Dynamical Patterns in Clapping Behavior

Paula Fitzpatrick and R. C. Schmidt
Tulane University and CESPA, University of Connecticut

Claudia Carello
CESPA, University of Connecticut and Haskins Laboratories

A nonlinear dynamics framework that has been applied successfully to several laboratory idealizations of rhythmic behaviors was applied to a more naturally occurring behavior, clapping. Inertial loading of limbs and frequency of oscillation were manipulated. Displacement of relative phase from perfectly in phase and the variability of relative phase, both of which are used as indexes of coordination dynamics, increased with greater inertial imbalance between limbs. Increasing frequency exaggerated these effects. These hallmark properties of coupled oscillator dynamics appeared whether or not the hands contacted, albeit with the latter condition revealing a significant asymmetry in the dynamics. Results highlight the generality of the coupled oscillator regime in interlimb coordination as well as its appropriateness for characterizing behaviors that involve contact of limb surfaces and suggest one way in which perceptual information may tune the dynamical regime.

Because of the ubiquity of rhythmicity in animal life, rhythmic behaviors have been the subject of much experimental investigation, particularly from a dynamical systems perspective. This perspective interprets biological action (or motor) systems as self-organizing systems, that is, systems whose behavior emerges from the interaction of a number of components without requiring an internalized prescription or blueprint (e.g., Beek, 1989; Haken & Wunderlin, 1990; Kugler, Kelso, & Turvey, 1980; Kugler & Turvey, 1987; Schöner & Kelso, 1988a). A variety of rhythmic interlimb coordinations have been modeled using coupled oscillator regimes in which the individual limbs are treated as limit cycle oscillators that are coordinated by a low-energy coupling function. Whether the oscillators are an individual’s two index fingers (e.g., Kelso, 1984), an arm and a leg (Jeka, Kelso, & Kiernel, 1993; Kelso & Jeka, 1992), pendulums held in each hand (e.g., Kugler & Turvey, 1987), pendulums held by two individuals (e.g., Amazeen, Schmidt, & Turvey, 1995; Schmidt & Turvey, 1994; Schmidt, Christianson, Carello, & Baron, 1994), or the legs of two individuals (e.g., Schmidt, Carello, & Turvey, 1990), the principles of coordination are the same. Although the foregoing tasks are idealizations of rhythmic behavior as compared with common rhythmic activities, they nevertheless demonstrate the power of this perspective: Very general principles of coordination dynamics are harnessed by very different coordinators.

Characteristics of dynamical systems (e.g., phase transitions, stability, energy minima) have been identified in more naturally occurring coordinations such as quadrupedal (Hoyt & Taylor, 1981) and bipedal (Diedrich & Warren, 1995) locomotion, finger tapping (Peper, Beek, & van Wieringen, 1991), handwriting (Newell & van Emmerik, 1989), and juggling (Beek & Turvey, 1992). However, the nature of the observations and manipulations did not allow tests of specific predictions that follow from formal dynamical models, in particular, the coupled oscillator regime that has provided the basis for much theorizing. The coordinations between two fingers, two hands, two pendulums, or two legs have been construed as adhering—in formal detail—to a coupled oscillator model. Because the implication of this construal is a powerful one—that control is relegated to a dynamical control structure that requires little attention or intervention on the part of the actor—the model should be tested with respect to a naturally occurring rhythmic behavior. If successful, its status as what Kelso (1994) refers to as the elementary coordination dynamics will be further reinforced.

Previous studies that have tested how interlimb coordination conforms in formal detail to coupled oscillators have not investigated the effect of omnipresent perturbations through force contact of the limbs with each other or other surfaces. As such, the appropriateness of this model in
characterizing movement patterns that involve interaction between limb and surfaces should be explored as an important extension of the elementary coordination dynamics. As Hogan (1985) pointed out, a large class of purposeful movements involve an interaction between limbs and surfaces (e.g., in the use of tools such as a hammer or in the contact of limb surfaces as in clapping). Whether control strategies for movements involving mechanical impedance are similar to those strategies adopted for free motions raises interesting questions. Furthermore, movements involving contact with environmental surfaces require that issues regarding the role of perceptual information in maintaining or tuning the coordination dynamics be addressed.

This research examines whether a coupled oscillator model is appropriate for a coordination pattern that involves contact between limb surfaces and is commonly exhibited outside the laboratory. Clapping is a behavior that involves such contact but nonetheless lends itself to the sorts of manipulations that allow specific tests of coordination dynamics. Through manipulations of the inertial loading of the limbs and the frequency of clapping we look for evidence that the relative phasing of the limbs is being influenced—that one of the hands takes the lead or that the phasing is more or less variable—under particular circumstances as predicted by the model. These manipulations also are examined under a variety of clapping styles that address whether the dynamic is affected by mechanical impedance and the availability of perceptual information. To provide a context for the manipulations and their relationship to the sought-after properties, we present the dynamical model in some detail.

Coupled Oscillator Dynamics

Interlimb coordination in which two limbs oscillate at a common tempo has been referred to as absolute coordination (von Holst, 1939/1973). A hallmark property of absolute interlimb coordination is that two limbs can oscillate at the same frequency (i.e., achieve 1:1 frequency locking) regardless of the inertial difference between the limbs. That is, two limbs differing in size and hence preferred frequency of oscillation (eigenfrequency) oscillate at a common frequency in spite of their differences. As von Holst observed in the phasing of fish fins, the rhythmic unit that prefers to oscillate more slowly (that has the lower natural frequency or eigenfrequency) lags slightly behind the unit that prefers to oscillate faster (higher eigenfrequency) while still maintaining frequency locking. Furthermore, the magnitude of the lag depends on the magnitude of the difference between the two rhythmic units. von Holst referred to this tendency for each rhythmic unit to maintain its own preferred frequency as the maintenance tendency. Absolute interlimb coordination can thus be characterized as a balancing of cooperative forces (each rhythmic unit is drawn to the tempo of the other) and competitive forces (each unit attempts to maintain its own tempo).

The dynamical systems perspective offers an explanation of these cooperative and competitive tendencies in terms of the dynamics of the oscillatory system. The tack taken, following synergetics (Haken, 1983), is to capture the high-dimensional dynamics of a complex system—in which neuromuscular structure and function are defined at multiple scales—in a low-dimensional description of the macroscopic patterning of the component subsystems. Collective variables that capture the spatiotemporal organization or pattern of the component rhythmic units and that change more slowly than the variables that characterize the states of the units, referred to as order parameters, are identified. Equations expressing physical principles are then used to model the dynamical changes in the order parameter under manipulation of other properties, referred to as control parameters, that affect the collective dynamics indirectly (i.e., without specifying the nature of the changes that the order parameter might undergo).

In empirical investigations of interlimb rhythmic coordination, the relative phase angle ($\phi$) between two oscillating limbs has been identified as an order parameter (Haken, Kelso, & Bunz, 1985; Turvey, Rosenblum, Schmidt, & Kugler, 1986) and has been examined under the scaling of two control parameters, coupled frequency of oscillation $\omega$ (Kelso, 1984, 1990; Schmidt et al., 1990; Schmidt, Shaw, & Turvey, 1993; Sternad, Turvey, & Schmidt, 1992) and the difference in preferred frequencies of oscillation or eigenfrequencies of the component oscillators (the left–right inertial imbalance) $\Delta \omega$ (Rosenblum & Turvey, 1988; Schmidt et al., 1993; Sternad et al., 1992).

Changes in $\phi$ under the scaling of these two control parameters have been dynamically modeled by using the principles of coupled physical oscillators. Each of the two individual oscillators is assumed to maintain a steady-state limit cycle. That is, a recording of an oscillator’s movement over time reveals that its trajectory (the history of its state or position over time) forms a closed orbit; the oscillator is attracted to or prefers certain regions or points in space and continually revisits those regions. This closed orbit is called a limit cycle attractor, and a system exhibiting such behavior is said to have an underlying limit cycle dynamic (Jackson, 1989; Thompson & Stewart, 1986).

Equations that capture the behavior of a system of rhythmic units over time (i.e., a system of coupled oscillators) require a variable that indicates where each oscillator is in its cycle. Phase angle ($\theta$) indexes cycle position in terms of the angle from the start of the limit cycle. The change in $\theta$ over time is a function of properties of the individual oscillator and the fact that it is coupled to another oscillator (Jeka et al., 1993; Rand, Cohen, & Holmes, 1988):

$$\dot{\theta}_1 = \omega_1 + H_1 (\theta_1 - \theta_2) \quad (1)$$

$$\dot{\theta}_2 = \omega_2 + H_2 (\theta_1 - \theta_2), \quad (2)$$

where $\omega_1$ is the uncoupled (preferred) frequency of oscillation and $H_1$ is a periodic coupling function that captures the effect of the behavior of one oscillator on that of the other.

