



Rocking together: Dynamics of intentional and unintentional interpersonal coordination

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Abstract

The current study investigated the interpersonal coordination that occurred between two people when sitting side-by-side in rocking chairs. In two experiments participant pairs rocked in chairs that had the same or different natural periods. By instructing pairs to coordinate their movements inphase or antiphase, Experiment 1 investigated whether the stable patterns of intentional interpersonal coordination were consistent with the dynamics of within person interlimb coordination. By instructing the participants to rock at their own preferred tempo, Experiment 2 investigated whether the rocking chair movements of visually coupled individuals would become unintentionally coordinated. The degree to which the participants fixated on the movements of their co-actor was also manipulated to examine whether visual focus modulates the strength of interpersonal coordination. As expected, the patterns of coordination observed in both experiments demonstrated that the intentional and unintentional interpersonal coordination of rocking chair movements is constrained by the self-organizing dynamics of a coupled oscillator system. The results of the visual focus manipulations indicate that the stability of a visual interpersonal coupling is mediated by attention and the degree to which an individual is able to detect information about a co-actor's movements.

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1. Introduction

In the performance of everyday behavior an individual often coordinates his or her movements with the rhythmic behavior of other individuals. Such interpersonal coordination or synchrony underlies the activities of ballroom dancing, rowing a canoe, or simply walking and talking with friends. Although coordination of this kind is sometimes *intentional* and overtly controlled through physical contact (e.g., when individuals are ballroom dancing) it can also be *unintentional* and occur during a visual interaction. That is, interacting individuals can coordinate their movements by detecting visual movement information (Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994; Temprado & Laurent, 2004), and in some cases the pick-up of such information can lead to coordination even when the interactional goal does not explicitly define the coordination itself (Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997; Schmidt & Richardson, in press).

From a dynamical systems perspective, such visually mediated interpersonal coordination can be understood as a self-organized entrainment process of biological rhythms (Bernieri & Rosenthal, 1991; Newton, Hairfield, Bloomingdale, & Cutino, 1987; Schmidt et al., 1990; Schmidt & Turvey, 1994; Turvey, 1990). Precedence for this theorizing has come from two sources. One source has been research on insect coordination that has demonstrated how the synchronized flashing of fireflies is governed by the dynamical entrainment processes of coupled oscillators (Hanson, 1978). The second source contributing to this theory is research on human interlimb coordination that has demonstrated how the coordination of intrapersonal rhythmic movements (e.g., between a person's left and right forearms or wrists) can also be understood using the dynamical entrainment processes of coupled oscillators (Haken, Kelso, & Bunz, 1985; Kelso, 1984; Kelso, DelColle, & Schöner, 1990; Kugler & Turvey, 1987; Schmidt, Shaw, & Turvey, 1993; Turvey, Rosenblum, Schmidt, & Kugler, 1986). Of particular interest is related research (De Rugy, Saless, Oullier, & Temprado, 2006; Schmidt & Turvey, 1994; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Temprado & Laurent, 2004) that has shown that the space/time organization of interpersonal rhythmic coordination (the relative phase angle ϕ of the two participants' movements) can also be predicted by the same coupled oscillator system (see Appendix A). These studies have shown that only inphase (near $\phi = 0^\circ$) and antiphase (near $\phi = 180^\circ$) coordination patterns can be stably maintained without practice (Schmidt et al., 1990), that the antiphase mode is less stable than the inphase mode (Amazeen, Schmidt, & Turvey, 1995; Schmidt et al., 1998), and that the degree to which inphase and antiphase coordination equal the canonical relative phase angles of 0° and 180° depends lawfully on the difference between the preferred periods of the two movements (Schmidt & Turvey, 1994; De Rugy et al., 2006). This period difference is commonly referred to as detuning (calculated as the arithmetic difference between the preferred frequencies or periods of the two movements), and the larger the period difference the greater the shift away from $\phi = 0^\circ$ and 180° and the larger the variability of movement becomes (Schmidt et al., 1998).

Schmidt and O'Brien (1997) and Richardson et al. (2005) have investigated whether the same dynamics also constrain the interpersonal coordination or synchrony that occurs *unintentionally* between two interacting individuals. In these studies, individuals were asked to swing a wrist-pendulum at their own preferred tempo while visual information about the rhythmic wrist-pendulum movements of a co-actor was available. Despite the fact that the pairs were not instructed to coordinate their movements, the results showed

that the movements of the two individuals became intermittently entrained. That is, the visually coupled participants exhibited more relative phase angles around 0° (inphase) and 180° (antiphase) relative to other relative phase relations and the number of relative phase angles around 0° was also found to be greater than the number around 180° .

The importance of these interpersonal coordination experiments is that they not only suggest that interpersonal rhythmic coordination is constrained by the same dynamical entrainment processes as intrapersonal rhythmic coordination, but that such rhythmic interlimb coordination is observed independent of whether the component limbs are physically coupled by means of the neural-muscular tissue of an individual's central and peripheral nervous systems, or by means of visual information. Thus, rhythmic interlimb coordination appears to be the result of the lawful relations that exist between the subcomponents of perceptual-motor systems, rather than a specific anatomical or neural mechanism (Schmidt et al., 1998; Schmidt et al., 1990; Temprado & Laurent, 2004).

Although the research to date makes a credible case for dynamic coupling as the basis for intentional and unintentional interpersonal coordination, conclusions about the generality of these findings are hampered in several ways. The first is methodological, in that the majority of experiments have employed the Kugler and Turvey (1987) wrist-pendulum paradigm, in which a pair of individuals sit side-by-side and swing a pendulum about the wrist. Although swinging a wrist-pendulum is a behavior that can be sustained comfortably with little monitoring, it is different from the incidental movements that might be the basis for synchrony in naturalistic interactions and, thus, might unduly predispose individuals to produce synchronous movements regardless of instructions. Schmidt, O'Brien, and Sysko (1999) attempted to address this issue by examining the interpersonal coordination that occurred between two individuals who performed a card sorting task in the presence of each other. The deliberate nature of the movements involved, however, meant that entrainment was only found to occur when the social context mandated the pick-up of coordinative information. Viewing rhythmic synchrony as a process high in automaticity (Bargh & Chartrand, 1999) implies that an ideal paradigm would involve incidental, potentially inadvertent, movement. Although postural sway is clearly such a movement (Fowler, *in press*; Shockley, Santana, & Fowler, 2003), its stochastic (i.e., non-rhythmic) nature prevents describing interpersonal postural coordination with the use of a coupled oscillator system.¹ A paradigm is needed where the movement is incidental, but where the social context and mechanical constraints naturally pull one toward spontaneous rhythmic movement. In the current set of studies, we develop such a methodology using rocking chairs.

A rocking chair is an object that has mechanics similar to a wrist-pendulum. Like a wrist-pendulum, the inertial properties of a rocking chair can constrain or 'dictate' the rhythmicity of movement (i.e., frequency and amplitude; see Appendix B). A rocking chair, like a wrist-pendulum, allows a seated individual to either sit still or to move. However, rocking chairs tend to amplify any existing predisposition towards movement without the need for instruction. That is, individuals often naturally rock in a rocking chair once seated. In contrast, individuals do not tend to spontaneously or correctly swing a

¹ Interpersonal postural coordination from auditory information also appears to be a secondary result of interacting individuals converging in their speaking patterns—it does not reflect the influence of one person's speech on another's postural activity—and, thus, has less social immediacy or impact than the rhythmic synchrony mediated by visual information (Shockley, Baker, Richardson, & Fowler, 2007).

wrist-pendulum without being given instructions to do so. Thus, for the study of unintentional interpersonal coordination having individuals sitting side-by-side in rocking chairs provides a more socially natural situation than having individuals swinging wrist-pendulums. Moreover, rocking chair movements can be produced in a more flexible manner than pendulum swinging—rocking is a global movement that involves posture in addition to a number of different arm, leg and/or head movements—and therefore requires much less instruction.

