Frequency detuning of the phase entrainment dynamics of visually coupled rhythmic movements

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Abstract. An order parameter equation for correlated limb movements was applied to rhythmic coordination between the limbs of two people. The interlimb coordination was established and maintained through vision. Manipulations of frequency competition, coupled frequency, and intended mode (in-phase or anti-phase) produced equilibria and fluctuations in relative phase predicted by the order parameter equation and confirmed originally in within-person coordination. It was concluded that there is an elementary coordination dynamics governing the rhythmic coordination between organisms as well as between components of a single organism.

1 Introduction

Biological coordination is an intriguing phenomenon largely because it requires the successful cooperation of multiple underlying subsystems. An essential feature of the subsystems in a coordinated state is that they are able to behave in a highly cooperative manner without relinquishing their distinctive individual qualities. In his pioneering research, von Holst (1937/1973) investigated coordination between and among the fins of the medullotranssected Labrus, a fish that swims with its main body axis immobile. Although the fins of Labrus oscillate independently of each other, and do so at particular preferred frequencies, the act of swimming requires the fins to oscillate at a common frequency. Von Holst observed that the individual fins do not abandon their preferred frequencies when they oscillate at the new, ‘cooperative’ frequency. Rather, each individual fin maintains its characteristic dynamical properties while at the same time adapting to the other fin’s frequency. Von Holst called the tendency for each fin to oscillate at its own preferred frequency the ‘maintenance tendency’ and the tendency for each fin to be attracted to the other fin’s frequency the ‘magnet effect’. Coordination between fins, therefore, is a combination of maintenance tendency and magnet effect, of both competition and cooperation between individual fins.

Von Holst did not limit this analysis to the level of the fins, however. Each fin is composed of fin rays, each of which can oscillate at its own preferred frequency. Just as swimming – an act of the entire fish, involving all fins – requires a careful balance of competition and cooperation among the component rhythmic units defined at the level of swimming, so it is that fin oscillation – an act of the entire fin, involving all the fin rays – requires a careful balance of competition and cooperation among the component rhythmic units defined at the level of individual fin oscillation. Similarly, the oscillations of the individual fin rays are expressions of competition and cooperation but now at the level of the individual muscles governing the fin rays. Further, the individual muscles can be considered as reflecting, in the unitary activity of their motor units, the same classes of processes shaping the coordinated states at the various levels above. In sum, von Holst saw common principles governing coordination at multiple levels of analysis, from the more macroscopic level of pectoral and dorsal fins, for example, to the more microscopic level of the underlying cellular mechanisms.

Von Holst made two very important contributions to the understanding of coordination in biological movement systems. First, he laid the groundwork for understanding coordination as a dynamical process of pattern formation or pattern selection: A particular intersegmental coordination pattern arises as an a posteriori consequence of the interplay of competition and cooperation. Second, in his application of basic coordination concepts to multiple levels of analysis, von Holst set a precedent for examining the possibility of underlying similarity across all types of coordination that is independent of the properties of the individual subsystems. He intimated that the basic laws of coordination may be very general and not specific to any particular (biophysical) degrees of freedom. Consequently, just as von Holst hypothesized common principles of coordination from the level of
Fig. 1. Manipulations of frequency competition between individual pendulums, $\Delta \omega$, and the coupling strength, $b/a$, in (1) (Haken et al. 1985; Kelso et al. 1990; Schöner et al. 1986) produce shifts in both negatively sloped zero crossings (equilibrium points) and slopes at the zero crossings (stability of the equilibrium points). In a, $\Delta \omega = 0$; negatively sloped zero crossings are at 0 and $\pm \pi$ for all three values of $b/a$ ($a = 1$ for all body segments downward to the level of individual motor units, so it can be hypothesized that the principles governing intersegmental coordination within a single individual organism extend upwards, to the more macroscopic system of intersegmental coordination between two individual organisms. The present research is directed at this hypothesis that between-organisms coordination is governed by the same dynamical laws that govern within-organism coordination.

1.1 Dynamical modeling of interlimb coordination

Intersegmental coordination can be modeled as a system of coupled limit-cycle oscillators with relative phase providing a macroscopic index of the underlying spatiotemporal details (Kopell 1988; Rand et al. 1988). Major characteristics of 1:1 frequency locking in human interlimb coordination are accommodated by the following equation in which the collective variable of relative phase is regarded as an order parameter (Haken et al. 1985; Kelso et al. 1990; Schöner et al. 1986):

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

In words, the first derivative of relative phase ($\dot{\phi}$) is dependent on both the frequency competition between individual oscillators ($\Delta \omega$) and the coupling strength ($b/a$), which is a function of the relative phase ($\phi = \theta_1 - \theta_2$) between the oscillators, where $\theta_i$ is the phase angle of the individual oscillator. The last right-hand term in (1) accounts for any unexplained variability in the system, assumed to be due to gaussian white noise, which arises from the multiplicity of the underlying subsystems (Haken 1983; Schöner et al. 1986).

