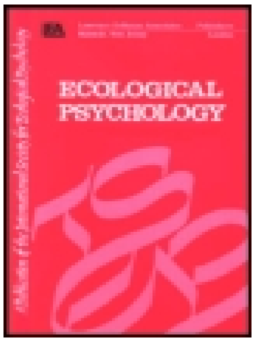

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Evaluating the Dynamics of Unintended Interpersonal Coordination

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Past research has shown that interpersonal interactions are characterized by a tacit coordination of motor movements of the participants and has suggested that the emergent synchrony might be explained by a coupled oscillator dynamic. This study investigates whether unintended between-person coordination can be demonstrated in a laboratory task that will allow an evaluation of whether such dynamical processes are involved. Ten pairs of participants performed a simple rhythmic task in which they had visual information about each other's movements but had no goal to coordinate. A cross-spectral analysis of the movements revealed higher coherence and a distribution of relative phase angles that was dominated by values near 0° and 180°. These results support the hypothesis that dynamical organizing principles are involved in natural interpersonal synchrony.

The foundation of all society's activity is the physical, motor coordination of people in social interactions. This very basic and important coordination phenomenon primarily has been studied by social psychologists. They have investigated *interactional synchrony*—the emergent, unintended coordination found in natural social interactions (Davis, 1982). An example of this kind of social coordination is the

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synchrony found between the speech rhythms of a speaker and the bodily gestures of a listener in a conversation. Such coordination has been observed at a great number of time scales. From the coordination of speech and hand gestures that are milliseconds long (Condon, 1982) to cycles of conversation that span about an hour (Hayes & Cobb, 1982), the timing of one individual's movements apparently is linked to the timing of the movements of another. The questions of this past research have focused on how social variables affect the coordination observed. For example, will dyads who report having better rapport (Bernieri, 1988) or women interacting with their own children (Bernieri, Reznick, & Rosenthal, 1988) have a higher degree of interactional synchrony? Although past studies have found positive answers to these questions, what has not been addressed in the research is how this coordination is possible without explicit control or awareness from the individuals involved. The unintended nature of the coordination makes it seem that these are coordinations in which the individuals implicitly participate rather than explicitly control. The question is how this entrainment is possible and by what mechanism it occurs.

Some social interaction researchers have suggested that the dynamics of coupled oscillators can be used to understand the processes underlying interactional synchrony (Bernieri & Rosenthal, 1991; Newtson, Hairfield, Bloomingdale, & Cutino, 1987). Such oscillatory dynamics have been used to understand the coordination of many different kinds of biological rhythms—the coordination of sinus and cardiac rhythms (Bellet, 1971), the coordination of respiratory and locomotory rhythms (Bramble & Carrier, 1983), and the coordination of limb segments in locomotory-type rhythmic acts (Haken, Kelso, & Bunz, 1985; Kugler & Turvey, 1987; Schmidt & Turvey, 1995). The coordination of rhythmic behaviors that emerges in such situations is dynamical—occurring through the free interplay of forces and mutual influence of components, that is, through a lawful, self-organizing process. Under the proper boundary conditions, the interaction of the biological rhythms across neural and metabolic pathways is sufficient for them to become entrained. The question that has interested social interaction researchers is whether the principles of a theory of self-organizing, oscillatory phenomena are general enough to explain the entrainment of rhythms on the interpersonal level of interaction. If so, the coordinative properties of dynamical oscillatory regimes must be general enough to constrain the coordination of oscillations that are linked not materially, but only informationally (i.e., perceptually).

Past research on interpersonal coordination using laboratory interactions rather than natural social interactions has shed some light on this question (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, in press; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994). This research has studied the intended coordination of rhythmic movements between two people. Whereas in natural social interactions, the coordination that emerges is not an explicit goal of the interaction, in this research participants are explicitly told to coordinate their rhythmic movements and to "lock" their movements at a prescribed relative phase relation. Schmidt et al. (1990) investigated the differential stability of different relative phase patterns in between-person coordination of lower leg oscillations. They found that inphase movements (i.e., at the same points in the cycle at a given point in time—0° relative phase) were more stable than antiphase movements (i.e., at opposite points in their cycle at a point in time—180° relative phase), and antiphase movements broke down when scaled to higher frequencies of oscillation, whereas inphase movements did not. Because similar phenomenon had been observed in the within-person coordination of hand movements (Kelso, 1984) and have been dynamically explained using a coupled oscillator model (Haken et al., 1985; Schöner, Haken, & Kelso, 1986), Schmidt et al. (1990) argued that the interpersonal differential stability of relative phase patterns has an identical dynamical explanation.

Additional evidence for a dynamical organizing of intended interpersonal phase-locking was found using a wrist-pendulum methodology. Schmidt and Turvey (1994) had two participants sitting side-by-side coordinate the oscillation of weighted dowels—wrist-pendulums—in the sagittal plane using ulnar and radial flexion of their wrists (see Figure 1). Their task was to watch each other's pendulum and coordinate their oscillations in antiphase at a mutually comfortable tempo. What was manipulated on different trials was the differential inertial loading of the two wrist-pendulum systems: The two systems could be identical or different in their mass and length magnitudes to varying degrees. Such an inertial manipulation effectively scales the difference between the preferred frequencies or the eigenfrequencies of the pendulum pairs.

