 coefficients a and b from the estimated K s (see the introduction). Because K_0 was not significantly different from K_{180} , we used their average in the calculation, which yielded a constant value of zero for a and values of 0.180, 0.208, 0.156, 0.138, 0.134, 0.121, 0.108, and 0.099 Hz for b across the eight frequencies. As can be seen in the top panel of Figure 6, the resulting potential landscapes were of two equal-depth potential wells (for in-phase and anti-phase) that became more shallow with increasing frequency (with the exception of 0.6 Hz). Previous work has assumed that the b/a ratio, which has been used to index the transition from anti-phase to in-phase at $b/a = 0.25$, is an effective index of the strength of the coupling dynamic of the global model (i.e., Equation 2). However, it is apparent from these results that b/a is equal (to infinity) for all these conditions and hence does not distinguish between the strength of the attractors observed. In the General Discussion section, we suggest a different measure of coupling strength that accommodates these results.

Experiment 2

In Experiment 2 we used an adaptation of the wrist-pendulum paradigm to investigate the effects of frequency scaling and frequency detuning on the visual coordination of rhythmic movements made by two people. Previous researchers have investigated the effects of frequency scaling (Schmidt et al., 1990), frequency detuning (Schmidt & Turvey, 1994), and their combination (Amazeen et al., 1995) on interpersonal interlimb coordination. This study, using both frequency scaling and frequency detuning, allowed us to measure the strength of the between-person coupling dynamic at the various frequencies and to compare these strengths with those found in Experiment 1. As discussed earlier, one may expect the coupling of limbs across the optic array to be weaker than the coupling of limbs across the CNS given the relatively incorporeal nature of the optical coupling medium. However, because both coupling media (the CNS and the optic array) can be considered informational, it is possible that the two coordinations may be equally strong if the information linkage is equally robust. If the information linkage of the visual coupling is

Figure 6. Potential functions portraying the change in the dynamics of ϕ under frequency scaling in Experiment 1. In the bottom panel, the potential V is normalized by the magnitude of the coefficient b to allow a better comparison of the potential landscapes. Under this normalization, the concavity of the well (and hence the strength of the attractor) is correlated with the depth of the well.

weaker, it should produce less stable interlimb coordination: more coordination breakdowns and greater ϕ SDs. Indeed, at certain parameterizations of the control parameters, the coupling may be so weak that the dynamical regime (Equation 2) cannot be established at all if the coupling processes cannot overcome the eigenfrequency difference of the individual oscillators. Alternatively, if the strength of the visual coupling information linkage is equal to the information linkage of the intrapersonal coupling, the coordination in Experiment 2 should be as stable as in Experiment 1.

Table 3
Design of the Coupled Wrist-Pendulum Systems
and the Average Values of ω_{left} , ω_{right} , and $\Delta\omega$ (in Hertz)
for Experiment 2

System	Combination	ω_{left}	ω_{right}	$\Delta\omega$
1	A-D	1.061	0.762	0.299
2	A-C	1.061	0.871	0.190
3	A-B	1.061	1.063	-0.002
4	C-B	0.869	1.063	-0.194
5	D-B	0.762	1.063	-0.301

Method

Participants. Six female and 4 male students volunteered as participants. All were right-handed and free of perceptual-motor disabilities. These 10 participants were grouped into 5 participant pairs.

Materials. In general, the materials used were identical to those of Experiment 1. The four pendulums and five pendulum pairs were the same. The $\Delta\omega$ values were calculated as $\omega_{\text{left}} - \omega_{\text{right}}$, where ω_{left} is the eigenfrequency of the wrist-pendulum system belonging to the person swinging with his or her left hand and ω_{right} is that belonging to the person swinging with his or her right hand. The gravitational eigenfrequencies of the wrist-pendulum systems were again calculated to estimate ω_i . Note that the estimation of ω_i depended in part on the participant's hand mass. Because the participants of a participant pair tended to have different hand masses, the magnitudes of $\Delta\omega$ were not symmetrical around zero, as the values of Table 3 reveal.