Stable interlimb coordinations can be predicted from (1) by considering, for given values of the parameters $\Delta \omega$ and $b/a$, the values of $\phi$ when $\dot{\phi}$ goes to zero (e.g., Kelso and Ding 1993). Negative zero crossings identify stable equilibria of fixed points. Figure 1a shows that when $\Delta \omega = 0$ - that is, when there is no frequency competition between the coupled oscillators, and the coordination...
dynamics of (1) are symmetrical – the stable equilibria are at \( \phi = 0 \) and \( \phi = \pm \pi \). Figure 1a shows that when \( \Delta \omega = 0 \), the equilibrium points are unaffected by variations in \( b/a \). In contrast, Fig. 1b shows that when \( \Delta \omega \neq 0 \) – that is, when there is frequency competition between the coupled oscillators, and the coordination dynamics of (1) are asymmetrical – the equilibria are shifted by both the magnitude of \( \Delta \omega \) and the magnitude of \( b/a \). Specifically, for a given \( \Delta \omega \neq 0 \), a decrease in \( b/a \) is accompanied by a shift or drift of the equilibrium points from 0 and \( \pm \pi \). This will be referred to as fixed point drift (see Kelso and Jeka 1992).

The degree to which an equilibrium point attracts or repels is also specified by (1). In Fig. 1a and b, the slope, \( d \phi / d \phi \), at a zero crossing varies as a function of \( b/a \). The inverse of \( d \phi / d \phi \) is a time referred to as \( \tau_{\text{rel}} \), the local relaxation time, understood as the time taken to return to the equilibrium point following a small perturbation. The more stable the equilibrium point, the shorter is \( \tau_{\text{rel}} \). The standard deviation of \( \phi \) (SD\( \phi \)) is related to \( \tau_{\text{rel}} \) according to:

\[
\text{SD} \phi = \sqrt{(Q \tau_{\text{rel}})/2}
\]

(see Gilmore 1981; Schöner et al. 1986; Schöner and Kelso 1988). As Fig. 1a reveals, \( d \phi / d \phi \) at the stable equilibrium points for \( \Delta \omega = 0 \) decreases with decreasing \( b/a \), meaning that SD\( \phi \) will vary inversely with \( b/a \). As \( \Delta \omega \) deviates from zero (as in Fig. 1b), the slopes become shallower than they were for \( \Delta \omega = 0 \). With \( b/a \) held constant, \( d \phi / d \phi \) becomes smaller the greater the magnitude of \( \Delta \omega \). When \( b/a \) is manipulated, the pattern of slopes is similar to the pattern seen at \( \Delta \omega = 0 \), where larger \( b/a \) values produce steeper slopes (and, therefore, smaller expected values of SD\( \phi \)) than smaller \( b/a \) values.

Finally, slopes at the zero crossings located in the vicinity of \( \phi = 0 \) are steeper than slopes at the zero crossings located in the vicinity of \( \phi = \pi \). SD\( \phi \) is expected, therefore, to be greater at a phase mode on or about \( \pi \) than at a phase mode on or about 0.

The above predictions of (1) based on Fig. 1a and b can be expressed most usefully for experimental purposes through the corresponding Fig. 1c and d. Figure 1c presents the predictions with respect to fixed point drift, measured as \( \phi_{\text{ave}} - \phi_{\text{e}} \), where \( \phi_{\text{ave}} \) is the average relative phase during an experimental run of 1:1 frequency locking of two limbs, and \( \phi_{\text{e}} \) is the intended (\( \psi \)) phase. Figure 1d presents the predictions of equilibrium point stability as measured by \( \tau_{\text{rel}} \). For an experimental run of 1:1 frequency locking of two limbs, this quantity would be reflected in the SD\( \phi \) [see (2)] of \( \phi_{\text{ave}} \). Confirmation of (1)'s predictions of fixed point drift and relative phase variability can be found in a large number of studies on interlimb coordination for a person (e.g., Bingham et al. 1991; Rosenblum and Turvey 1988; Schmidt et al. 1991, 1993; Sternad et al. 1992; Trefnner and Turvey 1995; Turvey et al. 1986).