If $\phi$, the relative phase angle, is defined as $\theta_1 - \theta_2$ and the periodic coupling functions, $H_1$ and $H_2$, are assumed to be
equal and operate the same in both directions, $H = H_1, 2$, then subtracting Equation 2 from Equation 1 gives the equation for the change of $\phi$ over time:

$$\dot{\phi} = \Delta \omega - 2H(\phi).$$  \hspace{1cm} (3)

where $\Delta \omega = \omega_1 - \omega_2$, $\phi$ indicates whether the oscillators are in the same parts of their cycles at the same time (i.e., $\theta_1 = \theta_2$) or whether one oscillator is ahead of the other. Equation 3 states that the behavior or pattern exhibited by two oscillators is a function of both the competition, $\Delta \omega$, and the cooperation, $2H(\phi)$, between the two oscillators (e.g., Turvey, Schmidt, & Beek, 1993). Periodic functions composing the cooperation have been derived from experimental observations suggesting that interlimb coordination is bistable under some frequencies, exhibiting both in-phase and anti-phase patterns, and monostable under other conditions, exhibiting only the in-phase pattern (e.g., Kelso, 1984). Capturing these phenomena requires, minimally, that the periodic functions defining the interlimb cooperation include terms in $\phi$ and $2\phi$ whose coefficients change systematically with $\omega_c$ (Haken et al., 1985). In consequence, $\phi$ behavior has been modeled by

$$\dot{\phi} = \Delta \omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q \xi_n}.$$  \hspace{1cm} (4)

where $a$ and $b$ are coefficients that determine the relative strengths of inphase and antiphase coordination, and $\sqrt{Q \xi_n}$ is a stochastic noise process (generated by the very many interacting subsystems underlying the coordination; Haken, 1983; Schöner, Haken, & Kelso, 1986). In addition, modeling empirical results, Haken et al. (1985) proposed that $\omega_c$ functions as a control parameter on the dynamic such that $b/a$ decreases (and concomitantly the strength of antiphase) as $\omega_c$ increases.

Solutions to Equation 4 (excluding $\sqrt{Q \xi_n}$) provide predictions about patterns of interlimb coordination. Consider first the situations for which $\Delta \omega = 0$. When $b$ is large with respect to $a$ (e.g., the ratio $b/a > 1$), there are two stable states (equilibria or attractors), one at $\phi = 0$ (the in-phase mode in which the oscillators are in the same point of the cycle at the same time) and one at $\phi = \pi$ (the anti-phase mode in which the oscillators are in opposite points of the cycle at the same time). The relative attractiveness of $\phi = 0$ and $\phi = \pi$ is given by the rate of change of $\phi$ evaluated at the two stable points. The sign of $d\phi/d\phi$ is negative for stable points, and its magnitude is greater for the equilibrium at $\phi = 0$ than the equilibrium at $\phi = \pi$, meaning that values of $\phi$ near to $\phi = 0$ move toward $\phi = 0$ “faster” than values of $\phi$ near to $\phi = \pi$ move toward $\pi$. When noise is present, the disturbance away from an equilibrium will be smaller on average the greater the magnitude of $d\phi/d\phi$. As the coefficient $b$ decreases in its size with respect to $a$ (i.e., the $b/a$ ratio decreases), the strength of both attractors decreases; at $b/a = .25$, the attractor at $\pi$ disappears, and only the attractor at 0 remains. As for data from interlimb coordination, the prediction about the existence of two attractors is supported by the observation that two relative phase relations are most common, $\phi = 0$ and $\phi = \pi$. As expected, the inphase mode is more stable—evidenced by lower fluctuations—than the alternate mode (Kelso, Scholz, & Schöner, 1986; Schmidt et al., 1993; Schöner et al., 1986; Turvey et al., 1986). Furthermore, the stability of the steady-state phase modes decreases as the frequency of oscillation $\omega_c$ is increased (Schmidt et al., 1993; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1994) until at a critical $\omega_c$ the anti-phase mode can no longer be maintained and a transition to the in-phase mode occurs (Kelso, 1984; Kelso et al., 1986; Schmidt et al., 1990). No such breakdown occurs in the symmetric mode; fluctuations increase with an increase in $\omega_c$ but the attractor remains at $\phi = 0$. Given the relationship between $\omega_c$ and the stability of the attractor, Haken et al. (1985) proposed that $\omega_c$ scales the relative strength of the coupling terms—$b/a$ is inversely proportional to $\omega_c$—and, therefore, scaling $\omega_c$ alters the dynamical landscape of the coupled oscillatory regime such that at a critical $\omega_c$ the attractor at $\pi$ is annihilated.

When $\Delta \omega 
eq 0$ in Equation 4, the maintenance tendency of the rhythmic units underlies some other interesting properties of the relative phasing of rhythmic units. Consider first Equation 4, with $b/a$ held constant. The effect of $\Delta \omega 
eq 0$ is to displace the equation’s stable points from 0 and $\pi$, with a greater displacement accompanying larger deviations of $\Delta \omega$ from 0. Furthermore, the stability of these stable states as indexed by $d\phi/d\phi$ is reduced as $\Delta \omega$ deviates from 0. Decreasing the magnitude of $b/a$ while $\Delta \omega 
eq 0$ by lowering $\omega_c$ causes the displacement of the attractors and the reduction in stability to be amplified. Once again, these features of Equation 4 have been verified behaviorally. In experiments using bimanual coordination of hand-held pendulums swung from the wrist, in which $\Delta \omega$ is manipulated by varying the inertial properties of the pendulums, the behavior of $\phi$ changes as follows: (a) the mean observed $\phi$ deviates from the intended $\phi$ (i.e., $\Delta \phi$) such that the unit with the slower eigenfrequency $\omega_1$ lags behind the unit with the faster eigenfrequency, (b) the magnitude of this deviation $\Delta \phi$ depends on how much $\Delta \omega$ deviates from 0, and (c) the fluctuations in $\phi$ (defined either as the $SD\phi$ or the total spectral power of $\phi$) increase as the magnitude of $\Delta \omega$ deviates from 0 (Bingham, Schmidt, Turvey, & Rosenblum, 1991; Rosenblum & Turvey, 1988; Schmidt, Beek, Treffner, & Turvey, 1991; Treffner & Turvey, 1995; Turvey et al., 1986). Furthermore, studies in which $\Delta \omega$ and $\omega_c$ were simultaneously manipulated (Schmidt et al., 1993, 1994; Sternad et al., 1992) found (as predicted by Equation 4) an amplification of both $\Delta \phi$ and fluctuations in $\phi$ with increases in $\omega_c$. It is important to note, as alluded to earlier, this pairing of phase lag and phase variability does not hold for $\Delta \omega = 0$. The model particularly pre-

---

1 It is interesting that similar results for mean phase are found at the level of the neural substructure in the behavior of central pattern generators (see Kopell, 1988; Rand et al., 1988; Stein, 1973, 1974) and when the inertial magnitudes of the oscillators are manipulated by varying the limbs (arm-arm vs. arm-leg) to be coordinated (Kelso & Jeka, 1992).
dicts that when \( \Delta \omega = 0 \) and \( \omega_c \) is increased, the magnitude of \( \phi \) fluctuations should increase, but observed \( \phi \) should not deviate from intended \( \phi \) (i.e., \( \Delta \phi = 0 \)). This dissociation has also been verified (Schmidt et al., 1993, 1994).²

In summary, the behavior of the order parameter \( \phi \) (as indexed by mean \( \phi \), and its variability) changes under manipulation of two variables, coupled frequency of oscillation \( \omega_c \) and the difference in preferred frequencies of oscillation \( \Delta \omega \). Our enumeration of some major features of the coupled oscillator should serve as a set of predictions to be evaluated for clapping if this behavior can be characterized by such a model. The predictions for this model involving \( \omega_c, \Delta \omega, \text{mean } \phi, \text{and variability in } \phi \) are outlined as follows and are limited to the case of intended \( \phi = 0 \) (because clapping is, by definition, an inphase coordination):

**Prediction 1.** Two limbs can achieve 1:1 frequency locking regardless of their inertial difference.

**Prediction 2.** The oscillator that prefers to move more slowly lags in phase.

**Prediction 3.** This phase lag \( \Delta \phi \) is positively related to \( \Delta \omega \) such that the greater the \( \Delta \omega \) the greater the \( \Delta \phi \).

**Prediction 4.** Increasing \( \omega_c \) exaggerates \( \Delta \phi \), except that

**Prediction 5.** When \( \Delta \omega = 0 \), mean \( \phi = 0 \), regardless of \( \omega_c \).

**Prediction 6.** Variability in \( \phi \) increases with the magnitude of \( \Delta \omega \).

**Prediction 7.** Variability in \( \phi \) increases with increasing \( \omega_c \).

Terms are defined as follows: \( \phi \) is relative phase between the limbs; \( \Delta \phi \) is deviation of relative phase from 0; \( \Delta \omega \) is the difference between the preferred (uncoupled) frequencies of the two limbs; and \( \omega_c \) is the frequency imposed on the coupled system. Essentially, when \( \omega_c \) and \( \Delta \omega \) are manipulated, the observed mean \( \phi \) is some small deviation \( \Delta \phi \) from 0 rad even though the oscillators are moving at the same frequency. Mean \( \phi \) is positively related to \( \Delta \omega \), and \( \omega_c \) increases the slope of this relation. Furthermore, the variability in \( \phi \) increases as \( \Delta \omega \) deviates from 0 and as \( \omega_c \) is increased.

These patterns should hold if Equation 4 is an appropriate characterization of clapping. This test provides the focus of Experiment 1. Clapping is also a useful addition to the repertoire of empirically examined rhythmic behaviors that conform to the Haken et al. (1985) model because it involves a collision during every cycle. Although the collision does not force or maintain the oscillation, it does mark the occurrence of a collision during every cycle. Although this simpler equation has its usefulness (see Schmidt & Turvey, 1995), Equation 4 is the more general and, consequently, is used here.

**Experiment 1**

Although clapping is a seemingly straightforward act, distinctive individual characteristics in clapping style can be identified (Repp, 1987). For example, the hands can be parallel and flat, angled, or cupped to varying degrees; they can also vary in vertical alignment from palm-to-palm to finger-to-palm. The arms also can vary in alignment, from horizontal to vertical. Because of the variability in individual clapping style, clapping was restricted to a palm-to-palm clap (oscillation was about the elbow joint). This restriction of the biomechanical degrees of freedom of the movement standardized the experimental task and allowed for comparisons across participants. Restricting the movement also rendered data collection and phase angle calculation more manageable.