A dynamical, coupled oscillator model of the rhythmic coordination predicts that scaling the eigenfrequency difference should have two effects on the relative phasing. First, there should be a phase lag (i.e., the relative phase exhibited by the

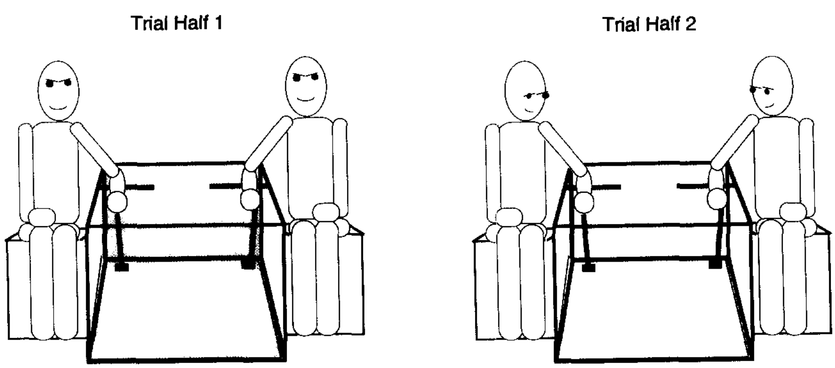

FIGURE 1 The between-person coordination methodology. The participants are asked to find a comfortable tempo of oscillation in the first trial half while not looking at each other (left panel). They are then required to look at the other person's pendulum but maintain their original tempo of oscillation in the second trial half (right panel).

oscillatory system should move away from perfect 180°) whose magnitude is in proportion to the eigenfrequency difference. Second, the model predicts that as the magnitude of the eigenfrequency difference increases, the stability of the system should decrease, and the fluctuation of relative phasing should increase. The results of the between-person wrist-pendulum experiment provided clear support for the dynamical, coupled oscillator model. As the eigenfrequency difference of the pendulum pair was scaled away from 0°, the mean relative phase of the system moved away from 180° such that the pendulum with the inherently lower eigenfrequency was lagging in its cycle, and the standard deviation of relative phase increased. This study and Schmidt et al. (1990) both suggest that *intended* interpersonal coordination can be understood in terms of the same dynamical processes of self-organization that underlie the intrapersonal coordination of biological rhythms. When two people intend to coordinate their rhythmic limb movements, the ensuing behavioral pattern is that of a dynamical coupled oscillatory system. It appears that the participants have assembled a dyadic coupled oscillatory control structure to produce a perceptual coordination.

But what about the unintended entrainment of movements that occurs in natural social interactions? Does it also have a dynamical basis? To answer this question, one must set up a methodology that elicits unintended coordination. Dyadic motor coordination occurs as part of a goal-directed activity and can be described on a continuum of task constraint. Most often the goal of the activity is not the coordination itself but rather a sharing of information or exchanging of a greeting, and so on. On this end of the continuum, the *unintended* coordination that ensues is only weakly constrained by the task, because the coordination is an implicit property that emerges from the dyadic interaction. Alternatively, on the other end of the continuum, the goal of some dyadic tasks is the coordination itself (dancing, aerobics, previously described between-person coordination experiments, etc.). Such *intended* coordination is strongly constrained by the task because the between-person coordination is the explicit goal of the interaction.

To study unintended coordination, one must create a situation in which the task only weakly constrains the coordination—that is, one in which the participants' goal is other than the interpersonal coordination that results from the interaction. To achieve this in our study, the previously described wrist-pendulum methodology was modified in the following way. Each participant of a dyad was told that his or her goal was to swing a hand-held pendulum at a tempo of oscillation that was most comfortable for each of them individually. Because the comfortable tempo selected is influenced by individual differences of hand size and strength as well as the length and mass of the pendulum that is being swung (Turvey, Schmidt, Rosenblum, & Kugler, 1988), the tempo selected should be different for the two individuals. Additionally, the participants were told to establish their own comfortable tempo when they were not looking at each other in the first trial half (control condition) and to maintain it when they were looking at each other's pendulum movements in the second trial half (experimental condition). Of interest is whether their movements would be more coordinated when they have information about the other person's movements than when there is no such information. Although the participants' explicit goal was to keep their own comfortable tempo while observing the other person's movements, what was being measured was the entrainment of their movements.

Because the movements of the two participants will have different frequencies, one can expect them not to be phase-locked and, consequently, the relative phase angle between the two movements may not be stationary (i.e., constant or centered around a mean value). Although most past dynamical modeling of interlimb coordination has relied upon frequency- and phase-locked coordination patterns that produce stationary relative phase time series, Kelso and colleagues (Kelso & Ding, 1994; Zanone & Kelso, 1990) have pointed out that nonsteady-state coordination behavior (what von Holst, 1939/1973, called "relative coordination") can be produced by weakly coupled dynamical systems that have intrinsic noise. Such dynamical systems demonstrate intermittent attraction to certain relatively stable values. In the coupled oscillatory dynamic that has been used to model intended interlimb coordination, one would expect intermittent attraction to values of relative phase that are specific to the stable inphase and antiphase modes, namely, 0° and 180°. Hence, in spite of the nonstationary relative phase of unintended coordination in our methodology, one would expect that if a dynamical constraining of the movement were occurring when information about the other participant's movement was available, the relative phasing of the movements would be intermittently drawn towards the dynamic's attractive regions of 0° and 180°.

In the phase-locked relative phasing of intended entrainment, attractive relative phases of an oscillatory dynamic are evaluated by measuring the mean phase, whereas the strength of the oscillatory dynamic is indicated by the standard deviation of relative phase (i.e., greater stability, more strength). However, for nonphase-locked entrainment, the mean and standard deviation of relative phase are not very meaningful. Because no one coordination pattern is apparent, the mean and variability of relative phase do not necessarily index the location and stability of the equilibrium states, and, consequently, one must use alternative measures to analyze the underlying dynamical processes. The cross-spectral analysis of the time series is a technique that yields a measure of the relative phase and the correlation of two periodic processes in its phase and coherence spectra, respectively. In this study, the coherence and cross-spectral relative phase will be evaluated at the dominant frequencies of oscillation. The former will provide an index of the strength of the coordination dynamic. Further, evaluating the distribution of the latter across trials of a given condition will provide an indication of which relative phase locations are attractive. In addition to the cross-spectral relative phase, distributions of the continuous relative phase will be used to corroborate the cross-spectral relative phase results.