1.2 Operationalizing \( b/a \)

Of particular relevance to the present experiment is the experiment of Sternad et al. (1992), in which predictions about fixed point drift were tested for within-person coordination of hand-held pendulums. The experimental design and manipulations of \( \phi_{\text{e}} \) and \( \Delta \omega \) were similar to other studies using the wrist pendulum paradigm (see Schmidt et al. 1993). Haken et al.'s (1985) assumption that \( b/a \) is inversely related to coupled frequency, \( \omega_{\text{c}} \), received direct empirical support in Schmidt et al. (1993).

A major difference in Sternad et al.'s (1992) study was that \( \omega_{\text{c}} \) was scaled to the (virtual) eigenfrequency, \( \omega_{\text{e}} \), of the coupled pendulum system. By assuming a rigid coupling, that is, a perfectly constant phase relation between the two pendulums, a single equivalent simple-pendulum length and, therefore, an eigenfrequency can be calculated for any two-pendulum system (Bingham et al. 1991; Kugler and Turvey 1987). Sternad et al. (1992) scaled \( \omega_{\text{e}} \) to \( \omega_{\text{c}} \) in an effort to match the dynamics of different two-pendulum systems. For example, if \( \omega_{\text{c}} \) for two-pendulum system A was 4 rad s\(^{-1} \) and \( \omega_{\text{c}} \) for two-pendulum system B was 8 rad s\(^{-1} \), then it was hypothesized that A and B would be dynamically identical if A oscillated at \( \omega_{\text{c}} = 4 \) rad s\(^{-1} \) and B oscillated at \( \omega_{\text{c}} = 8 \) rad s\(^{-1} \). Clearly, for any fixed ratio of \( \omega_{\text{c}} / \omega_{\text{e}} \), \( \omega_{\text{c}} \) for A would always be less than \( \omega_{\text{c}} \) for B. In analyzing the drift of \( \phi \) from \( \phi_{\text{e}} = 0 \) and \( \phi_{\text{e}} = \pi \) induced by \( \Delta \omega \), Sternad et al. (1992) found the same pattern of results observed by Schmidt et al. (1993) together with evidence that systems equated on \( \omega_{\text{c}} / \omega_{\text{e}} \) behaved similarly, that is, were equivalent in \( b/a \).

The hypothesis that \( b/a \) in (1) is operationalized by \( \omega_{\text{c}} / \omega_{\text{e}} \), rather than \( \omega_{\text{c}} \), can be evaluated through the fluctuations in \( \phi \). Let the two-pendulum systems A and B above be such that \( \Delta \omega \neq 0 \) for A and \( \Delta \omega = 0 \) for B, and let \( \omega_{\text{c}} > \omega_{\text{e}} \), for example, \( \omega_{\text{c}} = 1.50 \omega_{\text{e}} \). If \( b/a \) is operationalized by \( \omega_{\text{c}} / \omega_{\text{e}} \), then (1) predicts that SD\( \phi \) should be greater for A than for B – A's symmetry is less than B's, and \( b/a \) is less for A than for B. The patterning of SD\( \phi \) as a function of \( \Delta \omega \) and \( \omega_{\text{c}} \) would be that depicted in Fig. 1d. In contrast, if \( b/a \) is operationalized by \( \omega_{\text{c}} \), then (1) predicts that SD\( \phi \) should be less for A than for B. Although B is more symmetrical than A, \( b/a \) for B is much less than \( b/a \) for A. The situation would be that depicted in Fig. 2a, in which case the patterning of SD\( \phi \) as a function of \( \Delta \omega \) and \( \omega_{\text{c}} \) would be that depicted in Fig. 2b.

1.3 Extension of (1) to between-subjects coordination

The original extension of (1) to between-organisms coordination took the form of investigating whether its global predictions were upheld in a two-persons system (Schmidt et al. 1990). The importance of the extension was that if (1) predicted both the interlimb coordination within a subject, where the coupling between oscillators is achieved primarily through the haptic-perceptual system, and the interlimb coordination between subjects, where the coupling is primarily visual, then it is clear that the basis for coordination has less to do with the particular anatomical substrate and more to do with lawful relations among subcomponents of the coordination.

