

Leader-Follower Dynamics
Anisotropic Coupling and Influence in Social Coordination

by
Justin Fine

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2015 by the
Graduate Supervisory Committee:

Eric Amazeen, Chair
Gene Brewer
Marco Santello
Polemnia Amazeen

ARIZONA STATE UNIVERSITY

August 2015

ABSTRACT

The current work investigated the emergence of leader-follower roles during social motor coordination. Previous research has presumed a leader during coordination assumes a spatiotemporally advanced position (e.g., relative phase lead). While intuitive, this definition discounts what role-taking implies. Leading and following is defined as one person (or limb) having a larger influence on the motor state changes of another; the coupling is asymmetric. Three experiments demonstrated asymmetric coupling effects emerge when task or biomechanical asymmetries are imputed between actors. Participants coordinated in-phase ($\Phi = 0^\circ$) swinging of handheld pendulums, which differed in their uncoupled eigenfrequencies (frequency detuning). Coupling effects were recovered through phase-amplitude modeling. Experiment 1 examined leader-follower coupling during a bidirectional task. Experiment 2 employed an additional coupling asymmetry by assigning an explicit leader and follower. Both experiment 1 and 2 demonstrated asymmetric coupling effects with increased detuning. In experiment 2, though, the explicit follower exhibited a phase lead in nearly all conditions. These results confirm that coupling direction was not determined strictly by relative phasing. A third experiment examined the question raised by the previous two, which is how could someone follow from ahead (i.e., phase lead in experiment 2). This was tested using a combination of frequency detuning and amplitude asymmetry requirements (e.g., 1:1 or 1:2 & 2:1). Results demonstrated larger amplitude movements drove the coupling towards the person with the smaller amplitude; small amplitude movements exhibited a phase lead, despite being a follower in coupling terms. These results suggest leader-

follower coupling is a general property of social motor coordination. Predicting when such coupling effects occur is emphasized by the stability reducing effects of coordinating asymmetric components. Generally, the implication is role-taking is an emergent strategy of dividing up coordination stabilizing efforts unequally between actors (or limbs).

DEDICATION

Without a doubt, the culmination of this work is dedicated to Kimberly Ward. Your patience and love has demonstrated little bounds. You have provided the needed roots and foundation for me to see this through; you are my tree.

ACKNOWLEDGMENTS

For the countless moments of formal and informal lessons, laughs and headaches, and unyielding patience, I must thank my advisor (and friend) Dr. Eric L. Amazeen. Your willingness to guide me over the years is immeasurable. Dr. Polemnia G. Amazeen, I thank you not just for your academic, but life and moral support also. You have been more than an advisory figure for me, but friend and 2nd parent. I must also extend a special thanks to Dr. Gene Brewer, whose support has been more than intellectual. Your level of ambition and general curiosity set a standard to work and live by. I must also thank Dr. Marco Santello, and not just for being a committee member.

Several other people have been pivotal in my growth as an academic and individual. First and foremost are my colleagues, whom are lab mates and friends, including Aaron Likens, Cameron Gibbons, & Morgan Waddell. All of you have been more than supportive. Aaron, I thank you for the countless conversations, debates, and friendship. Similarly, it has been more than a pleasure to work alongside both Cameron and Morgan. Some of my close friends, Brittany Blair Braden and Candace Lewis, your friendship and belief in me has provided me with enough support for a lifetime. The unending support from my Mom and Dad has allowed me to grow from my rebellious younger self to now.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	vii
CHAPTER	
1 INTRODUCTION	1
Intra- and Interpersonal Coordination Dynamics.....	2
Asymmetries: Intrinsic Differences and Coupling.....	4
Stability and Effort: Leader-Follower Interactions	6
Summary and Predictions	10
2 EXPERIMENT 1	13
Methods	14
Results	17
Discussion	23
3 EXPERIMENT 2	26
Methods	27
Results	29
Discussion	33
4 EXPERIMENT 3	37
Methods	38
Results	39
Discussion	44
5 GENERAL DISCUSSION	49

CHAPTER	Page
Symmetry Breaking Changes Coupling and Stability	50
Beyond Phase Synchronization	53
Leader Dynamics and Traits: Common Ground	56
REFERENCES.....	62

LIST OF FIGURES

Figure	Page
1. Representative Sample Data from Experiment 1	72
2. Mean Relative Phase (degs) for Frequency Detuning Levels	73
3. SD Relative Phase (degs) for Frequency Detuning Levels	74
4. Mean Amplitude (mm) for all Pendulum Frequencies	75
5. Ratio of Mean Amplitudes from Left and Right Seated Participant for all Frequency Detuning Levels.....	76
6. Coupling Function Calculated from Phase Coupled Models with Amplitude Ratio Weights. Coupling Terms are Presented for all Frequency Detuning Levels.....	77
7. Mean Peak-to-Peak EMG Amplitude as a Function of Baseline Output for all Pendulum Frequencies.....	78
8. Mean Relative Phase (degs) for Frequency Detuning Levels in Experiment 2. Frequency Detuning is Calculated as the Difference in Leader and Follower Phase Angles	79
9. Follower Mean Amplitude (mm) across Pendulum Frequencies.....	80
10. Ratio of Mean Amplitudes for all Detuning Levels. Ratios are Calculated as Leader Divided by Follower.	81
11. Coupling Function from Phase Models with Amplitude Ratio Weights. Coupling was Calculated as the Normalized Difference in Leader and Follower Coefficeients.....	82

Figure	Page
12. Mean and SD EMG Peak-to-Peak amplitude (% Baseline) across all Pendulum Frequencies	83
13. Mean Relative Phase (degs) for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1).....	84
14. SD Relative Phase (degs) for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1).....	85
15. Mean Period (samples) for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1).....	86
16. Mean Amplitude (mm) for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1).....	87
17. Mean Amplitude Ratio (Left Divided by Right) for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1)	88
18. Coupling Function from Phase Models with Amplitude Ratio Weights. Normalized Coupling Function is Calculated as Difference of Left and Right Participants. Values are Displayed for Frequency Detuning and Amplitude Ratio Levels (1:1, 1:2, & 2:1).....	89
19. Mean Peak-to-Peak EMG Amplitude as a Function of Baseline Output for all Pendulum Frequencies and Amplitude Ratio Levels (1:1, 1:2, & 2:1)	90
20. SD Peak-to-Peak EMG Amplitude as a Function of Baseline Output for all Pendulum Frequencies and Amplitude Ratio Levels	

Figure

Page

(1:1, 1:2, & 2:1) 91

CHAPTER 1

INTRODUCTION

An important question in social interactions is concerned with how individuals influence the actions of one another. What characterizes leaders and followers? Answers have developed along different lines. This question has been investigated thoroughly in personality and social psychology (Bligh, 2011; Judge, Bono, Ilies, & Werner, 2002; Kirkpatrick, 1991). Individuals are typically studied in isolation, wherein traits are predictors for the propensity for leadership. The goal is predicting which individuals are likely to emerge as leaders, and how effective they will be. Minimal effort is given to characterizing the interactive, social nature of leaders and followers.

Examining real-time interactions (coordination) between people permits a different approach (Dumas, de Guzman, Tognoli, & Kelso, 2014; Oullier & Kelso, 2009). The question now becomes of what is entailed in the action of leading and following. Understanding how leaders and followers interact is a problem of coordinating actions and coupling. This tactic places a premium on the unfolding of events due to physical and informational exchanges (Kelso, Dumas, & Tognoli, 2013; Schmidt, Fitzpatrick, Caron, & Mergeche, 2011). The perceptual-motor dynamics of social coordination have been exhaustively studied (Amazeen, Schmidt, & Turvey, 1995; Coey, Varlet, Schmidt, & Richardson, 2011; Fine, Gibbons, & Amazeen, 2013; Fine & Amazeen, 2011; Fine & Amazeen, 2014; Mottet, Guiard, Ferrand, & Bootsma, 2001; Schmidt & Richardson, 2008; Schmidt & Turvey, 1994; Varlet, Marin, Lagarde, & Bardy, 2011). However, only a few studies have explicitly focused on the combination of motor interactions and

leader-follower dynamics (Konvalinka, Vuust, Roepstorff, & Frith, 2010; Rio, Rhea, & Warren, 2014; Sacheli, Tidoni, Pavone, Aglioti, & Matteo, 2013), with most employing scenarios that examine unidirectional coupling (Meerhoff, De Poel, & Button, 2014). Furthermore, past research examining rhythmic coordination has assumed the person exhibiting a spatiotemporal lead is the leader (Varlet et al., 2014). This is only an observation of being ahead, is a limited criterion in terms of prediction power, and is potentially unfounded. Generally, it doesn't guarantee the person in front drives the interaction.

What is needed is a fundamental definition of a leader and follower. Rather than assume a leader is solely a physical fact of coordination, it is proposed that the interaction of these roles requires considering actors as exchangers of information. The existence of roles implies a directionality or asymmetric coupling. Put differently, future actions of followers are influenced more by leaders than vice versa. In this current set of work, three studies were conducted to examine leader-follower dynamics during rhythmic social coordination. Questions were framed by asking how intrinsic dynamics of individuals and task constraints (e.g., explicit coupling direction) alter leader-follower dynamics.

Intra- and interpersonal coordination dynamics

Coordinating one's own limbs with another person requires integrating perceptual information with motor goals. Despite the variable patterns people could produce, it was acknowledged several decades ago that certain patterns may be preferred. Seminal work

examined bimanual coordination by having individuals oscillate index fingers at a metronome driven frequency (Kelso, 1984; Kelso, Scholz, & Schöner, 1986). Such coordination is readily described by the relative phasing (Φ ; degs) between limbs. In this paradigm, both in-phase ($\Phi = 0$) and anti-phase ($\Phi = 180^\circ$) are stable. If movements are initiated anti-phase, increasing their coupled metronome driven frequency (ω_c) leads to a breakdown. Movement patterns exhibit a phase-transition to in-phase (Kelso, 1984; Haken, Kelso, Bunz, 1985). In-phase, however, is stable across a range of slow to faster frequencies. These results were interpreted as the individual elements (limbs) operating as a synergy or coordinative structure (Bernstein, 1967; Kelso, 1997; Turvey & Carello, 1996).

The realization that certain patterns are more stable than others is not limited to neuromuscular linkages. Rhythmic coordination between individuals or with environmental objects exhibit similar stability driven pattern preferences (Schmidt, Carello, & Turvey, 1990; Wimmers, Beek & van Wieringen, 1992). In the case of social coordination, interaction is mediated by informational linkages (e.g., visual or verbal). Such a result implies a generality of these principles (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Fine & Amazeen, 2011; Fine et al., 2013; Schmidt et al., 1990). In effect, pattern selection based on stability is a seemingly invariant property of coordinating components. These relative phase dynamics have been modeled using Φ as an order parameter (i.e., dependent variable), according to (1):

$$(1) \quad \dot{\Phi} = -a\sin(\Phi) - 2b\sin(2\Phi)$$

In the equation of motion (1), the interaction between oscillatory elements are expressed as a system describing the stability of global coordination states. The equation reduces the system's dimensionality to a single equation, rather than examining all components (e.g., stiffness and friction of individual limbs) of the coupled oscillators (Fuchs, 2013; Beek, Schmidt, Morris, Sim, & Turvey, 1995). Coupling strength between oscillators is related to the a and b coefficients and their ratio (b/a). Experiments on two-limb, rhythmic coordination have suggested the coupling strength is inversely related to the coupled frequency (ω_c); coupling strength increases and ω_c decreases with an increasing ratio. Coupling strength operationalizes the *cooperative* tendency or stability between limbs or actors (Von Holst, 1937/1973). An important fact is that coupling strength is assumed symmetric; limbs have an equal influence on one another. Stable relative phases (Φ or fixed-points) are indexed as negative zero-crossings in a plot of $\dot{\Phi}$ and Φ ; fixed-point stability is measured by the gradient at the zero crossing. Both states occur at the canonical values of $\Phi = 0^\circ$ and 180° when the ratio is greater than 0.25. Less than 0.25, the state of 180° disappears. Only the in-phase attractor is left. This equation expresses an elementary coordination law. In effect, the coupling can be either anatomical or informational (between-persons; e.g., visual or auditory).

Asymmetries: intrinsic differences and coupling

Successful (social) coordination also relies on balancing differences (asymmetries) in intrinsic dynamics between actors. Asymmetries may be attributable to

a range of factors, including strength, skill, limb (e.g., mass or length) or cognitive attributes (e.g., attentional control) or task constraint. Given that rhythmic coordination is a spatiotemporal process, an important property of oscillatory systems is possessing a preferred uncoupled frequency (ω ; Guckenheimer & Holmes, 2002). Thus, a natural asymmetry to examine in coordination is the difference between each person's uncoupled ω .

Coordinating limbs with different frequencies (detuning) has been examined by manipulating the resonant frequency of coupled limbs. Participants are typically asked to coordinate swinging handheld pendulums having different inertial moments, often in different phase relations (in- or anti-phase; Amazeen et al., 1995; Schmidt et al., 1998). When movements are performed in-phase, for example, increasing detuning ($\Delta\omega = \omega_1 - \omega_2$) has two effects. First, the phase pattern exhibits a shift away from the intended pattern. Shifts are directionally specified by the person with the faster (or slower) pendulum. If the left person has a faster frequency ($\Delta\omega < 0$), the stable phase is negative ($\dot{\Phi} < 0$, see eq. 2). They exhibit a phase *lead*. Detuning also has the effect of increasing coordination variability ($SD\Phi$) or reducing stability. Despite each pendular limb having its own frequency, individuals will typically perform close to the average frequency. These findings have been demonstrated and modeled across studies looking at variations of limb symmetries (Fuchs, Jirsa, Haken, & Kelso, 1996; Jeka & Kelso, 1995; Schmidt et al., 1998). An extension of equation (1) indexes this asymmetry or *competition* between the limbs by inclusion of a $\Delta\omega$ symmetry breaking term:

$$(2) \quad \dot{\Phi} = \Delta\omega - a\sin(\Phi) - 2b\sin(2\Phi)$$

Frequency differences are not the only source of asymmetries. Fine & Amazeen (2011) showed similar relative phase effects when two people simultaneously tap between targets of unequal difficulty (indexed by amplitude and width). Surprisingly, frequency locking was highest with the largest joint task difficulty; both targets were large amplitude and small widths. Previous work has shown similar findings examining directional and spatial movement asymmetries (Fine et al., 2013; Fine & Amazeen, 2014; Richardson, Campbell, & Schmidt, 2009).

Stability and Effort: Leader-Follower Interactions

In all of these coordination tasks, performance was stabilized at some level. As previously noted, coupling between actors is often assumed symmetric. Intrinsic asymmetries as symmetry breaking terms are typically considered independent of coupling direction; though, they are assumed to impact stability (Amazeen et al., 1995; Fine & Amazeen, 2014; Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008). This presumes each person equally influences one another, with each person's contribution to maintaining stability being equivalent. Coordination likely involves an asymmetric coupling, wherein stabilizing efforts are non-homogeneously distributed between people. Considering when such coupling asymmetries emerge can be reframed as asking when leaders and followers materialize.

Direct examination of such role-taking has been minimal. Research on leader-follower dynamics has often examines scenarios when task or movement information is not provided equally across actors, or a leader is specified (Meerhoff & De Poel, 2014; Rio et al., 2014; Sacheli et al., 2013). For example, Rio et al. (2014) examined visual locomotion control between two people. One person walked behind the other. Participants employed a speed-matching strategy to maintain a following pattern. In this case, the follower presumably has no effect on the leader's walking patterns. Tasks of this nature may offer little insight into when these role emerge given their pre-assignment.

Leader and follower dynamics have also been implicated in mutually coupled scenarios (Konvalinka et al., 2014). In the frequency detuning studies discussed above (Amazeen et al., 1995; Schmidt et al., 1998; Schmidt & Richardson, 2008; Varlet et al., 2014), it is usually concluded the person with the faster uncoupled frequency is the leader. They exhibit a phase lead. Logically, this is similar to the locomotion scenario (Rio et al. 2014). Because one person is ahead, the slower person is deemed the follower. But it remains possible that both people contribute equally to stabilizing the coordination pattern. Put differently, a spatiotemporal lead in relative phase does not guarantee a greater coupling effect. Thus, no clear leader-follower demarcation has been made experimentally.

These example demonstrate that larger problem. Analysis and definitions of leader-follower interactions have always focused on the person who is spatially (or

spatiotemporally) ahead, explicitly labeled, or given privileged information. Most of these findings obfuscate the fundamental fact that roles are characterized by asymmetric influence (i.e., coupling). Properly defining a leader and follower requires a criterion that is neither task dependent nor circularly defined (e.g., phase lead equals leader).

Accordingly, a proper definition of leader-follower interactions can be considered as a case of coupling asymmetries; leaders have a larger impact on the states and state changes of followers than vice versa.