Figure 7 shows how the experimental apparatus of Experiment 1 was adapted to the interpersonal situation. The pendulums were swung within the movement acquisition enclosure but now the participants sat on stools on opposite sides of the enclosure and swung the pendulums using their inside hand. Each participant's swinging hand could then be supported by the enclosure's armrests. By turning his or her head inward, each participant could easily view the other person's pendulum. The same metronome tape was used as in Experiment 1 for the first two participant pairs, and an identical metronome stimulus was generated on a Macintosh computer for the last three participant pairs.

Procedure, design, and data reduction. Each participant was instructed to look at his or her partner's pendulum and visually coordinate the oscillation of the pendulum with that of his or her partner. During the experiment, the pairs were asked to coordinate

Figure 7. Front view of the experimental apparatus used in Experiment 2.

the five pendulum combinations in either in-phase or anti-phase mode at the frequency of oscillation prescribed by the auditory pulse. As in Experiment 1, each frequency plateau lasted 5 s. The participants were told that the coordination might be difficult to maintain in some conditions; in such cases, they were instructed to try to maintain the specified frequency of oscillation and attempt to stay in the original relative phase pattern. The experimental design and the calculation of dependent measures (i.e., the ϕ time series, the ϕ mean and ϕ SD at each frequency plateau, and the percentage of stable and unstable plateaus) were identical to those used in Experiment 1.

Results and Discussion

Breakdowns of intended phase mode. More coordination breakdowns occurred than in Experiment 1: Of the 1,200 frequency plateaus, 307 (~26%) were categorized as unstable. Of these unstable plateaus, 187 of them were categorized as transitional, 87 as errors, and 33 as other mode. Interestingly, unlike the within-person coordination of Experiment 1, the majority of the plateaus were identified as transitional or other mode, which is indicative of a dynamical breakdown in coordination as opposed to a momentary loss of control.

Because there were enough observations of each kind of unstable plateau, we performed three-way ANOVAs with the within-subjects variables of phase mode, pendulum combination, and frequency on each of them. The ANOVA performed on the transitional plateaus yielded a Phase Mode $\times$ Frequency interaction, $F(7, 28) = 3.68, p < .01$, as well as significant main effects of phase mode, $F(1, 4) = 15.47, p < .05$, and frequency, $F(7, 28) = 6.48, p < .001$. Figure 8 (top panel) demonstrates that the percentage of transitional plateaus increased with frequency for both modes but that the rate of change was faster for anti-phase. Simple effects analysis revealed that the two phase modes differed for the three highest frequencies ($ps < .05$). The ANOVA performed on the error plateaus revealed only a significant main effect of frequency, $F(7, 28) = 3.73, p < .01$, which indicated that momentary losses of control were more frequently observed at higher frequencies of oscillation. Interestingly, this more arbitrary form of coordination breakdown was not affected by phase mode. The ANOVA performed on the percentage of other mode plateaus, however, revealed a significant main effect frequency, $F(7, 28) = 3.01, p < .05$, as well as an interaction between phase mode and frequency, $F(7, 28) = 3.40, p < .01$. This latter effect, displayed in the bottom panel of Figure 8, indicated that other mode plateaus increased with frequency for the anti-phase mode but not for the in-phase mode.

These results portray a patterning of coordination breakdown that is consistent with the dynamical model. First, the model predicts that the strength of the attractors should decrease with frequency. The results indicate that all three kinds of breakdowns (i.e., transitional, nonstationary, and other mode) occurred more often at high frequencies. Furthermore, the model predicts a differential stability between the phase modes. The results indicate that transitional and other mode plateaus were more numerous in the anti-phase mode than the in-phase mode at the higher

frequencies. Although the model additionally predicts more coordination breakdowns for extreme $\Delta\omega$ s, and no significant effects for the pendulum combination variable were found, this negative result was somewhat mitigated by the predicted U-shaped patterning of means (20.0%, 16.7%, 11.7%, 12.9%, and 16.7% for $\Delta\omega$ s negative to positive) in the nonsignificant pendulum combination effect for the transitional plateaus' ANOVA. The lack of significance of this effect indicates that $\Delta\omega$ was not having a great effect upon the stability of the between-person coordination behavior of this experiment. The underlying reason for this weak effect may be in part the small range in which $\Delta\omega$ was manipulated (see the *Method* section of Experiment 1).