The focus of the original extension was the global prediction (1) makes about the attractiveness of in-phase and anti-phase coordination. In Fig. 1a, it is apparent
that although $\phi = 0$ at both $\phi = 0$ and $\phi = \pi$, the slope of the curve at $\phi = 0$ is steeper, indicating more stability than the slope at $\phi = \pi$. The expectation is that when $\Delta \omega = 0$, coordination should be more stable at $\phi = 0$ than at $\phi = \pi$. Furthermore, as $b/a$ decreases to a critical point of $b/a = 0.25$, the zero crossing point at $\phi = \pi$ is annihilated, which results in a dynamic that can only allow for in-phase behavior (Haken et al. 1985). Kelso (1984) reported, for within-person coordination and $\Delta \omega = 0$, a spontaneous transition from the anti-phase to in-phase pattern as $\omega_c$ increased but no return to anti-phase with a subsequent decrease in $\omega_c$. Further, when the interlimb coordination was prepared in-phase, increases in $\omega_c$ did not lead to a transition to anti-phase.

Schmidt et al. (1990) tested the phase-transition predictions of (1) in a task in which two people, sitting side by side, coordinated the oscillations of their lower legs by watching each other. Specifically, the coordination was between the right lower leg of one person and the left lower leg of the other. $\Delta \omega$ was assumed to be close to zero, so that an intentional maintenance of in-phase was expected to yield a mean relative phase measure of 0, and an intentional maintenance of anti-phase was expected to yield a mean relative phase measure of $\pi$. Schmidt et al. (1990) found evidence for the differential stability of the two phase modes in the form of the increased departures from intended phase and increased standard deviations of relative phase at $\pi$. Furthermore, when $\omega_c$ was increased, thereby bringing about a decrease in the coefficient ratio $b/a$, the anti-phase mode was annihilated, resulting in a sudden change to in-phase coordination (despite a shared intention of the subjects to maintain anti-phase) precipitated by critical fluctuations. Phase mode switching from 0 to $\pi$ was not witnessed.

Further evidence of similarities between two-persons interlimb coordination and single-person interlimb coordination comes from Schmidt and Turvey (1994), who used a pendulum task similar to the one used by Schmidt et al. (1993) and Sternad et al. (1992). Each member of a subject pair was instructed to swing a hand-held pendulum in anti-phase coordination with the pendulum held and oscillated by the other member. Manipulations of $\Delta \omega$ produced the predicted fixed point drift and increasing $SD\phi$ with deviations from $\Delta \omega = 0$, lending further support to the understanding that interlimb 1:1 frequency locking between two subjects abides by the same dynamical principles, namely (1), as does interlimb 1:1 frequency locking within a single subject.

1.4 Goals of the present experiment

In the study of equilibrium points and their corresponding $SD\phi$ under visual coupling, Schmidt and Turvey (1994) focused only upon anti-phase coordination and manipulations of $\Delta \omega$. In the present experiment, the effects of both $\Delta \omega$ and $\omega_c$ determined in the two-persons system for both in-phase and anti-phase coordination. Additionally, the effect of scaling $\omega_c$ to $\omega_c$, was evaluated. Fixed point drift as a function of $\phi$, $\Delta \omega$, and $\omega_c$ was expected to conform to Fig. 1c. $SD\phi$ was expected to reveal an effect of $\phi$ ($SD\phi$ greater for anti-phase) and a joint influence of $\Delta \omega$ and $\omega_c$ conforming to Fig. 1d or to Fig. 2b depending on whether $\omega_c$ or $\omega_c/\omega$, operationalizes $b/a$.

2 Method

Subjects. Three men and three women participated in the experiment: one faculty member, four graduate students, and one undergraduate student at the University of Connecticut. All subjects were right handed. They were selected on the basis of being able to behaviorally discriminate between the two pendulums used in the experiment (that is, each selected subject oscillated the two pendulums freely and comfortably at nonidentical frequencies). The selected subjects were grouped into three pairs according to how closely the difference between the frequencies produced freely by each member matched $\Delta \omega$, calculated as the difference between the respective
values of \((L/g)^{1/2}\) for the two hand-held pendulum systems (see Kugler and Turvey 1987).

**Design.** The data collected in this study included the movement trajectories of the two hand-held pendulum, one in the right hand of one subject and one in the left hand of the other subject. \(\phi_{av}\), the average relative phase between the two pendulums, was used as the estimate of the stable fixed point. Subjects were instructed to maintain a relative phase, \(\phi_{r}\), of either 0 (in-phase) or \(\pi\) (anti-phase). The physical properties of the pendulums were manipulated in the manner described by Kugler and Turvey (1987) in order to control \(\Delta \omega\). Pendulums of 0.22 and 0.58 m were coupled to yield \(\Delta \omega = 0\), \(\Delta \omega = -2.32\), and \(\Delta \omega = 2.32\) rad s\(^{-1}\). The frequency at which the pendulums were oscillated was 1:1 frequency locking was either \(\omega_r = 1.50 \omega_s\) or \(\omega_r = 0.75 \omega_s\). Therefore, subjects were run under 12 conditions (2 \(\phi_{r} \times 3 \Delta \omega \times 2 \omega_s\)), with six trials per condition, where each subject in a pair used his or her right hand for three trials and left hand for three trials.