A necessary next step is asking when a limb or person should exhibit a more dominant effect on another, yielding a coupling asymmetry. When do leaders and followers naturally emerge? These directed influence effects are expected when there is a pre-existing asymmetry in the coupling or of difference in intrinsic dynamics of coordinated components. This is generically known as symmetry breaking. The simplest example is when a leader is explicit (e.g., Rio et al., 2014). Roles are clearly delineated. If coupling is mutual, an asymmetry in the intrinsic dynamics or task constraints is likely required. For example, hand dominance can be asserted as a form of leadership (Amazeen, Amazeen, Treffner, & Turvey, 1997; Treffner & Turvey, 1995). One hand drives the behavior of the other to a greater extent. While the basis of handedness effects are debated, it could arise from a known asymmetric information-transfer system: corpus callosal fibers connecting lateralized hemispheres (Bloom & Hynd, 2005; Daffertshofer, Peper, & Beek, 2005). However, dynamics models of rhythmic coordination including handedness effects only capture shifts in the phasing and not informational or influence

effects (Treffner & Turvey, 1995); coupling asymmetries are only considered to the extent that they impact phase stability or lead.

An experimental example where task asymmetries do modify coupling direction is provided by Peper, de Boer, de Poel, & Beek (2008). They (Peper et al., 2008) found amplitude disparities between arms – an asymmetry in task constraints – yields a directed coupling. Participants bimanually coordinated in-phase oscillations at either the same or different amplitude ratios (1:1 or 2:1, and 1:2), while briefly perturbing (frictional load) one of the arms in a cycle. They measured how much the unperturbed arm changed phasing during a relaxation period. Critical were the 2:1/1:2 amplitude conditions. They found smaller amplitude movements contributed more to restoring the intended phase relationship, being affected more by the limb moving a large amplitude. Relative phase was also shifted in a manner similar to frequency detuning studies. Smaller amplitude movements exhibited a phase lead. An implication is that, although the small amplitude limb was ahead, it was actually influenced more by the large amplitude limb. The important conclusion is leading is not spatiotemporally derived. These and similar results (Spijkers & Heuer, 1995) found in bimanual coordination provide a secondary criterion for leader-follower dynamics. Coupling based followers are characterized by more effortful or corrective behavior than leaders. Potentially, followers may also exhibit less variability due to being driven (Fairhurst, Janata, & Keller, 2014; Sacheli et al., 2013; for a different perspective, Vesper, van der Wel, Knoblich, & Sebanz, 2011).

Although the preceding discussion implies coordination may naturally involve leaders and followers, this has yet to be explicitly tested. The following three studies were setup to test the hypothesis that leaders and followers represent a case of asymmetric coupling during social coordination, with followers typically exhibiting a stronger corrective effort to maintain task stability. Participants were asked to rhythmically coordinate the swinging of pendulums in a particular phase relationship. Using the pendulums to examine these interactions provides the benefit of controlling limb properties such as inertia, mass, and expected timing. All studies used a methodology where the effectors ranged from equivalent or differed in their inertial properties. Importantly, this approach has been used in past studies to make claims about leader-follower interactions (Schmidt & Richardson, 2008; Varlet et al., 2014). Effort was considered by measuring the neurophysiological movement drive via electromyographic (EMG) activity.

Summary and Predictions

The first experiment examined the potential for leader-follower effects during mutually coupled coordination. In particular, it was asked whether or not intrinsic asymmetries actually drive changes in the coupling direction. This was accomplished using the frequency detuning paradigm discussed above (Schmidt et al., 1993; Fine et al., 2015). Two points are necessary to consider: this paradigm has been used to make claims about such role-taking interactions, and the manipulation is assumed to not yield directional coupling differences; the main effect is lead or lag in the phasing (Amazeen, et al., 1995; Varlet et al., 2014). The main prediction was leader-follower coupling would

increase with increased limb asymmetry. An auxiliary prediction was increased leader-follower coupling would occur simultaneously with a larger increased effort from the follower.

The second experiment was designed to ask whether or not leader-follower coupling is specifically a function of relative phasing. Specifically, is leading and following strictly a spatiotemporal outcome (i.e., who leads or lags). The design employed a similar coordination task to experiment 1, except each person in a dyad was explicitly assigned the role of leader and follower. Only the follower had the task of coordinating. This setup imputes an already explicit asymmetric coupling. A similar detuning manipulation to experiment 1 was also implemented. The primary prediction is as follows: if leading and following is spatiotemporally driven (phase based), the explicit leader should generally exhibit a phase lead. Given that individuals often exhibit a phase lead when following an explicit environmental target (Fine, Ward, & Amazeen, 2014; Stepp, 2009; Vercher & Gauthier, 1992), it is possible explicit followers could still phase lead. Anticipating this result implies a non-spatiotemporal basis of leader-follower coupling. Pendulum differences (detuning) were also anticipated to modify the strength of coupling effects.

The final experiment examined the possibility that rhythmic coordination is not maintained strictly through phase coupling, but additionally amplitude control. In particular, a major prediction underlying all of these studies is that relative phasing is not the sole determinant of coupling effects. When coordinating, people have to produce a

force (or torque) that changes movement timing and amplitude. It is difficult to parse these apart because most rhythmic coordination tasks present a spatiotemporal requirement (e.g., in-phase). If coupling is based on amplitude, this could explain how someone could phase lead and be a follower simultaneously. This notion is drawn from experiment 2's predictions. Participants in experiment 3 also coordinated frequency detuned pendulums, but were additionally tasked with performing at the same or different amplitudes. A major prediction was leaders are generally characterized by larger amplitudes. Similar to Peper et al. (2008), larger movements were expected to drive the actions of a smaller amplitude limb by providing a larger entrainment signal. Amplitude disparity's effect on leader-follower coupling should also be accompanied by reduced phase stability if it is a significant component in the perceptual-motor coupling. This was anticipated based on the prediction that amplitude (or limit-cycle energy; Frank & Dotov, 2011; Guckenheimer and Holmes, 1983) is particularly relevant in strongly coupled systems (Aronson, Ermentrout, & Kopell, 1990); human motor coordination with explicit pattern goals represents a type of strongly coupled system.

CHAPTER 2

EXPERIMENT 1

Previous research examining rhythmic coordination has noted differences in limb biomechanics or dominance (Amazeen et al., 1995; Schmidt et al., 1993; Treffner & Turvey, 1995), or variable task requirements (Fine & Amazeen, 2011; Fine & Amazeen, 2014; Fine et al., 2015; Peper et al., 2008), yield a scenario wherein one limb will phase lead or lag the other. It is generally assumed the leading limb qualifies as a leader. According to dominant coordination models (e.g., HKB model), the coupling direction should remain unaffected by the detuning asymmetries (see eq. 2). Each person's role is effectively the same, having equal influence on one another. There is no leader or follower in coupling terms, just spatiotemporally.

This first experiment reconsidered the possibility that limb asymmetries actually alter the coupling structure between coordinated actors; leaders and followers will emerge with symmetry breaking. Therefore, leader-follower strength was anticipated to depend on differences in intrinsic dynamics. To test this hypothesis, dyads coordinated the swinging of pendulums differing in their uncoupled eigenfrequency (ω). It was predicted that role emergence would increase parallel to increased detuning ($\Delta\omega$). Put differently, if each person's uncoupled frequency is equivalent ($\Delta\omega = 0$), then minimal effort is needed from either person to maintain coordination (i.e., phase locking). Greater frequency differences require an increased effort to maintain stability. A secondary question was who will lead and follow? To answer this question, coupling measures and

electromyographic (EMG) data were jointly considered to examine the physiological drive employed during coordination.

Methods

Participants. Ten dyads were recruited for participation. Recruited individuals were students from Arizona State University Introductory Psychology courses and graduate students.

Design. Participants were paired in dyads for each experimental session. The dyad's goal was producing in-phase ($\Phi = 0^0$) coordination with handheld pendulums. To test the effect of asymmetries on leader-follower coupling, coordinated pendulum differed in their natural eigenfrequencies, frequency detuning ($\Delta\omega = \omega_{\text{Left}} - \omega_{\text{Right}}$). The left and right in $\Delta\omega$ refer to the person that was left or right seated during the experiment. Detuning was accomplished by creating 5 pendulums having different moments of inertia (see materials below). By crossing these into an asymmetry design, this yielded 5 levels of detuning ($\Delta\omega = -2, -1, 0, 1, \& 2$ rad/s). Each $\Delta\omega$ condition was collected three times, giving a total of 15 trials for coordination conditions. Participants also performed 10 baseline trials (2 per pendulum).

Materials. The pendulums used in this study were created using walking stick handles affixed to wooden rods (0.65 m in length, 1.3 cm diameter). An additional 200 g weight was added to the rod to manipulate the pendulum's moment of inertia or eigenfrequency

(ω). Note that eigenfrequency is related to either the actual length of the pendulum or its virtual length (l_{eq}). Changing the mass height allows manipulating l_{eq} . A pendulum's period is related to l_{eq} by $\frac{1}{2\pi} \sqrt{\frac{g}{l_{eq}}}$, where g is a gravitational constant. Mass heights needed to obtain particular pendulum periods (or frequencies) were calculated using the formula by Kugler & Turvey (1987). Custom built chairs were used to support the arms of each person in a fixed position, allowing for unobstructed swinging and EMG recording. Chairs were raised one foot off the ground.

Position time series were obtained using an Optotrak 3020 (Northern Digital, Waterloo) motion capture system. An infrared diode (1 cm diameter) was placed at the base of each pendulum. The camera system was 6 feet in front of participants. Position data was sampled at 500 Hz. All measures were calculated using only sagittal plane data. EMG data was collected at 1000 Hz, using an MP150 Biopac system (Biopac, Inc.). Before processing, it was downsampled to 500Hz. Control of the OPTOTRAK and EMG was handled using custom software in MATLAB.

Procedure. Participants were instructed to coordinate pendulum swinging in-phase ($\Phi = 0^0$). This was shown to them by the experimenter before beginning any trials.

Participants were asked to grasp the pendulum firmly, and not lift their arm off the rest.

The chair's design restricted motion to the sagittal plane. Because of the side-by-side configuration, one person used their right hand and the other their left. The person assigned to each side was maintained throughout each experimental session.

Each trial lasted a duration of 45 seconds. All coordination trials were presented in random order, but distinct from baseline trials (random presentation within participant). The order of baseline and coordination conditions were counterbalanced between dyads. At the beginning of each trial, participants were told to begin swinging and say “go” when they felt they reached a comfortable frequency. After the signal, the experimenter begin data collection. During baseline trials, participants were given vision blocking goggles to remove any cues available in the periphery regarding partner movements. Participants were allowed to rest between trials when necessary. The procedures used in this experiment conform to the ethical guidelines of the American Psychological Association, and were approved by the Institutional Review Board at Arizona State University.

Data Processing. Only the sagittal plane position coordinates were retained for analyses. To eliminate transients, the first 5 seconds of data were removed. Position data were filtered with a zero-phase shift, low-pass Butterworth filter (12 Hz cutoff, 2nd order). All derivatives were calculated using a gradient method, and then filtered the same as the position to remove increased noise due to differencing. EMG data was collected from the extensor carpi radialis longus, a major component in the control of wrist radial deviation. Digitized EMG was converted to a linear envelope by rectifying and filtering the rectified signal using a low-pass Butterworth filter (3 Hz cutoff, 6th order).

Coordination was assessed using the continuous relative phase (Φ). The phase angle series for each participant was calculated using the $\text{ATAN2} \left(\frac{\dot{x}}{x} \right)$ of the position and

velocity series. Before phase angle calculation, the position and velocity were normalized to the unit circle. This allows removal of arbitrary phase deviations due to intrinsic nonlinearities that distort the monotonic nature of phase angles. It should be noted that amplitude effects were analyzed separately and in conjunction with phase relationships (see below). Mean phase was calculated as the difference in unwrapped phases between the designated *left* and *right* ($\Phi = \theta_{\text{Left}} - \theta_{\text{Right}}$) seated participants. Phase variability was measured using the standard deviation of relative phase ($SD\Phi$). All phase statistics were calculated using circular statistics. Frequency locking was calculated using spectral coherence (see Fine & Amazeen, 2011 or Fine et al., 2013). For increased detuning ($\Delta\omega$), an increased shift in Φ from in-phase was expected. The expected shift is directional, wherein the person with the faster pendulum should exhibit a phase lead. To analyze coupling effects, a coupled phase modeling approach was used. The calculated coefficients were amended with amplitude ratio weights after fitting to the data. This approach allowed a parametric means to capture coupling effects between actors. A final component of this study was relating the amount of effort leaders and followers exert to changes in coupling. This was examined using the peak-to-peak amplitude of the EMG linear envelope. The within-trial means and SD of EMG activity were normalized by their values calculated during baseline trials, with the same pendulum.

[Insert Figure 1 Here]

Results

Coordination: relative phase and frequency locking

In general, mean Φ during bidirectional coordination scenarios tends to yield a phase shift that is dependent on the frequency detuning (Amazeen, et al., 1995; Schmidt et al., 1993; Fine et al., 2015); the faster limb tends to phase lead. A similar result was found in this study, wherein the degree of phase shift was driven by $\Delta\omega$ (Figure 2). A repeated-measures ANOVA on Φ exhibited an effect of detuning, $F(4,36) = 38.94, p < .05, \eta_p^2 = .81$. The linear contrast was also significant, $F(1,9) = 117.35, p < .05, \eta_p^2 = .93$. This follow-up combined with the means confirmed the expected effect. Coordination variability was assessed using SD Φ (Figure 3). The effect of SD Φ was only marginally significant using a Greenhouse-Geiser correction, $F(1.78, 16.02) = 3.59, p = .056, \eta_p^2 = .29$. As predicted from previous studies, the detuning yielded a quadratic form of variability with changes in $\Delta\omega$, $F(1,9) = 24.09, p < .05, \eta_p^2 = .73$.

[Insert Figures 2 & 3 Here]

Frequency locking was estimated using coherence. The grand mean (0.94) suggested that locking was nearly equivalent across conditions, with no effect of detuning, ($p > .05$). The coherent frequency across conditions was 6.8 rad/s. This is close to the average center frequency of 6.4 rad/s.

Kinematics: baseline

The cycle period (samples) mean and SD for baseline trials were analyzed using separate repeated-measures ANOVAs with a factor of pendulum ω (5.40, 5.90, 6.40, 6.90, 7.40 rad/s). As expected, the ANOVA revealed a main effect of ω , $F(4,76) = 22.68,$

$p < .05$, $\eta_p^2 = .54$. The mean periods scaled linearly with ω ; means ranged from 537 (samples; $\omega = 5.40$) to 454 (samples; $\omega = 7.40$). A linear trend confirmed this result, $F(1,19) = 32.68$, $p < .05$, $\eta_p^2 = .63$. The analyses of period SD revealed no effect ($p > .05$).

Amplitude (mm) means and SD were analyzed as well. Expected trade-offs between pendulum ω and amplitude were observed. A repeated-measures ANOVA showed a main effect of ω , $F(4,76)=4.19$, $p < .05$, $\eta_p^2 = .18$. The mean amplitude tended to decrease linearly with increasing ω , $F(1,19) = 6.07$, $p < .05$, $\eta_p^2 = .24$. The amplitude SD was non-significant ($p > .05$).

Kinematics: coordination

Both the means and SDs of period and amplitude were also analyzed for coordination trials. The mean and SD period exhibited no differences across pendulums ω 's (equal to $\Delta\omega$) conditions ($p > .05$). The grand mean period was 440 (samples; or 7.08 rads/s), and the grand SD period was 30 (samples; or 0.37 rads/s). This result generally agrees with the coherence output.

The mean and SD of amplitude were also examined for detuning effects. Amplitude modulation as a function $\Delta\omega$ was confirmed by an ANOVA with pendulum ω as a factor, $F(4,76)=10.51$, $p < .05$, $\eta_p^2 = .36$. The means (Figure 4) suggests a linear increase, wherein the faster ω pendulum elicited the larger amplitudes. Recent studies showed a similar pattern of results (Fine et al., 2015), wherein the highest ω counter

intuitively exhibited the largest amplitude. There was no effect of SD amplitude ($p > .05$).

Given the counterintuitive amplitude results, this suggests amplitude was modified across both actors with increasing $\Delta\omega$. Systematic trends were examined using the AMP-RATIO (defined as $\frac{AMP-LEFT}{AMP-RIGHT}$). The resulting ratios (Figure 5) revealed a significant effect across levels of $\Delta\omega$, $F(4,36) = 16.81$, $p < .05$, $\eta_p^2 = .65$. The trend was also linear, $F(1,19) = 22.05$, $p < .05$, $\eta_p^2 = .71$, confirming that participants swinging the faster pendulum tended to produce a larger amplitude (see $\Delta\omega = -2$ rad/s in Figure 5).