In research to date, eigenfrequency \( \omega_o \) has been manipulated explicitly only in the hand-held pendulum paradigm (Kugler & Turvey, 1987) by altering the length or mass, and hence inertial loadings, of the pendulums which are oscillated about a point in the wrist. In Experiment 1, the inertial load of a limb was altered by attaching different masses to the forearm. Manipulation of coupled frequency \( \omega_c \) can be accomplished by asking participants to elect a starting frequency as well as each increment in frequency or by having them track a metronome with preset tempos. Here, participants elected a comfortable frequency before the experiment. This tempo was used to establish one slower and one faster pace; all three were specified by a metronome during the experimental session.

It is expected that under scaling of \( \omega_c \) and \( \Delta \omega \), the relative phasing of the limbs during clapping will provide evidence for the oscillatory dynamics of Equation 4. Evidence is evaluated with respect to the properties identified earlier.

**Method**

**Participants.** Two participants were Tulane University graduate students, and 4 were undergraduates who participated in partial fulfillment of a course requirement. All participants were right-handed and female.

**Materials.** Commercial Velcro-attached wrist weights (0.45 kg and 0.90 kg) were used to manipulate the left-right imbalance of the limbs. These masses were chosen on the basis of pilot testing,

² A model first proposed by Cohen, Holmes, and Rand (1982; see also Rand et al., 1988) to handle the observed changes in \( \phi \) under manipulation of \( \Delta \omega \) in central pattern generators, namely, \( \phi = \Delta \omega + k \sin(\phi) \), can be considered a truncated version of Equation 4 (Fuchs & Kelso, 1994; Schmidt & Turvey, 1995). In this equation, whether the attractor is at 0 or \( \pi \) rad depends on the polarity of coupling strength \( k \). If \( k \) is positive, the stable point is near \( \phi = 0 \); if \( k \) is negative, the stable point is near \( \phi = \pi \). Assuming that the coupling strength decreases with increasing \( \omega_o \) (as Haken et al., 1985, did), this equation also accounts for changes in \( \phi \) under scaling of \( \omega_o \). It does not, however, predict the unequal attractiveness of \( \phi = 0 \) and \( \phi = \pi \). Although this simpler equation has its usefulness (see Schmidt & Turvey, 1995), Equation 4 is the more general and, consequently, is used here.
Together, they determine the primary angle of excursion for a longitudinal axis of the forearm; B is a vector across the body. A participant sat in front of the movement digitizer Figure 1. with markers attached to each arm. A is a vector along the clap in a smooth rhythmic fashion, with the limbs moving for the metronome. Once the participant had comfortably established the body. A metronome pulse generated on a Macintosh computer to the fingertip, and B extending to an arbitrary fixed point on the coordinates to locate the position of each IRED. The 3-D time from each of the three lenses; the sample rate was set at 100 Hz. The primary angle of excursion of each limb was calculated. The primary angle of excursion is the angle formed between two vectors originating at the biceps: A extending to the fingertip, and B extending to an arbitrary fixed point on the body.

\[ \alpha_i = \arccos \left( \frac{\mathbf{A} \cdot \mathbf{B}}{|\mathbf{A}| \cdot |\mathbf{B}|} \right). \]  

In other words, the primary angle represents the angle formed between the forearm segment of the arm and the vertical plane of the body. Thus, a 90° angle indicates the limb is straight out in front of the body; a 0° angle indicates the limb is flush across the body. A metronome pulse generated on a Macintosh computer specified the frequency of oscillation.

**Design and procedure.** Participants were tested one at a time, seated on a chair centered 2.5 m from the OptoTrak cameras. The participant was asked to clap her hands at each of three tempos (see later). The style of clapping was restricted, with instructions to keep the upper arms close to the body and relatively immobile, the forearms parallel to the ground plane, and the fingertips facing forward with the palms flat together on contact. At the start of each trial, the participant was instructed to begin clapping in time to the metronome. Once the participant had comfortably established the metronome rhythm (for approximately four clapping cycles), data collection began and lasted 22 s. Participants were instructed to clap in a smooth rhythmic fashion, with the limbs moving for the duration of the trial. Hand preference, weight, and length from fingertip to elbow were recorded.

The specific metronome frequencies for each participant were determined before the experimental session. Each subject was asked to clap at a comfortable tempo, defined as one that could be maintained the longest before tiring. Three 10-s trials were collected and analyzed, and the mean period for the three trials was calculated. This frequency of oscillation was taken as the baseline, \( \omega_\text{comfort} \), and was used to compute two other tempos, one slower and one faster than comfort mode for each individual participant. The frequencies 0.63 \( \omega_\text{comfort} \), \( 1.0 \omega_\text{comfort} \), and 1.5 \( \omega_\text{comfort} \) are comparable with frequency manipulations in previous research on 1:1 interlimb frequency locking (Schmidt et al., 1993; Sternad et al., 1992). Averaged over participants, the frequencies were 0.85 Hz, 1.34 Hz, and 2.01 Hz, respectively. All three frequencies were prescribed by the metronome during the experimental session.

Five \( \Delta \omega \) conditions were used. Unlike hand-held pendulums, the two limbs in the clapping task cannot be treated as gravitational pendulums for purposes of calculating actual eigenfrequencies. An ordered index of \( \Delta \omega \) was used, therefore, in which the direction of the imbalance between left and right is indicated by the sign, where \( \Delta \omega = \omega_L - \omega_R \). The inverse relation between frequency and inertia means that \( \Delta \omega > 0 \) when the right limb is loaded and \( \Delta \omega < 0 \) when the left limb is loaded. The inertial loadings and \( \Delta \omega \) indices are provided in Table 1.

A repeated measures design was used in which \( \omega_L \) (slow, comfort, fast) and \( \Delta \omega \) \((-2, -1, 0, 1, 2)\) variables were crossed; each of the resulting 15 experimental conditions was repeated three times for a total of 45 trials. The conditions were blocked with order of presentation randomized within each of the three blocks. An experimental session lasted approximately 90 min.

**Data reduction.** The angular excursion time series of each limb was smoothed by using a triangular moving average procedure. The frequency of oscillation of each limb and the \( \phi \) time series of the two limbs were determined by using software routines.

The time of maximum extension of each limb was calculated by using a peak picking algorithm. The frequency of oscillation was calculated using the peak extension times:

\[ f_n = \frac{1}{\text{time of peak extension}_n - \text{time of peak extension}_{n+1}}. \]  

This frequency time series was used to calculate the mean frequency of oscillation of each limb for each trial and condition. Coupled frequency of the two-limb system was calculated as the mean of the frequency of oscillation of each limb. The phase angle of each limb (\( \theta_i \)) was calculated at each sample (100/\( \omega \)) to get a time series of \( \theta_i \). The phase angle of limb \( i \) at sample \( j \) (\( \theta_{ij} \)) was calculated as

\[ \theta_{ij} = \arctan \left( \frac{x_j}{\Delta x_j} \right). \]  

where \( x_j \) is the velocity of limb \( i \) at sample \( j \) divided by mean trial frequency, and \( \Delta x_j \) is the displacement of the time series of limb \( i \) at sample \( j \) minus the average trial displacement. \( \phi \) between the right and left limbs was calculated as \( \phi_{left} - \phi_{right} \). Thus, if the right limb is ahead of the left in its cycle, \( \phi \) will be negative (\( \phi < 0 \)); if the left limb is ahead of the right in its cycle, \( \phi \) will be positive (\( \phi > 0 \)). In clapping, \( \phi \) should be near 0 rad. That is,

\[ \text{The eigenfrequency of a single hand-held pendulum can be approximated by its gravitational frequency. This requires assuming that the effective mass and length of the pendulum are equivalent to the simple pendulum mass and length of the compound pendulum (which consists of the attached mass, the dowel, and the hand).} \]
when the palms are together, the flexor muscle group of each arm is at peak flexion. For this task, relative phaseing refers to whether homologous muscle groups are extending or flexing at the same time. The \( \phi \) time series allows an evaluation of the stability of the coordination across the different conditions. This evaluation was accomplished by calculating the mean \( \phi \) and standard deviation of \( \phi \) (SD\( \phi \)) for each trial. Using graphical inspection of the \( \phi \) time series, instances in which the coordination was unstable were eliminated from certain trials before mean \( \phi \) and SD\( \phi \) were calculated. The transient portions of the trials were removed because the dynamical model predictions of steady states are being tested. Note that, because the intended \( \phi \) is 0 rad, the mean \( \phi \) is equivalent to phase lag \( \Delta \phi \).

### Results

**Frequency of oscillation.** To confirm that participants achieved the metronome-prescribed frequency of oscillation and that frequency locking between the two hands was achieved, a \( 2 \times 3 \times 5 \) analysis of variance (ANOVA) was conducted with within-subjects variables of hand, \( \omega \), and \( \Delta \omega \) on the frequency of oscillation. The only significant effect was for \( \omega \), \( F(2, 10) = 62.31, \) \( MSE = .15, p = .0001 \). For the three frequency conditions, which, averaged over participants, corresponded to metronome frequencies of 0.85 Hz, 1.34 Hz, and 2.01 Hz, the observed mean frequencies were 0.84 Hz, 1.33 Hz, and 1.97 Hz, respectively. The lack of any effect of \( \Delta \omega \) by itself, \( \Delta \omega : F(4, 20) = .60, \) or in interactions, \( \Delta \omega \times \omega : F(8, 40) = 1.38; \) \( \Delta \omega \times \text{Hand: } F(4, 20) = 1.11; \) \( \Delta \omega \times \text{Hand: } F(8, 40) = .89, \) indicates that metronome tracking was unaffected by the inertial difference between the limbs. The lack of any effect of hand alone, \( F(1, 5) = .20, \) or in interactions, \( \text{Hand} \times \omega : F(2, 10) = .90; \) \( \text{Hand} \times \Delta \omega : F(4, 20) = 1.11, \) verifies that the two limbs were oscillating at the same frequency and consequently that 1:1 frequency locking was achieved in all conditions, in support of Prediction 1 (see list of properties of a coupled-oscillator regime in the Coupled Oscillator Dynamics section).