Another limitation of the interpersonal coordination research to date concerns the fact that these studies (e.g., Richardson et al., 2005; Schmidt & Turvey, 1994) have required individuals to focus their visual attention directly towards the movements of their co-actor. Thus, although previous research has shown that visual information can couple the rhythmic movements of interacting individuals, the degree to which visual focus or attention to visual movement information modulates the strength and possibility of interpersonal coordination remains unclear. Identifying how visual focus influences the stability of interpersonal coordination would seem to be important given that natural between-person interactions do not always require that individuals focus their visual attention on the movements of a co-actor. Consequently, the influence of visual focus on the stability (and possible emergence) of interpersonal coordination was investigated in the current study by instructing participants to focus their visual attention on (look directly at) the rocking movements of a co-actor, or directly ahead, so that visual information about a co-actor's movements was only available in the periphery. By including this visual focus manipulation, the current study tested the possibility that coupling strength and, thus, the stability of interpersonal coordination, is weaker for instances where an individual only has peripheral access to the information about a co-actor's movement, compared to when an individual focuses his or her visual attention directly on the movements of a co-actor.

2. Experiment 1

As the first test of whether the interpersonal coordination of rocking chair movements is constrained by the same dynamics as interlimb coordination, pairs of individuals were instructed to intentionally coordinate the movements of chairs that had the same natural period or had different natural periods in both an inphase and an antiphase manner. If the dynamics that have previously been shown to constrain intra- and inter-personal interlimb coordination operate to constrain the interpersonal coordination of rocking chair movements and, thus, truly reflect a general behavioral model (one that is not component or coupling specific), then the following expectations should be met. First, pairs should be able to produce and maintain a stable inphase or antiphase pattern of coordination, with inphase coordination being more stable (lower $SD\phi$) than antiphase coordination. Second, for chairs that have different natural periods there should be a phase shift away from $\phi = 0^\circ$ and 180° , with this phase shift being more pronounced for antiphase than for inphase coordination. Note that when the left chair's natural period is less than the right the phase shift is expected to be negative (the movements of the left chair lag behind the right), whereas when the right chair's natural period is greater than the left chair's the phase shift is expected to be positive (the movements of the left chair lead the right). Finally, the $SD\phi$ should be greater when the chairs have different natural periods compared to when the chairs have the same natural period.

With respect to the manipulations of visual focus, we expected that coupling strength would be weaker when the individuals only had peripheral access to visual information about a co-actor's movements (participants looked directly ahead), compared to when their gaze was focused directly on the movements of a co-actor. Because the stability of the coordination is predicted to be a function of coupling strength (Haken et al., 1985; Kelso, 1995; Schmidt et al., 1998), we expected the $SD\phi$ to be greater for the peripheral condition than for the focal condition.

2.1. Method

2.1.1. Participants

Twenty-four undergraduates from the University of Connecticut participated in the experiment for partial course credit and were randomly grouped into 12 experimental pairs (five female pairs, and seven mixed gender pairs). The weight of participants ranged from 48 to 84 kg, with an average weight of 67 kg (SD 10.5 kg). The within-pair mass difference ranged from 0 to 29 kg, with an average mass difference of 14 kg (SD 8.2 kg).

2.1.2. Materials

The participants of each pair sat in identical wooden rocking chairs positioned 0.52 m apart (from inside armrest to inside armrest) in the center of a room (see Fig. 1a). To manipulate the natural period of the rocking chair, the chair's center of mass was lowered by positioning lead masses (weights) on a small platform that was attached at the base of the chair, just above the rocker bottoms. Six 9.07 kg lead masses were used to create two mass magnitudes of 0.0 and 27.22 kg for each chair, whereby the rocking chairs had an unseated natural period of 0.79 s for the 27.22 kg condition and 1.39 s for the 0.0 kg condition (see Appendix B). The two mass magnitudes were crossed to create four mass combinations for the two chairs (0.0_{Ch1}/0.0_{Ch2}, 0.0_{Ch1}/27.22_{Ch2}, 27.22_{Ch1}/0.0_{Ch2}, and

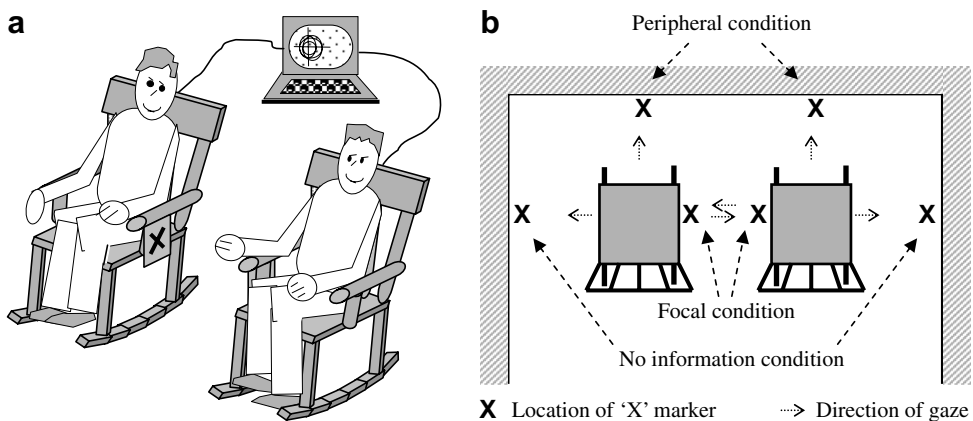


Fig. 1. (a) An illustration of the experimental setup used in Experiments 1 and 2. (b) A birds-eye-view of the experimental setup and the information conditions used in Experiments 1 and 2.

27.22_{Ch1}/27.22_{Ch2}), such that the experiment contained mass difference conditions of -27.22 , 0.0 , and $+27.22$ kg.

Visual focus was manipulated by having each participant in a pair fix their gaze on a 10 by 10 cm red target ('X' marker) located either directly in front of themselves (peripheral access to movement information), or on the armrest of their co-actor's chair (focal access to information; see Fig. 1b).

The motion of each rocking chair was recorded at 60 Hz using a magnetic tracking system (Polhemus Fastrak, Polhemus Corporation, Colchester, VT) and 6-D Research System software (Skill Technologies, Inc., Phoenix, AZ). A sensor was attached unobtrusively to the headrest of each chair.

2.1.3. Procedure

Upon arrival, pairs of participants were randomly assigned to either the peripheral or focal group and were informed that the experiment was investigating the coordination of rocking chair movements. The participants in a pair were instructed to sit in one of the two chairs so that both feet were placed firmly on the floor and their back was against the backrest. Each pair then completed four baseline trials, two trials in the weighted and un-weighted chairs, so that each participant's uncoordinated comfort tempo could be measured and the magnitude of the period difference between the participants' natural rocking tempo for the ± 27.22 mass difference conditions could be determined. These baseline trials involved having the participants rock at a comfortable tempo with a curtain placed between them so that no visual information about each other's rocking movements was available. Participants also wore industrial sound-occluding earmuffs so that there was no auditory information about the other's rocking motion.

Following the baseline trials, the participants were informed that they would be completing a number of experimental trials in which they were required to coordinate their rocking movements with one another in an inphase or antiphase manner. Participants in the peripheral group were informed that they should produce these coordination modes while fixing their gaze on the red X positioned on the wall directly in front of their chair and that they were to keep their gaze fixed on their own X for the entire length of each trial. Pairs in the focal group were informed that they should produce these coordination modes while fixing their gaze on the red X position on the armrest of their co-actor's chair and that they were to keep their gaze fixed on their co-actor's X for the entire length of each trial.