Mean ϕ . Because of the many coordination breakdowns and the fact that mean ϕ and ϕ SD can be calculated only from stable data, mean values could not be obtained for some of the higher frequency conditions, thus creating empty cells for a number of participant pairs. Consequently,

Figure 8. Coordination breakdowns as a function of frequency and phase mode. Top panel shows the percentage of transitional plateaus; bottom panel shows the percentage of other mode plateaus.

Figure 9. Deviation of mean ϕ from intended phase as a function of frequency, frequency detuning ($\Delta\omega$), and phase mode in Experiment 2.

the frequency factor for the ANOVAs was adjusted to contain only the four lowest frequencies. A three-way ANOVA performed on the normalized mean ϕ revealed a significant main effect of pendulum combination, $F(4, 16) = 7.95$, $p < .001$, a significant two-way interaction between pendulum combination and frequency, $F(12, 48) = 2.76$, $p < .01$, and a significant three-way interaction, $F(12, 48) = 2.05$, $p < .05$. These effects indicated, respectively, that the deviation of mean ϕ from 0° and 180° changed linearly with $\Delta\omega$, that this deviation was exaggerated by frequency, and that this exaggeration was greater for the anti-phase than the in-phase mode at the higher frequencies. This interaction is displayed in Figure 9. The greater drift for the anti-phase mode is predicted by Equation 2 and is statistically confirmed in the regression modeling of coupling strength presented later. Why the difference between the phase modes was found here and not in Experiment 1 can be explained by the difference in the stability of the coordinative regime assembled. Moreover, as evidenced by the number of breakdowns, the control processes involved in the coordina-

Figure 10. Standard deviation of ϕ as a function of frequency and phase mode in Experiment 2.

tion seemed to be much weaker than the intrapersonal coordination in Experiment 1. A weaker dynamic would exaggerate differences between in-phase and anti-phase fixed-point drift so that they could be statistically differentiated (i.e., an increase in effect size caused an increase in the power of the analysis). As stated earlier, mean ϕ at the higher four frequencies could not be analyzed in the ANOVA because of the many coordination breakdowns. The regression modeling of fixed-point drift, however, will allow a comparison of the drift at the higher frequencies.

ϕ SD. Past results suggest that ϕ SD should be higher for anti-phase than in-phase, generally increase with frequency, and be a U-shaped function of $\Delta\omega$. Figure 10 shows how ϕ SD changed as a function of phase mode and frequency. Anti-phase fluctuations were marginally greater than in-phase fluctuations (21.3° vs. 20.6°) and, as in Experiment 1, the ϕ SD was found to decrease across the first three frequencies and then increase. A three-way ANOVA with only four levels of frequency was performed on ϕ SD. It revealed a significant main effect of frequency, $F(3, 12) = 4.91, p < .05$, and an interaction of phase mode, pendulum combination, and frequency, $F(12, 48) = 1.94, p = .05$. Simple effects analyses of the interaction revealed that only for the 1.2-Hz frequency plateau was the U-shaped function of $\Delta\omega$ significant (Phase Mode $\times$ Pendulum Combination), $F(4, 16) = 6.44, p < .01$, and anti-phase fluctuations greater than in-phase, $F(1, 4) = 46.90, p < .01$. At the other three frequencies, ϕ SD was not significantly affected by either phase mode or $\Delta\omega$.