METHOD

Participants

Twenty-two students were recruited from undergraduate psychology classes to serve as participants. They were between 18 and 30 years of age, were right-handed, and had no perceptual–motor disabilities. The participants were paired randomly to form 11 participant dyads. Because one pair's frequency data indicated that they were not following the task instructions to find a comfortable oscillation frequency, this pair was not used in the analyses. The resulting data set consisted of 10 participant pairs: Six pairs had male and female participants, and four pairs had 2 female participants.

Materials

Participants sat on chairs approximately 1 m from one another facing in the same direction. Between the participants was a 1 m^3 enclosure with microphones in each corner of its base. Armrests attached to the inside of the enclosure supported the arms of the participants so that handheld pendulums would oscillate parallel to the sagittal plane approximately about the adduction–abduction axis of the wrist. The enclosure around the microphones was shielded from auditory reflections from hard surfaces in the room by a 0.7 m foam-padded surface (see Figure 1).

Pendulums swung by the participants were constructed of a 12 cm wooden handle attached to an aluminum rod with a 0.03 kg weight bolted onto the end of the rod. Two different pendulum lengths were used, 0.32 m and 0.62 m (including the handle). Manipulating the length of the pendulum manipulates the preferred frequency of oscillation or eigenfrequency of the wrist-pendulum system. Previous studies (e.g., Turvey et al., 1988) have found that the preferred frequencies of oscillation are near the gravitational frequency of the wrist-pendulum system: $F_g = \frac{1}{2\pi}(g/L_e)^{1/2}$ where L_e is the equivalent length of the compound pendulum comprised of the hand, pendulum shaft, and pendulum mass. Given these results, one can expect that the preferred frequency of the shorter pendulum length will be higher than the preferred frequency of the longer length.

Each participant pair was asked to oscillate two combinations of the pendulum lengths. In the same length condition, both participants used short (0.32 m) pendulums. In the different length condition, one participant used the short pendulum and the other the long (0.62 m) pendulum—which participant had the short pendulum was counterbalanced across trials. If physical pendulums of these lengths were coupled, one would expect the frequency competition to be small for the same length condition and larger for the different length condition. This frequency competition can be indexed by the absolute value of the difference between the estimated preferred frequencies, $\Delta\omega = |\omega_1 - \omega_2|$. This magnitude was indeed greater for the different length condition. The different length condition had a mean $\Delta\omega$ equal to 0.213 Hz, whereas the same length condition had a mean $\Delta\omega$ of 0.018 Hz. These frequency differences (which were averaged across participants) are equivalent to differences of 336 ms and 21 ms in the period of oscillation of the two wrist-pendulum systems. Note that for the same length condition, the $\Delta\omega$ does not equal 0 because the L_e for each participant (and, hence, the resultant gravitational frequency) takes into account the mass of the participant's hand, which will not be identical for the two individuals of a given participant pair.

Wrist-pendulum movement trajectories were collected using a three-space sonic digitizer (Science Accessories Company, Stamford, CT). A sonic emitter was affixed to the end of each pendulum, and a sonic "spark" issued from each emitter 90 times per sec. The digitizer operates by registering each emission using four microphones arranged in a square grid. It calculates the distance of each emitter from each microphone, thereby locating the position of the emitters in three dimensions at the time of emission. These slant range distances of the emitters to the microphones were stored on an 80386-based microcomputer using MASS digitizer software (Engineering Solutions, Columbus, OH).

Procedure and Design

Each participant pair was given instructions and allowed three practice trials. They were told to place their forearms squarely on the armrests and to hold the pendulums firmly in their hands so that as much of the rotation of the pendulum as possible was created about the wrist joint rather than about the finger joints. Participant pairs performed thirty 24-sec experimental trials. For the first 12 sec of each trial, participant pairs were instructed to look straight ahead so that they could not see one another and to swing the pendulum at a comfortable rate, one that they could "perform all day." During the last 12 sec of each trial, participants were told to maintain their preferred tempo from the first half of the trial while looking at the other participant's moving pendulum. Every few trials, the participants were reminded of the instructions to maintain their preferred tempo for the duration of the trial. Recording of the data for a trial began a few seconds after participants began oscillating the pendulums. On 15 of the trials, the participants oscillated the same length pendulums, and on the other 15 trials, they oscillated different length pendulums. The order of pendulum combinations was randomized.

After the first five participant pairs were tested, two additional methodological controls were added to the experimental procedure. First, participants wore caps with black shields on the side facing the enclosure. These shields served to control for any influence of peripheral vision on coordination during the not-looking trial half condition (i.e., the first trial half). Second, to ensure that participants were paying attention to the movement of their partner's pendulum during the looking trial half condition (i.e., the second trial half), participants were required immediately after each trial to rate on a scale of 1 to 7 the degree to which their movements were coordinated (1 = *not at all synchronized*, 3 = *somewhat synchronized*, and 7 = *perfectly synchronized*). As a consequence of these additional controls, the first five and the second five pairs were analyzed as different groups. Hence, the design of the experiment was a 2 × 2 × 2 factorial with a between-subject variable of group (with and without methodological controls) and within-subjects variables of pendulum combination (same or different), and trial half (not-looking or looking).