**Relative phase.** Inspection of representative angle of excursion (\( \alpha \)) time series (Figure 2) illustrates the effect of manipulating \( \Delta \omega \) on \( \phi \). In the top panel, neither limb is weighted, and it is evident that each hand reaches peak extension and flexion at the same time, with neither limb lagging or leading. The angular position trajectories of the right and left hands are nearly coincident, indicating a nearly constant \( \phi \) of 0 rad. In the middle panel, when the right limb is loaded, the left hand achieves peak flexion and extension before the right hand. The opposite effect is demonstrated in the bottom panel when the left limb is loaded—the right hand achieves peak extension and flexion before the left hand.

A \( 3 \times 5 \) ANOVA with within-subjects variables of \( \omega \) and \( \Delta \omega \) was conducted on the mean \( \phi \) for each condition. The analysis revealed a significant main effect of \( \Delta \omega \), \( F(4, 20) = 15.99, \) \( MSE = 24.311, p = .0001 \), and a significant interaction between \( \omega \) and \( \Delta \omega \), \( F(8, 40) = 4.43, \) \( MSE = 4.96, p = .0007 \). Figure 3 (panel A) displays mean \( \phi \) across \( \Delta \omega \) at each \( \omega \). Several features of the plot and analysis speak to Predictions 2–5. First, the effect of \( \Delta \omega \) is such that when the right limb is loaded (its eigenfrequency is lower, producing positive values of \( \Delta \omega \)), it lags in phase (mean \( \phi > 0 \)) and when the left limb is loaded (its eigenfrequency is lower, producing negative values of \( \Delta \omega \)), it lags in phase (mean \( \phi < 0 \)). On average, for positive \( \Delta \omega \) the right hand lagged by 8 ms, whereas for negative \( \Delta \omega \) the left hand lagged by 12 ms. This reinforces the description of the time series in Figure 2 and supports Prediction 2. Second, as the difference between the inertial loadings of the two limbs deviates from 0, deviation of \( \phi \) from 0 rad increases, in...
DYNAMICS OF CLAPPING

Figure 3. The change in mean $\phi$ (A) and $SD\phi$ (B) as a function of $\Delta \omega$ and $\omega_c$ in Experiment 1.

To further bolster our claims regarding the appropriateness of the coupled oscillator model, we estimated the fit of the dynamical model to the data by regressing $\Delta \omega$ on $\sin(\phi)$. As suggested by Schmidt and Turvey (1995), the $r^2$ is a measure of the fit of the data to the dynamical model, whereas the slope of such regressions estimates the coupling strength of the dynamic. We conducted analyses separately on the data of the three frequencies. Results indicate that the model is significant for all three frequencies, with resulting $r^2$ of .35, $F(1, 28) = 14.82, MSE = 1.40, p < .01$; .52, $F(1, 28) = 30.05, MSE = 1.03, p < .01$; and .66, $F(1, 28) = 54.24, MSE = .73, p < .01$, for slow, comfort, and fast, respectively. The slopes of the regressions indicate a tendency for coupling to decrease with increasing frequency as predicted: 12.03 for slow, 9.57 for comfort, and 9.48 for fast (where higher slopes indicate stronger coupling).

Variability of $\phi$. A $3 \times 5$ ANOVA with the same design as earlier was conducted on $SD\phi$, revealing significant main effects of both $\omega_c$ and $\Delta \omega$, $F(2, 10) = 5.67, MSE = .003, p < .05$, and $F(4, 20) = 4.89, MSE = .003, p < .01$, respectively. The interaction of $\omega_c$ and $\Delta \omega$ revealed a trend toward significance, $F(8, 40) = 1.92, MSE = .0004, p = .08$. As Figure 3 (panel B) shows, variability in $\phi$ increases both with increasing positive and negative deviation of $\Delta \omega$ from 0 and with increasing $\omega_c$ in support of Predictions 6 and 7, respectively.

Discussion

Each of seven very specific predictions about the behavior of the order parameter $\phi$, derived from Equation 4, were affirmed in this examination of a naturally occurring rhythmic behavior involving limb contact. The results of Experiment 1 indicate that a coupled oscillator regime is appropriate for modeling the coordination of the two limbs in clapping. Finding these properties in a behavior that involves an inelastic (i.e., dissipative) collision reinforces the usefulness of the dynamical perspective for understanding an even broader class of coordinations, that is, rhythmic coordinations that involve surface contact as well as those that do not. The instantaneous loss of energy at hand contact appears not to matter to the dynamic. To say that a coupled oscillator is used in coordination, then, is to say that control of the rhythmically moving limbs is relegated to a dynamical control structure: The coordination does not require constant control and intervention on the part of the actor. Moreover, this is as true of a naturally occurring rhythmic behavior in which the limbs collide as of laboratory idealizations in which no limb or surface contact occurs.

Experiment 2

A major theme of research on the self-assembly of rhythmic movement is that the oscillations are coupled perceptually (Kugler & Turvey, 1987; Schmidt et al., 1990, 1994). That is to say, their interaction is not dictated by a mechanical coupling—oscillating one limb does not necessarily
cause the other limb to oscillate—but, rather, is permitted by an informational coupling. In within-person coupled oscillator tasks, information is available primarily through deformation of the tissues of the hands and forearms (participants are typically instructed to look ahead rather than at the pendulums). In their between-persons counterparts (Amazeen et al., 1995; Schmidt et al., 1990, 1994; Schmidt & Turvey, 1994), information about one’s own limb is still haptic but information about the other person’s limb is optic. Clapping has available haptic and optic information to specify the ongoing movements of both limbs, together with cutaneous and acoustic information from the contact between the hands, to specify when the limbs are at an important control point in their cycles. The fact that the smooth rhythmicity of clapping is punctuated by a collision seems, so far, not to matter to the dynamic: As seen in Experiment 1, inertial loading of one or the other limb produced relative phase lags and variability as expected from Equation 4.

Even with what might be considered a disruption of rhythmicity, the properties of clapping seem not to differ from the properties of other rhythmic behaviors whose phase-locking behavior has been investigated to date. To buttress this conclusion, we compared clapping with and without contact directly so that we could assess the contribution of the collision to the oscillatory dynamic. When the hands do not collide, there is no cutaneous or acoustic information about limb phasing; haptic and optic information remain. At issue is whether eliminating the collision strengthens the coupling (e.g., by eliminating an extracortical layer) or weakens the coupling (e.g., by eliminating information specific to the control point at peak flexion).

Method

Participants. Five undergraduates at Tulane University participated as partial fulfillment of a course requirement. One was male and 4 were female; all participants were right-handed.

Materials and apparatus. The same wrist weights and data acquisition system from Experiment 1 were used.

Design and procedure. Some modifications of Experiment 1 were introduced. Participants were instructed to clap in one of two styles: (a) clapping with contact, the constrained clapping described in Experiment 1 in which the hands contact in a normal clapping manner; or (b) clapping without contact, a similarly constrained style of clapping (upper arm relatively immobile, forearm parallel to the ground, fingertips facing forward) in which the hands are brought approximately to midline but do not actually contact. Three preset metronome frequencies were chosen on the basis of the results of Experiment 1: slow (0.88 Hz), moderate (1.40 Hz), and fast (2.09 Hz). The moderate frequency was within the \( \omega_{\text{comfort}} \) range of Experiment 1. Experimentally determined comfort modes were not obtained so as to keep the length of the experiment reasonable. The same five \( \Delta \omega \) conditions as in Experiment 1 were used.

A repeated measures design was used in which clapping style (contact, no contact), \( \omega_{\text{c}} \) (slow, moderate, fast), and \( \Delta \omega \) (\(-2, -1, 0, 1, 2\)) were crossed for a total of 30 experimental conditions, with each repeated twice for a total of 60 trials. Clapping style was blocked, with half of the participants commencing with contact trials and half with no-contact trials. Each experimental condition occurred once before being repeated; order of presentation of conditions was randomized within each block. The experimental session lasted approximately 90 min.

Data reduction. The coupled frequency of oscillation and relative phase \( \phi \) measures were obtained as in Experiment 1.

Results

Frequency of oscillation. How well the participants achieved the metronome-prescribed frequency of oscillation and 1:1 frequency locking was evaluated in a 2 \( \times \) 3 \( \times \) 5 ANOVA with within-subjects variables of hand, clapping style, \( \omega_{\text{c}} \), and \( \Delta \omega \) and dependent variable of mean observed frequency of oscillation. Although the effect of clapping style was significant, \( F(1, 4) = 7.28, MSE = .00002, p < .05 \), with a tendency to clap slightly faster when the limbs do not contact (\( M = 1.431 \)) than when they do (\( M = 1.430 \)), the actual magnitude of the difference is less than 1 ms and consequently the import of this effect is questionable. The effect of \( \omega_{\text{c}} \), \( F(2, 8) = 7.63889 \), MSE = .005, \( p < .001 \), demonstrated that the observed frequency (0.87 Hz, 1.37 Hz, and 2.06 Hz) tracked the slow, moderate, and fast metronome frequencies (0.88 Hz, 1.40 Hz, and 2.09 Hz, respectively). The lack of any significant \( \Delta \omega \) effects reveals that metronome tracking was unaffected by the inertial difference between the limbs (with observed frequencies of 1.43 Hz for all \( \Delta \omega \) conditions). Moreover, no significant effects of hand were found, verifying that the two limbs oscillated at the same frequency (mean left = 1.43 Hz, mean right = 1.43 Hz). In other words, 1:1 frequency locking was achieved for all conditions in support of Prediction 1.