[Insert Figures 4 & 5 Here]

Coupling

As prefaced in the experimental introduction, the main prediction was detuning would elicit a phase shift and change in coupling direction. To assess this claim, phase modeling with amplitude weights was calculated. Coupling coefficients were first calculated using a phase-modeling approach (for details, see Kramann, Cimponeriu, Rosenblum, Pikovsky, & Mrowka, 2008; Rosenblum & Pikovsky, 2001). In short, the assumption is that weakly nonlinear oscillations are compressible to phase only models. The equations of motion of each oscillator can be generally stated as follows:

$$(3) \quad \dot{\theta}_1 = \omega_1 + \left(\frac{R_2}{R_1}\right) Q_1(\theta_1, \theta_2)$$

$$(4) \quad \dot{\theta}_2 = \omega_2 + \left(\frac{R_1}{R_2}\right) Q_2(\theta_1, \theta_2)$$

In eq. 3 & 4, $\dot{\theta}$ represents the phase derivative. On the r.h.s, ω represents that oscillator's autonomous frequency. Specifically, it indicates phase velocity without additional forcing or coupling terms. The Q term represents the overall coupling-forcing term. Simply, it can be broken down into the product of forcing from the other oscillator and phase-response curve. This is the main term to be estimated. An inclusion of the current work is $\left(\frac{R_i}{R_j}\right)$, representing the ratio of amplitudes from the other oscillator and current one.

This term is usually assumed to be unity. More precisely, both oscillators' amplitudes are presumed to be weakly correlated and approximately equal. The AMP-RATIO results, however, show this is generally not the case. Negligence of amplitude terms is only applicable in weak coupling scenarios (Aronson et al., 1990), unlike the current findings (e.g., see SD Φ results). After calculating necessary coupling terms (Qs), they were weighted by the amplitude ratios from the corresponding trial. All calculations were completed using the DAMOCO toolbox (Kralemann et al., 2008). Normalized coupling coefficients and directed coupling terms were calculated as following with the amended equations:

$$(5) \quad \dot{\theta}_{Left} = \omega_{Left} + \left(\frac{R_{Right}}{R_{Left}}\right) Q_{Left}(\theta_{Left}, \theta_{Right})$$

$$(6) \quad \dot{\theta}_{Right} = \omega_{Right} + \left(\frac{R_{Left}}{R_{Right}}\right) Q_{Right}(\theta_{Left}, \theta_{Right})$$

$$(7) \quad C_{Left} = \left(\frac{R_{Right}}{R_{Left}}\right) \frac{\|Q_{Left}\|}{\omega_{Left}}$$

$$(8) \quad C_{Right} = \left(\frac{R_{Left}}{R_{Right}} \right) \frac{\|Q_{Right}\|}{\omega_{Right}}$$

$$(9) \quad Coupling = \frac{C_{Left} - C_{Right}}{C_{Left} + C_{Right}}$$

Formula 9 restricts the range of the output to a bounded (and unit less) interval [-1,1]. For example, a value of 1 represent a completely directed coupling effect of the right-seated person driving the left. The ANOVA revealed a main effect of $\Delta\omega$ on Coupling, $F(4,36)=7.56, p < .05, \eta_p^2 = .46$. As expected, there was also a significant linear trend (Figure 6), $F(1,9)=10.55, p < .05, \eta_p^2 = .54$. Coupling direction changed as a function of detuning. Examination of the values suggests that faster frequency pendulums tended to have a greater driving effect on slow frequency pendulums.

[Insert Figure 6 Here]

Neuromuscular Effort

The EMG peak AMP was analyzed individually for both people, at each pendulum ω . Note again that ω still represents the appropriate level of detuning. It was predicted that EMG AMP would scale with changes in coupling. The effect of ω for mean AMP was significant, $F(4,76)=5.65, p < .05, \eta_p^2 = .23$. Follow-up polynomial contrasts also revealed a significant linear ($F(1,19)=10.41, p < .05, \eta_p^2 = .35$) and quadratic trend ($F(1,19)=7.63, p < .05, \eta_p^2 = .29$). This result is visible in the graph of mean AMP (Figure 7). Effort increased for both people, high and low inertia pendulums, as detuning increased. The quadratic trend indicates this result was not an artifact of

inertia. Moreover, simple comparisons show the main difference was between $\omega = 5.4$ and $\omega = 7.4$ (rad/s), $F(1,19)=5.31$, $p < .05$, $\eta_p^2 = .22$. There was no variability effect as estimated by SD AMP ($p > .05$).

[Insert Figure 7 Here]

Discussion

Previous research on rhythmic coordination has treated asymmetries as exclusively altering phase dynamics (e.g., shift and stability). The specifically employed asymmetry (detuning) is presumed to not modify the coupling directionality, just its strength (indexed by relative phase variability). Leading and following has been treated as a simple phase lead-lag effect. This experiment tested the proposal that detuning asymmetries alter the coupling asymmetry during coordination; system asymmetry was expected to yield an emergent leader and follower.

On the basis of these predictions, it was necessary to show a simultaneous change in Φ and coupling. As expected, mean Φ exhibited a directional shift expected from $\Delta\omega$ manipulations. Participants with the faster pendulum tended to phase lead. Establishing the phase-shift allows asking what effects detuning had on coupling. As predicted, coupling measures (phase coupling) confirmed an effect of $\Delta\omega$ (Figure 6). This result shows increasing detuning enhanced the driving effects one person had on the other. Examining the plots (Figure 2 and 6) shows the coupling based leader was the person

with the faster pendulum. Together, both results show increased limb asymmetry (detuning) yielded an asymmetric coupling.

A change in detuning was also predicted to modify the amount of effort exerted by leaders and followers. Followers were expected to exert more effort to maintain task stability. This does not imply effort would not increase for leaders, but would increase to a greater extent for followers. Support for this prediction is found in the EMG-AMP (Figure 7.) results. First, $\Delta\omega = 0$ (rad/s) conditions should yield a result close to baseline if effort follows coupling. This result is seen Figure 7. The relationship between coupling and effort is further elaborated by the quadratic EMG effect. Increased $\Delta\omega$ showed effort increased for low and high inertia pendulums, indicating a larger amount of control from both participants. An important result was the comparison between $\omega = 5.4$ and $\omega = 7.4$ (rad/s; equal to $\Delta\omega \pm 2$). They were significantly different from one another, with the coupling indicated follower ($\omega = 5.4$) exerting a larger effort. The mean difference was approximately 18%.

The predicted increased effort was based on the notion that it is a means to mitigate coordination instability. In other words, increased effort was not accompanied by a weaker coordination dynamic. There was only a marginal effect of SD Φ . SD Φ effects are often found in detuning studies, to the point of being considered ubiquitous (Amazeen et al., 1995; Schmidt et al., 1993). Similar observations of no effect have been observed elsewhere (Fine et al., 2015). The detuning range in this experiment (2 rad/s) is also comparable to others (Amazeen et al., 1995) showing an effect on stability. Methodologically, the studies diverge because these paradigms typically use a

metronome to drive movement speed. This external coupling source is difficult to account for, and is a likely cause of an exaggerated $SD \Phi$ effect. In general, both of these results indicate increased effort may have played a substantial role in stabilizing coordination as task difficulty increased. These efforts were not distributed equally among participants, supporting an emergent distribution of roles.

A final outcome to consider is the mean amplitude and amplitude ratio. Previous experiments (Fine et al., 2015) also found detuning effects on amplitude. The inverse frequency-amplitude relationship of unimanual (baseline) movements predict that faster frequency pendulums should produce the smaller of the two amplitudes. However, the faster frequency pendulum elicited the larger of the two. An implication is amplitude asymmetries, not necessarily detuning, could yield differential coupling effects. The effects of amplitude asymmetries are given detailed consideration in a later experiment (see experiment 3).

Overall, these results clearly demonstrate symmetry breaking alters the coupling symmetry. However, it is unclear whether or not these effects are solely attributable to relative phase arrangement. If the coupling asymmetry is phase based, this creates a prediction for scenarios with explicit leaders in such rhythmic tasks. If each person is assigned a lead and follow role, knowing the direction of coupling anticipates the leader should generally exhibit a phase lead. The following experiment was designed to test this prediction.

CHAPTER 3

EXPERIMENT 2

The results from experiment 1 and previous research have indicated a general phase lead-lag effect of detuning manipulations. Experiment 1 also demonstrated detuning yields a coupling asymmetry. The faster pendulum tended to phase lead and drive in terms of coupling. To conclude unequivocally that the coupling is phase driven, it is necessary to test for coupling asymmetries when roles are established a priori.

If phase leading was the main cause of experiment 1's results, a general prediction can be made when an explicit leader-follower structure is imposed under detuned conditions. Explicit leaders should always phase lead. Alternatively, coupling results from experiment 1 could arbitrarily shift as a function of detuning ($\Delta\omega$). This would imply insensitivity to actual coupling effects. A third possibility stems from work on unimanual (environmental) tracking. During tracking, participants often phase lead the driving target (Stepp, 2009; Fine, Ward & Amazeen, 2014; Vercher and Gauthier, 1992; Voss, 2000). This occurs despite the unidirectional drive, and even under artificially imposed delays (Stepp, 2009). Results of this kind suggest the coupling effects in experiment 1 may not be readily attributed to relative phase lead-lag. If the relative phasing of leader and followers exhibit a pattern similar to unimanual tracking, this would imply the coupling effect from experiment 1 is not strictly spatiotemporal. To test this, dyads again coordinated the swinging of pendulums differing in their uncoupled eigenfrequency (ω). One participant was assigned an explicit leader role in each trial, ignoring the actions of the other. If the coupling approach is sensitive to the true leader-

follower dynamics, coupling from leader to follower should be larger in all conditions. Coupling effect strength was also expected to be modulated by the difference in follower and leader pendulum frequency (detuning; $\Delta\omega$).

Methods

Participants. Eleven dyads were recruited for participation. Recruited individuals included students from Arizona State University Introductory Psychology courses for participation and graduate students.

Design. Participants were paired in dyads for each experimental session. Because the coupling is unilateral in this experiment, only one person in each trial was tasked with performing in-phase ($\Phi = 0^0$) coordination. The pendulum's moment of inertia for the follower was altered to manipulate the uncoupled frequency difference ($\Delta\omega$). Leaders always used a pendulum of fixed frequency ($\omega = 6.4$ rads/s). This allowed constancy of the driving (leader) frequency throughout trials. The followers' pendulums consisted of 5 different values of ω (5.4, 5.9, 6.4, 6.9, & 7.4 rads/s), such that it was either faster or slower, compared to the leader's. These pendulums yielded 5 levels of detuning (-1.0, -0.5, 0, 0.5, 1 (rads/s)). For $\Delta\omega = 0$, the only asymmetry was the coupling arrangement. Combining the factors of leading participant (left or right) and $\Delta\omega$ yielded ten conditions. Each trial was conducted twice, with a total of 20 coordination trials. $\Delta\omega$ in statistical analysis refers to the difference between leader and follower, not left minus right; for clarity, notation was changed to $\Delta\omega_{L-F}$. This arrangement still maintains detuning, with

negative values for faster follower pendulums; for example, the condition with the follower $\omega = 7.40$ (rad/s) is equivalent to $\Delta\omega_{L-F} = -1$ (rad/s). Participants also performed two baseline trials for each pendulum. A total of 10 baseline trials (2 per pendulum) per person were collected. All coordination trials were fully randomized, but performed separately from randomized baseline trials. Again, the order of baseline and coordination trials was counterbalanced across dyads.

Materials. The pendulums used in this study were identical to experiment 1. Data collection was handled in a similar manner, including sampling rates, muscles sites and system control.

Procedure. The procedure in this experiment was nearly identical to experiment 1. Given the specified leader, each person was designated as a leader and follower for each trial. Followers were instructed to visually attend to the pendulum of the other person and maintain in-phase. Leaders were instructed to look forward and ignore the follower's movements. Leaders were also given vision blocking goggles to ensure peripheral information was not available. Each trial lasted a duration of 45 seconds.

Data Processing. Calculation of relevant variables was nearly identical to experiment 1. Main differences are found in the calculation of dyadic level measures, including relative phase and coupling variables. Instead of taking differences as left from right, mean Φ , for example, was calculated as the difference in unwrapped phases between the

designated *leader* and *follower* ($\Phi = \theta_{\text{Leader}} - \theta_{\text{Follower}}$). A similar variation was also created for the coupling measure (explained below).

Results

Coordination: relative phase and frequency locking

Relative phasing was analyzed using mean Φ across all 5 detuning levels ($\Delta\omega_{\text{L-F}}$). Differences in mean Φ (Figure 8) showed the follower exhibited a phase lead across most detuning conditions. A repeated-measures ANOVA confirmed this effect of $\Delta\omega_{\text{L-F}}$, $F(4,40) = 50.69, p < .05, \eta_p^2 = .84$. This result contrasts scenarios involving bidirectional coupling between two people or arms (Amazeen, et al., 1995; Fine et al., 2015), wherein the person with the faster pendulum typically exhibits a lead. Importantly, the explicit follower phase lead across detuning levels. Relative phase variability was analyzed using SD Φ . The effect was not significant ($p > .05$), with a grand mean of 17.5^0 across conditions. These results are similar to experiment 1 and other recent detuning studies (Fine et al., 2015). This mean SD Φ is approximately equal to that commonly observed within this detuning range (SD $\Phi \approx 20^0$).

[Insert Figure 8 Here]

Frequency locking was analyzed using coherence. No effect ($p > .05$) of coherence implied equivalent locking across conditions. Average coherence and SD across conditions was 0.94 and 0.08, indicating strongly coupled frequencies. The

average coherent frequency was 5.88 rads/s ($SD = 0.56$ rad/s), indicating performance was close to the fixed frequency of the leader pendulum (6.40 rads/s).

Kinematics: baseline

The cycle period (samples) mean and SD for baseline trials were analyzed using separate repeated-measures ANOVAs with a factor of pendulum ω (5.40, 5.90, 6.40, 6.90, 7.40 ,rads/s). As expected, the ANOVA revealed a main effect of ω , $F(4,84)=91.18$, $p < .05$, $\eta_p^2 = .81$; mean periods scaled linearly, whereby performance was close to the resonant frequency. There was no effect of period SD ($p > .05$).

Amplitude (min-to-max and vice versa; mm) means and standard deviations were analyzed as well. The expected decrease in amplitude with increasing ω was confirmed by a repeated-measures ANOVA, $F(4,40)=4.29$, $p < .05$, $\eta_p^2 = .30$. There was no effect of amplitude SD ($p > .05$). In combination with mean period, these results confirm the canonical inverse relationship between frequency and amplitude.

Kinematics: coordination

The same variables analyzed for baseline trials were also examined for coordination trials. However, these were considered separately for leaders and followers. They are presented accordingly for each variable. Mean and SD period for leaders exhibited no differences across $\Delta\omega_{L-F}$ conditions ($p > .05$). The grand mean was 530 (samples; or 5.90 rads/s), and the mean SD period was 43 (samples; or 0.54 rads/s). The

same variables for the follower did not yield any differences across conditions. The follower mean period mean and SD were 527 (samples; 5.95 rads/s) and 42 (samples; 0.53 rads/s), respectively. This result agrees with the coherence output.

The mean and SD amplitude for leaders were also consistent across $\Delta\omega_{L-F}$ conditions ($p > .05$). Grand means for mean amplitude and SD were 613 mm and 43 mm. Importantly, mean amplitude for followers did change according to $\Delta\omega_{L-F}$. A repeated-measures ANOVA yielded an effect, $F(4,84)=6.30$, $p < .05$, $\eta_p^2=.23$. Follow-up polynomial contrasts revealed mean amplitude (Figure 9) exhibited an inverse quadratic trend, $F(1,21)=25.20$, $p < .05$, $\eta_p^2=.55$. Amplitude was highest at $\Delta\omega_{L-F} = 0$ rads/s, and lowest at $\Delta\omega_{L-F} \pm 1$ rads/s. No effect for follower SD amplitude was evident ($p > .05$).

[Insert Figure 9 Here]

The follower amplitude result implies it was modulated according to the task difficulty ($\Delta\omega_{L-F}$). Amplitude decreased for faster and slower pendulums. This indicates the possibility of a systematic relationship between leader and follower amplitude.

Amplitude effects were again measured using the amplitude ratio (AMP-RATIO = $\frac{AMP_{Leader}}{AMP_{Follower}}$). AMP-RATIO was analyzed according to $\Delta\omega_{L-F}$. The ANOVA yielded an effect of $\Delta\omega_{L-F}$, $F(4,84)=5.84$, $p < .05$, $\eta_p^2=.22$, and a significant inverse quadratic trend, $F(1,21)=27.93$, $p < .05$, $\eta_p^2=.57$. Mean ratios (Figure 10) demonstrate follower's typically exhibited smaller amplitudes than the leader. Comparing followers with a slower (e.g., $\omega = 5.4$ rad/s) and faster pendulum ($\omega = 7.4$ rad/s) showed a closer to unity

ratio for faster pendulums. Counterintuitively, using the faster pendulum yielded larger amplitudes.