After the instructions, the participants completed two practice trials, one inphase and one antiphase, under the appropriate visual focus conditions. Following this, the participants were told that on some of the trials different weights would be attached to the bottom of the chair, but that on any given trial they should simply coordinate their rocking movements in the phase mode the experimenter instructed them to perform at the beginning of each trial. As in the baseline trials, the participants wore earmuffs during the experimental trials to eliminate auditory information.

For each trial, 60 s of movement data was recorded. A trial began once participants were rocking at the required phase relation. The experiment consisted of two trials for each phase mode by mass difference condition (with results averaged across trials for analysis), yielding a total of 16 trials. The order of trials was counterbalanced across participants. At the end of the experiment each participant was weighed and their weight recorded in kilograms (kg).

2.1.4. Dependent measures

For the baseline trials, each participant's natural rocking period in the weighted and un-weighted chair was calculated as the time between the points of maximum angular extension as defined by the peaks of the movement time series.

To determine the coordination in the experimental trials, the motion time series for each chair was centered around zero and low-pass filtered with a cut off frequency of 5 Hz using a Butterworth filter. These two movement time series for each trial were then differentiated to obtain two velocity time series. These velocity time series were then normalized by angular frequency and the movement phase angles (θ°) calculated for each rocking chair as

$$\theta_i = \arctan(\dot{x}_i/x_i), \quad (2)$$

where \dot{x}_i is the normalized angular velocity at the i th sample (normalized in terms of the mean angular frequency for the trial) and x_i is the angular displacement of the i th sample. The difference between the phase angles of the two rocking chairs was then computed ($\phi = \theta_{\text{Ch1}} - \theta_{\text{Ch2}}$), and the relative phase variables of phase shift (mean relative phase – intended phase mode) and $\text{SD}\phi$ were calculated from the resulting relative phase time series.

2.1.5. Data reduction and design

In order for the analysis of phase shift and $\text{SD}\phi$ to be a function of mass difference (-27.22 , 0.0 , and $+27.22$) and thus reflect period difference, the values of these dependent measures were averaged across the $0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$ mass combination conditions. Specifically, the -27.22 and $+27.22$ kg mass difference conditions reflect the $0.0_{\text{Ch1}}/27.22_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/0.0_{\text{Ch2}}$ mass combination conditions, respectively, whereas the 0.0 kg mass difference condition equals the average of the $0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$ mass combination conditions. Pilot testing, as well as an examination of the data obtained for the current experiment, revealed no significant differences between the $0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$ conditions. Although the weight of a participant decreases the natural rocking period of a chair by raising the chair's center of mass (see [Appendix B](#)), participant weight was not a significant covariate. That is, differences in the weight of participants in a pair did not have a significant impact on the observed coordination. Consequently, the experiment was treated as a 2 (Visual Focus: peripheral and focal) $\times 2$ (Phase Mode: inphase, antiphase) $\times 3$ (Mass Difference: -27.22 , 0.0 , and $+27.22$ kg) mixed design with within-subject variables of phase mode and mass difference.

2.2. Results

In all but six experimental trials, participants completed the intended phase mode. For the other six trials (one inphase trial and five antiphase trials), participants exhibited a transition between phase modes. These trials were extracted from the analysis and the dependent measures were calculated from the remaining stable trial for that condition.

2.2.1. Baseline period and period difference

Consistent with the expectation that the participants' comfort period would increase when a mass was added to the base of the rocking chair (see [Appendix B](#)), a t -test revealed that on average participants rocking on their own produced a significantly faster rocking

period, $t(23) = 10.65$, $p < .01$, for the 27.22 kg weighted chairs (1.49 s) than for the un-weighted chairs (1.71 s).

As an estimate of the period difference for the three mass difference conditions the difference between the corresponding weighted or un-weighted period of the participant in the left chair was subtracted from the corresponding weighted or un-weighted period of the participant in the right chair. For the 0.0 kg mass difference condition (the $0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$ mass combinations) the mean period difference between participants in a pair was -0.04 s. For the -27.22 and $+27.22$ kg mass difference conditions the mean period difference between participants in a pair was $+0.19$ s and -0.26 s, respectively.

2.2.2. Phase shift

The $2 \times 2 \times 3$ ANOVA conducted on phase shift revealed a significant main effect of mass difference, $F(1, 10) = 20.12$, $p < .01$, with the average angle of relative phase being shifted away from the canonical values of 0° and 180° by -2.56° and $+9.01^\circ$ for the -27.22 and $+27.22$ mass difference conditions, respectively. The analysis also yielded a significant Phase Mode \times Mass Difference interaction, $F(2, 20) = 4.14$, $p < .05$, with phase shift being more pronounced for antiphase than for inphase coordination (see Fig. 2a). Post hoc t -tests revealed that for antiphase coordination the phase shifts for the -27.22 and $+27.22$ mass difference conditions were significantly different from 0 ($p < .04$ and $.01$, respectively) and from the average phase shift observed for the 0.0 kg mass difference condition (both $p < .01$). For inphase coordination the phase shift for the $+27.22$ condition was found to be significantly different from 0 ($p < .01$) and from the phase shift observed for the 0.0 kg mass difference condition ($p < .01$). The phase shift for the -27.22 condition was not significantly different from 0 ($p > .05$), nor was it significantly different from the phase shift observed for the 0.0 kg mass difference condition ($p > .05$). The phase shift observed for the 0.0 kg mass difference condition was not significantly different from 0 for both inphase and antiphase coordination ($p > .15$). There was no main effect of phase mode, $F(1, 10) < 1$, nor any main or interactive effects of visual focus (all $p > .4$), with pairs in the peripheral and focal conditions exhibiting the same shifts in relative phase across conditions.

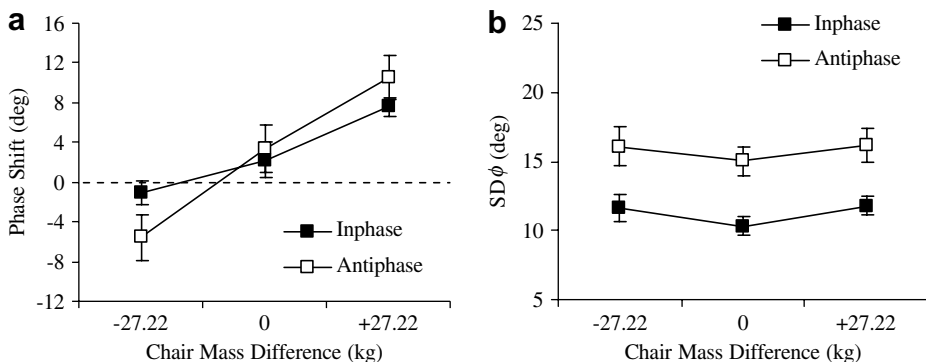


Fig. 2. (a) The phase shift and (b) the standard deviation of relative phase ($SD\phi$) for Experiment 1, as a function of intended phase mode and mass difference. The vertical lines depict standard errors of the means.

2.2.3. Standard deviation of relative phase

The analysis of $SD\phi$ revealed a significant effect for phase mode, $F(1, 10) = 20.12$, $p < .01$, with participants exhibiting a greater $SD\phi$ for antiphase than inphase coordination (see Fig. 2b). Although participants exhibited a greater $SD\phi$ for the +27.22 kg (13.9) and -27.22 kg (14.0) mass difference conditions than for the 0.0 kg (12.6) mass difference condition, the effect of mass difference on $SD\phi$ was not found to be reliable, $F(1, 10) = 2.49$, $p = .11$. There was also no significant Phase Mode \times Mass Difference interaction, $F(1, 10) < 1$, nor any effects of visual focus (all $p > .3$), with pairs exhibiting the same $SD\phi$ for the peripheral and focal conditions.