Relative phase. A 2 \( \times \) 3 \( \times \) 5 ANOVA with within-subjects variables of clapping style, \( \omega_{\text{c}} \), and \( \Delta \omega \) was performed on mean \( \phi \). The analysis revealed a significant main effect of \( \Delta \omega \), \( F(4, 16) = 30.41, MSE = .005, p < .001 \), and a significant interaction between \( \omega_{\text{c}} \) and \( \Delta \omega \), \( F(8, 32) = 4.75, MSE = .001, p < .001 \). The effect of \( \Delta \omega \) is such that the weighted oscillator lags in the cycle (Prediction 2): For negative \( \Delta \omega \) the left hand lagged by 11 ms, whereas for positive \( \Delta \omega \) the right hand lagged by 4 ms. As shown in Figure 4 (top), deviation of \( \phi \) from 0 rad increases as \( \Delta \omega \) deviates from 0, supporting Prediction 3, and this is amplified with increasing \( \omega_{\text{c}} \), supporting Prediction 4.

Note that when \( \Delta \omega = 0 \), the values of \( \phi \) are twice as far removed from 0 rad as in Experiment 1 (\( \phi = -0.039 \) presently vs. \( \phi = -0.020 \) in Experiment 1). This observation is unexpected from Prediction 3 and is related to a marginal effect of clapping style, \( F(1, 4) = 5.89, MSE = .009, p = .07 \). There is a tendency for the left hand to lag more when the hands do not contact (\( \phi = -0.057 \) rad) than when they do (\( \phi = -0.019 \) rad). Regressions of \( \phi \) on \( \Delta \omega \) for each \( \omega_{\text{c}} \) condition revealed that the \( \Delta \omega = 0 \) intercept magnitudes were not significantly different from 0 for any \( \omega_{\text{c}} \) in the contact condition (\( p > .05 \)). However, identical regressions performed for the no-contact condition found that the intercept was significantly different from zero (\( p < .05 \)) for all three \( \omega_{\text{c}} \) (\(-0.034, -0.068, \) and \(-0.069 \)) for slow, moderate,
and fast, respectively. The deviations from $\phi = 0$ at $\Delta \omega = 0$ that are apparent in Figure 4 (panel A) are a consequence of the no-contact condition. Prediction 5, therefore, seems to hold for the contact condition but not for the no-contact condition.

Regression of $\Delta \omega$ on $\sin(\phi)$, estimating the fit of the dynamical model to the data (Schmidt & Turvey, 1995) were conducted separately on the data from the three frequencies for both contact and no-contact conditions. Results indicate that a significant fit of the model for all three frequencies in the contact condition with resulting $r^2$ of .39, $F(1, 23) = 14.50, MSE = 1.33, p < .01$; .29, $F(1, 23) = 9.60, MSE = 1.53, p < .01$; and .54, $F(1, 23) = 26.54, MSE = 1.01, p < .01$, for slow, moderate, and fast, respectively. In a similar manner, the $\sin(\phi)$ model was appropriate for the no-contact conditions: $r^2 = .40, F(1, 23) = 15.65, MSE = 1.29, p < .01$, for slow; $r^2 = .42, F(1, 23) = 16.87, MSE = 1.25, p < .01$, for moderate; and $r^2 = .55, F(1, 23) = 28.22, MSE = .98, p < .01$, for fast. The estimated coupling strengths from the above regressions were 12.51, 8.58, and 8.67, for the slow, moderate, and fast contact conditions, respectively, and 13.12, 10.58, and 9.79, for the slow, moderate, and fast no-contact conditions, respectively, once again indicating a tendency for the coupling strength to decrease with increasing frequency as expected.

Variability of $\phi$. A $2 \times 3 \times 5$ ANOVA with the same design as before was conducted on $SD\phi$. The results displayed in Figure 4 (bottom) are very similar to those obtained in Experiment 1. The main effect of $\Delta \omega$, $F(4, 16) = .54, MSE = .0013, p < .001$, supports Prediction 6 in that variability increased with increasing deviation of $\Delta \omega$ from 0. However, a significant interaction between clapping style and $\Delta \omega$, $F(4, 16) = 4.79, MSE = .001, p < .01$, reveals that the U-shaped increase with $\Delta \omega$ was much greater in the contact (.233, .205, .151, .171, .190 rad) than in the no-contact condition (.143, .143, .128, .132, .130 rad). The main effect of $\omega_c, F(2, 8) = 43.29, MSE = .0012, p < .001$, supports Prediction 7 in showing increased variability with increased tempo (.134, .154, and .199 rad for slow, moderate, and fast, respectively). None of the interactions with $\omega_c$ were significant.

Discussion

In clapping without contact, the left hand tends to lag more: $\Delta \phi$ is significantly negative even at $\Delta \omega = 0$ for which no lag is predicted. This kind of pattern has, in fact, been observed before in a hand-held pendulum task and was interpreted as an indication of the functional asymmetry of the body (cf. Treffner & Turvey, 1995, in press). In that study, $\phi$ and the variability of $\phi$ were found to be affected systematically by the handedness of the participants, with right-handers producing the kind of pattern we see here. Treffner and Turvey (1995, in press) proposed an elaboration of the coupled oscillator model of rhythmic movement to include an asymmetric coupling term in addition to the symmetric coupling term:

$$
\dot{\phi} = \Delta \omega - a \sin(\phi) - 2b \sin(2\phi) - c \cos(\phi) - 2d \cos(2\phi) + \sqrt{Q} \xi. \quad (8)
$$

The terms of Equation 5 that are the same as terms in Equation 4 define the fundamental coordination dynamics; the additional terms break the symmetry of the dynamics. The magnitudes of the coefficients $c$ and $d$ are assumed to

![Figure 4](image_url). The change in mean $\phi$ (A) and $SD\phi$ (B) as a function of $\Delta \omega$ and $\omega_c$ in Experiment 2. Note the decrease in the $\Delta \omega = 0$ intercept values compared with Experiment 1 (Figure 3) due to the no-contact condition.
be small relative to \( a \) and \( b \) and, therefore, the contribution of the asymmetric coupling term may not always be readily apparent. The intuitive interpretation of our results in terms of this equation is that contact in clapping decreases the magnitude of the asymmetric coupling terms and, consequently, the functional asymmetry of the body is less apparent when contact is made. Hence, we speculate that the collision more or less enforces the symmetry of the behavior. When the hands do not collide, the functional asymmetry is more apparent.

In addition, a numerical analysis of Equation 8 reveals that the influence of the asymmetric coupling term at \( \Delta \omega = 0 \) can be exaggerated by decreasing the coupling strength \( b/a \) of the symmetric part of Equation 8 (Treffner & Turvey, in press). As previously noted, this weakening of the coupling (i.e., decreasing \( b/a \)) can be implemented by increasing \( \omega_c \) (Haken et al., 1985; Schmidt et al., 1993). It is interesting that, for clapping without contact, we found that \( \phi \) at \( \Delta \omega = 0 \) becomes increasingly negative with increases in \( \omega_c \) (\(-.033, -.068, \) and \(-.069 \) for slow, moderate, and fast clapping, respectively). Using the magnitudes of \( a, c, \) and \( d \) used by Treffner and Turvey (1995) in their modeling of pendulum data for right-handers (namely, \(.5, 0, \) and \(.05, \) respectively), and decreasing the \( b/a \) ratio by decreasing \( b \) (\(.75, .30, .20 \)), \( \phi \) at \( \Delta \omega = 0 \) becomes increasingly negative (\(-.025, -.055, -.075 \) rad) is quite similar to the intercept magnitudes we observed. For clapping with contact, we found that \( \phi \) at \( \Delta \omega = 0 \) was less negative than for no contact (\(-.004, -.029, \) and \(-.028 \) rad) and not significantly different from 0 for all three \( \omega_c \)'s. On the assumption that contact decreases the influence of the asymmetric portion of Equation 8, the foregoing simulation was repeated with the same \( b/a \) ratios but with a decreased magnitude of \( d \) (e.g., \( d = .025 \)). Calculated \( \phi \) values at \( \Delta \omega = 0 \) were in the range found for clapping with contact (\(-.015, -.025, -.035 \)). In summary, Equation 8 can model the mean \( \phi \) results of this experiment if one assumes that (a) \( \omega_c \) modulates \( b/a \), and (b) contact during clapping modulates the magnitude of the functional asymmetry term \( d \).

Although both clapping with contact and clapping with no contact confirmed Prediction 6, \( SD\phi \) for no contact is greatly suppressed. The greater variability of the contact conditions means either that the coordination dynamics in this condition are weaker (\( b/a \) is smaller) or that there is more noise in the system. There is no evidence for the former. If the dynamic assembled was stronger for no-contact conditions, then the rate of change of mean \( \phi \) with \( \Delta \omega \) should be less for no contact than contact. A multiple regression analysis of mean \( \phi \) on \( \Delta \omega, \omega_c \), category, and clapping style revealed no significant difference between the \( \phi-\Delta \omega \) slopes for the contact and no-contact conditions (\( p > .05 \)). Examination of relative phase time series reveals that the collision in the contact condition increases the noise inherent in the measurement of \( \phi \) (Figure 5, panel A) in support of the second alternative. Note also that the spike that identifies the collision functions as a perturbation to the relative phasing: The time series of \( \phi \) continues after the collision along the same trajectory as before the perturbation. Hence, the collision seems neither to add energy to the rhythmic cycles nor to function as a forcing of the oscillation. In summary, \( SD\phi \) increased in the contact condition because the collision functions as a perturbation to the coordination, adds noise to the time series of \( \phi \), and, hence, increases its variability. There is no evidence that the symmetric part of the dynamic (Equation 4) is weaker in the contact condition.