Data analysis was performed on six experimental pairs, two effective pairs for each subject pair in the experiment. Consider Subject Pair 2 with members A and B. For trials in which A and B each held 0.22 m pendulums, the individual eigenfrequency, \(\omega_s\), of each pendulum was calculated to be 7.07 rad s\(^{-1}\). Under these conditions, \(\Delta \omega = 0\). When A was asked to freely swing the pendulum, however, the frequency produced, \(\omega_{av}\), varied slightly according to whether he was swinging the pendulum in his left hand (8.00 rad s\(^{-1}\)) or in his right hand (9.39 rad s\(^{-1}\)). Similarly, B produced a different frequency with her left hand (9.55 rad s\(^{-1}\)) than with her right hand (10.35 rad s\(^{-1}\)). When Subject Pair 2 was configured so that A was using his left hand and B was using her right hand (AB), the difference in 'preferred' frequencies, \(\Delta \omega_p\), was 2.35. When Subject Pair 2 was configured so that B was using her left hand and A was using his right hand (BA), \(\Delta \omega_p = -0.16\). Whereas BA was close enough to zero to produce a pattern of results from (1) expected by a manipulation of \(\Delta \omega = 0\), AB was far enough away to produce a different pattern of results expected by a manipulation of \(\Delta \omega \neq 0\). For the purposes of the \(\Delta \omega\) manipulation, the difference between \(\Delta \omega_p\) and \(\Delta \omega\) was negligible, since asymmetric pairing of pendulums produced both larger \(\Delta \omega_p\) and \(\Delta \omega\) than symmetric pairings. It is clear, however, that although AB and BA were composed of the same subjects, A and B, results expected from AB were notably different than results expected from BA. Data produced by the two different configurations of each subject pair were therefore treated effectively as data from two experimental pairs of subjects.

**Apparatus.** Pendulums were aluminum rods, 0.22 and 0.58 m in length and 0.025 m in diameter, attached to a wooden handle 0.12 m long. The total mass of each pendulum was 124.20 and 247.70 g, respectively. The equivalent length of each pendulum was calculated using the algorithm specified by Kugler and Turvey (1987) in order to compute the pendulum’s gravitational eigen-frequency, \(\omega\). To simplify computations, all subjects were assumed to have an equal mass (75 kg) and equal offset distance from the axis of rotation (0.06 m from the center of the palm to the wrist); any differences in actual subject data were considered to be negligible in their effects on the expected qualitative features of the data. The eigenfrequencies of the 0.22 and 0.58 m pendulums were 7.07 and 4.75 rad s\(^{-1}\), respectively. In the \(\Delta \omega = 0\) condition, both pendulums were 0.22 m, and \(\omega_s\) was 7.07 rad s\(^{-1}\). In the two asymmetric conditions, one subject held a 0.22 m pendulum while the other subject held a 0.58 m pendulum. \(\omega_s\) was 5.13 rad s\(^{-1}\), and \(\Delta \omega\) was ± 2.32 rad s\(^{-1}\), where \(\Delta \omega\) was negative when the longer pendulum was held by the subject who was swinging with his right hand and positive when the longer pendulum was held by the subject who was swinging with his left hand.

An electronic metronome was used to pace the pendulums at either \(\omega_s = 1.50 \omega_s\) or \(\omega_s = 0.75 \omega_s\), the high and low coupled frequency conditions, respectively. For \(\Delta \omega = 0\), the metronome paced the pendulums at either 5.32 or 10.64 rad s\(^{-1}\); for \(\Delta \omega = ± 2.32\), the metronome paced the pendulums at either 3.85 or 7.66 rad s\(^{-1}\).

Subjects were seated on either side of a padded experimental cube, so that the person on the right side of the cube was holding the pendulum in his left hand and the person on the left side of the cube was holding the pendulum in his right hand. Subjects’ wrists were positioned on a padded metal bar that was affixed to the desktop on their chairs. A cardboard blind was placed in between each subject’s body and forearm so that the subject could not see his own hand but was able to view his partner’s entire arm and pendulum, as shown in Fig. 3.