In summary, only at the 1.2-Hz frequency plateau did the results support the model-generated predictions. Underlying the partial support is perhaps the most striking property of the ϕ SD data, the overall magnitude of the fluctuations. In Experiment 1, the mean ϕ SD across all conditions was 16.23°; in this experiment, it was 20.95°. Past researchers who have investigated the breakdown of relative phasing have found ϕ SD magnitudes as high as 20° only at critical frequencies of oscillation that occur just before coordination breakdowns (Schmidt et al., 1990; Scholz & Kelso, 1990). The mean ϕ SDs for the majority of the frequency plateaus

in this experiment were near or greater than this previously observed critical magnitude. It is not surprising, then, that the only condition that affirmed the model-generated steady state predictions was one that had mean fluctuations below 20°. (Why the predictions were not also affirmed for the 1.0-Hz plateau, which had similar magnitudes, was not clear.) The greater instability that was observed in this experiment, however, might not have been due to the fact that the visual coupling had a weaker dynamic. Another possibility is that the participants were intentionally resisting the coordination breakdown, creating a steady state (albeit, an unstable one) in which one would not exist if they did not intentionally intervene. To accommodate this fact, the dynamical model of the behavior may need to be adapted to include an intentional forcing term in addition to the intrinsic dynamics found in Equation 2 (see the General Discussion section).

Measuring the coupling strength of interpersonal coordination. As in Experiment 1, an analysis was performed for each frequency plateau in which $\sin(\phi)$ was regressed on $\Delta\omega$ to estimate local model coupling strength K (see Table 4). For the in-phase mode, K was significant for all but the highest frequency. The regressions for the anti-phase mode, however, were significant for only four of eight frequencies, those with the greatest stability in Figure 10. The local analysis of fixed-point drift using Equation 4 suggested that for anti-phase, the coupling dynamic was not successfully harnessed at the higher frequencies. This fact is consistent with the many observed breakdowns of ϕ at these frequencies (see Figure 8 and the sample sizes in Table 4). Importantly, as predicted by the dynamical model, the mean magnitude of K in general decreased with frequency, $r(7) = -.71, p < .05$, although, as suggested by the ϕ SD analysis, the lowest frequency did not have the strongest dynamic. As further predicted by the dynamical model, the mean magnitude of K was greater for in-phase than anti-phase, $t(7) = 7.75, p < .001$, a result not obtained in Experiment 1. The change of the global attractor layout was derived by calculating Equation 2 coefficients a and b from the estimated K s. The resulting potential functions for each frequency are shown in the top panel of Figure 11. For the first seven frequency plateaus (those in which at least one K was significant), the values of a were 0.096, 0.036, 0.059, 0.106,

Table 4
Regression Evaluation of Coupling Term K in Equation 4 in Experiment 2

Frequency	In-phase			Anti-phase		
	r^2	K	n	r^2	K	n
0.6	.20	0.37***	70	.04	-0.18	66
0.8	.25	0.40***	74	.09	-0.23**	71
1.0	.34	0.46***	72	.28	-0.34***	68
1.2	.28	0.42***	68	.14	-0.21**	57
1.4	.14	0.30**	65	.14	-0.22**	47
1.6	.10	0.25*	60	.06	-0.15	30
1.8	.22	0.35**	54	.07	-0.16	27
2.0	.42	0.14	48	.02	-0.06	16

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 11. Potential functions portraying the change in the dynamics of ϕ under frequency scaling in Experiment 2. In the bottom panel the potential V is normalized by the magnitude of the coefficient b to allow a better comparison of the potential landscapes. Under this normalization, the concavity of the well (and hence the strength of the attractor) is correlated with the depth of the well.

0.040, 0.054, and 0.099 Hz, and the values of b were 0.068, 0.065, 0.099, 0.070, 0.065, 0.050, and 0.064 Hz. As can be seen in Figure 11, the resulting potential landscapes had two unequal-depth potential wells that became more shallow with increasing frequency such that the well at 180° nearly disappeared at the highest frequencies.