The overall decrease of \( \Delta \phi \) in the contact condition can be interpreted as improving the accuracy of the coordination. If the collision makes available more information about a particularly important point of interlimb phasing, then it is not unreasonable to expect more accurate and less variable coordination with contact. If, in contrast, the collision disrupts the rhythmicity, then less accurate and more variable coordination might be expected with contact. However, in fact, the obtained pattern was more accurate and more variable. This pair of features may result from the contact having informational value while simultaneously a perturbation to the coordination.

Experiment 3

Clapping without contact eliminated the collision and its attendant cutaneous and acoustic consequences. However, it did not eliminate all extramuscular information about the phasing of the limbs because vision was not occluded. If the availability of optic information in both conditions enforced a similarity between the two styles of clapping by allowing continuous tuning of the rhythmic behavior, then its elimination should heighten the differences that were obtained in Experiment 2. An alternative, less intuitive possibility, is that the availability of optic information actually served to strengthen the functional asymmetry of the body so that its elimination should reduce the differences that were obtained in Experiment 2. Reasoning strictly from the pattern of data, because clapping without contact was under visual control and this style of clapping was more asymmetric, then visual control was responsible for the asymmetry. Removing the opportunity for visual guidance, therefore, should make the task more symmetric.

In this experiment, clapping without contact was limited strictly to haptic information. This was compared with clapping with contact, in which information about limb phasing was available through haptic, cutaneous, visual, and auditory perceptual systems.

Method

Participants. Six undergraduates (1 man and 5 women) at Tulane University participated in partial fulfillment of a course requirement. The data of one participant, a left-hander who had overlooked the recruiting restriction, were eliminated from the overall analysis.

Materials and apparatus. The same wrist weights and data acquisition system from the previous experiments were used.

Design and procedure. One modification was made to the procedure of Experiment 2: The no-contact condition was con-
ducted without optic information. This was achieved by having participants wear occluding goggles. The same three preset metronome frequencies as in Experiment 2 were used (slow = .88 Hz, moderate = 1.40 Hz, and fast = 2.09 Hz) as well as the same five Δφ conditions. In all other respects (e.g., the clapping style instruction), the procedure was the same as that of Experiment 2.

**Figure 5.** Representative position and φ time series for the contact (top) and no-contact (bottom) conditions. Note that the spikes in the contact plot indicate the point of hand collision within a cycle.
Data reduction. The coupled frequency of oscillation and relative phase $\phi$ were obtained as in the previous experiments.

Results

Frequency of oscillation. Confirmation that participants achieved the metronome-prescribed $\omega_c$ was obtained in a $2 \times 2 \times 3 \times 5$ ANOVA with within-subjects variables of hand, clapping style, $\omega_c$, and $\Delta \omega$, performed on the mean observed frequency of oscillation. The only significant effect was for $\omega_c$, $F(2, 8) > 10,000.00$, $MSE < .0001$, $p < .0001$. Mean $\omega_c$ at each metronome frequency was constant across $\Delta \omega$, with observed mean values for the slow, moderate, and fast conditions (.87 Hz, 1.36 Hz, and 2.07 Hz, respectively) approximating the metronome-specified values and indicating that participants accomplished the task. The lack of any significant $\Delta \omega$ effects reveals that metronome tracking was unaffected by the inertial difference between the limbs (mean $\omega_c = 1.43$ Hz for all $\Delta \omega$). Furthermore, lack of any effects of the variable of hand verifies that the two limbs were oscillating at the same frequency (left = 1.43 Hz, right = 1.43 Hz) and, consequently, that 1:1 frequency locking was achieved in all conditions in support of Prediction 1.

Relative phase. A $2 \times 3 \times 5$ ANOVA with within-subjects variables of clapping style, $\omega_c$, and $\Delta \omega$ was performed on mean $\phi$ for each condition. The analysis revealed a significant main effect of $\Delta \omega$, $F(4, 16) = 40.62$, $MSE = .008$, $p < .0001$, and a significant interaction between $\omega_c$ and $\Delta \omega$, $F(8, 32) = 7.67$, $MSE = .003$, $p < .0001$. Supporting Prediction 2, the effect of $\Delta \omega$ was such that the limb with the greater inertia lagged (the left hand lagged by 13 ms for $-\Delta \omega$; the right hand lagged by 9 ms for $+\Delta \omega$). Furthermore, as seen in Figure 6 (panel A), increasing $\Delta \omega$ is accompanied by increasing deviation of $\phi$ from 0, supporting Prediction 3. Also apparent in Figure 6 (panel A) is the interaction: The effect of $\Delta \omega$ is amplified with increasing $\omega_c$, supporting Prediction 4.

The ANOVA yielded no significant effects of clapping style. Note that the magnitudes of $\phi$ when $\Delta \omega = 0$ are more comparable with those of Experiment 1 than Experiment 2 and not far removed from 0 rad. Following the analyses conducted in Experiment 2, regressions of $\phi$ on $\Delta \omega$ for the contact condition revealed that the $\Delta \omega = 0$ intercepts were not significantly different from zero for any of the $\omega_c$ conditions ($p > .05$). However, these regressions for the no-contact condition revealed that the intercept was significantly different from zero ($p < .05$) for the slow and moderate tempos ($-.037$ rad and $-.060$ rad, respectively) but not the fast tempo (.010 rad). Although clapping style itself did not reach significance, the $\phi - \Delta \omega$ regressions again suggest that Prediction 5 holds for the contact condition but not for the no-contact condition (at least not uniformly), echoing the broken symmetry interpretation of Experiment 2.

Regressions of $\Delta \omega$ on $\sin(\phi)$, estimating the fit of the dynamical model to the data, were conducted separately on the data from the three frequencies for both contact and no-contact conditions. Results indicate a significant fit of the model for all three frequencies in the contact condition, with resulting $r^2$ of .49, $F(1, 23) = 24.43$, $MSE = 1.11$, $p < .01$; .69, $F(1, 23) = 51.0$, $MSE = .68$, $p < .01$; and .73, $F(1, 23) = 63.43$, $MSE = .58$, $p < .01$, for slow, moderate, and fast, respectively. In a similar manner, the $\sin(\phi)$ model was appropriate for the no-contact conditions: $r^2 = .43, F(1, 23) = 17.41, MSE = 1.24, p < .01$, for slow; $r^2 = .62, F(1, 23) = 37.72, MSE = .82, p < .01$, for moderate; and $r^2 = .68, F(1, 23) = 49.65, MSE = .69, p < .01$, for fast. The estimated coupling strengths from the above regressions...
were 14.70, 10.63, and 7.96 for the slow, moderate, and fast contact conditions, respectively, and 11.86, 10.06, and 7.64 for the slow, moderate, and fast no-contact conditions, respectively, indicating a tendency for coupling strength to decrease with increasing frequency as predicted.

Variability of $\phi$. A $2 \times 3 \times 5$ ANOVA with the same design as before was conducted on $SD\phi$. This analysis revealed significant main effects of clapping style, $F(1, 4) = 7.91, \ MSE = .008, p < .05; \omega_c, F(2, 8) = 9.42, \ MSE = .004, p < .01; \text{and } \Delta \omega, F(4, 16) = 20.04, \ MSE = .0007, p < .001$, respectively. The main effect of clapping style reveals that, as in Experiment 2, variability was greater when the hands contacted than when they did not (.205 and .166 rad, respectively). Figure 6 (panel B) displays the main effects of $\omega_c$ and $\Delta \omega$. The main effect of $\Delta \omega$ reveals that variability increased with deviation of $\Delta \omega$ from zero (.209, .185, .152, .182, .199 rad for the five conditions, respectively), suggesting that $\Delta \omega$ affected the variability of $\phi$ in the contact and no-contact conditions more uniformly than in Experiment 2. Furthermore, as the bottom of Figure 6 suggests, there was also a marginally significant interaction between $\omega_c$ and $\Delta \omega$, $F(8, 32) = 2.81, \ MSE = .002, p = .06$, suggesting that $\Delta \omega$ affected the variability of $\phi$ in the no-contact conditions more uniformly as a function of $\omega_c$. Variability is greater than for $\Delta \omega > 0$.

Discussion

As in Experiment 2, $\phi$ tended to deviate from zero at $\Delta \omega = 0$ when the hands did not contact. As before, we take this to suggest that the functional asymmetry of the body is more apparent in clapping without contact than clapping with contact. The removal of visual guidance from the no-contact condition did not exaggerate these effects as would have been expected if removing the visual information weakened the symmetric coupling. For mean $\phi$, clapping style did not reach significance, although numerical differences were generally in the same direction as they had been in Experiment 2 (the one left-hander removed from the data set tended to lead with the left, consistent with the results of Treffner & Turvey, 1995). If anything, the asymmetric coupling term was weaker without contact or vision than it had been without contact but with vision. This provides tentative support for the involvement of optic information in the kind of fine-grained perceptual tuning that amplifies functional asymmetry. One rationale for this interpretation comes from observations that hand preferences are more apparent in behaviors that are guided visually (Bryden & Steenhuis, 1987; MacNeillage, Studdert-Kennedy, & Lindblom, 1987). Important for present purposes, this appears to be so, even for tasks that are not inherently complex (MacNeillage et al., 1987).