2.3. Discussion

Overall, the patterns of interpersonal coordination observed for the rocking chair movements in Experiment 1 are consistent with those predicted by the coupled oscillator dynamic and, thus, provide further evidence that visually mediated interpersonal coordination is governed by such entrainment processes. First, the results demonstrated that the visually coupled individuals coordinated their rocking chairs in a stable inphase and antiphase manner, and the variability ($SD\phi$) of coordination was found to be significantly greater for antiphase compared to inphase coordination. Second, the pairs' movements were shifted away from the values of $\phi = 0^\circ$ and 180° when there was a difference in the natural period of the chairs. For the -27.22 and +27.22 mass difference conditions, the movements of the participant in the un-weighted chair lagged behind the movements of the participants in the weighted chair. Lastly, consistent with the prediction that the magnitude of the shift away from $\phi = 0^\circ$ and 180° would be proportional to attractor strength, the phase shift for antiphase was found to be more pronounced than the phase shift for inphase.

The one prediction not substantiated was the effect of mass difference on $SD\phi$. Although participants did exhibit an increase in $SD\phi$ for the -27.22 and +27.22 mass difference conditions compared to when the chairs had the same mass attached at the base, this difference was not found to be significant. This may be due to the -27.22 and +27.22 mass difference conditions only resulting in an average period difference of ± 0.22 s (see the analysis of the baseline trials above). This period difference may have been too subtle to significantly increase the observed $SD\phi$. Indeed, a period difference of ± 0.22 s is lower than that typically used in previous research on intra- and interpersonal coordination—period differences greater than 0.3 s (e.g., Fuchs, Jirsa, Haken, & Kelso, 1996; Kelso et al., 1990; De Rugy et al., 2006; Schmidt et al., 1998). The strength and design of the rocking chairs employed in the current study restricted the maximum possible amount of mass that could be safely added to the base of the chair to less than 30 kg. Thus, the period difference between the weighted and un-weighted chairs could not have been increased by adding more mass.

Although the weight of participants was not found to be a significant covariate, not matching participants in weight may have still added noise to the mass difference manipulation. For certain pairs the difference in chair mass may have been lessened by the difference in participant weight. Recall that the weight of the participant increases the chair's center of mass and decreases the chair's natural period (see Appendix B). This possibility might account for the asymmetric effect of the -27.22 and +27.22 mass difference conditions and explain why the absolute period difference for the -27.22 kg mass difference

condition was estimated to be smaller (0.19 s) than for the +27.22 kg mass difference condition (0.26 s).

Finally, in contrast to the expectation that peripheral access to movement information would result in weaker (more variable) coordination than focal access to movement information, the results of Experiment 1 found no difference between the focal and peripheral conditions. This suggests that the visual movement information necessary for the production of intentional interpersonal coordination is available and can be picked-up in both peripheral and focal situations. This visual focus manipulation was included because during a natural social interaction two coordinated individuals do not always look directly at each other and, thus, may only have peripheral information about each other's movements. Hence, verifying that both types of visual coupling allow for the coordination of rocking chair movements is an important finding. However, during a natural social interaction, the movements of two individuals often become coordinated unintentionally, rather than intentionally (Richardson et al., 2005; Schmidt & O'Brien, 1997). Experiment 2 therefore examined whether the rocking chair movements of visually coupled individuals become unintentionally coordinated and whether the visual focus manipulation would have an influence on this weaker kind of coordination.

3. Experiment 2

Like the research on intentional interpersonal coordination, the previous research on unintentional interpersonal coordination (Richardson et al., 2005; Schmidt & O'Brien, 1997) has demonstrated that the rhythmic wrist-pendulum movements of two visually coupled individuals are constrained by the dynamics of coupled oscillators even when participants are instructed to produce rhythmic movements but perform another focal task (e.g., dyadic problem solving). This research has demonstrated that unintentional interpersonal coordination is of a form known as relative coordination (Kelso & Ding, 1994; Von Holst, 1939/1973). Relative coordination reflects the tendency for individuals to become coordinated near the stable states at relative phase angles near 0° (inphase) and 180° (antiphase), but to do so intermittently. That is, relative coordination refers to when individuals are *more likely* to be observed at the relative phase relations of 0° and 180° . This is in contrast with absolute coordination, in which individuals become phase locked at these two relative phase relations (i.e., like in Experiment 1), and completely uncoordinated movement, in which individuals exhibit all possible relative phase angles equally.

To investigate whether such unintentional coordination occurs between individuals in rocking chairs, pairs of participants were instructed to rock at their *individually* preferred tempos while in presence of each other. As in Experiment 1, period difference was manipulated by adding mass to the base of the chairs. It is important to appreciate that although unintentional interpersonal coordination is typically relative, relative coordination is still consistent with the coupled oscillator model used to understand intentional and intrapersonal coordination. The only difference is that the coupling strength that links the rhythmic movements is too weak to fully overcome the inherent differences in the natural periods of these movements (Kelso, 1995; Richardson et al., 2005; Schmidt & O'Brien, 1997). Thus, in addition to the expectation that the rocking chair movements of visually coupled individuals would become unintentionally phase-entrained and exhibit a tendency towards phase angles around 0° and 180° , the magnitude of this phase entrainment was

expected to decrease with an increase in the difference between the natural periods of the two rocking chairs (i.e., an increase in the mass difference between chairs).

As in Experiment 1, visual focus was manipulated. Although the results of Experiment 1 demonstrated that the strength of the peripheral coupling was sufficient for the movements of two individuals to produce and maintain the stable patterns of coordination, the question of whether peripheral access to movement information is sufficient to bring about unintentional coordination remains to be answered. Having only peripheral access to information may decrease the strength of, and even prevent the emergence of, unintentional coordination because, unlike individuals in an intentional situation, individuals in an unintentional situation are not required to attend to movement information. That is, the stability of visual interpersonal coordination might not simply be a matter of whether visual information is available, but whether individuals attend to and are able to detect this information.

3.1. Method

3.1.1. Participants

Sixteen undergraduates from the University of Connecticut participated in the experiment for partial course credit and were randomly grouped into eight experimental pairs (three male pairs, two female pairs, and three mixed gender pairs). A pre-experiment interview verified that all of the participant pairs did not know each other prior to the experiment—a participant may have seen their co-participant on campus or in class, but had never interacted with them directly.

3.1.2. Materials

The same rocking chairs, mass combinations and motion capture system used in Experiment 1 were employed. In addition to the peripheral and focal information conditions used in Experiment 1, the current experiment included a no information condition, in which each participant in a pair fixed their gaze on a 10 by 10 cm red target located in the direction opposite to their co-actor (see Fig. 1b). This condition provided a baseline control, so that the degree of coordination observed in the peripheral and focal conditions could be compared to a chance level of coordination.

3.1.3. Procedure

Upon arrival, the participants were informed that the experiment was investigating the ergonomics of rocking chair movements and that the current study was investigating what the optimal mass of a rocking chair should be to produce the most stable and comfortable rocking motion. The participants were informed that they would be required to complete a number of trials in which they would have to rock with different magnitudes of mass attached to the base of the chair. It was casually mentioned to the pair that they would be completing the task at the same time because running two people at the same time was a more efficient (quicker) way of collecting data. Participants were informed that the current study was also interested in how different postural configurations affected the stability of rocking chair movements and that in order to investigate this they would have to turn their head and focus on the red target located on the wall directly in front of them (peripheral access to information), on the wall to either side of them (no information), or on the arm rest of the other participant (focal access to information). It was

explained to participants that this final red target was placed on the armrest of the other participant's rocking chair so they did not have to awkwardly stare at each other.