General Discussion

The main purpose of this research was to compare the relative phase patternings of intra- and interpersonal rhyth-

mic coordination. Previous research has shown that the relative phasing of both kinds of interlimb coordination can be modeled by a coupled oscillator system (Equation 2) and, consequently, that the underlying control processes involved in the two cases do not differ in kind. However, do the two control structures produce equally strong coordination? There are several ways to answer this question. One is to scale the frequency of oscillation to determine where within the frequency range the intra- and interpersonal coordinations break down. The coordination that breaks down more often or at a lower frequency is weaker. Another way is to compare the fluctuations of the coordination index (e.g., ϕ SD) as the two coordination systems are moved through the frequency range. Finally, by combining a measure of mean relative phase under frequency detuning (fixed-point drift) with an explicit dynamical model, one can estimate the model's coupling strength (e.g., coefficients a and b in Equation 2). We used identical manipulations of frequency scaling and frequency detuning to compare intra- and interpersonal coordination in terms of coordination breakdowns, relative phase fluctuations, and coupling strengths.

The Relative Strength of Within- and Between-Persons Coordination

The fact that the between-person coordinative regime is weaker than the within-person regime is strikingly indicated in the number of coordination breakdowns. In both experiments, there was a progressive increase in the number of breakdowns with increases in frequency. However, at the highest frequencies, half the trials had breakdowns for interpersonal coordination and few trials had breakdowns for intrapersonal coordination. For the four highest frequencies, 25%, 40%, 46%, and 57% of the trials had breakdowns in Experiment 2, whereas 1%, 4%, 3%, and 6% of the trials had breakdowns in Experiment 1. Furthermore, the breakdowns in Experiment 1 were momentary losses of control rather than transitional. In Experiment 2, the majority of breakdowns were extended instances of transitions between modes or phase-wrapping behavior.

The fluctuations in relative phase provide another index of comparison for the two kinds of coordination. Given the number of coordination breakdowns for the interpersonal experiment, one expects the ϕ SDs to be higher in this experiment as well. Indeed, a comparison of the mean ϕ SD at each frequency plateau for the two experiments indicated that the fluctuations were significantly greater for Experiment 2 (21.1° vs. 16.2°), $t(14) = 4.27$, $p < .001$. This result suggests that the interpersonal coordination had more coordination breakdowns because it is inherently less stable, presumably because the control processes involved are weaker (i.e., the coupling dynamic is weaker).

The regression analysis of fixed-point drift, which estimates the model coupling strength, however, is the most explicit means of comparing the strength of the two kinds of coordination. A comparison of the K magnitudes for the two experiments (see Tables 2 and 4) indicated that the strength for within-person coordination was significantly stronger (0.57 vs. 0.27 Hz), $t(30) = 6.61$, $p < .001$, than between-

person coordination. This remained true for the two phase modes separately as well. For the in-phase and the anti-phase modes, within-person coordination (0.57 and 0.58 Hz, respectively) was stronger than between-person coordination (0.34 and 0.19 Hz, respectively; both $ps < .01$). Another criterion of strength is the significance of these regressions. All regressions for Experiment 1 were significant, whereas only 11 of 16 were significant for Experiment 2. The lack of significance of these regressions suggests that the coupling dynamic for these high frequency conditions could not be established at all or was so weak that it could not be successfully maintained interpersonally. Note that Experiment 1's mean K is still significantly greater than Experiment 2's if only the significant coefficients are compared (0.57 vs. 0.32 Hz), $t(25) = 5.1$, $p < .001$.