**Data collection.** Movement trajectories of each pendulum were collected using a Sonic 3-Space Digitizer (SAC Corporation, Stratford, CT). A sonic emitter attached to the end of each pendulum emitted sparks at the rate of 90 Hz. Microphones positioned in the four corners of the experimental cube registered the position of the emitter by computing its distance from three of the four microphones that registered the least number of errors during that trial. This slant range time series was stored for use on a 80486-based microcomputer using MASS digitizer software (Engineering Solutions, Columbus, Ohio). MAss was then used to calculate the primary angle of excursion of each of the pendulums and the relative phase angle, \(\phi\), between the two.

**Procedure.** Each subject in a pair was instructed to hold the pendulum flush with the top of the hand and to position the wrist on the padded metal bar affixed to the desktop. Each subject was instructed to create as smooth and as continuous a trajectory as possible with the pendulum and to hold the pendulum firmly in the hand so as to guarantee rotation about the wrist rather than rotation about the finger joints. Pedal motion was restricted to the plane parallel to the subject’s sagittal plane. The two subjects in a pair were asked to coordinate the oscillations of their pendulums. They were reminded not to look around the cardboard blinds, but to
Fig. 3. Experimental arrangement for the study of interlimb coordination between two subjects. Subjects are asked to coordinate the swinging of their pendulums to obtain an intended relative phase, $\phi_v$, of either 0 or $\pi$. Characteristics of the pendulums are manipulated in order to introduce frequency competition, $\Delta \omega$, and a metronome is used to pace subjects at the desired coupled frequency, $\omega_c$. A cardboard blind is positioned in between each subject's body and forearm so that the subject cannot see his own hand but is able to view his partner's entire arm and pendulum.

Visually track the other person's pendulum throughout the course of the experiment. In any given trial, subjects were instructed to oscillate the hand-held pendulum with the oscillations of their partner's pendulum in time to the metronome beat to establish either in-phase ($\phi_v = 0$) or anti-phase ($\phi_v = \pi$) 1:1 frequency locking. Although most subject pairs were able to satisfy both goals of establishing a phase and maintaining the metronome beat, they were instructed to maintain the intended phase, even if they ran slightly faster or slower than the metronome. On average, subjects were not more than 1% faster or slower than the metronome beat. The metronome was started, and subjects were instructed to begin oscillations. They were given ample practice time before the start of the actual trial; only after both subjects had indicated to the experimenter that they felt their coordination was stable did data collection begin. Each trial was 30 s. Trials with a greater than 5% error rate in data collection were repeated. Data collection was split into two experimental sessions, each of which lasted 1–2 h.

2.1 Results

2.1.1 Mean relative phase. Mean deviations of relative phase from intended phase, $\phi_{ave} - \phi_v$, collapsed across both intended phase modes of 0 and $\pi$ are shown in Fig. 4. Mean deviation from intended phase did not differ across phase modes (for $\phi_v = 0$, $\phi_{ave} - \phi_v = 0.06$ rad; for $\phi_v = \pi$, $\phi_{ave} - \phi_v = 0.03$ rad), $F(1, 5) < 1$. For $\Delta \omega = 0$, $\phi_{ave}$ was only 0.05 and 0.03 rad greater than $\phi_v$ under conditions of low and high $\omega_c$, respectively. This supports the first prediction that under conditions of symmetry, stable phase modes are $\phi = 0$ and $\phi = \pi$. For $\Delta \omega = 0$, $\omega_c$ had no effect on the equilibrium points of the interlimb coordination.

Figure 4 also lends support to the second prediction, that deviations of mean relative phase from intended phase increase as $\Delta \omega$ deviates from zero and do so in a direction that depends on the sign of $\Delta \omega$. $\phi_{ave} - \phi_v$ was minimal (0.04 rad) when $\Delta \omega = 0$ and increased in the negative direction to $-0.09$ rad for $\Delta \omega = -2.32$ and increased in the positive direction to 0.18 rad for $\Delta \omega = 2.32$. An analysis of variance revealed this observed trend to be significant, $F(2, 10) = 34.44$, $P < 0.0001$. Tukey pairwise comparisons revealed all three levels of $\Delta \omega$ to be significantly different from each other at the 0.01 level. Therefore, deviations from intended phase magnified as $\Delta \omega$ deviated from zero.