After explaining this (bogus) purpose of the study to participants, each participant was assigned to one of the two (un-weighted) rocking chairs and asked to practice rocking back and forth while keeping their feet placed on the floor and their backs against the backrest. It was made clear to each participant that they should ignore the other participant and rock at their own self-selected tempo—a tempo they could maintain comfortably for an extended period of time—and maintain that tempo for the entire length of each trial. Each participant was then given a pair of industrial sound occluding earmuffs and told that they should wear them throughout the experiment so that the noise of the chairs did not interfere with their rocking tempo. Of course, this was actually done to eliminate any auditory information that may cause the movement of the two participants in a pair to become unintentionally coordinated. To avoid the possibility that the movements of the participants would be trivially coordinated from the outset of the trial due to starting their rocking motions in the same direction and at the same time, the participants were instructed to start rocking at different times—within 2–5 s of each other (see Richardson et al., 2005).

The experiment consisted of two 90 s trials for each visual focus (none, peripheral, focal) by mass combination condition ($0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$, $0.0_{\text{Ch1}}/27.22_{\text{Ch2}}$, $27.22_{\text{Ch1}}/0.0_{\text{Ch2}}$, and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$), yielding a total of 24 trials. The order of these trials was different for each participant pair. A post-experimental funneled debriefing was included to assess suspicions about the true purpose of the experiment.

3.1.4. Design and dependent measures

As in Experiment 1, the dependent measures were averaged across the $0.0_{\text{Ch1}}/0.0_{\text{Ch2}}$ and $27.22_{\text{Ch1}}/27.22_{\text{Ch2}}$ mass combinations. Thus, the experiment was a 3 (Mass Difference: -27.22 , 0.0 , $+27.22$ kg) \times 3 (Visual Focus: none, peripheral, focal) within-subjects design.

Given that in the current experiment the coordination is expected to be relative rather than absolute, phase shift and $SD\phi$ are not appropriate for measuring the stability of coordination (see Richardson et al., 2005; Schmidt & O'Brien, 1997). Two different dependent measures were therefore used to determine whether the rocking movements of the two individuals became unintentionally coordinated or entrained across the different conditions. The first of these measures, cross-spectral coherence, evaluated the coordination that occurred between the rocking movements by estimating the correlation between the movements of the chairs at their peak frequencies. Coherence measures the degree of coordination between the two time series on a scale from 0 to 1. A coherence of 1 reflects perfect correlation of the movements (perfect phase entrainment) and 0 reflects no correlation (no phase entrainment; see Richardson et al., 2005; Schmidt & O'Brien, 1997). As a measure of the type of coordination that emerged, the distribution of relative phase angles formed between the movements of the two rocking chairs was employed as the second measure. These distributions consisted of nine 20° regions of relative phase between 0° and 180° and were determined by calculating the continuous time series of relative phase (at 60 Hz) for each trial and then calculating frequency of occurrence in each of the nine relative phase regions (Richardson et al., 2005; Schmidt & O'Brien, 1997). Phase-entrainment or relative coordination that is consistent with the dynamics of coupled oscillators is indicated by a concentration of relative phase angles in the portions of the distribution near 0° and/or 180° .

3.2. Results

3.2.1. Cross-spectral coherence

The 3×3 ANOVA conducted on the coherence values averaged across the two trials for each mass difference by visual focus condition revealed a significant main effect of mass difference, $F(2, 14) = 4.09$, $p < .05$, with less coherence being observed for the -27.22 and $+27.22$ mass difference conditions compared to the 0.0 kg mass difference condition. Although the Visual Focus \times Mass Difference interaction was not a reliable effect, $F(2, 14) = 2.16$, $p > .09$, Fig. 3 shows that the decrease in coherence for the -27.22 and $+27.22$ mass difference conditions was more pronounced for the focal condition. Specifically, for the focal condition the average coherence for the 0.0 kg condition equaled .45, whereas the coherence for the -27.22 and $+27.22$ mass difference conditions was equal to .33 and .26, respectively.

In addition to the main effect of mass difference, the ANOVA revealed a significant effect of visual focus, $F(2, 14) = 16.01$, $p < .01$. As Fig. 3 indicates, the peripheral condition resulted in an average coherence value (.085) that was equivalent to that found for the no information coordination (.071), whereas the average coherence value for the focal condition (.35) was much greater than in both the peripheral and no information conditions.

3.2.2. Distribution of relative phase

The distribution of relative phase angles across the nine phase regions was submitted to a 3 (Visual Focus) \times 3 (Mass Difference) \times 9 (Phase Region) repeated measures ANOVA. Using the Greenhouse–Geisser correction this analysis yielded a significant main effect of phase region, $F(1.17, 8.21) = 13.62$, $p < .01$, as well as significant interactions between visual focus and phase region, $F(1.38, 9.63) = 16.37$, $p < .01$, mass difference and phase region, $F(2.26, 15.82) = 5.79$, $p < .02$, and visual focus, mass difference, and phase region, $F(3.39, 23.79) = 3.47$, $p < .03$. Fig. 4 plots the percentage of relative phase angles that occurred for the nine different phase regions as a function of the visual focus conditions and mass difference. In the no information condition (Fig. 4a) participant pairs exhibited an equal concentration of relative phase angles across the nine phase regions irrespective of mass difference. No simple effects were significant in this condition (all $ps > .05$). Given

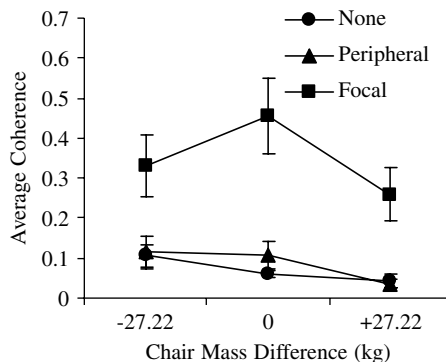


Fig. 3. Average coherence for Experiment 2, as a function of visual information and mass difference. The vertical lines depict standard errors of the means.

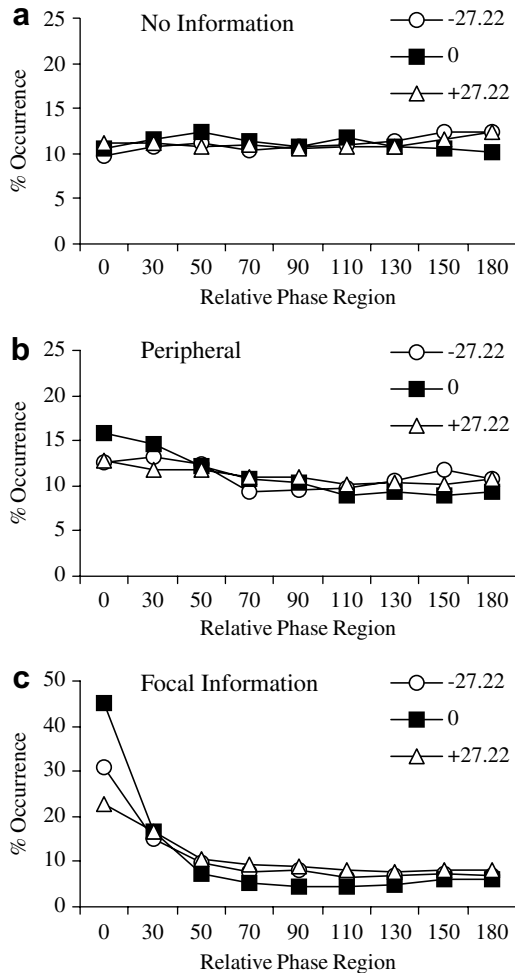


Fig. 4. The distribution of relative phase angles for Experiment 2, as a function of mass difference and visual information.

that relative or unintentional coordination is characterized by a concentration of relative phase angles around 0° and 180° , this indicates that participants did not become unintentionally coordinated when there was no visual information about their co-actor's movements.