[Insert Figure 10 Here]

Coupling measures

This study's main goal was to compare the relative phase dynamics and coupling effects. To this end, the same phase modeling methods were applied. The two model phase equations are similar to that employed in experiment 1, excepted corrected for *leader-follower* arrangements:

$$(10) \quad \textit{Coupling} = \frac{C_{\textit{Leader}} - C_{\textit{Follower}}}{C_{\textit{Leader}} + C_{\textit{Follower}}}$$

This formulation is designed so negative values represent greater coupling going from leader to follower. Mean *Coupling* values followed the $\Delta\omega_{L-F}$ asymmetry (Figure 11). A repeated-measures ANOVA across levels of $\Delta\omega_{L-F}$ confirmed the predicted effect, $F(4,84)=4.36, p < .05, \eta_p^2 = .18$. The follow-up quadratic trend was also significant, $F(1,21)=18.39, p < .05, \eta_p^2 = .47$. Coupling means (Figure 11) suggest driving effects were highest when the follower had the slower pendulum.

[Insert Figure 11 Here]

Neuromuscular effort

The mean and SD EMG-AMP for followers were both analyzed. A repeated-measures ANOVA on mean AMP revealed a significant effect of $\Delta\omega_{L-F}$, $F(4,84) = 2.68$, $p < .05$, $\eta_p^2 = .13$. Follow-up contrasts revealed a significant quadratic trend ($F(1,21) = 8.85$, $\eta_p^2 = .30$). Effort increased for both the lowest and high inertia pendulums. The means (Figure 12) suggest peak activity was largest with the high inertia pendulum (lowest ω). There was also an effect of AMP SD $F(4,84) = 3.41$, $p < .05$, $\eta_p^2 = .14$. AMP SD effects interestingly show (Figure 12) that EMG activity was more variable for lower inertia pendulums during coordination.

Discussion

This experiment's aim was examining leader-follower coordination in a manner that was explicit: one person was assigned the job of coordinating with the other (i.e., leader). This was accomplished using a rhythmic coordination task, wherein intrinsic dynamics of leader and follower were controlled through frequency detuning. While obvious that coupling should flow from leader to follower, less apparent are effects of intrinsic dynamics and phasing. Previous research and experiment 1 imply leader-follower coupling is driven by relative phasing, i.e., who is ahead and behind. These types of conclusions are based on results showing a directional phase shift of Φ according to $\Delta\omega$ (Amazeen et al., 1995; Sternad et al., 1995; Schmidt et al., 1993). Following such a logic has implications for combining detuning and an explicit role design. The leader

should generally exhibit a phase lead along with coupling drive. This was not supported by this study's results. Coupling was not driven by spatiotemporal lead-lag.

Coupling estimates (phase model) revealed a directed influence of the leader to the follower in all cases. An important prediction was coupling changes would scale with $\Delta\omega_{L-F}$. Coupling effects were lowest at $\Delta\omega_{L-F} = 0$, growing quadratically with increased detuning. This verifies the prediction that coupling asymmetry is altered by symmetry breaking in intrinsic and task (role structure) dynamics. Combining these results with mean Φ provides confirmation that coupling was not driven explicitly by phase lead or lag. Specifically, the follower tended to phase lead across all detuning conditions (Figure 8). In terms of Φ they were leading, in coupling terms they were driven.

Another key question was how do coupling effects drive effort at the control level? While all followers in this experiment were explicit, a prediction congruent with experiment 1 was effort would scale with coupling. This prediction was verified by the EMG AMP results. Means exhibited a quadratic trend that scaled with coupling strength (see Figures 11 & 12); peak effort was generally greater than baseline in nearly all detuning conditions. Overall effort was slightly larger for high inertia pendulums compared to low inertia. This difference between the slowest and fastest ω , though, was not significant. A second notable result was the EMG variability. SD AMP was larger for low inertia pendulums. Combined examination of the mean and SD AMP shows a differential relationship between mean effort and variability across pendulum ω (Figure 12).

Both mean and variability EMG findings may be attributed to two dual processes: as $\Delta\omega_{L-F}$ increases in either direction, the need to exert control increases. An unlikely result is detuning having an equivalent effort effect for high ($\Delta\omega_{L-F} = 1$) and low inertia ($\Delta\omega_{L-F} = -1$) pendulums. To maintain a stable phase pattern, low inertia followers only need to increase or lengthen the overall force across the movement cycle extent. Control of force in this manner would essentially lengthen the swing period and amplitude to a point needed to match leader frequency. Though speculation, this is supported by the larger amplitude exhibited by high inertia pendulums. In contrast, following with the high inertia pendulum requires a different control process. It is necessary to speed up. Inevitably, this requires a larger stiffness. Stiffness control would have resulted in a larger EMG signal. The reason for less variability with the high inertia is likely due to the pendulum's filtering response. The higher a pendulum's inertia, the less it will respond to a given torque. Essentially this implies the larger inertia pendulums can receive a large impulse while producing a larger damping or filtering response. The main implication is followers do exert more effort, but in a means that potentially minimizes variability.

A last issue is disagreement between relative phase and coupling across both experiments 1 & 2. If relative phase dynamics do not explain the changes in coupling, another candidate control variable needs identification. Park & Turvey (2008; see also, Fine et al., 2015; Kudo et al., 2006; Peper et al., 2008) suggested rhythmic coordination may require inclusion of amplitude terms. However, phase only models ignore oscillation amplitude for two reasons: the amplitude is a slowly changing variable compared to

phase (Strogatz, 2001), and both limbs' (oscillators) amplitudes are approximately equal (Fuchs, 2011). Focusing on the latter, results obtained from the AMP-RATIO showed amplitude was not constant across trials. Followers always maintained a lower amplitude than the leader. The potential for amplitude coupling effects are clarified by comparison of coupling strength and AMP-RATIO. In general, the farther away AMP-RATIO was from unity, the larger the coupling effect. While this could be related to weighting the phase coupling by amplitudes, similar significant effects were obtained by phase coupling estimates without amplitude weights ($p < .05$). Given the disagreement between relative phases and coupling in experiments 1 & 2, the amplitude ratios suggest the coupling is largely amplitude based. This proposal implies that altering the amplitude ratio between individuals should change the direction of coupling. Experiment 3 was designed to test this hypothesis.

CHAPTER 4

EXPERIMENT 3

The previous experiments were designed to examine leader-follower dynamics in mutually coupled and explicit scenarios. Combined results of both studies suggest the leader-follower coupling is potentially not contingent on phase leading (see Experiment 2). While in experiment 1 the phase leader happened to be the leader, experiment 2 revealed the explicit follower nearly always phase lead. This latter result implies a mechanism allowing someone to follow from ahead (i.e., phase leading). To fully understand the relationship in leader-follower coordination requires consideration of which variables individuals are controlling: what constitutes the coupling relation in these rhythmic dynamics?

An imperative result in both experiments 1 and 2 was the amplitude ratio changed systematically with coupling. Increased amplitude disparity was accompanied by an increase in coupling asymmetry. A similar relationship was not observed between relative phase and coupling. This suggests amplitude control may play a distinct role. This proposal further agrees with Peper et al.'s (2008) results on bimanual amplitude disparities. They showed disparities favored a stronger influence of large movements onto small, which was accompanied by reduced phase stability and shifts. If amplitude plays a significant role in rhythmic-motor coupling, introducing a disparity between participants should alter the leader-follower dynamics. Specifically, assigning a person a larger amplitude should put them in a position as a coupling leader. This hypothesis was tested in this experiment by, again, using a frequency detuning paradigm. Participants

were also instructed to coordinate either naturally or at half (or double) the amplitude of their partner.

Methods

Participants. Ten dyads were recruited for participation. Participants included students from Arizona State University Introductory Psychology courses and graduate students.

Design. Participants paired in dyads were asked to coordinate pendulum swinging in an in-phase ($\Phi = 0^0$) pattern. Symmetry breaking will be implemented using the same frequency detuning ($\Delta\omega$) manipulation from experiment 2 ($\Delta\omega = -2, -1, 0, 1, 2$ rads/s). The main manipulation was asking people to coordinate at difference ratios of one another's amplitude (1:1, 2:1, & 1:2). Amplitudes were self-selected to not bias participant's exerted force. With 2 trials in each condition, the combined factors yielded a total of 30 trials for coordination conditions. Each participant also performed 10 baseline trials, 2 for each pendulum.

Materials. All of the materials in this experiment were identical to experiment 1 and 2.

Procedure. The procedure used in this experiment was identical to the other studies. Each trial lasted a total of 45 seconds. All coordination trials were presented in random order. Baseline trials were randomly presented, but performed within a single session. Coordination and baseline order was counterbalanced across dyads.

Data Processing. Only the sagittal plane position coordinates were retained for analyses. Again, the data were handled the same as previous experiments. Given both factors $\Delta\omega$ and Ratio (1:1, 1:2, & 2:1), any reference to Ratio in dyad level measures refers to the amplitude asymmetry. On individual level measures, such as mean period (mm), it refers to the amplitude requirement assigned to the person on the left of the ratio. For example, 2:1 indicates the analyses is directed at the person performing the larger relative amplitude.

Results

Coordination: relative phase and frequency locking

Coordination was analyzed using mean Φ . As expected for the 1:1 Ratio condition (see Figure 13), there was a phase shift as a function of detuning. The 1:2 and 2:1 amplitude ratios also shifted Φ , whereby the person with the smaller amplitude always phase lead. This was confirmed by a two-way, repeated-measures ANOVA with the factors $\Delta\omega$ (5) and Ratio (3). Both main effects of $\Delta\omega$ ($F(4,36) = 65.28, p < .05, \eta_p^2 = .87$) and Ratio ($F(2,18) = 22.88, p < .05, \eta_p^2 = .72$) were significant. There was no interaction ($p > .05$). The Ratio variable shifted the intercept of the curve across levels $\Delta\omega$, while detuning effects were similar within a Ratio.

The analyses of SD Φ was analyzed to test the prediction that coupling is amplitude driven. Confirmation of this would result in significantly higher variability for the 1:2 and 2:1 scenario compared to 1:1. While the two-way ANOVA revealed no effect of $\Delta\omega$, the effect of Ratio was significant as predicted, $F(2,18) = 20.47, p < .05, \eta_p^2 = .70$.

As seen in Figure 14, the 1:1 Ratio was more stable than both the 1:2 and 2:1. This difference was verified using the combined average of 1:2 and 2:1 compared to 1:1. This effect was confirmed with a simple contrast (bonferroni adjusted, $p < .05$).

Frequency locking was estimated using coherence. The grand mean (0.93) suggested strong frequency locking across conditions. There was no effect of $\Delta\omega$ or Ratio (both $p > .05$). In general, the coherent frequency was consistent across conditions was 7.4 rads/s.

[Insert Figure 13 & 14 Here]

Kinematics: baseline

The cycle period (samples) mean and SD for baseline trials were analyzed using separate repeated-measures ANOVAs with a factor of pendulum ω . As expected, the ANOVA revealed a main effect of ω , $F(4,76)=53.92$, $p < .05$, $\eta_p^2 = .74$. The mean periods scaled linearly with ω , ranging from 573 (samples; $\omega = 5.40$) to 410 (samples; $\omega = 7.40$). A linear trend confirmed this result, $F(1,13) = 131.50$, $p < .05$, $\eta_p^2 = .87$. Analysis of period SD revealed no effect ($p > .05$).

Amplitude (mm) means and SD were analyzed as well. The one-way ANOVA revealed a main effect of ω , $F(4,76)=8.15$, $p < .05$, $\eta_p^2 = .36$. The mean amplitude decreased linearly with increasing ω , $F(1,19) = 16.65$, $p < .05$, $\eta_p^2 = .46$. There was no effect on amplitude SD ($p > .05$).

Kinematics: coordination

Analyses of mean period yielded a significant two-way interaction between pendulum ω and Ratio, $F(8,152)= 3.54, p < .05, \eta_p^2= .20$. While comparisons (Bonferonni adjusted) revealed several differences between levels of pendulum for Ratios, the interaction source is likely due to no differences among Ratios between pendulum $\omega = 6.9$ (rad/s) and another ω s. Despite this interaction, the graph (Figure 15) is explanatory. The plot of means shows a strong match of period between pendulums at the 1:1 Ratio. Though, in the 1:2 Ratio the person with the smaller amplitude movement tended to produce a shorter period; the person with the larger amplitude assignment consequently produced a longer period. The SD period analysis also revealed an effect of Ratio, $F(2,38)= 6.23, p < .05, \eta_p^2= .25$, but not of pendulum ω . The means for the 3 ratios (1:1 = 23, 1:2=31, & 2:1 = 25 samples) suggests smaller amplitude movements yielded slightly more variability.

[Insert Figure 15 Here]

The amplitude (mm) mean and SD were also examined. The ANOVA revealed an effect of Ratio, $F(2,38)=98.94, p < .05, \eta_p^2= .84$, and of pendulum ω , $F(4,76)=3.83, p < .05, \eta_p^2= .17$. The means of all 3 ratios (1:1 = 438, 1:2 = 321, & 2:1=550 mm) suggest people performed the 1:2 and 2:1 requirements of the task (Figure 16). The effect of ω indicates amplitude was generally higher for faster (low inertia) pendulums ($\omega = 7.4$ rads/s) across ratios. Amplitude disparity was accompanied by an increase in amplitude

SD. Analysis revealed only a main effect of Ratio, $F(2,38)=22.41$, $p < .05$, $\eta_p^2 = .54$. Consideration of the means across Ratio (1:1 = 39, 1:2 = 36, & 2:1=49 mm) and follow-up comparisons showed the 2:1 Ratio was different from 1:1 and 1:2 ($p < .05$), but they were not different from each other ($p > .05$). Variability was highest for the person performing the larger of both amplitudes.

[Insert Figure 16 Here]

The main amplitude effect of interest is the ratio between participants. AMP-RATIO was analyzed for both $\Delta\omega$ and Ratio. Analysis revealed both the $\Delta\omega$, $F(4,36)=7.84$, $p < .05$, $\eta_p^2 = .47$, and Ratio, $F(2,18)=47.33$, $p < .05$, $\eta_p^2 = .85$, main effects were significant. The means (Figure 17) show the effect of $\Delta\omega$ linearly shifting the AMP-RATIO across all amplitude disparities. A linear contrast for $\Delta\omega$ substantiates this, $F(1,9)=18.04$, $p < .05$, $\eta_p^2 = .67$. The Ratio effect was confirmed by the means in the 1:2 and 2:1 amp condition, wherein people performed close to the required relative amplitude.

[Insert Figure 17 Here]

Coupling Measures

This study's main prediction was amplitude control underlies the coupling dynamics. Manipulating amplitude disparity therefore should affect the leader-follower

interaction. This was examined using phase modeling. Model coefficients were weighted with amplitude ratios, while Coupling was calculated in a left-right arrangement (see Experiment 1). The ANOVA revealed a significant interaction of $\Delta\omega$ and Ratio, $F(8,72) = 3.16, p < .05, \eta_p^2 = .26$. Examination of Figure 18 shows a similar coupling result to experiment 1 for the 1:1 Ratio. The faster pendulum tended to drive the slower. For the 1:2 and 2:1 Ratios, it is clear that the coupling was driven by the person with the larger amplitude requirement. These differences are the likely interaction source. Follow-up analyses using simple contrasts revealed no $\Delta\omega$ effect when comparing the 1:2 and 2:1 Ratios. When comparing the average absolute values of the 1:2 and 2:1 Ratios to the 1:1 there was a $\Delta\omega \times$ Ratio interaction, $F(4,36) = 9.17, p < .05, \eta_p^2 = .51$. This result suggests detuning had an effect on the 1:1, but not disparate amplitude Ratios. Amplitude asymmetries yielded a stabilizing effect on coupling, whereby the switch seen across $\Delta\omega$ levels in the 1:1 Ratio were mitigated.

[Insert Figure 18 Here]

Neuromuscular Effort

The EMG AMP mean and SD were again analyzed to examine changes in effortful control. Analyses revealed an effect of Ratio on mean AMP, $F(2,38) = 22.36, p < .05, \eta_p^2 = .54$, and an effect of ω , $F(4,76) = 11.08, p < .05, \eta_p^2 = .37$. Follow-up analyses for Ratio revealed that all levels differed from one another (Bonferonni adjusted, $p < .05$). Interestingly, the lowest AMP was in the 1:2, with the highest in the 2:1 (Figure 19). The

effect of ω was analyzed using polynomial contrasts. The linear ($F(1,19) = 28.37, p < .05, \eta_p^2 = .60$) and quadratic ($F(1,19) = 11.41, p < .05, \eta_p^2 = .38$) trends were both significant. Overall, these trends indicate higher inertia pendulums exhibited a larger effort across Ratio levels.