The third prediction was that variations in $\omega_c$ would affect fixed point drift under the conditions of broken symmetry, $\Delta \omega = \pm 2.32$. Inspection of Fig. 4 reveals the expected interaction between $\Delta \omega$ and $\omega_c$. The fixed point drift induced by $\Delta \omega = \pm 2.32$ was amplified more by $\omega_c = 1.50 \omega_v$ than by $\omega_c = 0.75 \omega_v$. This interaction was significant, $F(2, 10) = 22.29$, $P < 0.0005$. Simple effects analyses revealed that there was a significant effect of $\Delta \omega$ at both low and high $\omega_c$, $F(2, 10) = 9.11$, $P < 0.01$ and $F(2, 10) = 35.68$, $P < 0.001$, respectively. The main effect of $\Delta \omega$ seen in the previous analysis was manifest, therefore, at both high and low $\omega_c$. The difference between high and low $\omega_c$ was found to be nonsignificant at all three levels of $\Delta \omega$, $F(1, 5) = 5.49$, $P > 0.05$, $F(1, 5) < 1$, and $F(1, 5) = 5.54$, $P > 0.05$ for $\Delta \omega = -2.32$, 0, and 2.32, respectively. Control for Type I error was achieved by using a familywise Bonferroni adjustment of the alpha level for all post hoc analyses.

$\phi_v$ did not interact with $\Delta \omega$, $F(2, 10) = 1.36$, $P > 0.05$. Fixed point drift, then, was not significantly greater for $\phi_v = \pi$ than it was for $\phi_v = 0$. As expected, there was no main effect of $\omega_c$ on $\phi_{ave} - \phi_v$, $F(1, 5) < 1$, nor did $\phi_v$
interact with any of the other independent variables, $\phi_0 \times \omega_0$, $F(1,5) < 1$, and $\phi_0 \times \Delta \omega \times \omega_0$, $F(2,10) < 1$.

2.1.2 Standard deviation of relative phase. Figure 5 depicts SD$\phi$ as a function of $\Delta \omega$, $\omega_0$, and $\phi_0$. SD$\phi$ was greater at $\Delta \omega = 0$ (0.366 rad) than at $\Delta \omega = -2.32$ (0.291 rad) and $\Delta \omega = 2.32$ (0.296 rad). This $\Delta \omega$ trend was significant, $F(2,10) = 41.74$, $P < 0.0001$. Tukey pairwise comparisons at the 0.01 level revealed SD$\phi$ at $\Delta \omega = 0$ to be significantly higher than SD$\phi$ at $\Delta \omega = -2.32$ and $\Delta \omega = 2.32$. As predicted, equal deviations from $\Delta \omega = 0$, i.e., $\Delta \omega = -2.32$ and $\Delta \omega = 2.32$, produced identical SD$\phi$. By experimental design, $\omega_0$ was greater at $\Delta \omega = 0$ than at $\Delta \omega = \pm 2.32$, but $\omega_0 / \omega_0$ at $\Delta \omega = 0$ was the same as that at $\Delta \omega = \pm 2.32$. The implication, therefore, is that $b/a$ is operationalized by $\omega_0$ rather than by $\omega_0 / \omega_0$.

As predicted, there was a main effect of $\omega_0$, with SD$\phi$ less at $\omega_0 = 0.75 \omega_0$ (0.278 rad) than at $\omega_0 = 1.0 \omega_0$, (0.356 rad), $F(1,5) = 26.46$, $P < 0.005$. Also as predicted, SD$\phi$ was consistently greater at $\phi_0 = 0$ (0.336 rad) than at $\phi_0 = 0$ (0.299 rad), $F(1,5) = 12.56$, $P < 0.05$. There was a significant interaction between $\omega_0$ and $\phi_0$, $F(1,5) = 9.08$, $P < 0.05$, such that the increase in SD$\phi$ with increasing $\omega_0$ under $\phi_0 = 0$ was amplified under $\phi_0 = \pi$. Simple effects analyses revealed that the $\omega_0$ manipulations produced significant differences in SD$\phi$ for both $\phi_0 = 0$ and $\phi_0 = \pi$, $F(1,5) = 21.77$, $P < 0.01$ and $F(1,5) = 24.19$, $P < 0.005$, respectively. Furthermore, the difference in SD$\phi$ between $\phi_0 = 0$ and $\phi_0 = \pi$ was not significant at $\omega_0 = 0.75 \omega_0$, $F(1,5) = 5.09$, $P > 0.05$, but was significant at $\omega_0 = 1.5 \omega_0$, $F(1,5) = 12.74$, $P < 0.05$, indicating that the difference in SD$\phi$ between the two modes occurred primarily at the higher $\omega_0$.