In contrast, Fig. 4c illustrates that for the focal condition participant pairs exhibited a large concentration of relative phase angles around 0° . Fig. 4c also reveals that the degree of relative coordination exhibited by the pairs was influenced by mass difference, with the concentration of phase angles around 0° being greater for the 0 kg mass difference condition than for the -27.22 and $+27.22$ kg mass difference conditions—hence the significant Mass Difference \times Phase Region and Visual Focus \times Mass Difference \times Phase Region interactions reported above. Simple effect analyses using the Greenhouse–Geisser correction verified these conclusions. That is, for the focal condition there was a significant

simple effect for phase region, $F(1.15, 8.03) = 16.96$, $p < .01$, which was moderated by a significant Mass Difference \times Phase Region simple interaction, $F(1.76, 12.33) = 6.05$, $p < .02$.

Fig. 4b reveals that there was also a larger concentration of phase angles around 0° for the peripheral condition, particularly for the 0.0 kg mass difference condition. Again, a simple effect analyses using the Greenhouse–Geisser correction verified this conclusion, with the analysis revealing a significant simple effect for phase region, $F(1.70, 11.93) = 3.86$, $p = .056$, $\eta_p^2 = 0.36$. Although an inspection of Fig. 4b also suggests that the concentration of phase angles around 0° was greater for the 0.0 kg mass difference condition than for the -27.22 and $+27.22$ kg mass difference conditions, the simple effects analysis found no Mass Difference \times Phase Region simple interaction, $F(2.86, 19.99) = 1.02$, $p > .05$. However, this effect was somewhat confirmed by comparing the average concentration of phase angles in the middle phase regions ($60\text{--}80^\circ$, $80\text{--}100^\circ$ and $100\text{--}120^\circ$) with the concentrations in the region near 0° ($0\text{--}20^\circ$) using post-hoc t -tests within each mass difference condition. For the -27.22 and $+27.22$ kg mass difference conditions, the average concentration of phase angles in the middle phase regions were not significantly different from the concentrations in the region near 0° ($ps > .25$). For the no mass difference condition, however, the average concentration of phase angles in the region near 0° was significantly greater than the concentrations in the middle phase regions ($p < .05$).

3.3. Discussion

The current experiment investigated whether rocking chair movements of visually coupled participants would become unintentionally coordinated and if so, whether the coordination observed reflected the self-organizing entrainment process of coupled oscillators. As expected, the results of the cross-spectral coherence analysis indicated that unintentional coordination did occur for visually coupled rockers, but only when the individuals directed their visual attention directly towards the movements of their co-actor. That is, the pairs' movements were correlated at a greater than chance level (no information condition) for the 0.0, -27.22 and $+27.22$ kg mass difference conditions when participants had focal, but not peripheral access to movement information. Consistent with the predicted effects of mass difference, the magnitude of coherence for the -27.22 and $+27.22$ kg mass difference conditions was significantly less than for the 0.0 kg mass difference condition (again, despite the possible noise effects of not matching participants in weight).² Recall that the -27.22 and $+27.22$ kg mass difference conditions create a difference in the natural period of the chairs (see Experiment 1) and that the coupled oscillator model (Appendix A) predicts that entrainment strength will be weaker for movements with different natural periods than for movements with the same natural period. Finding lower coherence for -27.22 and $+27.22$ kg mass difference conditions is consistent with this prediction in that lower coherence values reflect weaker entrainment.

² The weight (kg) of the participants was not recorded in Experiment 2, so the influence of participant weight difference on the stability and emergence of unintentional coordination could not be examined. However, the results of Experiment 1, in which participant weight difference was not found to have a significant influence on the stability of coordination, suggest that the effects of participant weight would have been minimal. Observing the expected influence of the mass difference manipulation in Experiment 2 would seem to be an indication of this.

Interestingly, the coherence values found for the focal condition were comparable to the coherence values reported by Schmidt and O'Brien (1997) and Richardson et al. (2005) when examining the unintentional coordination of wrist-pendulum movements between people. Thus, the coherence results not only provide evidence that a focal visual coupling is sufficient for the movements of two individuals to become unintentionally coordinated, but that this is true for both globally (whole body) and locally controlled (limb, wrist) movement systems.

Like the results for coherence, the results for the distributions of relative phase indicate that the visually coupled rocking movements became unintentionally coordinated and that the stability (strength) of this coordination was weaker for the -27.22 and $+27.22$ kg mass difference conditions compared to the 0.0 kg mass difference condition. As expected, the analysis also revealed that the observed coordination was relative. That is, pairs exhibited a tendency to become coordinated at relative phase angles near 0° (inphase), but that rather than becoming phase locked at this phase relation, the pairs also exhibited periods of uncoordinated behavior (i.e., exhibited all possible phase relations).

In contrast to the coherence results, however, the analysis of the distributions of relative phase revealed that the pairs' movements were attracted towards an inphase pattern of coordination not only for the focal condition, but also the peripheral condition. Although the concentration of relative phase angles around 0° was much less for the peripheral condition, compared to the focal condition, and only occurred for the 0.0 kg mass difference condition, the existence of this increased concentration reveals some degree of coupling. More importantly, given that Experiment 1 found that the peripheral coupling was sufficient for two individuals to coordinate their movements intentionally, finding a small amount of coordination for the peripheral condition indicates that the necessary movement information was available in both the peripheral and focal movement conditions and that the strength of an interpersonal visual coupling is mediated by attention and the possibility of detecting the relevant movement information. The results of a recent experiment performed by Schmidt, Richardson, Arsenault, and Galantucci (in press) support this conclusion. In this experiment the authors instructed a participant to intentionally coordinate a wrist-pendulum with an oscillating visual stimulus, while concurrently reading letters that appeared on the oscillating visual stimulus or just above the center of the visual stimulus's motion. The results demonstrated that the stability of coordination was greater when the letters appeared on the visual stimulus than when the letters appeared just above the center of the stimulus's motion. The authors concluded that the strength of the visual coupling was not simply a matter of whether visual information is available, but whether the perceptual system attended to the detection of that information. Research by Temprado and Laurent (2004) also supports this conclusion by demonstrating that the stability of interpersonal coordination decreases as participants focus more attention on a concurrently performed reaction time task. Other research on visual and within-person interlimb coordination has also demonstrated that attentional focus can modulate the stability (and perhaps strength) of rhythmic coordination (e.g., Amazeen, Amazeen, Treffner, & Turvey, 1997; Roerdink, Peper, & Beek, 2005; Temprado, Zanone, Monno, & Laurent, 1999, 2001).

Finally, the tendency of participant pairs to only exhibit phase angles around 0° , instead of around 0° and 180° is worth mentioning. As indicated above, relative coordination is typically characterized by a tendency of the movements of visually coupled individuals to wander between the phase angles of 0° and 180° (Richardson et al., 2005; Schmidt

& O'Brien, 1997). Richardson et al. (2005) have highlighted that finding an overall tendency towards inphase coordination can sometimes be a sign that pairs may have exhibited trivial coordination—were coordinated inphase from the start of the trial—or may have intentionally coordinated their movements. With respect to the former, however, recall that participants were instructed to start rocking at different times to avoid this possibility (as suggested by Richardson et al., 2005). Furthermore, a close inspection of the data revealed that no one pair exhibited inphase coordination (exhibiting only relative phase angles with the 0–20° phase bin) for 100% of any trial.³ With respect to the possibility of the coordination being intentional, post-experimental interviews revealed that the participants were unaware of the study's purpose and had believed the cover story. In fact, none of the participants were aware that they had altered their self-selected rocking tempo in any way during the experiment—which was necessary for coordination to occur, particularly in the –27.22 and +27.22 kg mass difference conditions—and the majority of the participants indicated that they were oblivious to the fact that their movements may or may not have been coordinated with their partner. Thus, finding that visually coupled rocking movements only exhibit a tendency towards phase angles around 0° in both the peripheral and focal information conditions suggests that in this unintentional situation, the attractor at $\phi = 180^\circ$ is too weak to sustain any significant coordination. Note that this finding is still consistent with the coupled oscillator model used to understand within-person interlimb coordination (Richardson et al., 2005; Schmidt & Richardson, *in press*). More specifically, because the attractor at $\phi = 180^\circ$ is inherently weaker than the attractor at $\phi = 0^\circ$, the model predicts that for an extremely weak coupling the presence of behavior at or around $\phi = 180^\circ$ would almost completely disappear and that inphase rather than antiphase movement would dominate the system's behavior (Repp, 2006; Richardson et al., 2005).