Analysis of SD AMP also revealed an significant interaction of Ratio and ω , $F(8,152) = 3.24, p < .05, \eta_p^2 = .15$. To find the source of the interaction, follow-up analyses comparing the 1:1 and 1:2 across levels of ω was conducted using a repeated-measures ANOVA. As anticipated from Figure 20, the interaction was significant, $F(4,76) = 4.14, p < .05, \eta_p^2 = .18$. Comparisons within this analyses showed that both Ratios were different for all levels of ω except $\omega = 5.9$ (rad/s). The Mean SDs (Figure 20) across Ratios actually indicate variability was lowest for 1:2 (89 % baseline), with 1:1 (102 % baseline) and 2:1 (129 % baseline) exhibiting a more variable response.

[Insert Figure 19 & 20 Here]

Discussion

Past research on rhythmic coordination has generally pursued coupling mechanisms based on phase and its derivatives. This has garnered conclusions about leader-follower coupling based on phase lead and lag. Effects related to amplitude are often not considered. However, the previous two studies and others (de Poel, Peper, & Beek, 2009; Fine et al., 2015; Kudo et al., 2006; Park & Turvey, 2008; Peper et al., 2008) indicate the amplitude may exert a large influence on such coupling. This study

tested this possibility, predicting that amplitude asymmetries should alter the coupling asymmetry or leader-follower direction. The results confirmed the prediction that coupling direction and stability (indexed by $SD \Phi$) were modified by differential amplitude requirements.

The correspondence between amplitude and coupling is revealed by comparing the mean Φ and coupling results. Overall, coupling and mean Φ during 1:1 trials were similar to experiment 1. Coupling was driven by the person with the faster (high inertia) pendulum. As noted in these other experiments, the faster person also produced a larger amplitude. Currently, the important conditions are the 1:2 and 2:1 ratios. In this case, participants tasked with the larger amplitude drove the coupling. The person producing a smaller amplitude exhibited a phase lead across all detuning levels, however. Put simply, phase leading had little distinguishable impact on coupling compared to amplitude manipulation.

A possible explanation is amplitude manipulations just displaced the relative phase curves, such that a switch between the left and right person phase leading across $\Delta\omega$ was slowed. However, constraining the amplitude in 1:2 or 2:1 stabilized the coupling effect; the large amplitude movements always drove the coupling. This is supported by the interaction and follow-up of Coupling. Removing the amplitude constraint (i.e., 1:1) yielded the expected switch in coupling across $\Delta\omega$, but was clearly driven by amplitude ratios.

Another concern was the effect of amplitude disparity on stability. If amplitude drives coupling, and the most stable coordination appears during a match of amplitude,

stability should decrease significantly when manipulated. First, detuning's impact on SD Φ results were generally negligible. Again, this result agrees with previous studies (Fine et al., 2015). The effect of Ratio was large, as anticipated. Stability was significantly degraded in differential amplitude conditions. This result further demonstrates the pertinence of amplitude based coupling.

A final hypothesis throughout all experiments was that followers would exhibit a larger stabilizing effort. Support for this was less clear in the current EMG results. Mean AMP did show differences across levels of detuning or pendulum. The previous two experiments showed mean AMP was higher for the high inertia pendulum, which was also found in the current work. However, the previous studies revealed an effect whereby there were similar increases in effort for high and low inertia pendulums. In the current work, the AMP generally declined from high to low inertia. However, the quadratic effect does suggest there still was a slight increase going from $\Delta\omega = 0$ to high inertia pendulums. This effect was clearly smaller than expected, particularly in the 1:1 scenario. Potential reasons for this divergence are suggested below.

One possible reason for this trend is the movements were not scaled by appropriate baselines. The other experiments had no amplitude requirement; though, this should not impact the 1:1 condition. Regardless, the same standard baseline used in the other experiments was used to normalize in this study as well. One unknown is whether or not baseline swinging a pendulum at a self-chosen small and large amplitude has a

different change in activity over the different inertias. Thus, normalizing only on the standard baseline could have altered the coordination outcome.¹

Although the effect of ω is less clear, the effect of Ratio also requires interpretation. At first glance, it suggests followers did not exert more effort. The means for each ratio (1:1 = 103%, 1:2 = 97%, and 2:1 = 120% of baseline) show that the least effort was exerted by followers in the 1:2 condition. Moreover, the difference between 1:2 and 1:1 was significantly different (see results above). This does imply follower's effort was lower than leaders, even below baseline. Producing the larger amplitude also yielded the largest output. A possible explanation for this result is found in the amplitude manipulation. For example, when required to produce a small amplitude, individuals may switch to a different means of control. Rather than increasing force, people may have accommodated the amplitude requirement by producing less force in shorter impulses; this resulted in less force than baseline. A consequence of this control scheme would yield shorter and potentially faster oscillations. This would explain the emphasized phase lead. The opposite may have occurred for larger amplitudes. By manipulating amplitude, this also may have switched the roles in terms of who exerted the largest effort to coordinate.

In general, the amplitude manipulation made the task more difficult. When allowed to self-choose amplitude (e.g., 1:1 conditions), coordination variability was

¹ The possibility that a different rate-of-change of activity over small and large amplitudes, across pendulums, was examined with three new participants. Changes in mean peak amplitude over different pendulums, with both amplitudes, were approximately equivalent. However, the intercepts of the differences across pendulums were slightly lower for small amplitude. This indicates the usage of lower force with decreasing amplitude.

distinctly lower (indexed by SD Φ) compared to a 1:2 or 2:1 task. This fact seemed to result in changes in EMG variability as well. Not only was effort higher for 2:1 compared to 1:1 and 1:2, but SD Amp followed a similar rank ordering (1:1= 102% , 1:2= 89% , & 2:1= 120%). It seems follower's (1:2) contribution to stability was not in terms of effort, but reducing within-trial variability.

Both of the mean and SD results become clear when considering the effects of generic oscillators (linear and nonlinear) under external forcing. Both oscillators will have equal effects on each other's states when coupled equivalently. Increasing the forcing (or coupling) one system has on another while leaving the other fixed alters this relationship. This yields an asymmetric coupling. Assuming each oscillator exhibits some intrinsic variability (i.e., noise), the system exhibiting the larger input will tend to stabilize the variability of the system receiving this forcing. An increased forcing in this sense is equivalent to a larger coupling in the current work. Assuming amplitude is equivalent to forcing, the EMG results seem to accurately reflect the dominant coupling going from large to small amplitude movements. Leaders and followers switched in terms of effort, while followers exhibited larger consistency or lower variability.

CHAPTER 5

GENERAL DISCUSSION

The notion of leader-follower coupling was considered in the current work by examining social motor coordination. In sensorimotor coordination, roles are typically demarcated by which person exhibits a spatiotemporal lead or lag, or has privileged information (Bosga, Meulenbroek, & Cuijpers, 2010; Rio et al., 2014; Varlet et al., 2012; 2014; Vesper & Richardson, 2014). For rhythmic tasks, this implies the phase leader is the leader. Such an approach precludes what is actually entailed in role-taking: one person has a larger effect on another person's actions. Therefore, to delineate leader from follower requires identifying individual roles in terms of coupling asymmetries or influence. Following this proposal, three experiments examined the emergence of such leader-follower coupling in a rhythmic coordination task. The main prediction was that imputing some form of symmetry breaking would lead to increase role-taking. Across all studies, participants coordinated (in-phase) the swinging of handheld pendulums differing in their natural frequency (detuning). The first two experiments aimed to identify when leaders and followers emerge during coordination, and how these roles are reflected in physiological responses or effort produced to stabilize coordination. This was accomplished by either not constraining (Experiment 1) or explicitly assigning roles (Experiment 2). A third prediction, specific to motor coordination, was examined in experiment 3. This experiment tested the proposal that coupling direction is largely based on amplitude. The main manipulation was asking people to self-select amplitude (1:1) or produce half (or double) that of the other dyad member (1:2 or 2:1).

Symmetry breaking changes coupling and stability

All of the current studies aimed to show that including some form of symmetry breaking – attributable to biomechanical differences (i.e., pendulums; experiment 1), explicit roles (experiment 2), or task requirements (amplitude disparity; experiment 3) – alters the leader-follower (asymmetric) coupling during rhythmic coordination. This prediction was generally supported. The experiments as a whole demonstrated coupling was not driven by spatiotemporal lead or relative phase.

First, Experiment 1 showed phase leaders did drive (see Figure 2 & 6) phase followers. Alone, this result agrees with other's consensus (Bosga et al., 2010; Varlet et al., 2012; 2014) that rhythmic leading may surmount to relative phasing. However, other work (Fine, Ward, & Amazeen, 2014; Stepp, 2009) on rhythmic target tracking has shown people actually will exhibit a phase lead with an environmental driver; this is comparable to an explicit leader. Therefore, the second experiment used a similar coordination task, but with an explicit leader and follower. Followers surprisingly phase lead the explicit leader (Figure 8) across all frequency detuning conditions. This occurred even when a follower's uncoupled frequency was slower ($\Delta\omega = 1$ rad/s). This follower phase lead effect would not be predicted if the leader-follower coupling is spatiotemporally based. Moreover, the degree of asymmetric coupling also changed as a function of $\Delta\omega$. The incongruence between both experiments results were clarified by experiment 3. Coupling direction changed as function of symmetry breaking via amplitude disparities (1:2 and 2:1). The person with the larger amplitude drove the

coupling, despite the smaller amplitude movements exhibiting a phase lead across detuning conditions. The important conclusion is that asymmetries – whether physical (pendulums), task requirement (amplitude disparity) or specified (explicit) – altered the coupling directionality.

The fact that leader-follower coupling was not based on phase leading suggests prior claims about such directionality are potentially misleading (Bogsa et al., 2010; Konvalinka et al., 2010; Mörtl, Lorenz, Vlaskamp, Gusrialdi, Schubo, & Hirche, 2012; Varlet et al., 2012; 2014). For example, Varlet et al. (2014) showed people with social anxiety disorder (SAD) may have more difficulty in leading another person. They employed a similar frequency detuning task to that presently used. Their main finding was that assigning the faster pendulum to people with SAD yield larger variability (SD Φ). From this, they concluded people with SAD had trouble *leading*. However, based on their results, there is no guarantee this person had a diminished driving effect on the other. Aside from relative phasing, these results imply differentiating people in terms of intrinsic properties can lead to an overall differentiation of roles. By identifying when pertinent task asymmetries exist, it is possible to predict when such role-taking would emerge.

Although role-taking can occur in an emergent fashion, an issue worth discussion is why a person would take on either role. The impetus for role emergence and who performs which role are interrelated. Coordinating asymmetric components without increased corrections would inevitably lead to decreased stability. Thus, the fact of a coupling asymmetry implies two-people (or limbs) may split their efforts unequally. How

are these efforts distributed among leader and followers? A possible explanation for why effort should change unequally is based on the cost to perform necessary corrections. Specifically, followers may incur a lower cost to produce increased forces or effort in terms of motor variability.

Close examination of the present results provides support for cost based roles. In experiment 1 and 2, a larger coupling effect was directed at high inertia pendulums. Effort in terms of EMG output was also higher. Larger forces, however, are typically accompanied by noisier output (Harris and Wolpert, 1999). This presents a paradox when claiming they became the follower because it minimizes overall variability. Considering a reversed outcome of experiment 1 and 2 clarifies why the larger inertia pendulum following is more stable. If the lower inertia pendulum followed, this would imply they produced a larger effort. The lower resistance of this pendulum to imputed forces, compared to a higher inertia, would yield noisier kinematic output (Russell & Sternad, 2001). The lower a limb's inertia, the less it filters out the noise for a fixed level of torque. Because the high inertia pendulum tended to follow, they could exhibit larger control signals without the accompanying noise. The overall cost to correct was lower. Experiment 3's results differ because participants were required to produce movements that were distinctly larger or smaller. The means of controlling movement likely switched from the other experiments. This was due to constraints on the force-amplitude relationship. While the small amplitude follower's exhibited a lower effort, they still exhibited less variability.

Overall, these findings indicate leader-follower coupling emerges during coordination as a result of biomechanical or task asymmetries. The reason for changes in coupling are stability reducing effects of stability. Inevitably, this leads to leaders and followers exerting different levels of effort to maintain stability while minimizing variability. Such an emergent act reflects a group-level decision about role structure. Whomever has the lower cost to correct in terms of minimizing task relevant variability may take on the follower role (Jarasse, Charalambous, & Burdet, 2012). A further implication is that, by identifying the person with the lower cost, it may be possible to predict role structuring during coordination. Clearly this division of roles will depend on the type of asymmetry.

Beyond phase synchronization

Most models of rhythmic coordination assume a homogeneous coupling between components; handedness research is an exception (de Poel et al., 2006; Treffner & Turvey, 1995). In making this assumption, two systems of coupled oscillators are reduced to a singular equation of motion. A prime example is the HKB system (eq. 2 & 3). For clarity, this equation is repeated here:

$$(11) \quad \dot{\Phi} = \Delta\omega - (\alpha + 2\beta r^2)\sin(\Phi) - (\beta r^2)\sin(2\Phi)$$

It is important to note the detuning term only shifts the stable relative phase and decreases its stability. There is no effect on coupling direction. Experiment 1's results

show detuning also modified coupling directionality. This result is not predicted by eq. 10. One extension of eq. 10 that could accommodate this coupling effect is the addition of cosine terms, included to model handedness effects (Amazeen et al., 1997; Treffner & Turvey, 1995). Even with the addition of these terms, it still predicts the limb driving the coupling would phase lead. To capture these asymmetric coupling effects in modeling terms may require going beyond the lower-dimensional equations.

Another issue presented by all three experiments is reconsidering the role of amplitude (for a similar proposal, see de Poel et al 2009; Peper et al., 2008). While the HKB equation (eq. 10) includes amplitude in the coupling, the assumption is amplitude is equivalent for both oscillators. This reduces amplitude down to a single r^2 term. The predicted equivalent amplitude, however, was not supported by the AMP-RATIO results in the first two experiments. This ratio drove the coupling direction and stability (see Experiment 3) beyond effects of Φ . The more disparate the amplitude, the larger the variability (see Figure 13). Moreover, changes in the amplitude also altered the coupling direction. Others have suggested amplitude asymmetries are actually linked to manipulations of $\Delta\omega$ (de Poel et al., 2009). This claimed is based on the expected change in limb amplitude as a function of its natural frequency. This frequency-amplitude effect (Kay, Saltzman, Kelso, & Schoner, 1987) was found in the baseline amplitude and period in all current experiments. de Poel et al. (2009) proposed such frequency driven amplitude asymmetries could explain differences in the oscillator's relative amplitudes. However, this predicts lower inertia pendulums should exhibit a larger amplitude and the opposite for high inertia (assuming detuning). The present results revealed the opposite.

Even with experiment 3's manipulation, the effect of ω on mean amplitude showed the low inertia pendulums exhibited a larger amplitude within an amplitude asymmetry level (e.g., 1:2 or 2:1). Amplitude was generally higher for the faster pendulum across all experiments (see Figures 4, 9, & 16; see also Fine et al., 2015). This result implies the amplitude ratios were not a byproduct of the pendulum's eigenfrequencies.

This raises the question of how amplitude modulates coordination coupling (de Poel et al., 2009; Kudo et al., 2006; Park & Turvey, 2008). All experiments showed the person driving the coupling tended to exhibit a larger amplitude. Proposing amplitude as a basis for coupling asymmetries has been advanced in bimanual coordination (de Poel et al., 2009; Peper et al., 2008), and even in synchrony of neural networks (Daffertshofer & van Wijk, 2011). For bimanual coordination, the proposal was based on the notion that larger amplitudes should yield increased afferent signals and cross-talk between limbs. The current experiments only examined interpersonal coordination. Similarities between bimanual and interpersonal coordination implies amplitude may operate as a general entrainment signal (Varlet, Coey, Schmidt, & Richardson, 2011), driving the coupling physiologically or visually. Moreover, it is possible that what is perceptually salient to participants on a cycle-by-cycle is amplitude and not phase.

Some models have explicitly included separate amplitude terms for both oscillators (for examples, see Aronson et al., 1990; Jirsa, Fink, Foo, & Kelso 2000). The model of Jirsa et al. (2000) predicts a positive and negative stable relative phase for a given detuning (e.g., ± 2 rad/s) and non 1:1 amplitude ratio (e.g., 1:2 or 2:1). However, results from experiment 3 suggest the relative phase was always negative for a 1:2 ratio.