Data Reduction

Spectral analyses were performed on the two participants' position time series to determine the mean cycle periods of the two (i.e., not-looking and looking) trial halves. The power spectra were calculated for each trial half, and the dominant peaks of the spectra were determined. These dominant frequencies of oscillation were subsequently converted to estimate the mean cycle period by taking their reciprocals. The difference in the mean oscillation periods of two wrist-pendulum systems was calculated from these values for the two trial halves.

Further, cross-spectral analysis of the two participants' position time series was performed to obtain the coherence and phase spectra for the two trial halves (Gottman, 1981). The coherence spectrum measures the degree of correlation between the time series over a range of possible component frequencies, and hence, measures the degree of coordination on a scale ranging from 0 to 1, where 0 indicates no coordination and 1 indicates perfect coordination at a given frequency. Given time series x and y, the coherence (K_{xy}) at a given frequency f_i is computed as the ratio of the square of the cross-spectrum (F_{xy}) divided by the product of the spectra of the individual series (F_{xx} and F_{yy}):

$$K_{xy}(f_i) = |(F_{xy}(f_i)|^2/[F_{xx}(f_i)F_{yy}(f_i)] \tag{1}$$

The phase spectrum of the cross-spectral analysis measures the relative phase angle of the two rhythmic processes at each frequency component of the spectra and varies in a range from 0° to 180°. It is computed as

$$\phi_{xy}(f_i) = Arg(F_{xy}(f_i))/2\pi \tag{2}$$

The coherence and the cross-spectral estimate of the relative phase angle used in the subsequent analyses were those of the dominant frequency of oscillation of the position time series spectra because it is indicative of the main oscillatory behavior. If the two participants' position time series spectra did not have equal dominant frequencies, the frequency of the largest spectral peak of the two spectra was used as the frequency for the coherence and the cross-spectral relative phase estimates.

In addition to the cross-spectral estimate of the average phase angle for a given trial half, the continuous relative phase angle of the two wrist-pendulum systems—the more standard index of interlimb coordination—was also calculated. The phase angles of wrist pendulum i at sample j (θ_{ij}) were calculated as

$$\Theta_{ij} = arctan(\dot{x}_{ij} / \Delta x_{ij}) \tag{3}$$

where $\dot{x}_{ij}$ is the velocity of the time series of wrist pendulum i at sample j divided by the mean frequency for the trial, and Δx_{ij} is the position of the time series at sample j minus the average position for the trial. The relative phase angle (ϕ_i) between the two coupled wrist-pendulum systems was calculated as the $\theta_{left\,j} - \theta_{right\,j}$. The resulting time series of relative phase allows one to evaluate how the phasing changed for the different trial halves, to determine which phase angles were dominant, and hence, to see whether phase attraction occurred near 0° and 180°. To perform this evaluation, the relative phase angles (ϕ) that range from 0° to 360° were first normalized to a range of 0° to 180° (i.e., if $\phi \geq 0°$ and $\leq 180°$ then $\phi = \phi$; if $\phi >$ 180°, then $\phi = 360° - \phi$). In this way, measurements close to 0° and 180° would indicate that the phasing of wrist motions was near the modes of phase-locking observed in intended rhythmic coordination.

RESULTS AND DISCUSSION

Of interest in this experiment is whether any unintended coordination occurs between rhythmic movements of two people when each person has visual information about the other's movement. In brief, is a perceptual linkage without explicit intention to coordinate sufficient for the movements of two people to become entrained? To evaluate this question, the coordination of the rhythmic movements using a variety of indexes will be measured when perceptual information is and is not available (i.e., in the first and second trial halves, respectively).

Differences in Periodic Timing

We instructed the participants to find a preferred frequency of oscillation in the first trial half and maintain it in the second trial half in spite of viewing the other person's movements. We can check how well they followed our instructions by determining whether the participants maintained their preferred frequency in both trial halves or whether some frequency entrainment occurred. The absolute value of the difference between the periodic cycle times of the two pendulums was calculated for each trial, and the condition averages for each participant were submitted to a 2 × 2 × 2 analysis of variance (ANOVA) with a between-subject variable of participant group and within-subjects variables of trial half (not-looking and looking) and pendulum combination (same and different). The analysis revealed a main effect of pendulum combination, $F(1, 8) = 8.38$, $p < .05$, in which the period difference of the different length pendulums (160 m) was greater than that of the same length pendulums (100 m). There were no significant effects of participant group or trial half.

It is interesting that the means for both trial halves were nonzero (146 and 114 m for the first and second trial halves, respectively). This result indicates that with and without information available, the movements of the two participants were at different frequencies and were not frequency-locked (although they were closest to a 1:1 frequency ratio). Any coordination that is occurring in the second trial half would then necessarily be *relative* rather than *absolute* coordination in which the relative phase of the oscillators would be constantly changing. von Holst (1939/1973) found that interacting biological oscillators in relative coordination (fins of the fish *Labrus*) demonstrate a magnet effect—each tries to pull the other to its preferred frequency of oscillation. The small decrease in period difference in the second trial half that is possibly indicative of a magnet effect is nonsignificant. But this result is good as far as the present experimental methodology is concerned. The participants' task was to intentionally maintain their own preferred tempos, and, consequently, to intentionally resist the magnet effect. The nonsignificance of the trial half effect is evidence that the participants have satisfied this requirement. The significant effect of the pendulum combination also verifies that the pendulum manipulation was successful. Same and different length pendulum combinations were used to vary the amount of inherent frequency competition that would exist between the wrist-pendulum systems. The significant result suggests that the different length pendulum systems are exhibiting more frequency competition than the same length systems. It is this frequency competition that any coupling of the movements must overcome.