The graphical depictions of the potential functions in Figures 6 and 11, whose components were derived from these estimated K s, provide an illuminating explanation of these comparisons. In the lower parts of these figures, the potential V has been normalized by the coefficient b so that the strength of the attractor (i.e., its concavity) is indexed by the depth of the potential well. Note that the between-person attractors have shallower basins of attraction than those of intrapersonal coordination and are consequently weaker attractors. This is particularly apparent for the anti-phase attractor at 180° , which is shallow for the between-person coordination and hence weak. The more shallow the basin of attraction, the greater the fluctuations and the greater the probability that a breakdown in coordination will occur (i.e., a fluctuation will knock the system out of the current basin of attraction). Indeed, in Experiment 2, more breakdowns and greater ϕ SDs occurred in the anti-phase mode. Note that independent observations led to the estimation of the attractor layouts and the estimates of instability: Mean ϕ (fixed-point drift) was used in recovering the coupling strengths, which is independent of the measurement of fluctuations and number of breakdowns. Yet, there was the expected correlation between the magnitude of the coupling K and the ϕ SD for both experiments: combined, $r(15) = -.87$, $p < .001$; Experiment 1, $r(6) = -.71$, $p < .05$; and Experiment 2, $r(6) = -.67$, $p = .07$.

Hence, the local model's coupling strength K was a good predictor of coordination stability. As stated earlier, previous researchers have assumed that the b/a ratio, which has been used to index the transition from anti-phase to in-phase at $b/a = .25$, is an effective index of the strength of the coupling dynamic of the global model (i.e., Equation 2). However, it is obvious from the magnitudes of a and b reported for Experiment 1 that their ratio did not differentiate the strength of attractors of the different frequencies (see Figure 6) because the a coefficient was estimated to be zero for all frequencies. A more pragmatic index of individual strengths of the two attractors was the normalized depth of the potential wells (see the bottom of Figures 6 and 11) in which the 0° minimum was equal to $-a - 2b$ and the 180° minimum was equal to $a - 2b$. These global attractor indexes of coupling strength correlated highly with the local attractor index K , $r(30) = .96$, $p < .001$. Furthermore, the relative strength of the 0° attractor (compared with that of

the 180° attractor) was indexed by the difference in height of the normalized potential well and was equal to $2a$.

Why Didn't Anti-Phase Break Down in Experiment 1?

The comparison of Figures 6 and 11 also provides an explanation for what seems at first to be an anomalous finding of Experiment 1: that the anti-phase mode did not break down at high frequencies. It seems that the oscillator regime did not become unstable enough for a breakdown to occur. The data-derived coupling strengths suggested that at even the highest frequency, the attractor at 180° phase was strong. This strength and lack of breakdown of the anti-phase mode has precedence in both anecdote and experiment. For example, bipedal running (which is anti-phase) does not become unstable (and turn into hopping) at high frequencies. Furthermore, Kelso and Jeka (1992) found few anti-phase breakdowns in the coordination of arm movements about the elbow and leg movements about the knee. In explaining their results, they suggested that the interlimb system was not put in a critical region of its parameter space because the control parameter scaled to extreme enough values to weaken the coordination dynamics significantly. In our research, $\Delta\omega$ and frequency could not have been scaled too much higher given the limits on stable single wrist-pendulum oscillation (see the *Method* section of Experiment 1).

However, the small number of anti-phase breakdowns and the mode's high coupling strength may be explained further. Interestingly, the coordinations thus far observed that have not exhibited anti-phase breakdown (this research and Kelso and Jeka, 1992) seem to be coupling movements in the sagittal plane of the body. The anti-phase mode may be inherently more stable for these movements for reasons of postural stability: When pendulums are swung, the center of gravity of the body oscillates in the sagittal plane for in-phase movements, but for anti-phase movements it remains constant. This factor of enhanced stability for anti-phase movements in the sagittal plane may interact with its inherent instability and lead to a near equality of stability for the two modes for intrapersonal coordination.

Was the Coordination Dynamic Influenced by Intentional Forces?

Another explanation for the small number of breakdowns in Experiment 1 may be that the participants were intentionally resisting the transition. However, no participant reported experiencing such resistance in any of the conditions. Furthermore, such resistance would be accompanied by high ϕ SDs. Scholz and Kelso (1990) reported that when participants were intentionally resisting anti-phase breakdowns in bimanual index finger oscillation, the observed ϕ SDs were between 24° and 27° . The ϕ SDs observed in Experiment 1 never reached these magnitudes. Only the 21.97° ϕ SD of the highest frequency in anti-phase, which puts the stability only in the pretransitional critical range, is a candidate for being a manifestation of intentional forces. With this one exception, the ϕ SD magnitudes observed in Experiment 1 were consistent with previous intrapersonal

wrist-pendulum studies. For example, Schmidt et al. (1993; using a "do not intervene" instruction) observed ϕ SDs of 14°, 17°, and 19° for 0.8-, 0.94-, and 1.15-Hz frequencies, respectively.