These models also still present no mechanism for asymmetric coupling. To this end, others have proposed that modeling rhythmic dynamics should focus on the oscillator or physiologically limb coupled level (Beek et al., 2002; de Rugy et al., 2006). Generally, rhythmic movements are often modeled as self-sustaining limit-cycles (Beek et al., 1995; Fine et al., 2015; Fuchs, 2014). The movement cycle energy (i.e., movement related effort) is related to its amplitude, the radius. It can be approximated as the peak-to-peak amplitude (Dotov & Frank, 2011) as presently done. Examining amplitude results of experiment 1 and 2 implies low inertia movements elicited a larger energy output. Comparison with the EMG-AMP (Figure 7 & 12) reveals this is not the case. Higher inertia pendulums typically revealed a larger effort (de Rugy et al., 2006; Hatsopoulos & Warren, 1996). Models focusing on dimensionality reduction (eq. 10) would not predict this dissociation between kinematic and physiological output. By modeling at the physiology plus coupled limb level, predictions such as the effects of feedback delays (Stepp, 2009; Stepp & Turvey, 2010; Voss, 2000) and coupling asymmetries can be simulated and tested against experimental results.

Leader Dynamics and Traits: common ground

Because people can readily coordinate their actions in a directed (coupling) and stable manner suggests the notion of leading and following are not restricted to individual traits. The present approach was to consider how these roles change during the interaction of two people. Leading (and following) was presently defined as a larger influence from one person to another or coupling asymmetry. Because this was pursued in a motor

coordination paradigm, this questions its relevance to individual traits thought to underlie leadership (e.g., agreeableness; Judge et al., 2002).

Trait-based approaches to leadership generally have two major aims, uncovering the factors that predict leader *emergence* and their *effectiveness* (for a review, see Zaccaro, Kemp, & Bader, 2003). Traits are typically considered a fixed component, not unlike the treatment of personality factors (e.g., extroversion; Judge et al., 2002; Zaccaro et al., 2003). In a constrained sense, motor coordination displays trait-like properties. The pendulums provided to each person on a given trial are akin to a trait. They provide a task relevant indicator about the individual's properties. However, these pendulums alone did not dictate roles. Interaction with another person's 'trait' (pendulum) yielded an emergent leader and follower (i.e., coupling asymmetry). There exists a situational contingency. For example, no person would be expected to dominantly lead given identical pendulums or a $\Delta\omega = 0$ (rad/s) scenario. The necessity of situational contingency to understand leader emergence is similar to trait models of leadership emergence referred to as situationism models (Fiedler, 1964; Murphy, 1941). Such conceptual models mainly stipulate leadership resides in scenarios (combinations of other's traits or task type), not people.

Leadership qualities are also defined by how effective someone is predicted to be in a given situation. While effectiveness possesses a broad and task-contingent definition, a common ground is stability. Leaders drive non-leaders in a flexible way, which results in stable follower responses. The current experiments express this in terms of coupling direction and coordination variability. Effective leading is marked by increased coupling

direction and follower responsiveness (e.g., EMG-AMP). Both are accompanied by a certain level of joint-task stability; in terms of motor coordination, this is represented as a consistent SD Φ across detuning manipulations. Acceptance of this comparison allows stepping outside the limiting bounds of leadership described primarily in terms of personality traits. Namely, it emphasizes the proposal that leading and following should be considered in terms of information-transfer or coupling in a given task.

Conceptual similarities exist between trait-based leadership components, emergence and effectiveness, and the social coordination presently investigated. Though, these are not the traits typically considered in trait-based research (e.g., extroversion or agreeableness; Judge et al., 2002; Kim-Yin & Fritz, 2001). Attempts have been made to connect similar factors such as rapport (Bernieri, 1988; Miles, Nind, & Macrae, 2009) or social pathologies (e.g., social anxiety disorder; Varlet et al., 2014) to social motor interactions. Specifically related to leadership was the examination of social competence (intelligence) and social coordination (Schmidt, Christianson, Carello, & Baron, 1994). Employing a similar pendulum task, Schmidt et al. (1994) created dyads composed of people ranked either both high, low, or both high and low on a social competence scale. They found the high-low group performed best. Stability or effectiveness was highest for this group. Importantly, degree of competence was mostly correlated with a subscale on leadership. High competence individuals tended to phase lead, with low competence individuals following.

Although these traits may embody themselves in interactive movements, their effects are likely task dependent as expressed by situational models (Fiedler, 1964). The

current paradigm created a situation for the pendulum traits to engender a leader-follower coupling. Not all leader-follower dynamics, though, should be considered in terms of motor coordination. Leadership is task driven, foregoing explicit role assignment. An example not contingent on motor control is conversational turn-taking (Wilson & Wilson, 2005). Some individuals may tend to dominate and drive conversations, but these roles may switch in a time-resolved manner. Applying methods not restricted to phase coupling, such as transfer entropy (Choi, Yu, Smith, & Sporns, 2011; Schreiber, 2000) or granger causality (Barnett, Barrett, & Seth, 2009), would allow examining role emergence, switching, and dissipation in more ecologically realistic scenarios. Future research on leader-follower interactions can examine traits as they relate to real social interactions. This provides a means to step beyond subjective report indices, while testing a variety of scenarios under which certain people are predicted to emerge as leaders.

CONCLUSIONS

A largely unanswered question in (social) coordination research is under what circumstances individuals will take on differential roles. This was presently examined by considering when leaders and followers emerge during rhythmic coordination. The novel approach was – rather than identifying leaders and followers as merely spatiotemporal positions – identifying when asymmetric coupling effects (i.e., influence) between people emerge. A central thesis was the coordination must involve some form of asymmetry between people, whether it is between limb properties (inertia), role (explicit leader or follower), or task requirement (amplitude). This proposal's basis was the stability reducing effects asymmetries have on coordination. Across all studies, changing the type and degree of asymmetry altered the coupling direction between participants. Importantly, coupling identified leaders and followers were not phase lead (or lag) contingent. Comparing the kinematic output to EMG (measure of effort) also revealed individuals produced larger forces with increased coupling asymmetry. This physiological effort, however, was typically stronger for followers. The drawn conclusion was leader and follower roles materialize based on a simple principle: whomever can produce the necessarily larger corrections while minimizing variability, yielding maximizing coordination stability, settles into the follower role. The systematic means by which these roles occurred given each person's pendulum and asymmetry supports this. In summary, research on inter-limb or interpersonal interactions, whether it is motor coordination or conversation, should aim to describe the moment-by-moment states in terms of causal coupling. Taking this approach has applications beyond theory. It could

provide a unique window into the effectiveness of instructional or therapeutic interactions.

REFERENCES

- Amazeen, E.L., Amazeen, P.G., Treffner, P.J., & Turvey, M.T. (1997). Attention and handedness in bimanual coordination dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, 23(5), 1552.
- Amazeen, P.G., Schmidt, R.C., & Turvey, M.T. (1995). Frequency detuning of the phase entrainment dynamics of visually coupled rhythmic movements. *Biological Cybernetics*, 73, 499-507.
- Beek, P.J., Peper, C.L., & Daffertshofer, A. (2002). Modeling rhythmic interlimb coordination: beyond the Haken-Kelso-Bunz model. *Brain and Cognition*, 48(1), 149-165.
- Beek, P.J., Schmidt, R.C., Morris, A.W., Sim, M-Y., & Turvey, M.T. (1995). Linear and nonlinear stiffness and friction in biological rhythmic movements. *Biological Cybernetics*, 73, 499-507
- Bernstein, N. (1967). The coordination and regulation of movement. Pergamon: London.
- Bligh, M. C. (2011). Personality theories of Leadership. *Encyclopedia of Group Processes and Intergroup relations*. Sage.
- Bloom, J.S., & Hynd, G.W. (2005). The role of the corpus callosum in interhemispheric transfer of information: excitation or inhibition? *Neuropsychol Rev.*, 15(2), 59-71.
- Bosga, J., Meulenbroek, R.G., & Cuijpers, R.H. (2010). Intra- and interpersonal movement coordination in jointly moving a rocking board. *Motor Control*, 14(4), 440-459.
- Coey, C., Varlet, M., Schmidt, R.C., & Richardson, M.J. (2011). Effects of movement stability and congruency on the emergence of spontaneous interpersonal coordination. *Experimental Brain Research*, 211(304), 483-493.
- Daffertshofer, A., & van Wijk, C.M. (2011). On the influence of amplitude on the connectivity between phases. *Frontiers in Neuroinformatics*, 5.
- Daffertshofer, A., Peper, C.E., & Beek, P.J. (2005). Stabilization of bimanual coordination due to active interhemispheric inhibition: A dynamical account. *Biological Cybernetics*, 92, 101-109
- de Poel, H.J., Peper, C.L., & Beek, P.J. (2007). Handedness-related asymmetry in coupling strength in bimanual coordination: furthering theory and evidence. *Acta Psychologica*, 124(2), 209-237.

- de Poel, H.J., Peper, C.L., & Beek, P.J. (2009). Disentangling the effects of attentional and amplitude asymmetries on relative phase dynamics.
- de Rugy, A., Salesse, R., Oullier, O., & Temprado, J.J. (2006). A neuro-mechanical model for interpersonal coordination. *Biological Cybernetics*, *94*(6), 427-443.
- Dumas, G., de Guzman, G.C., Tognoli, E., & Kelso, J.A.S. (2013). The human dynamic clamp as a paradigm for social interaction. *PNAS*, *111*(35), 3726-3734.
- Fairhurst, M.T., Janata, P., & Keller, P.E. (2014). Leading the follower: an fMRI investigation of dynamic cooperativity and leader-follower strategies in synchronization with an adaptive virtual partner. *NeuroImage*, *84*, 688-697.
- Fine, J.M., & Amazeen, E.L. (2011). Interpersonal Fitts' Law: When two perform as one. *Experimental Brain Research*, *211*(3-4), 459-469.
- Fine, J.M., & Amazeen, E.L. (2014). Stabilizing perceptual-motor asymmetries during social coordination. *Human Movement Science*, *34*, 91-108.
- Fine, J.M., Gibbons, C.T., & Amazeen, E.L. (2013). Congruency effects in interpersonal coordination. *Journal of experimental psychology: Human Perception and Performance*, *39*(6), 1541-1556.
- Fine, J.M., Likens, A.D., Amazeen, E.L., & Amazeen, P.G. (2015). Emergent complexity matching in interpersonal coordination: local dynamics and global variability. *Journal of experimental psychology: Human Perception and Performance*.
- Fine, J.M., Ward, K.L., & Amazeen, E.L. (2014). Manual coordination with intermittent targets: velocity information for prospective control. *Acta Psychologica*, *149*, 24-31.
- Fuchs, A. (2014). *Nonlinear Dynamics in Complex Systems: Theory and Applications for the Life- Neuro- and Natural Sciences*. Springer.
- Fuchs, A., Jirsa, V.K., Haken, H., & Kelso, J.A.S. (1996). Extending the HKB model of coordinated movement to oscillators with different eigenfrequencies. *Biological Cybernetics*, *74*(1), 21-30.
- Guckenheimer, J., & Holmes, P. (2002). *Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields*. Vol. 42. Springer-Verlag: New York.
- Haken, H., Kelso, J.A.S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*(5), 347-356.

- Harris, C.M., & Wolpert, D.M. (1998). Signal-dependent noise determines motor planning. *Nature*, 394(6695), 780-784.
- Hatsopoulos, N.G., & Warren, W.H. (1996). Resonance tuning in rhythmic arm movements. *Journal of Motor Behavior*, 28(1), 3-14.
- Jarrasse, N., Charalambous, T., & Burdet, E. (2012). A framework to describe, analyze and generate interactive motor behaviors. *PloS one*, 7(11).
- Jeka, J.J., & Kelso, J.A.S. (1995). Manipulating Symmetry in the Coordination Dynamics of Human Movement. *Journal of Experimental Psychology: Human Perception and Performance*. 21(2), 360-373.
- Jirsa, V.K., Fink, P., Foo, P., & Kelso, J.A.S. (2000). Parametric stabilization of biological coordination: a theoretical model. *Journal of Biological Physics*, 26(2), 85-112.
- Judge, T. A., Bono, J. E., Ilies, R., & Werner, M. (2002). Personality and leadership: A qualitative and quantitative review. *Journal of Applied Psychology*, 87, 765-780.
- Kay, B.K., Saltzman, E.L., Kelso, J.A.S., & Schoner, G. (1987). Space-time behavior of Single and Bimanual Rhythmical Movements: Data and Limit Cycle models, *Journal of Experimental Psychology: Human Perception and Performance*. 13(2).
- Kelso, J.A.S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology: Regulatory, Integrative and Comparative*, 15, R1000 R1004.
- Kelso, J.A.S. (1997). *Dynamic Patterns: The self-organization of brain and behavior*. MIT press.
- Kelso, J.A.S., Dumas, G., & Tognoli, E. (2013). Outline of a general theory of behavior and brain coordination. *Neural Networks*, 37, 120-131
- Kelso, J.A.S., Scholz, J., and Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: Critical fluctuations. *Physics Letters A*, 118(6), 279-284.
- Kirkpatrick, S. A., & Locke, E. A. (1991). Leadership: Do traits matter? *Executive*, 5, 48-60.
- Konvalinka, I., Bauer, M., Stahlhut, C., Hansen, L.K., Roepstorff, A., & Frith, C.D. (2014). Frontal alpha oscillations distinguish leaders from followers: Multivariate decoding of mutually interacting brains. *NeuroImage*, 94, 79-88.

- Konvalinka, I., Vuust, P., Roepstorff, A., & Firth, C.D. (2010). Follow you, follow me: continuous mutual prediction and adaptation in joint tapping. *Quarterly Journal of Experimental Psychology*, 63(11), 2220-2230.
- Kralemann, B., Cimponeriu, L., Rosenblum, M., Pikovsky, A., & Mrowka, R. (2008). Phase dynamics of coupled oscillators reconstructed from data. *Physical Review E*, 77.
- Kudo, K., Park, H., Kay, B., & Turvey, M.T. (2006). Environmental coupling modulates the attractors of rhythmic coordination. *Journal of Experimental Psychology: Human Perception and Performance*.
- Kugler, P.N., & Turvey, M.T., (1987). Information, Natural-law, and the self-assembly of rhythmic movement.
- Meerhoff, L.A., De Poel, H.J., & Button, C. (2014) How visual information influences coordination dynamics when following the leader. *Neuroscience Letters*, 17(582), 12-15.
- Mörtl, A., Lorenz, T., Vlaskamp, B.N., Gusrialdi, A., Schubö, A., & Hirche, S. (2012). Modeling inter-human movement coordination: synchronization governs joint task dynamics.
- Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R.J. (2001). Two-Handed Performance of a Rhythmical Fitts Task by Individuals and Dyads. *Journal of Experimental Psychology: Human Perception and Performance*, 27(6), 1275-1286.
- Oullier, O., & Kelso, J.A.S. (2009). Social coordination from the perspective of coordination dynamics. In R. Meyers (Ed.) *Encyclopedia of complexity and systems science* (pp. 8198-8212). Berlin: Springer-Verlag.
- Osu, R., Franklin, D.W., Kato, H., Gomi, H., Domen, K., Yoshioka, T., & Kawato, M. (2002). Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface EMG. *Journal of Neurophysiology*, 88(2), 991-1004.
- Park, H. & Turvey, M.T. (2008). Imperfect symmetry and the elementary coordination law. In A. Fuchs, V.K., Jirsa (Eds.), *Coordination: Neural, Behavioral and Social Dynamics* (pp. 3-25). Berlin: Springer.
- Peper, C.E., de Boer, B.J., de Poel, H.J., Beek, P.J. (2008). Interlimb coupling strength scales with movement amplitude. *Neuroscience Letters*, 437, 10-14.

- Reed, K.B., Peshkin, M., Hartmann, M., Grabowekcy, M., Patton, J., & Vishton, P. (2006). Haptically linked Dyads: Are two motor-control systems better than one? *Psychological Science, 17*(5), 365-366.
- Richardson, M.J., Campbell, W., Schmidt, R.C. (2009). Movement interference during action observation as emergent coordination. *Neuroscience Letters, 449*, 117-122.
- Richardson, M.J., Lopresti-Goodman, S.M., Mancini, M., Kay, B., & Schmidt, R.C. (2008). Comparing the attractor strength of intra- and inter-personal interlimb coordination using cross-recurrence analysis. *Neuroscience Letters, 438*, 340-345.
- Rio, K. W., Rhea, C. K., & Warren, W. H. (2014). Follow the leader: Visual control of speed in pedestrian following. *Journal of Vision, 14*(2), 4.
- Russell, D.M. & Sternad, D. (2001). Sinusoidal visuomotor tracking: intermittent servo-control or coupled oscillations? *Journal of Motor Behavior, 33*(4), 329-349.
- Sacheli, L.M., Tidoni, E., Pavone, E.F., Aglioti, S.M., & Candidi, Matteo (2013). Kinematic fingerprints of leader and follower role-taking during cooperative joint actions. *Experimental Brain Research., 226*(4), 473-486.
- Sebanz, N., & Knoblich, G. (2009). Prediction in Joint Action: What, When and Where. *Topics in Cognitive Science, 1*(2), 353-367.
- Schmidt, R.C., Bienvendu, M., Fitzpatrick, P.A., & Amazeen, P.G. (1998). A comparison of within- and between-person coordination: Coordination breakdowns and coupling strength. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 884-900.
- Schmidt, R.C., Carello, C., & Turvey, M.T. (1990). Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *Journal of Experimental Psychology: Human Perception and Performance 16*(2), 227-247.
- Schmidt, R. C., Fitzpatrick, P., Caron, R., & Mergeche, J. (2011). Understanding social motor coordination. *Human Movement Science, 30*(5), 834-845.
- Schmidt, R.C., & Richardson, M.J. (2008). Dynamics of interpersonal coordination. In A. Fuchs & V. Jirsa (Eds.), *Coordination: Neural, Behavioural and Social Dynamics* (pp. 281-308). Heidelberg: Springer-Verlag.
- Schmidt, R.C., & Turvey, M.T. (1994). Phase-entrainment dynamics of visually coupled rhythmic movements. *Biological Cybernetics, 70*, 369-376.