Cross-Spectral Coherence

Although the differences in average periodic timing did not yield evidence for unintended coordination when visual information was available, a more fine grained index of entrainment may show otherwise. Such an index is the cross-spectral coherence of the two position time series. The coherence is essentially an index of how correlated two time series are at a given frequency. If two movements are in absolute coordination, their correlation is near perfect and their coherence should be near 1. If the two movements are absolutely unrelated (e.g., different frequencies), they are uncorrelated and their coherence should be near 0. If the two movements are at nearly the same frequencies, but are uncoordinated, then there should be some correlation between them, and their coherence should be some low nonzero value. Because the movements of the two participants in the experimental task are at comparable frequencies, we should expect low nonzero values even when there is no coupling in the first trial half. However, if unintended entrainment occurred in the second trial half when visual information was available, then the coherence should be greater in the second trial half than in the first.

The coherence was calculated for each trial half and the condition averages for each participant were submitted to a $2 \times 2 \times 2$ ANOVA. It revealed main effects of trial half, $F(1, 8) = 32.45, p < .001$, and pendulum combination, $F(1, 8) = 10.12$, $p < .05$. No other effects were significant. As can be seen in Figure 2, the coherence was greater in the second trial half (.54) than in the first (.41). This increase indicates that the time series are more correlated when information about the other person's pendulum was available and is prima facie evidence that some unintended coordination is occurring in the second trial half. But given the magnitude of the coherence (much less than 1), it is obvious that any coordination in the second trial half is not absolute but relative: There is not a *phase-locking* but rather a *phase entrainment* of the movements; that is, the phase angles of the two oscillators are attracted to one another but not perfectly locked (Keith & Rand, 1984; Schmidt, Shaw, & Turvey, 1993). As can also be seen from Figure 2, the coherence is greater for the same length pendulums (.53) than for the different length pendulums (.42). This result makes sense given the relative similarity of the preferred frequencies of the similar length pendulums compared to the different pendulums. Lastly, post-hoc t-tests comparing the two trial halves for the same and different length pendulum combinations individually found significantly greater coherence in the second trial half for both pendulum combinations (both $p < .02$).

Cross-Spectral Relative Phase

The previous analysis provides evidence that merely having information about the other person's moving limb in the absence of a goal to coordinate is sufficient for the entrainment of two participants' moving limbs to occur. An evaluation of the relative phasing of the two moving limbs will allow one to ascertain whether this entrainment occurs at particular relative phase angles. Importantly, if dynamical processes of coupled oscillators that have been shown to operate in intended coordination are operating here in unintended coordination, one would predict that relative phase angles near 0° and 180° should dominate the distribution of relative phase in the second half of the trial but not in the first.

As noted previously, an index of the relative phase can be obtained from the phase spectrum generated by the cross-spectral analysis of the position time series. In this analysis, the relative phase at the dominant frequency of the phase spectrum was determined for each trial half. Next, the distribution of the relative phase angles across nine 20° regions of relative phase between 0° and 180° was determined by calculating the frequency of occurrence in each of the nine relative phase regions for each condition. These counts (in percentage) were submitted to a $2 \times 2 \times 2 \times 9$ ANOVA with a between-subject variable of participant group and within-subjects variables of trial half (not-looking and looking) and pendulum combination (same and different) and relative phase region (0° to 20°, 21° to 40°, ... 161° to 180°). The analysis revealed a significant main effect of relative phase region, $F(8, 64) = 5.12$, $p < .001$, and a phase region by trial half interaction, $F(8, 64) = 5.49$, $p < .001$. The latter effect is displayed in Figure 3. As can be seen, the occurrence of relative phase angles across the phase regions is rather flat in the first half of the trial, but

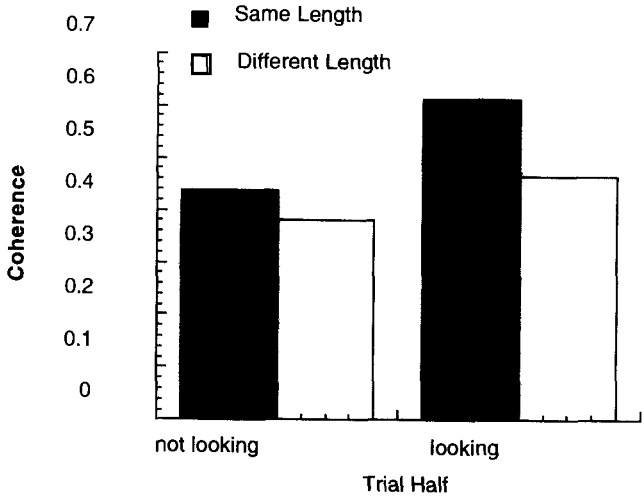

FIGURE 2 A plot of the cross-spectral coherence as a function of not-looking and looking (trial half) and pendulum combination.