4. General discussion

The current study investigated the dynamics of interpersonal coordination of rocking chair movements. We hypothesized that the stable patterns of coordination would be consistent with the dynamical model used to explain and understand other forms of rhythmic interpersonal and intrapersonal coordination. To test these predictions, we conducted two experiments that examined the movement patterns of pairs of individuals rocking together who either intentionally (Experiment 1) or unintentionally (Experiment 2) coordinated their movements. In both experiments, the degree to which the participants visually focused on the movements of their co-actor was manipulated by instructing participants to fixate on a red target that was either positioned on their co-actor's chair (focal condition) or on the wall directly ahead of them (peripheral condition). This

³ For the focal condition, the percentage of time participants exhibited relative phase angles in the 0–20° phase bin ranged from 8.7% to 88%, with a mean of 35.86% and a SD of 25.40% (in only 11% of the trials did near inphase coordination occur for more 75% of a trial; in 45% of the trials, near inphase coordination was intermittently observed for 25–75% of a trial). For the peripheral condition, the percentage of time participants exhibited relative phase angles in the 0–20° phase bin ranged from 2.3% to 46.1%, with a mean of 14.23% and a SD of 8.57%.

latter manipulation was included to investigate the hypothesis that peripheral access to movement information would result in a weaker visual coupling than focal access to movement information.

Overall, the results supported the hypothesis that the patterns of intentional and unintentional visual coordination are constrained by the dynamics of coupled oscillators and provide evidence that these dynamics reflect a general principle of perceptual-motor coordination. This principle can not only explain the coordination of locally controlled movements (e.g., wrist, arm and leg movements), but also the coordination of globally controlled movements (ones that entail many parts of an individual's body). This latter point was further evidenced by the fact that the predicted patterns of coordination were observed in Experiments 1 and 2 irrespective of whether the participants used the same or different body components to maintain the chair's motion—while some participants only used their left and right legs, others (not always in the same pair) also used torso and/or head displacements.

In replicating the previous research on intentional and unintentional interpersonal coordination (e.g., Richardson et al., 2005; Schmidt et al., 1990; Schmidt & Turvey, 1994; Schmidt & O'Brien, 1997), the current results also provide more evidence that visual information can couple the oscillatory movements of interacting individuals. This is important, as it reveals that the dynamics that constrains rhythmic coordination independent of whether the coupling that links the oscillator components is mechanical or visual (Schmidt et al., 1998; Schmidt & Turvey, 1994; Wimmers, Beek, & Van Wieringen, 1992). An auditory coupling can also constrain the rhythmic limb movements of individuals intrapersonally (e.g., Kudo, Park, Kay, & Turvey, 2006; Repp, 2004, 2006; Repp & Penel, 2004) and interpersonally (Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000), just as physical vibrations⁴ through a common support synchronize the motions of mechanical pendulum clocks (Huygens, 1673/1986, see Pikoovsky, Rosenblum, & Kurths, 2001; for a review). An auditory coupling is also known to constrain the synchronous chirping of crickets (Walker, 1969) in a similar way to how a visual coupling constrains the synchronous flashing of fireflies (e.g., Hanson, 1978). Taken together, this evidence indicates that stable coordination has less to do with the physical qualities of the coupling medium and more to do with whether the coupling provides the appropriate information about the movements in question (Bingham, 2004; Bingham, Schmidt, & Zaal, 1998; Meschner, Kerzel, Knoblich, & Prinz, 2001; Roerdink et al., 2005; Schmidt et al., 1998; Wilson, Bingham, & Craig, 2003; Wilson, Collins, & Bingham, 2005).

It was originally hypothesized that peripheral access to movement information would result in a weaker coupling for both intentional and unintentional interpersonal coordination. Finding that the peripheral condition only modulated the strength of the visual coupling during unintentional coordination, however, lends empirical support to the assertion that the strength of interpersonal coordination is influenced by attention (Temprado & Laurent, 2004) and the importance of an individual's ability to detect movement information

⁴ In addition to the visual coupling, physical vibrations through the ground might also have coupled the rocking chair movements. However, given that no coordination was observed in the no-vision control condition, it appears as though physical vibrations through the ground alone did not provide a strong enough coupling for unintentional coordination to occur.

(Schmidt & Richardson, *in press*). That is, because the stability of the coordination observed in Experiment 1 was the same for the peripheral and focal conditions, the differences between the focal and peripheral conditions in Experiment 2 could not have resulted from differences in the amount or availability of movement information. Instead, the differences between the focal and peripheral conditions were most likely due to participants not being forced to attend to the motion of their co-actor's chair for the peripheral information condition. However, because of the between- versus within-subjects nature of the visual focus manipulation in Experiments 1 and 2, respectively, an alternative explanation is that a within-subjects design reduces participants' sensitivity to the visual focus manipulation in some unknown way.

Finally, the current study has important implications for future research on the social psychological aspects of interpersonal coordination and synchrony (e.g., Semin, 2007) in that the rocking chair paradigm provides a natural and ecologically valid way of examining the effects of social psychological variables, such as in-group/out-group status (Yabar, Johnston, Miles, & Peace, 2006) on the amount of coordination observed between people. The naturalness of the rocking chair paradigm might also provide a basis for examining the interpersonal processes involved in the formation of a social connection (Marsh, Richardson, Baron, & Schmidt, 2006; Schmidt, Christianson, Carello, & Baron, 1994). Furthermore, manipulating the degree (or possibility) of unintentional coordination that can occur between interacting individuals by increasing or decreasing the difference in the natural period of the rocking chairs should provide a way of examining the effects of interpersonal coordination (or lack thereof) on rapport. To date, the relationship between interpersonal coordination and the social psychological variables of interpersonal interaction have been most widely investigated using mimicry phenomena (e.g., Bargh & Chartrand, 1999; Dijksterhuis & Bargh, 2001; Lakin & Chartrand, 2003; Van Baaren, Holland, Steenaert, & Van Knippenberg, 2003). Such mimicry-based approaches to interpersonal coordination, however, have not systematically examined the relationship between the stability of interpersonal coordination and the social psychological aspects of interpersonal interaction (Marsh et al., 2006; Richardson et al., 2005; Sebanz, Bekkering, & Knoblich, 2006). Clearly, the specific predictions of the coupled oscillator model used to understand within and between person coordination mean that the rocking chair paradigm could offer a powerful way of systematically examining the relationships between interpersonal coordination and the social psychological aspects of interpersonal interaction. Moreover, by drawing on dynamical systems theory, the rocking chair paradigm should help in uncovering the degree to which interpersonal interaction itself needs to be understood as a dynamically constrained self-organized process.