- Schöner, G. (2002). Timing, Clocks, & Dynamical Systems. *Brain and Cognition*, 48, 31-51.
- Selen, L.P.J., Beek, P.J., & van Dieen, J.H. (2006). Impedance is modulated to meet accuracy demands during goal-directed arm movements. *Experimental Brain Research*, 172(1), 129-138.
- Spijkers, W., & Heuer, H. (1995). Structural constraints on the performance of symmetrical bimanual movements with different amplitudes. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, 48(3).
- Stepp, N. (2009). Anticipation in feedback-delayed manual tracking of a chaotic oscillator. *Experimental Brain Research*, 198(4), 521-525.
- Stepp, N. & Turvey, M.T. (2010). On strong anticipation. *Cognitive Systems Research*, 11(2), 148-164.
- Sternad, D., Collins, D.R., & Turvey, M.T. (1995). The detuning factor in the dynamics of rhythmic interlimb coordination. *Biological Cybernetics*, 73, 27-35.
- Strogatz, S.H. (2001). *Nonlinear dynamics and Chaos: With applications to Physics, Biology, Chemistry, and Engineering (studies in nonlinearity)*. Perseus.
- Treffner, P.J., & Turvey, M.T. (1995). Handedness and the asymmetric dynamics of bimanual rhythmic coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 21(2), 318.
- Turvey, M.T., & Carello, C. (1996). Dynamics of Bernstein's level of synergies. In M. Latash & M.T. Turvey (Eds.), *Dexterity and its development* (pp. 339-376). Hillsdale, NJ: Erlbaum.
- Varlet, M., Coey, C., Schmidt, R.C., & Richardson, M.J. (2011). Influence of stimulus amplitude for spontaneous visual coordination. *Human Movement Science*, 31, 541-552.
- Varlet, M., Marin, L., Lagarde, J., & Bardy, B.G. (2011). Social postural coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 37(2), 473.
- Varlet, M.,... Bardy, B. (2012). Impairments of Social Motor Coordination in Schizophrenia. *PlosOne*.

- Varlet, M.,... Raffard, S. (2014). Difficulty leading interpersonal coordination: towards an embodied signature of social anxiety disorder. *Frontiers in Behavioral Neuroscience*, 8(29).
- Vercher, J.L., & Gauthier, G.M. (1992). Oculo-manual coordination control: ocular and manual tracking of visual targets with delayed visual feedback of the hand motion. *Experimental Brain Research*, 90, 599-609.
- Vesper, C., van der Wel, RPD, Knoblich, G., & Sebanz, N. (2011). Making oneself predictable: reduced temporal variability facilitates joint action coordination. *Experimental Brain Research*, 211(3-4), 517-530.
- Vesper, C., & Richardson, M.J. (2014). Strategic communication and behavioral coupling in asymmetric joint action. *Experimental Brain Research*, 232, 2945-2956.
- Von Holst, E. (1973). *The behavioral physiology of animals and man: The collective papers of Erich von Holst*. Coral Gables: University of Miami Press.
- Voss, H. (2000). Anticipating chaotic synchronization. *Physical Reviews E*, 61(5), 5115-5119.
- Wimmers, R.H., Beek, P.J., van Wieringen, P.C.W. (1992). Phase transitions in rhythmic tracking movements: A case of unilateral coupling. *Human Movement Science*, 217-226.

FIGURE CAPTIONS

Figure 1. Representative sample data from Experiment 1. The top graphs show the normalized position series from both participants. Data is from a trials with a $\Delta\omega = 0$. Middle graphs show the scaled EMG linear envelopes (a.u.) from the same trial. The bottom graph displays the corresponding relative phase (degs). Note the graphs only include a portion of the trial length.

Figure 2. Mean Φ (degs) across all levels of frequency detuning ($\Delta\omega$). Relative phase is calculated as the difference of the left and right-seated participant. A reference shows the zero line.

Figure 3. Coordination variability as $SD\Phi$ for all levels of $\Delta\omega$.

Figure 4. Mean min-to-max and max-to-min amplitude (mm) for all pendulum frequencies (ω).

Figure 5. Mean AMP-RATIO for all $\Delta\omega$ levels. Values were calculated as the ratio of left and right-seated participants' amplitudes. A reference line is added at the unity ratio.

Figure 6. Mean coupling function values calculated from phase coupled models with amplitude ratio weights. Coupling values are presented across levels of $\Delta\omega$. Positive values imply a stronger drive to the left and negative values to the right.

Figure 7. Mean peak EMG amplitude extracted from the linear envelope. Means are normalized by pendulum ω according to their baseline value. All values are considered as a % of baseline by pendulum ω .

Figure 8. Mean Φ (degs) across all levels of detuning ($\Delta\omega_{L-F}$). Note that detuning and Φ are calculated as the difference in leader and follower frequencies and phase angles.

Figure 9. Follower mean amplitude (mm) for all pendulum ω . Although presented as a function of ω , each frequency still corresponds to the referential detuning (e.g., $\omega = 5.4$ is equivalent to $\Delta\omega = 2$).

Figure 10. Mean AMP-RATIO for all $\Delta\omega_{L-F}$ levels. Values were calculated as the ratio of leader and follower amplitudes. A reference line is added at the unity ratio.

Figure 11. Mean coupling function values calculated from phase coupled models with amplitude ratio weights. Coupling values are presented across levels of $\Delta\omega_{L-F}$. Negative values indicate driving effects from leader to follower. The strength is marked by increasingly negative values.

Figure 12. Mean and SD EMG-AMP are both plotted for comparison for each pendulum ω . Both variables are calculated as a % baseline.

Figure 13. Mean Φ (degs) across all levels of detuning ($\Delta\omega$) and amplitude Ratio (1:1, 1:2, & 2:1). Detuning is calculated as left-right.

Figure 14. SD Φ (degs) across all levels of detuning ($\Delta\omega$) and amplitude Ratio (1:1, 1:2, & 2:1). The figure shows the significant impact of amplitude disparity on coordination compared to detuning.

Figure 15. Mean period (samples) for frequency detuning and amplitude ratio levels (1:1, 1:2, & 2:1).

Figure 16. Mean amplitude (mm) for frequency detuning and amplitude ratio levels (1:1, 1:2, & 2:1).

Figure 17. Mean amplitude ratio (left divided by right) for frequency detuning and amplitude ratio levels (1:1, 1:2, & 2:1).

Figure 18. Mean coupling function values calculated from phase coupled models with amplitude ratio weights. Coupling values are presented across levels of $\Delta\omega$ and amplitude Ratio. Positive values imply a stronger drive to the left and negative values to the right.

Figure 19. Mean peak EMG amplitude extracted from the linear envelope. Means are normalized by pendulum ω according to their baseline value. All values are considered as a % of baseline by pendulum ω . Means are presented for all frequencies and the amplitude the person performed in a given Ratio. For example, in 1:2 the person being analyzed was performing the smaller amplitude.

Figure 20. SD peak EMG amplitude from linear envelope. Values are normalized by pendulum ω according to their baseline value. All values are considered as a % of baseline by pendulum ω . Means are presented for all frequencies and the amplitude the person performed in a given Ratio. For example, in 1:2 the person being analyzed was performing the smaller amplitude.

Figure 1.

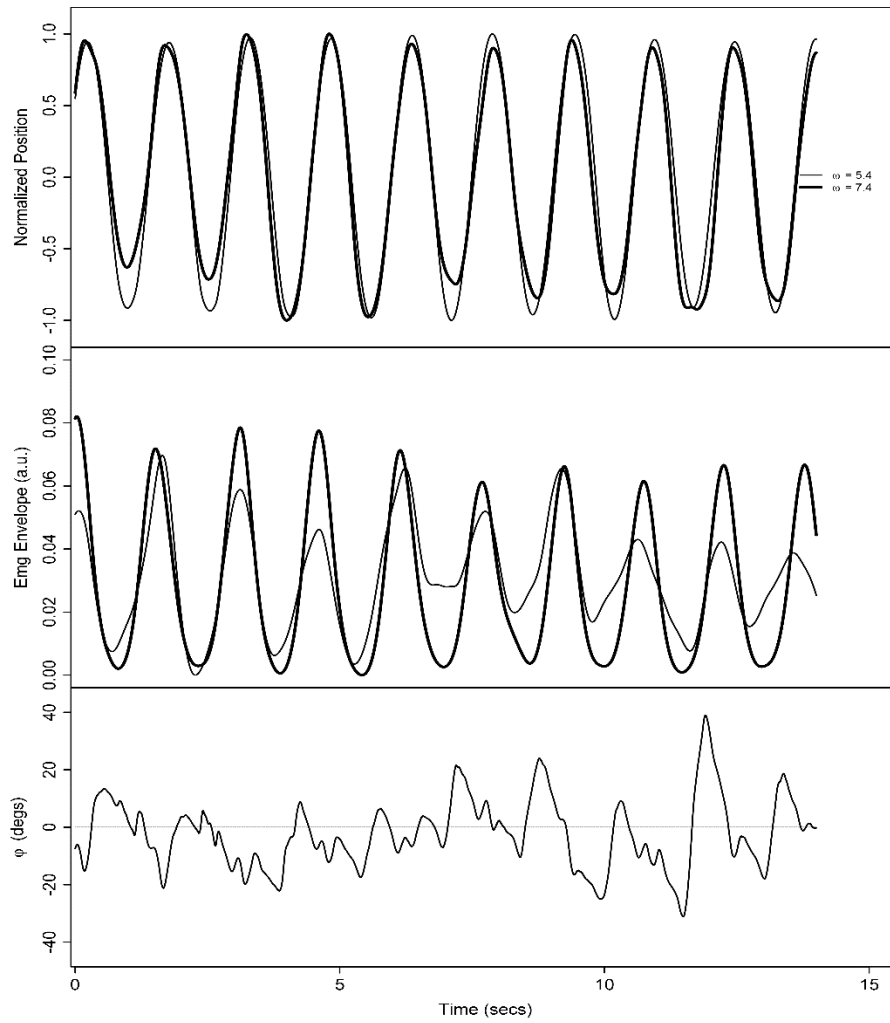


Figure 2.