In Experiment 2, however, the majority of the ϕ SDs were above 20° (11 of 16 frequency plateau means), and 4 of these were in or near the 24°–27° range identified by Scholz and Kelso (1990). These results suggest that intentional processes were possibly affecting the maintenance of steady states in the interpersonal coordination of Experiment 2. The dynamical models thus far presented represent the intrinsic dynamic of a motor control synergy without any intentional force terms. However, other studies (Kelso, Scholz, & Schöner, 1988; Schöner & Kelso, 1988) have modeled the intentional forces underlying the intentional switching between phase modes. It is possible that the intentional forcing dynamics used for the switching of modes in those studies could be adapted to our situation of maintaining a current mode of coordination.

The task instructions to return to the original phase mode presumably caused the creation of intentional forces to maintain the correct mode when a breakdown was imminent. The temporary implementation of such intentional processes in response to potential breakdowns would have two consequences. First, such on-line intentional corrections could function as a perturbation and cause transients in the relative phase time series. There is support for this in the relatively high ϕ SDs observed in this research. As mentioned earlier, steady state ϕ SDs of the magnitude observed have been found only in experiments in which the participants were told to intentionally resist the transition (Scholz & Kelso, 1990). The transients caused by the addition of this temporary intentional forcing are probably all the more noisy when they were dyadically implemented (e.g., initiated by one participant and then the other). Second, the temporary implementation of intentional forces could have caused the measurement of mean ϕ to result in values closer to 0° and 180° and cause an effective deepening of the potential wells as indexed by the regression methodology. Hence, one must countenance that the potential wells in Figure 11 and their strengths in Table 4 (particularly those at the higher frequencies) are possibly the product of intentional forcing operating in conjunction with Equation 2. However, it is apparent that Equation 2's predictions about the strength of the dynamic still hold. That is, the strength of the anti-phase mode was less than that of the in-phase mode and that the strength of both phase modes decreased with increasing frequency. Indeed, the lack of significance of the high-frequency coupling strength regressions in the anti-phase mode suggested that the dyadic intentional processes, if present, were not successful in maintaining the integrity of the dynamical interlimb regime. This might have been the result of their intermittent application in time or their weak application in strength. Either of these possibilities would increase the transients produced (and the ϕ SD) while not necessarily affecting the strength of the dynamic (as measured by mean ϕ).

In summary, the magnitude of the ϕ fluctuations observed in Experiment 2 suggested that intentional forces might have

been operating in some conditions, thus creating transients in the behavior of ϕ . Given this outcome, one may well ask why use the "stay in the original phase mode" methodology rather than the "do not intervene" methodology previously used. The problem with the latter methodology is that one does not know whether a participant experiences the transition once in the anti-phase mode and then intentionally forces a transition in subsequent anti-phase mode trials. In short, the participant may succumb to task demands. Although one can evaluate the involvement of intentional forces in the "stay in the original phase mode" methodology, it is much harder to evaluate whether intentional processes are involved in forcing transitions. In any event, our research and that of others using the "stay in the original phase mode" methodology (e.g., Diedrich & Warren, 1995) demonstrate the robustness of the predictions of the dynamical model. Regardless of the specific task instructions and the possible operation of intentional stabilizing forces, the patternings of relative phase observed are those predicted by the dynamical model.

Why Is Interpersonal Coordination Weaker Than Intrapersonal Coordination?