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Appendix A

The coordinated behavior of two rhythmic limb or body movements is consistent with the dynamics of coupled limit-cycle oscillators. Thus, for 1:1 frequency locked coordination, the dynamic stabilities of such coordination can be captured using a motion equation for the collective variable of relative phase $\phi = (\theta_L - \theta_R)$, the difference in the phase angles of the left and right movements/oscillators. This variable is referred to as ‘collective’ because it quantifies in a single measure the spatial and temporal details of the two movements, as well as the multiple neural and muscular processes inherent to the movements. Typically, the motion equation takes the form:

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

where $\dot{\phi}$ is the rate of change of the relative phase and indexes where one movement is in its cycle relative to the other (Haken et al., 1985). The sine functions of ϕ and 2ϕ , along with their respective coefficients a and b , index the relative strength of the stable relative phase modes (when $\dot{\phi} = 0$) at $\phi = 0^\circ$ (inphase coordination) and $\phi = 180^\circ$ (antiphase coordination). $\Delta\omega$ is the frequency competition or detuning parameter and indexes the difference between the oscillators’ inherent uncoupled frequencies (Fuchs et al., 1996; Kelso et al., 1990; Schmidt et al., 1993; Sternad, Collins, & Turvey, 1995). Finally, ζ_t is a Gaussian white noise process that dictates a stochastic force of strength Q (Schöner, Haken, & Kelso, 1986).

Stable coordination (absolute coordination, Von Holst, 1939/1973) is said to occur when $\dot{\phi}$ is zero. Attractor states emerge at $\phi = 0^\circ$ and 180° —when the interlimb coordination is inphase (same parts of the cycle at the same time) or antiphase (opposite parts of the cycle at the same time)—and repellors emerge at $\phi = 90^\circ$ and 270° . However, phase-locked states at $\phi = 0^\circ$ and 180° only emerge when the coupling strength of the dynamic (dictated by the coefficients a and b) is strong enough to overcome $\Delta\omega$, the difference in the inherent frequencies of the two oscillators. When the coupling strength is not strong enough to produce phase locking, no stable phase angle will emerge but the oscillations will still be coordinated because they are still attracted to 0° and 180° (Kelso, 1995; Kelso & Ding, 1994). Such phase entrainment is known as relative coordination (Von Holst, 1939/1973).

Appendix B

The period of a person rocking in a rocking chair is constrained by the chair’s eigenfrequency. The eigenfrequency of an unseated rocking chair (a chair without sitting person) is a function of the chair’s center of mass and the distance of the center of mass from the point of rotation. A chair’s eigenfrequency can be calculated (Hahn, 2003) as

$$p = \frac{1}{\omega} = \frac{1}{2\pi} \sqrt{g \frac{R-h}{h^2}}. \quad (B1)$$

Here, ω and p are the eigenfrequency and natural period of a rocking chair, respectively, g is acceleration due to gravity, R is the chair’s center of rotation (center of curvature), and h is the chair’s center of mass (see Fig. B1).

As Eq. (B1) makes clear, a rocking chair’s natural period can be altered by changing h , such that the lower the center of mass is (the smaller the value of h), the faster a rocking

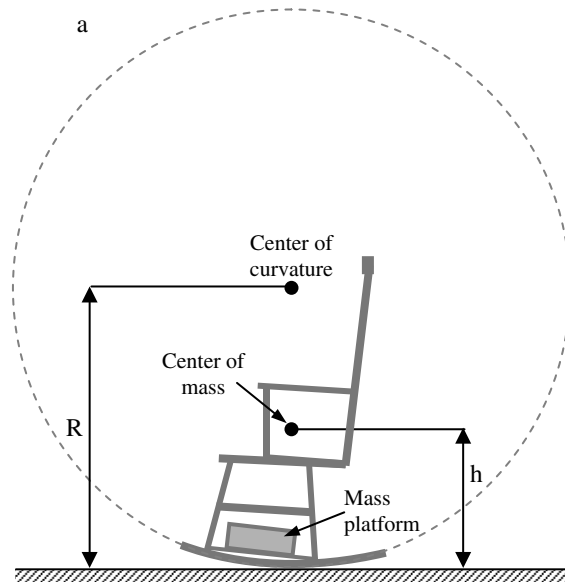


Fig. B1. A schematic diagram of the experimental rocking chair including its center of curvature (rocking radius R) and its center of mass (h)—adapted from Hahn (2003).

chair's natural period. Conversely, the higher the center of mass is, the slower a rocking chair's natural period. The location of a chair's center of mass can be manipulated experimentally by adding mass to the base of the rocking chair, whereby the more mass added, the lower is the center of mass and the faster is the natural period of the chair. The rocking chair(s) used in the current study had an approximate center of curvature (rocker radius) of 1 m and an estimated center of mass of 0.49 m (see Fig. B1). To determine the effects of adding mass, three 9.07 kg lead masses (weights) were used to create the four mass magnitude conditions (0.0, 9.07, 18.14, and 27.22 kg) and were positioned side-by-side at the center of a platform that was attached to the legs of the chair just above the rocker bottoms. Table B1 shows the center of mass, eigenfrequency, and natural period of the rocking chairs used in the current study with different amounts of mass attached at its base. These estimates were obtained empirically by recording the cycle-to-cycle movement of the chairs after releasing them from a fixed position—rotating the chairs backwards so that the top of the chair's headrest was 25 cm from its equilibrium position. Five time series were recorded for each chair mass. The chair's unseated natural frequency (i.e.,

Table B1
The rocking chair's properties without a seated participant

	Chair mass condition (kg)			
	0	9.07	18.14	27.22
Center of mass (cm)	.49	.40	.36	.32
Eigenfrequency (Hz)	.72	.96	1.13	1.27
Natural period (s)	1.39	1.04	.89	.79

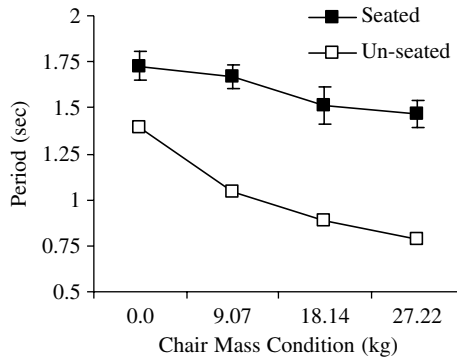


Fig. B2. The period of the experimental rocking chair for four mass conditions. The seated periods are the mean comfort periods averaged across participant. The un-seated periods are the estimated periods of the chair for the four mass conditions using Eq. (B1). The vertical lines depict standard errors of the means.

eigenfrequency) for each mass condition was calculated as the average frequency from these trials (the results were almost identical for each trial).

It is important to note that although the tempo of a person rocking in a rocking chair is constrained by a chair's unseated eigenfrequency, the actual period of an individual will be different from this eigenfrequency because a seated individual raises the chair's center of mass and, consequently, increases the natural period of the chair. As a demonstration of this, five participants (different from those used in Experiment 1) were instructed to rock in a rocking chair at a comfortable tempo—a tempo they could maintain for an extended period of time. The participants completed two 60 s trials for each of the different mass conditions described above (i.e., 0.0, 9.07, 18.14, and 27.22 kg). As can be seen from an inspection of Fig. B2, the participants rocked at a comfort period of 1.73 s for the unweighted condition, and 1.67, 1.51, and 1.47 sec for the 9.07, 18.14, and 27.22 kg mass conditions, respectively ($F(3, 12) = 18.46, p < .01$). As predicted, the participant's comfort rocking period was not only observed to be constrained by a chair's center of mass (a participant's rocking period became slower the greater the mass), but was also much slower than the chair's unseated eigenfrequency due to the participant's own weight increasing the chair's center of mass. This was also verified by performing a regression analysis with period as the outcome variable, and added mass and participant weight as predictor variables. The analysis yielded an R^2 of .743, with both mass condition ($\beta = -.535$) and participant weight ($\beta = .676$) found to be significant predictors of period ($ps < .001$).

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