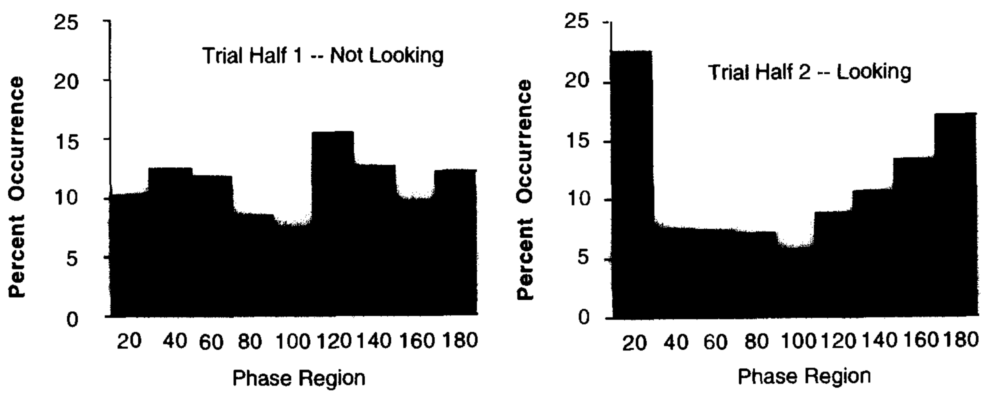

FIGURE 3 A plot of the distribution of cross-spectral relative phase for the not-looking (left panel) and looking (right panel) trial halves.

there is a greater occurrence of relative phase angles near 0° and 180° for the second trial half. In brief, this means that when visual information was available in the second trial half, there was a greater tendency to entrain at phase angles near the attractors found in intended interlimb coordination. This interpretation is complicated somewhat by a marginally significant four-way interaction, $F(8, 64) = 2.08$, $p = .05$, which indicates that the entrainment to 0° and 180° in Trial Half 2 is not equally true for both the same and different pendulum combinations. In brief, the attraction to 180° was more prominent for the same pendulum combination, and this was particularly true for the second group of participants who received the additional methodological controls.

Continuous Relative Phase

The information revealed by the cross-spectral estimate of relative phase can be corroborated by a more standard measure of relative phase—the continuous relative phase. As in the preceding analysis, the average relative phase was determined for each trial half, the distribution of the relative phase angles across nine 20° regions of relative phase between 0 and 180° was determined, and the resultant frequencies of occurrence were submitted to a four-way ANOVA. As for the cross-spectral estimate of relative phase, the ANOVA revealed a significant main effect of relative phase region, $F(8, 64) = 10.31, p < .001$, and a phase region by trial half interaction, $F(8, 64) = 8.93, p < .001$. The latter effect is plotted in Figure 4. When no visual information is available, all relative phase angles were equally likely. But when the two participants were looking at one another's limb, there was a tendency for them to coordinate at angles near 0° and 180°. A three-way interaction between trial half, pendulum combination, and phase region, $F(8, 64) = 3.07, p < .01$, was also significant, however. A simple effects analysis performed at each level of pendulum combination revealed that whereas both the same and different pendulum combinations had a greater number of phase angles near 0° for the second trial half (same: 12% in Trial Half 1 vs. 23% in Trial Half 2; different: 11% vs. 16%, both $p < .05$), only the same pendulum combination had a greater number of phase angles near 180° for the second trial half (same: 11% in Trial Half 1 vs. 13% in Trial Half 2; different: 11% vs. 10%, both $p > .05$). In brief, these results suggest that there is entrainment to phase angles near inphase for both pendulum combinations when

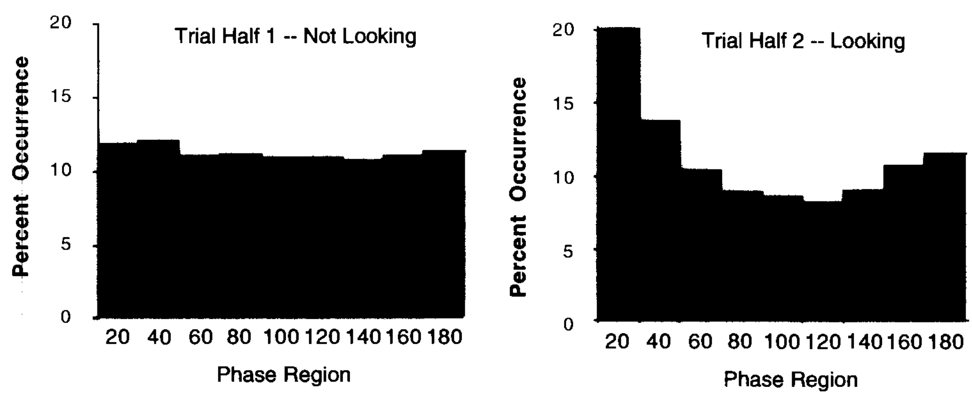

FIGURE 4 A plot of the distribution of continuous relative phase for the not-looking (left panel) and looking (right panel) trial halves.

information is available and that there is a tendency (though nonsignificant) for entrainment to antiphase in the same length pendulum condition but not the different length pendulum condition. These findings about the entrainment to the 180° attractor can be clarified by asking whether evidence exists for it in the cross-spectral relative phase measure. A comparison of the cross-spectral relative phase angles for the two pendulum conditions separately revealed a significantly greater percentage of relative phase angles near 180° when information was available for the same pendulums (21% vs. 12%, $p < .05$) but not the different pendulums (14% vs. 13%, $p > .05$). These results are understandable if the oscillatory dynamic at 180° is quite weak though strong enough to create an alignment in phase angles when the difference in frequencies is small (same pendulum condition) but not when the difference in frequencies is large (different pendulum condition).

CONCLUDING REMARKS

Interpersonal motor coordination is a tacit aspect of most social interactions. The involved interactional synchrony often has been studied *in vivo*. However, the control that an experimenter has over naturally occurring coordination is limited and, consequently, so are the questions that can be asked. This experiment's aim was to ask questions about the principles underlying unintended coordination that cannot be asked by studying naturally occurring interpersonal coordination. The first goal of the experiment was to create unintended coordination in a laboratory task. This was achieved by devising an interaction task in which the goal of the participants was not the production of interpersonal coordination itself. In this case, the goal was to produce the most comfortable oscillation tempo possible and maintain it while viewing the other person's rhythmic movements. The methodological convenience of the chosen task was that the sinusoidal movements can be summarized in terms of a dominant frequency, and traditional methods for studying coupled oscillators can be used to evaluate the coordination. Further, different pendulum combinations allow the experimenter to control the degree of frequency competition that any unintended coupling would have to overcome. The question was whether an entrainment of the movements occurs in spite of its not being intended under different degrees of frequency competition.