In Experiment 2, the $SD\phi$ difference between the contact and no-contact conditions was ascribed to noise present in the contact conditions rather than to a putatively weaker coordination dynamic during the contact condition. In Experiment 3, the $SD\phi$ difference between contact and no-contact persisted but was smaller. This change was due to an increase in the no-contact $SD$ from Experiment 2 to Experiment 3 (.135 and .166 rad, respectively); contact $SD$ was fairly constant (.190 and .205 rad for Experiments 2 and 3, respectively). The major difference between these experiments was the lack of visual information in Experiment 3’s no-contact condition. Once again, one can assess whether the increase in variability stems from a weakening of the coordination dynamics or an increase in noise. As before, the former was tested by comparing the slopes of corresponding $\phi-\Delta \omega$ regressions, this time for the no-contact conditions in Experiments 2 and 3. If the elimination of the visual information weakened the dynamics, then a greater slope would be expected in Experiment 3. The regression analysis revealed a significantly greater $\phi-\Delta \omega$ slope for Experiment 3 than Experiment 2 (.06 vs. .04, $p < .01$), indicating that the increase in $SD\phi$ as a consequence of the elimination of the visual information arose from a weakening of the assembled coordination dynamics (decreasing $\theta$).

Overall, Experiments 1 through 3 reveal that, to coordinate the two limbs in clapping, individuals assemble the limbs into a system of coupled oscillators: Scaling $\omega_c$ and $\Delta \omega$ affect observed coupled frequency, mean $\phi$, and variability in $\phi$ in accord with predictions from the elementary coordination dynamics of Equation 4 or its elaboration in Equation 8. Taken together with previous research on the in-phase coordination of hand-held pendulums (e.g., Kugler & Turvey, 1987), interlimb coordination of leg segments (e.g., Schmidt et al., 1990), and bimanual index finger oscillation (e.g., Kelso, 1984), our results highlight the generality of coupled oscillator dynamics in performing interlimb coordinations: The same dynamic is implicated regardless of the limb segments being coordinated or the point of oscillation (i.e., knuckle, wrist, elbow, knee). Moreover, both oscillations in which the influence of gravity is constant throughout the cycle (forearms) and oscillations in which gravity plays a significant role (pendulums, legs) respond the same way to manipulations of $\Delta \omega$ and $\omega_c$. The data from Experiments 2 and 3 suggest the intriguing possibility that the assembled oscillatory regime can be modified by information. In particular, the hand collision seems to be important in overcoming the functional asymmetry of the body, whereas visual feedback heightens the asymmetry and increases the strength of the dynamic in no-contact clapping.

Experiment 4

The rhythmic pattern in which two limbs or limb segments move at the same frequency is basic to very many everyday activities. It has been argued that the coupled oscillator regime is essentially the only coordination option
for achieving such a pattern: It is the elementary coordination dynamics (Kelso, 1994). A corollary is the bold hypothesis that this regime, as instantiated in Equation 4, does not care about the details of the coordination: what kinds of units are oscillating, the plane of oscillation, what kind of information is guiding the phasing, whether the units are colliding, and so on. To put it more cautiously, to the extent that task parameters affect the coordination, there must be a place for them in Equation 4, in particular as influences on $\Delta \omega$ or $bla$. We have already seen this demand satisfied by the elaboration of the order parameter equation to include the functional asymmetry of the body in Equation 8. The foregoing experiments have found that this asymmetry becomes exaggerated in rhythmic clapping when the contact between the hands is eliminated and that this asymmetry tends to increase as the symmetric coupling becomes weaker.

Experimental results (Haken et al., 1985; Schmidt et al., 1993; Sternad et al., 1992) have demonstrated that the coupling strength $bla$ of the symmetric term is inversely related to the driving frequency $\omega_c$. The relationship between $bla$ and $\omega_c$ means that the faster the oscillation, the weaker are the attractors at 0 and $\pi$. In the first three experiments, frequency did not exceed 2.1 Hz. However, clapping can naturally occur at much faster tempos. One study found clapping tempos ranging from 2.7 to 5.1 Hz with an average of 4.0 Hz under instructions to clap "as you would normally clap after an average concert" (Repp, 1987, p. 1101). To date, the coupled oscillator regime has not been examined experimentally at such high frequencies. In this experiment, we explore constrained clapping with contact at frequencies between 1 and 4 Hz, with the upper limit chosen to keep hand excursions in the range that would be encountered in natural applause (Repp, 1987). Given that these frequencies permit ordinary "successful" clapping, the predictions from Equation 4 should be substantiated. However, as is apparent in Treffner and Turvey (in press), when the symmetric coupling part of Equation 8 is weakened by increases in $\omega_c$, the effect of handedness on $\Delta \omega$ is increased. Of interest in our experiment is whether increasing $\omega_c$ to such high frequencies will weaken the symmetric coupling term sufficiently such that the functional asymmetry of the body appears in clapping with contact. If so, mean $\phi$ should depart from zero at $\Delta \omega = 0$, in accord with Equation 8.

Method

Participants. Four participants volunteered for the experiment. One was a faculty member at Tulane University and 3 were graduate students. All participants were right-handed (3 men and 1 woman).

Materials. Only the .90 kg masses were used.

Apparatus. The data acquisition arrangement was the same as in Experiment 1.

Design and procedure. Participants were instructed to clap as in Experiment 1. Four preset metronome frequencies (1, 2, 3, and 4 Hz) were crossed with three $Aw$ conditions ($-2$, 0, and 2) with one repetition. Order of presentation of conditions was randomized within each block. The experimental session lasted approximately 30 min.

Data reduction. The coupled frequency of oscillation and relative phase $\phi$ were obtained as in the previous experiments.

Results

Frequency of oscillation. As in the previous experiments, how well the participants achieved the metronome-prescribed frequency of oscillation and 1:1 frequency locking was evaluated in a $2 \times 4 \times 3$ ANOVA with within-subjects variables of hand, $\omega_c$, and $\Delta \omega$ conducted on the mean observed frequency of oscillation. A significant main effect was obtained for $\omega_c$, $F(3, 9) = 1,130.80$, $MSE = .033$, $p < .001$. Mean observed $\omega_c$ for the four frequencies approximated the metronome-prescribed frequencies (0.99, 1.94, 3.01, and 3.83 Hz for the 1 through 4 Hz conditions, respectively), confirming that participants did indeed track the preset metronome frequencies. As in previous experiments, no significant effects of hand or $\Delta \omega$ were found, indicating that 1:1 frequency locking was obtained for all three metronome frequencies across $\Delta \omega$ in support of Prediction 1.

Relative phase. A $4 \times 3$ ANOVA with within-subjects variables of $\omega_c$ and $\Delta \omega$ was conducted on mean $\phi$. The analysis revealed a significant main effect of $\Delta \omega$ only, $F(2, 6) = 6.76$, $MSE = .029$, $p < .05$. The significance of this effect, as in the previous experiments, supports Prediction 2: the limb with the greater inertia lagged (the left hand lagged by 8 ms for $-\Delta \omega$; the right hand lagged by 6 ms for $+\Delta \omega$). It also supports Prediction 3 in that increasing the difference in the inertial loadings of the two limbs is accompanied by increasing deviation of $\phi$ from 0 rad. As can be observed in Figure 7 (panel A), this effect is amplified with increasing $\omega_c$, supporting Prediction 4. However, this amplification was not significant, $\omega_c \times \Delta \omega$: $F(6, 18) = 1.60$, $MSE = .009$, $p = .20$. Underlying the lack of significance may be increased variability. The average standard deviation for the means in Figure 7 (panel A) was .13 rad, whereas for previous experiments the standard deviations were half of this value (approximately .07 rad for Experiments 1–3). This increase in variability may be due to fewer observations per condition or the increased $\omega_c$ magnitudes, or both. As expected for clapping with contact, regressions of $\phi$ on $\Delta \omega$ performed for each $\omega_c$ condition indicated that at $\Delta \omega = 0$, $\phi$ is not significantly different from zero for any of the frequency conditions. These findings corroborate the results of the contact clapping conditions of the previous experiments that are supportive of Prediction 5.

Regressions of $\Delta \omega$ on $\sin(\phi)$ were performed separately on the data from the four frequencies to estimate the fit of the dynamical model to the data. A significant fit of the model was found for three of the four frequency conditions:

The collision in clapping is incidental to the oscillation of the limbs in the sense that it does not force the oscillation. In another task, the collision may be physically crucial. For example, when a paddle pendulum is used to bat a tethered ball pendulum, the collision keeps the oscillation going. The equation is adjusted appropriately for this physical fact, but the essential details remain the same (Sim, Shaw, & Turvey, in press).
Figure 7. The change in mean $\phi$ (A) and $SD\phi$ (B) as a function of $\Delta\omega$ and $\omega_c$ in Experiment 4.

Discussion

The dynamical model of rhythmic coordination proposed by Haken et al. (1985) maintains that increasing the control parameter $\omega_c$ decreases the strength of the coupling as indexed by the ratio of the coupling coefficients $b/a$. In this experiment, the values of $\omega_c$ were relatively high compared with the previous experiments but not high with respect to natural clapping frequencies. The model predicts that a weakening of the oscillatory dynamic will be accompanied by an increase in the rate of change of mean $\phi$ with $\Delta\omega$ and an amplification of $SD\phi$ at all $\Delta\omega$. The present experimental results affirm these predictions. Furthermore, the model predicts that the magnitudes of mean $\Delta\phi$ and $SD\phi$ should be greater than those in the previous experiments. The mean $SD\phi$ across conditions (.36 rad) are twice as large as in Experiments 1 through 3 (.16, .19, and .21 rad in the contact conditions, respectively). However, the absolute mean $\phi$ across $\Delta\omega$ ($|\phi|$ = .086), though numerically greater than the other experiments (.067, .056, .080 rad, respectively), is in the same basic range. This dissociation of mean $\phi$ and $SD\phi$ magnitudes is not predicted by the model. It is possible that the contact in clapping limits the range of possible mean $\phi$ by enforcing an enhanced accuracy. The continual weakening of the dynamic under scaling $\omega_c$ is apparent, however, in the increase of the $SD\phi$.