The results of our research indicate that general dynamical principles are involved in the coordination of rhythmic movements regardless of whether the coordination is established between the limbs of a single person or the limbs of two different people. The similarity of the manipulations in the within- and between-person settings allowed the two kinds of coordination to be directly compared and their relative strengths measured. Using a number of indexes, it has been demonstrated that interpersonal coordination of wrist pendulums is weaker than intrapersonal coordination of wrist pendulums. If the interlimb coupling in each case is informational, one can conclude that the informational linkage across the optic array is less robust than the informational linkage across the CNS. However, what makes the visual linkage less robust?

One possibility is that this informational linkage is constructed out of just peripheral information for the between-person situation but from peripheral and higher order coupling of effector control structures in within-person coordination. For example, there is evidence that bimanual coordination results not only from an integration of feedback from the periphery but also from a coordination of the two limbs at the highest levels of the nervous system (Wiesendanger, Wicki, & Rouiller, 1994). Obviously, these higher levels are not able to control both limbs in between-person coordination. Because the between-person coordination is coupled only at the periphery, this kind of coordination could be expected to be weaker.

Additionally, the peripheral information linkage in within- and between-person coordination may not be equally strong. Assume that the kinematic form of wrist-pendulum trajectories constitute the information necessary for the information linkage regardless of the medium (Bingham, 1995). That is, it is by virtue of the availability of certain kinematic properties of the wrist pendulums in the informational

mediums that the coordinative linkage can be formed. Assuming this, the visual coupling may in fact be weaker because the requisite aspects of the kinematics are not as available in the optic array as they would be in the CNS. We are currently investigating what kinematic properties of the visual information are important for visual coordination of rhythmic movements. For example, we have been using visual occlusion of various portions of the wrist-pendulum trajectories to determine whether certain portions of a wrist-pendulum trajectory are important for stable coordination (O'Brien, 1993). Additionally, we are currently investigating whether the distance between two people, which manipulates the effective size of the optical image, has an effect on the strength of the visual coupling. If certain kinematic properties of the wrist-pendulum trajectories are important for establishing visual coordination, then an important question is whether this information can be exaggerated or emphasized sufficiently so that the strength of the visual coordination of wrist pendulums can be improved. The interpersonal coordination paradigm then provides a forum for investigating what information is used to form perceiving-acting couplings and how manipulations of the information affects the strength of such couplings and hence the stability of the actor-environment coordination.

Of course, the strength of the interlimb coupling depends not only on the availability of the requisite kinematic properties at the periphery but also on the efficiency of the information pickup mechanisms to resolve this information. The difference in strength observed between these two kinds of coordinations may be a consequence of the differences in the information pickup mechanisms being used and their ability to "tune" the efferent control processes. That is, the proprioceptive information pickup processes of intrapersonal coordination may be more efficient than the visual information pickup processes of interpersonal coordination and consequently create a stronger informational linkage.

One way that this difference in efficiency could be rationalized is in terms of Bernstein's (1996) hierarchical characterization of biological movement systems. According to this theory, the level of muscular-articular links or synergies consists of coordinative relations between muscles and joints. The control processes on this level are used to create patternings of body segments without regard for use or function. The level of space, alternatively, is an appropriate description for control processes involved in coordinating movements in an environmental context. The control processes are characterized by the translating of environmental spatial coordinates into muscular coordinates. Whereas proprioception is used for constraining movements at the level of synergy, visual perception is used for constraining actions at the level of space. Given this distinction, one can speculate that the control structure assembled for intrapersonal coordination is primarily at the level of synergies, whereas the control structure assembled for interpersonal coordination uses both the level of synergies and the level of space. Furthermore, given the intimacy between proprioception and movement at the level of synergies, it makes sense that information pickup here is more efficient than the visual information pickup that must coordinate processes at the

level of synergies with processes at the level of space. The ramification is that the cross-level cooperativity that is set up between people has a weaker dynamical constitution than the within-levels cooperativity that is set up within a person. Although the same laws seem to operate in intra- and interpersonal coordinative structures, the implementation of the dynamics involves processes at different levels of the action system and results in differences in the strength of the dynamic assembled.

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