There was a marginally significant interaction between $\Delta \omega$ and $\phi_0$, $F(2,10) = 4.09$, $P = 0.05$. Simple effects analyses revealed that $\Delta \omega$ was significant at both intended phase modes, $F(2,10) = 14.37$, $P < 0.001$ at $\phi_0 = 0$ and $F(2,10) = 27.12$, $P < 0.001$ at $\phi_0 = \pi$. Therefore, predictions that SD$\phi$ would be greatest at $\Delta \omega = 0$ because the scaling of $\omega_0$ to $\omega_0$ yielded a larger value of $\omega_0$ at $\Delta \omega = 0$ was upheld at both phase modes. The simple implication is that $\omega_0$ operationalizes $b/a$ better than $\omega_0 / \omega_0$.

The phase modes were significantly different at $\Delta \omega = 0$, $F(1,5) = 7.78$, $P < 0.05$, and at $\Delta \omega = 2.32$, $F(1,5) = 42.65$, $P < 0.001$, but not at $\Delta \omega = -2.32$, $F(1,5) < 1$. Finally, there was a significant interaction between $\Delta \omega$ and $\omega_0$, $F(2,10) = 23.88$, $P < 0.0005$. Simple effects analyses revealed that differences between levels of $\Delta \omega$ were not significant at $\omega_0 = 0.75 \omega_0$, $F(2,10) = 1.99$, $P > 0.05$, but were significant at $\omega_0 = 1.5 \omega_0$, $F(2,10) = 65.03$, $P < 0.001$. There was a significant effect of $\omega_0$ at $\Delta \omega = 0$, $F(1,5) = 99.22$, $P < 0.001$, but not at $\Delta \omega = -2.32$, $F(1,5) = 5.28$, $P > 0.05$, or $\Delta \omega = 2.32$, $F(1,5) = 5.37$, $P > 0.05$. Control for Type I error was achieved by using a familywise Bonferroni adjustment of the alpha level for all post hoc analyses.

3 Discussion

In the present project we have examined the hypothesis that (1) expresses the elementary coordination dynamics governing the rhythmic coordination between organisms as well as between components of a single organism (Kelso 1994). The following predictions of (1) (with $a > 0$, $b > 0$, $b/a >$ critical), previously upheld in the single organism case (e.g., Schmidt et al. 1993; Sterndel et al. 1992; Treflner and Turvey 1994), have been shown now to hold for the between-organisms case:

1. When $\Delta \omega = 0$, $\phi$ equals 0 and $\pi$, whatever the magnitude of $b/a$.
2. When $\Delta \omega = 0$, SD$\phi$ is less at $\phi = 0$ than at $\phi = \pi$.
3. When $\Delta \omega > 0$, $\phi > 0$ and $\phi > \pi$; when $\Delta \omega < 0$, $\phi < 0$ and $\phi < \pi$.
4. When $\Delta \omega \neq 0$, SD$\phi$ at $\phi$ close to 0 is less than at $\phi$ close to $\pi$.
5. For a constant $b/a$, larger values of $\Delta \omega \neq 0$ induce greater fixed point drift.
6. For a given $\Delta \omega \neq 0$, SD$\phi$ at $\phi$ close to 0 is less than at $\phi$ close to $\pi$.
7. For a constant $b/a$, larger values of $b/a$ induce smaller fixed point drift.
8. For both $\Delta \omega = 0$ and $\Delta \omega \neq 0$, the smaller the magnitude of $b/a$, the larger is SD$\phi$.

Predictions (1), (3), (5), and (7) were confirmed for the two-persons system by Schmidt and Turvey (1994). Predictions from (1) about the dissolution of anti-phase with decreasing $b/a$, and its presaging by critical fluctuations, were confirmed in between-persons coordination by Schmidt et al. (1990). The success of (1) in predicting both the stationary and transitional qualities of interlimb coordination between people strengthens the idea that the

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1 Although this result is consistent with (1), an independent reason for the greater variability with the shorter pendulums is that they will tend to involve a more pronounced relaxation dynamic as contrasted with the harmonic dynamic of pendular motion (see Rosenblum and Turvey 1988; Schmidt et al. 1994).
basic laws of coordination are very general, applying with (reasonable) equanimity across different levels of biological organization and within different physical realizations. Relatedly, the successful outcome of the present research encourages examination of the possibility that social interactions more generally might be addressable through dynamical principles (Baron et al. 1994; Schmidt et al. 1994).

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References