Of interest in this experiment was whether the weakening of the symmetric coupling component of Equation 8 caused by extreme values of $\omega_c$ would increase the effect of the bodily asymmetry in spite of the hand contact. In brief, in spite of the high $\omega_c$ and the weakening of the regime, the estimated values of mean $\phi$ at $\Delta\omega = 0$ at all $\omega_c$ were not significantly different from zero, indicating that the bodily asymmetry did not become apparent with regime weakening. Hence, the accuracy enforced by the contact overcomes the functional asymmetry of the body even at high $\omega_c$ conditions in which the bodily asymmetry should be more easily revealed.

General Discussion

The results of these experiments indicate that a coupled oscillatory regime is a viable model of interlimb phasing in a naturally occurring rhythmic behavior involving contact between limb surfaces—clapping. In replicating previous research findings from more idealized laboratory tasks that did not involve surface compliance, these experiments reveal properties of $\phi$ as predicted from the coupled oscillator...
model of Equation 4. Namely, even though both limbs are oscillating at the same frequency, \( \phi \) and its variability are affected in highly predictable ways by \( \Delta \omega \) and \( \omega_c \). Figures 3, 4, 6, and 7 explicitly affirm Predictions 2 through 7. This evidence suggests that the control of clapping is relegated to a dynamical control structure that requires little attention or intervention on the part of the actor. It is a self-organizing process that abides by order parameter dynamics.

**Functional Asymmetry of the Body**

Interesting to note is that one prediction—Prediction 5—was not confirmed for all conditions. For all of the contact conditions, it was confirmed: \( \phi \) was not significantly different from zero when \( \Delta \omega = 0 \). For five of the six no-contact conditions, however, \( \phi \) was significantly different from zero when \( \Delta \omega = 0 \). As observed in Tables 2 and 3, which summarize the \( \Delta \omega = 0 \) intercepts for the contact and no-contact conditions averaged across \( \omega_c \) conditions, the intercepts tended to be more negative when no contact was used in clapping. Treffner and Turvey (1995, in press) found that handedness influenced the departure of \( \phi \) from 0 when \( \Delta \omega = 0 \). They found negative values for right-handers and positive values for left-handers, indicating that the dominant hand leads within the cycle. The negative \( \Delta \omega = 0 \) intercept values observed in 17 of the 18 conditions of the present experiments corroborate the past finding for right-handers. This tendency for the right hand to lead was exaggerated in the no-contact conditions, reaching significance at \( \Delta \omega = 0 \) only in these conditions.

Additional evidence for the functional asymmetry of the body has been found in the patternning of mean \( \phi \) at \( \Delta \omega \neq 0 \) and \( SD\phi \) (Treffner & Turvey, 1995): When the preferred hand has the higher eigenfrequency (\( -\Delta \omega \) for right-handers, \( +\Delta \omega \) for left-handers), subjects exhibit greater \( \Delta \phi \) and greater \( SD\phi \). These measures are presented in Tables 2 and 3 for the contact and no-contact conditions of Experiments 1 through 4, respectively. Across both tables, \( \Delta \phi \) and \( SD\phi \) are greater at \( -\Delta \omega \) than at \( +\Delta \omega \). Once again, note that in the experiments in which both contact and no-contact conditions were present (i.e., Experiments 2 and 3), the asymmetry—indexed by the difference between the negative and positive \( \Delta \omega \) conditions—is greater for the no-contact condition than the contact condition for both \( \phi \) (0.087 vs. 0.027 rad for the contact and no-contact conditions) and \( SD\phi \) (0.046 vs. 0.021 rad). These results corroborate the presence of handedness effects in bimanual rhythmic coordination and lead to the conclusion that the contact in clapping lessens the natural asymmetry of the body.

Functional asymmetry of the body has been accommodated in principled expansions of the coupled oscillator equation, namely, Equation 8. Treffner and Turvey (1995, in press) have modeled the pattern of results displayed in Tables 2 and 3 by using this equation. However, the question remains how contact in clapping is to be understood in terms of this equation. There are two ways that Equation 8 can accommodate this fact. First, as mentioned in the Discussion of Experiment 2, the presence of the collision may scale the magnitude of the asymmetry coefficient \( d \) in much the same way that \( \omega_c \) scales \( \phi \). If \( d = .05 \), then the \( \Delta \omega = 0 \) intercept magnitudes for the three \( \omega_c \) conditions are in the range observed for no-collision conditions; if \( d = .025 \), then the intercept magnitudes are in the range observed for the collision conditions.

An alternative strategy is one that expands Equation 4 to include terms that model the effect of environmental information on the coordination. The dynamical theory of behavioral patterns (Schöner & Kelso, 1988a, 1988b) assumes that environmental factors can be incorporated into order parameter equations as additional coupling terms. For example, Tuller and Kelso (1987) have modeled bimanual rhythmic coordination under the influence of an environmental metronome that exhibits an intended phase relation (\( \phi_{\text{metr}} \) between 0 and \( 2\pi \) to be obtained by adding a \( c \sin(\phi - \phi_{\text{metr}}) \) term to Equation 4. Under these circumstances, the intrinsic dynamic expressed by Equation 4 persists under extrinsic criteria or the required dynamic imposed by the environment. In short, the required dynamic is captured by the additional coupling term in the order parameter model. Likewise, Sim, Shaw, and Turvey (in press) have modeled the cyclic batting of a ball suspended from a string using an order parameter equation that captures the intrinsic \( \phi \) dynamics between the bat and the ball. Furthermore, changes in the coordination behavior produced by resistive and nonresistive targets are modeled by incorporating a similar required dynamic term—\( k_c \sin(\phi_{\text{bat}} - \phi_{\text{ball}}) \)—that captures the influence of these extrinsic environmental criteria.

### Table 2
**Functional Asymmetry of the Body Evidence: Contact Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
<th>Experiment 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercepts</td>
<td>-.022</td>
<td>-.020</td>
<td>-.005</td>
<td>-.021</td>
</tr>
<tr>
<td>Absolute ( \Delta \phi )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -\Delta \omega )</td>
<td>.101</td>
<td>.085</td>
<td>.101</td>
<td>.093</td>
</tr>
<tr>
<td>( +\Delta \omega )</td>
<td>.056</td>
<td>.046</td>
<td>.095</td>
<td>.097</td>
</tr>
<tr>
<td>( SD\phi )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -\Delta \omega )</td>
<td>.176</td>
<td>.219</td>
<td>.221</td>
<td>.491</td>
</tr>
<tr>
<td>( +\Delta \omega )</td>
<td>.160</td>
<td>.181</td>
<td>.199</td>
<td>.345</td>
</tr>
</tbody>
</table>

*Note. Units are radians. Intercepts are estimates of \( \phi \) at \( \Delta \omega = 0 \) from \( \phi - \Delta \omega \) regressions. All measures are means across \( \omega_c \) conditions.*

### Table 3
**Functional Asymmetry of the Body Evidence: No-Contact Conditions**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercepts</td>
<td>-.057</td>
<td>-.030</td>
</tr>
<tr>
<td>Absolute ( \Delta \phi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -\Delta \omega )</td>
<td>.122</td>
<td>.128</td>
</tr>
<tr>
<td>( +\Delta \omega )</td>
<td>.013</td>
<td>.068</td>
</tr>
<tr>
<td>( SD\phi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -\Delta \omega )</td>
<td>.143</td>
<td>.245</td>
</tr>
<tr>
<td>( +\Delta \omega )</td>
<td>.131</td>
<td>.165</td>
</tr>
</tbody>
</table>

*Note. Units are radians.
that both force-based and nonforce-based environmental influences have been modeled by this strategy using, in fact, the same term. Consequently, it may be possible to model the collision as an extrinsic criterion by including a required dynamic term that constrains the asymmetric portion of Equation 8 and effectively reduces the influence of the functional asymmetry of the body.

Conclusion

This research extends interlimb coordination research in several ways. First, these experiments highlight the generic nature of the coupled oscillator regime in interlimb coordination, revealing invariance over limb segments, frequency, and movement style. Second, this is the first time that the elementary coordination dynamics (and their asymmetric expansion) have been demonstrated in a naturally occurring movement that involves contact between limb surfaces. In addition, clapping is a useful addition to the repertoire of rhythmic behaviors that have been formally modeled by using coupled oscillator dynamics in that they suggest a more natural paradigm for the study of developmental dynamics. That is, because clapping is an interlimb coordination exhibited at a relatively early age, and one shown to adhere to oscillatory dynamics, it provides a useful window through which to view dynamical patterns in the development of interlimb coordination (e.g., Fitzpatrick, 1993). Finally, the tuning of the dynamic by perception has been supported. The decrease in the effect of the asymmetry of the body when visual feedback is eliminated (Experiment 3) demonstrates one way that visual information plays a role in establishing coordination dynamics.

References

of rhythmic movements in vertebrates (pp. 333-367). New York: Wiley.


Received December 7, 1993
Revision received March 8, 1995
Accepted April 20, 1995