The first newsworthy result is with respect to the methodological controls used. To ensure that the participants were without information in the first half of the trial and were necessarily picking up information about the other person's limb in the second half of the trial, occlusion shields and posttrial synchronization ratings were used for participants 6 through 10. Consequently, a subject group variable was added to all ANOVAs. However, none of the analyses yielded any important subject group effects. Hence, one can assume that these controls were largely unnecessary, and that all participants were picking up information (or not) at the appropriate times.

The analysis of the differences in periodic timing revealed that the participants did not become frequency-locked when viewing the other person's pendulum. They on average each moved at their own preferred frequency when the frequency competition was high or low (i.e., different or same length pendulum conditions). Consequently, the frequency ratio of the two movements was near, but not equal to, 1:1. This result indicates that the participants were following the task instructions and maintaining their comfortable oscillation frequency in the second half of the trial. In spite of the different frequencies of oscillation, the analysis of cross-spectral coherence demonstrated that the movements were more correlated when the participants were viewing the other person's pendulum (Figure 2). One way to understand this is that even though the average timing of the movements was not significantly affected by the presence of visual information, the relative timing of the movements was affected. Importantly, the correlation of the two movements increased in the second trial half when the frequency competition was both high and low.

The cross-spectral coherence demonstrates that entrainment occurs. But why? The second goal of the experiment was to determine whether the unintended between-person coordination observed is being produced by a coupled oscillatory dynamic. Such a dynamic has been previously shown to operate across a perceptual (visual) linkage and operate in intended between-person coordination (Schmidt et al., 1990; Schmidt & Turvey, 1994). The question is whether the states of a coupled oscillatory dynamic that are attractive in intended coordination (at 0° and 180° relative phase) are also predominant in coordination observed in the second trial halves. Two measures of the average relative phase were used, the cross-spectral relative phase and the continuous relative phase. They provided nearly identical results. When no visual information about the other person's movements was available in the Trial Half 1, all relative phase angles were equally likely; however, when information was available in the Trial Half 2, relative phase angles near 0° and 180° dominated. It appears that the swinging of the pendulums was attracted to inphase and antiphase modes even though these patterns were not stably maintained. Further, for both indexes of relative phase, there was evidence that the attraction to antiphase (180°) was weaker than to inphase (0°): The frequency of occurrence tended to increase near 180° for the identical length pendulums but not for the different length pendulum combination. It appears that the attractor at 180° was strong enough to overcome the small frequency competition of the same length combination but not strong enough to overcome the large frequency competition of the different length combination. Alternatively, given that the frequency of occurrence of relative phase angles increased for both pendulum combinations near 0°, one can conclude that the attractor at 0° was strong enough to overcome both degrees of frequency competition.

Our results indicate that unintended interpersonal rhythmic coordination can be modeled by the same coupled oscillatory equations that have been used to model intended interpersonal rhythmic coordination, namely, the Haken et al. (1985) model and its modifications (Fuchs & Kelso, 1994; Kelso & Jeka, 1992; Schmidt & Turvey, 1995). Importantly, this dynamic models the simultaneous existence of attractive states near 0° and 180°, a weaker attractor at 180°, and the effects of frequency competition. Of course the regime would have to be parameterized differently to model unintended coordination: The coupling strength would have to be very small so that neither the attractive states near 180° nor those near 0° were actually fixed points but instead just "ghosts" of fixed points. The fact that such a dynamic can be assembled without the participants intending to indicates the basic nature of this coordination dynamic. It seems that even the most elementary form of a perceiving–acting coupling can sustain such a regime.

This study additionally previews some new methodological procedures. The near identical distributions of the cross-spectral and continuous relative phase suggest that the former can be used to calculate relative phase. The benefit of cross-spectral calculation is that the evaluation of relative phase can be performed using commercial statistical software (e.g., SPSS) instead of custom-programmed software. The continuous relative phase algorithm (as well as the often-used point relative phase in which the relative phase is evaluated only at the peaks of the periodic time series) assumes a sinusoidal nature to the underlying time series so that reliable cycle frequencies can be measured. To the extent that this assumption is violated, these calculation methods become unreliable. For analysis of data that violates this assumption (and note that the majority of past studies that have used this method did not violate them), the cross-spectral relative phase may provide a valuable alternative. Further, the cross-spectral calculation is useful as in the present case in which the relative phase angle is not stationary. For nonstationary time series, the mean state is not indicative of the location of the attractor, and the standard deviation fails to be an appropriate measure of the stability, and, hence, strength of the dynamic. The cross-spectral coherence, however, gives a correlational measure of the strength of the coupling regardless of whether the two time series are at a constant phase angle. Although the cross-spectral relative phase does provide a measure of the average ("mean") relative phase at a given frequency, the lack of reliability of the mean as an index of the location of the attractor for nonstationary time series can be overcome by looking at the distribution of relative phases over the entire range of possible values as was done in this study. The importance of studying the long-term distributional properties of noisy dynamical systems has yet to be fully appreciated, although there have been notable examples of this method (Schmidt, Beek, Treffner, & Turvey, 1991; Treffner & Kelso, 1997). Note, however, that the continuous relative phase measure also can be used to evaluate the distribution of relative phase angles in different conditions and was used successfully for our data. Indeed, the similarity of patterning in the distribution of the continuous and cross-spectral relative phases is quite striking.