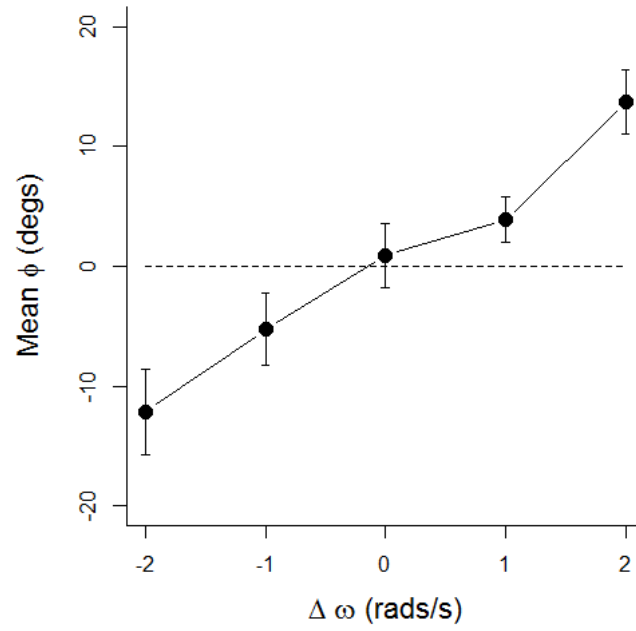


Figure 3

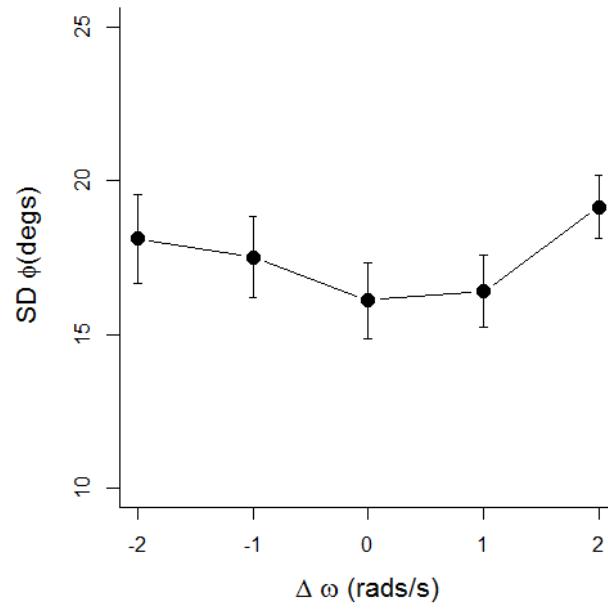


Figure 4

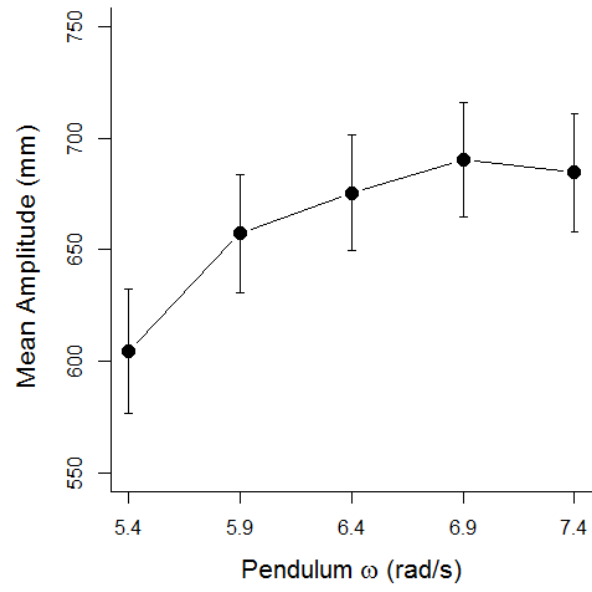


Figure 5

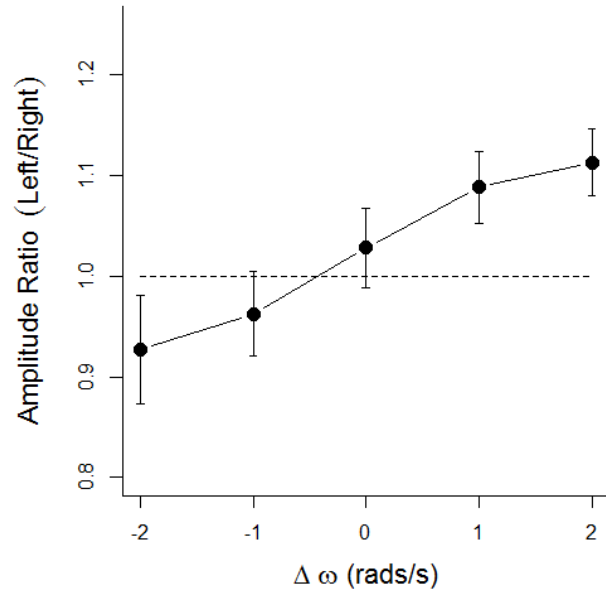


Figure 6

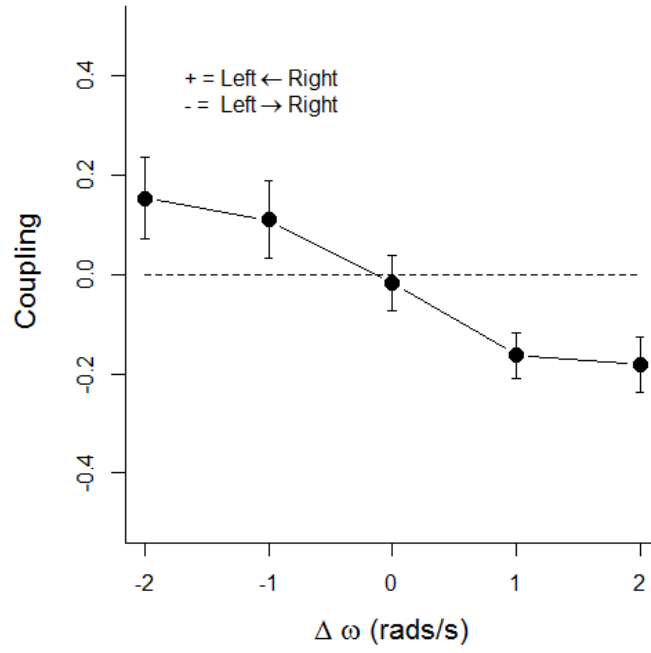


Figure 7

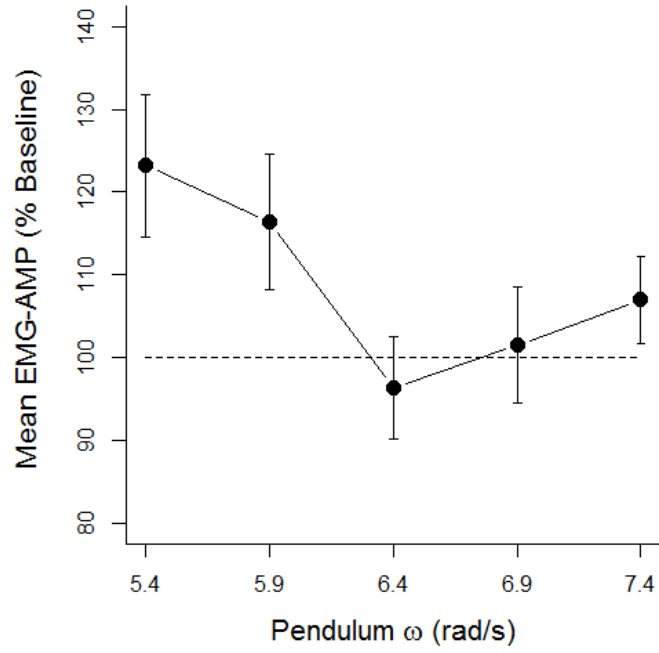


Figure 8

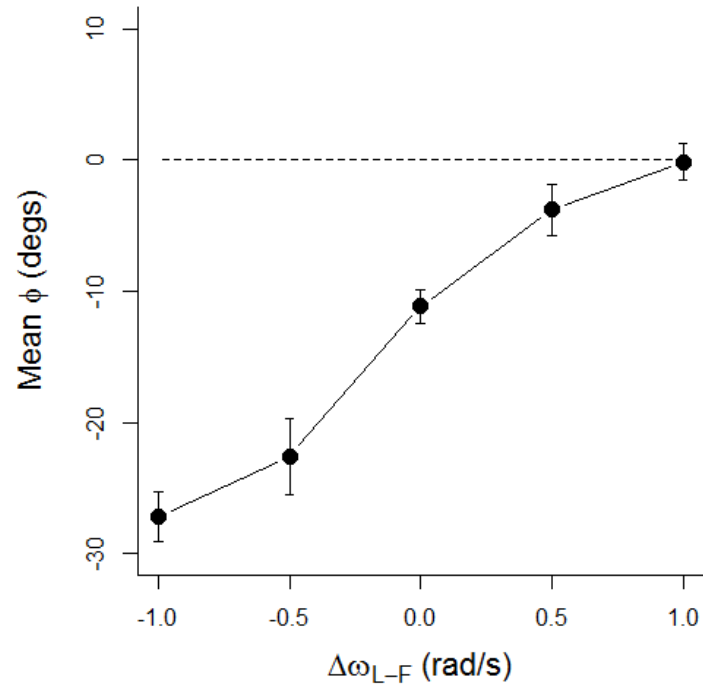


Figure 9

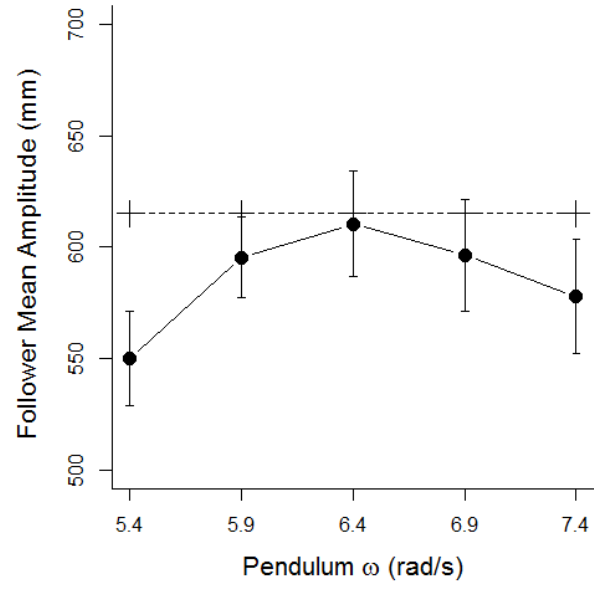


Figure 10

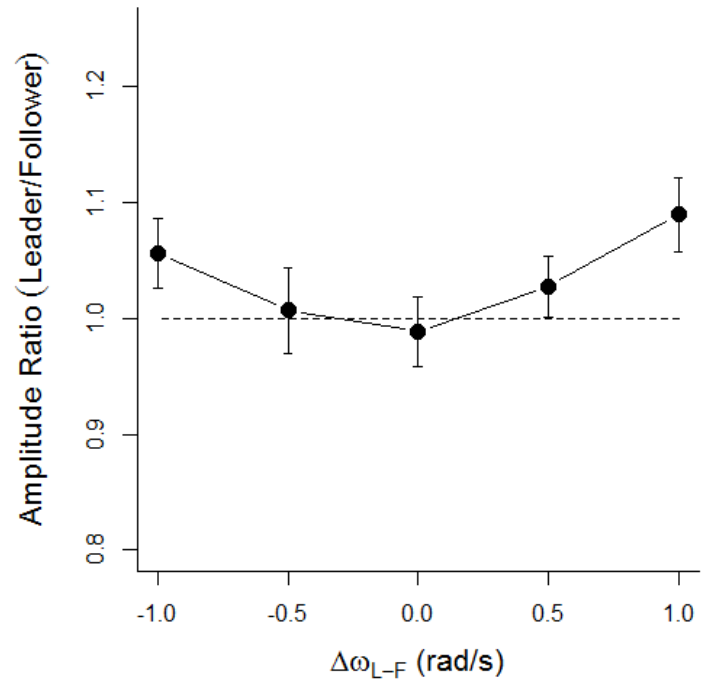


Figure 11

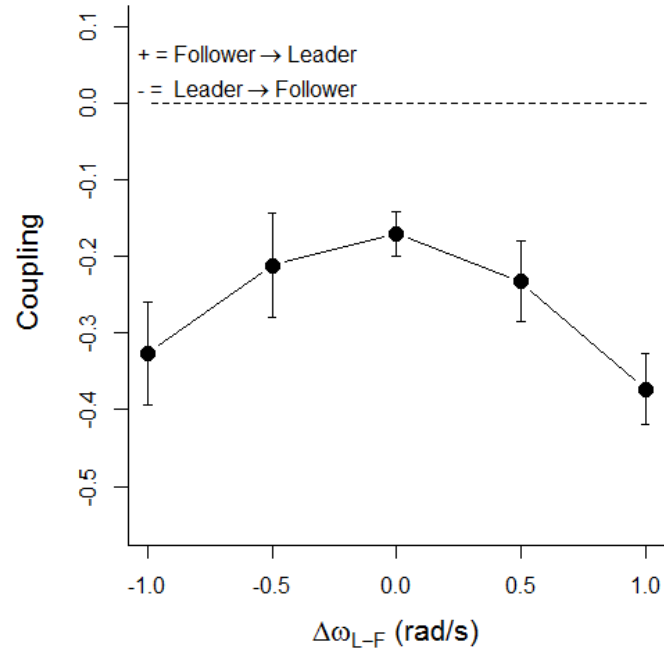


Figure 12

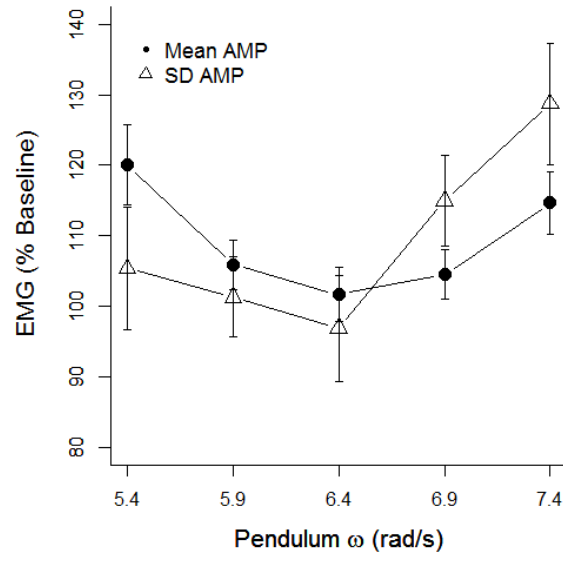


Figure 13

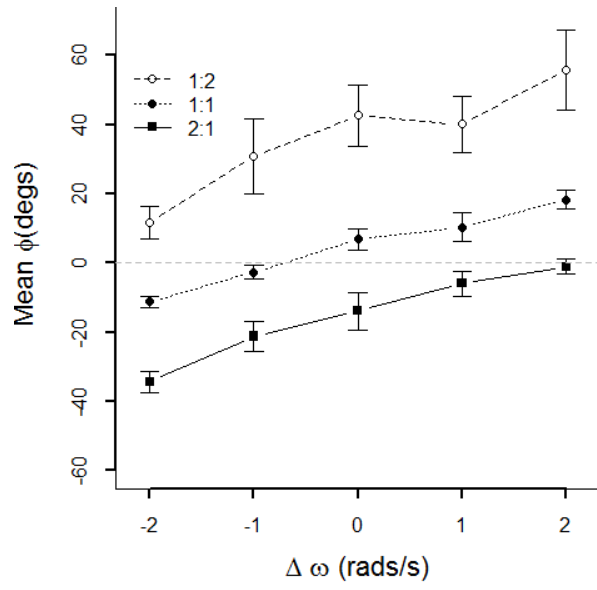


Figure 14

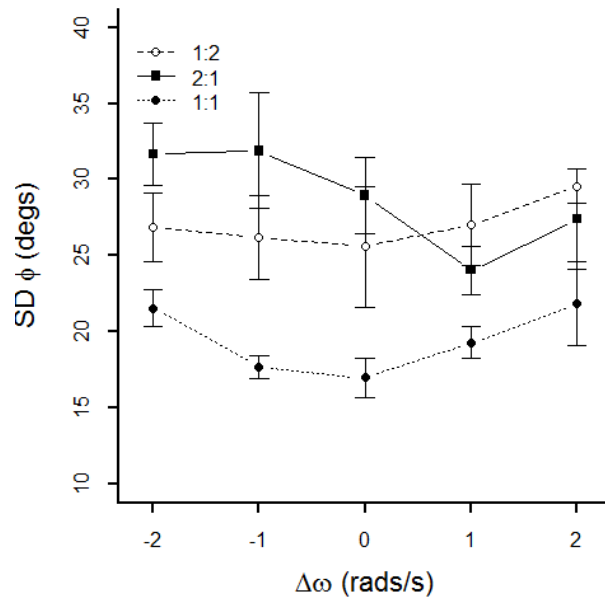


Figure 15

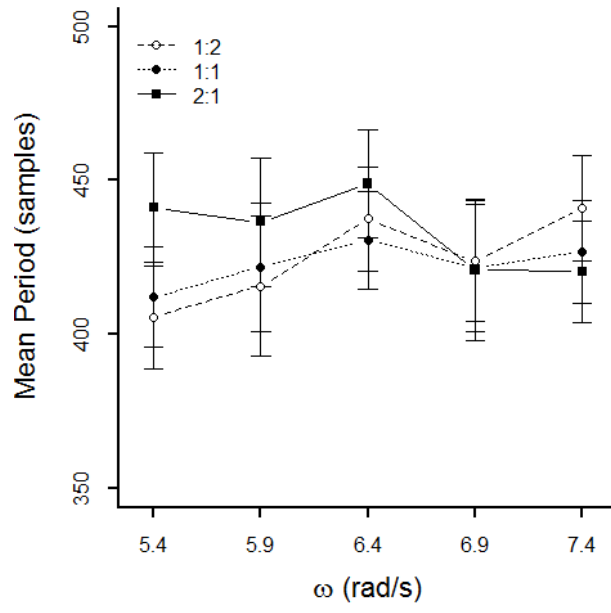


Figure 16

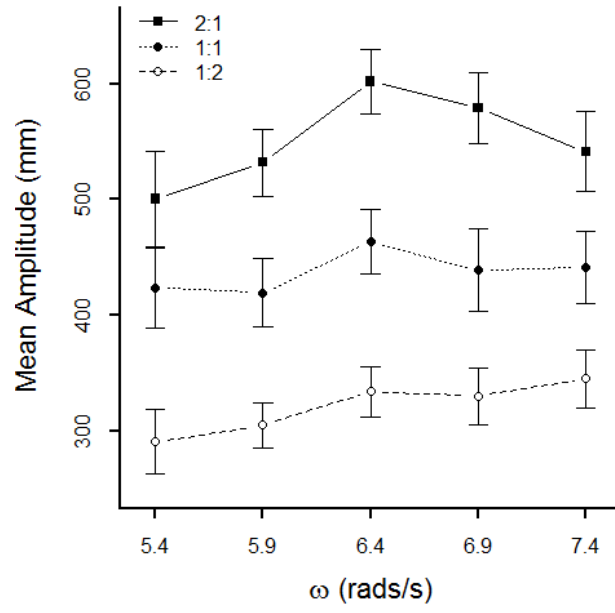


Figure 17

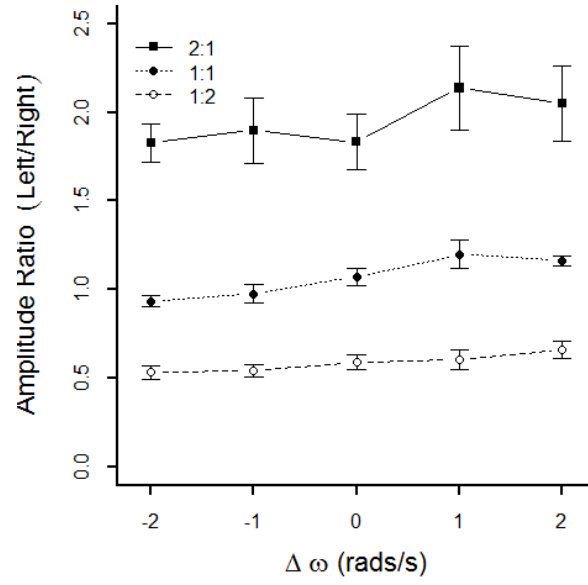


Figure 18

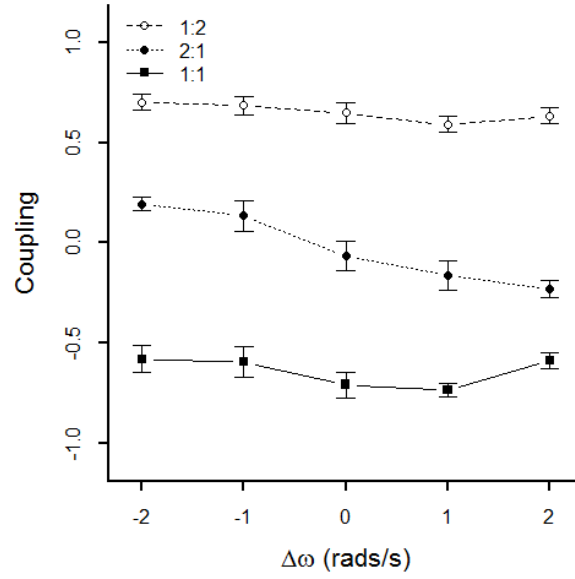


Figure 19

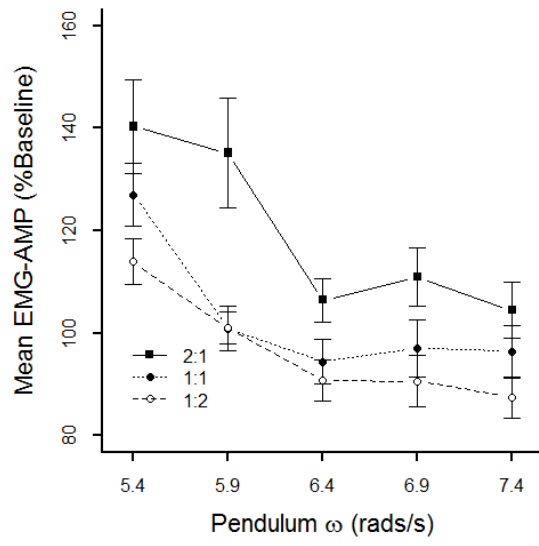


Figure 20