Although this study has succeeded in demonstrating and evaluating the dynamical basis of unintended coordination in a laboratory task, the naturalness of the interpersonal interaction has been constrained in ways that need to be addressed in future research. The interaction task used, producing comfortable pendular movements from the wrist while just viewing one another's movements, is very artificial. One may argue that the artificiality may have led the participants to intuit the purpose of the experiment and succumb to the task demand characteristics. However, our debriefing of the participants did not lead us to this conclusion. Nevertheless, future research should address the real world validity of the present results by choosing a more natural task (e.g., card sorting) that is more like everyday interpersonal interactions and whose purpose can be more deliberately hidden. The results of such a less artificial experiment are required to evaluate fully the dynamical basis of unintended coordination in natural interpersonal interactions.

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REFERENCES

Bellet, S. (1971). *Clinical disorders of the heart.* Philadelphia: Lea & Febiger.

Bernieri, F. J. (1988). Coordinated movement and rapport in teacher–student interactions. *Journal of Nonverbal Behavior, 12,* 120–138.

Bernieri, F., Reznick, J. S., & Rosenthal, R. (1988). Synchrony, pseudosynchrony, and dissynchrony: Measuring the entrainment process in mother–infant interactions. *Journal of Personality and Social Psychology, 54,* 243–253.

Bernieri, F., & Rosenthal, R. (1991). Interpersonal coordination: Behavior matching and interactional synchrony. In R. S. Feldman & B. Rime (Eds.), *Fundamentals of non-verbal communication* (pp. 401–432). New York: Cambridge University Press.

Bramble, D. M., & Carrier, D. R. (1983). Running and breathing in mammals. *Science, 219,* 251–256.

Condon, W. S. (1982). Cultural microrhythms. In M. Davis (Ed.), *Interaction rhythms: Periodicity in communicative behavior* (pp. 53–77). New York: Human Sciences.

Davis, M. (Ed.). (1982). *Interaction rhythms: Periodicity in communicative behavior.* New York: Human Science.

Fuchs, A., & Kelso, J. A. S. (1994). A theoretical note on models of interlimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1088–1097.

Gottman, J. M. (1981). *Time-series analysis: A comprehensive introduction for social scientists.* Cambridge, England: Cambridge University Press.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51,* 347–356.

Hayes, D. P., & Cobb, C. (1982). Cycles of spontaneous conversation and long-term isolation. In M. Davis (Ed.), *Interaction rhythms: Periodicity in communicative behavior* (pp. 319–339). New York: Human Sciences.

Keith, W. L., & Rand, R. H. (1984). 1:1 and 2:1 phase entrainment in a system of two coupled limit cycle oscillators. *Journal of Mathematical Biology, 20,* 133–152.

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology: Regulatory, Integrative and Comparative, 246,* R1000–R1004.

Kelso, J. A. S., & Ding, M. (1994). Fluctuations, intermittency, and controllable chaos in biological coordination. In K. M. Newell & D. M. Corcos (Eds.), *Variability in motor control* (pp. 291–316). Champaign, IL: Human Kinetics.

Kelso, J. A. S., & Jeka, J. J. (1992). Symmetry breaking dynamics of human multilimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 645–668.

Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law and the self-assembly of rhythmic movement.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Newtson, D., Hairfield, J., Bloomingdale, J., & Cutino, S. (1987). The structure of action and interaction. *Social Cognition, 5,* 191–237.

Schmidt, R. C., Beek, P. J., Treffner, P. J., & Turvey, M. T. (1991). Dynamical substructure of coordinated rhythmic movements. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 635–651.

Schmidt, R. C., Bienvenu, M., Fitzpatrick, P. A., & Amazeen, P. G. (in press). A comparison of within- and between-person coordination: Coordination breakdowns and coupling strength. *Journal of Experimental Psychology: Human Perception and Performance.*

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,* 227–247.

Schmidt, R. C., & O'Brien, B. (1998). Modeling interpersonal coordination dynamics: Implications for a dynamical theory of developing systems. In P. C. Molenaar & K. Newell (Eds.), *Dynamics systems and development: Beyond the metaphor* (pp. 221–240). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Schmidt, R. C., Shaw, B. K., & Turvey, M. T. (1993). Coupling dynamics in interlimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 397–415.

Schmidt, R. C., & Turvey, M. T. (1994). Phase-entrainment dynamics of visually coupled rhythmic movements. *Biological Cybernetics, 70,* 369–376.

Schmidt, R. C., & Turvey, M. T. (1995). Models of interlimb coordination: Equilibria, local analyses, and spectral patterning. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 432–443.

Schöner, G., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movement. *Biological Cybernetics, 53,* 247–257.

Treffner, P. J., & Kelso, J. A. S. (1997). Scale-invariant memory in functional stabilization. In M. Schmuckler (Ed.), *Studies in Perception and Action IV: Posters presented at the 9th International Conference on Perception and Action* (pp. 275–279). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Turvey, M. T., Schmidt, R. C., Rosenblum, L. D., & Kugler, P. N. (1988). On the time allometry of coordinated rhythmic movements. *Journal of Theoretical Biology, 130,* 285–325.

von Holst, E. (1939/1973). Relative coordination as a phenomenon and as a method of analysis of central nervous system function. In R. Martin (Ed. and Trans.), *The collected papers of Erich von Holst: Vol. 1. The behavioral physiology of animal and man* (pp. 33–135). Coral Gables, FL: University of Miami Press.

Zanone, P. G., & Kelso, J. A. S. (1990). Relative timing from the perspective of dynamic pattern theory: Stability and instability. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 69–92). Amsterdam: Elsevier.