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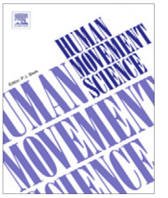

Understanding social motor coordination

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ABSTRACT

Recently there has been much interest in social coordination of motor movements, or as it is referred to by some researchers, joint action. This paper reviews the cognitive perspective's common coding/mirror neuron theory of joint action, describes some of its limitations and then presents the behavioral dynamics perspective as an alternative way of understanding social motor coordination. In particular, behavioral dynamics' ability to explain the temporal coordination of interacting individuals is detailed. Two experiments are then described that demonstrate how dynamical processes of synchronization are apparent in the coordination underlying everyday joint actions such as martial art exercises, hand-clapping games, and conversations. The import of this evidence is that emergent dynamic patterns such as synchronization are the behavioral order that any neural substrate supporting joint action (e.g., mirror systems) would have to sustain.

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1. Introduction

We often perform actions in a social setting and coordinate our movements in relationship with other people. Consequently, many of our actions are often best understood as joint or interpersonal actions. The coordination in these joint actions is sometimes deliberate and intended as when two people carry a large object together or pass the ball and move together to score a goal in football or is sometimes spontaneous and unnoticed, as when two people avoid walking into one another in a crowded plaza or take turns in a conversation. But how is one to understand the structure of such interpersonal coordination, such joint action, the ability to coordinate one's actions with others in

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time and space? This paper describes how two perspectives answer this question and argues that although the cognitive or "mirror neuron" perspective on joint action has garnered much attention from the field, the behavioral dynamics perspective on joint action offers a deeper understanding of how social motor coordination unfolds in time by incorporating the dynamics of synchronization. After detailing two empirical studies of how the dynamics of social coordination are evaluated in everyday activities, we close with an argument for why cognitive theorists should care about the dynamics of synchronization.

1.1. Cognitive perspective on joint action

Although the study of interpersonal coordination has been around for some time (Condon & Ogston, 1966; Newtson, Hairfield, Bloomingdale, & Cutino, 1987; Schmidt, Carello, & Turvey, 1990), it has recently gotten new attention from cognitive psychologists who are interested generally in the mechanisms by which social stimuli influence cognitive processing (Knoblich & Sebanz, 2006) and specifically how such mechanisms may allow us to understand the phenomenon of joint action (Sebanz, Bekkering, & Knoblich, 2006). The intuitive starting point of this perspective is the everyday experience of the fact that observing others' actions spontaneously activates our own motor system in a like fashion. For example, we may brace our self when we see someone fall or immediately hold our arm when we see someone painfully twist theirs. To explain such phenomena, cognitive theorists argue that there is a common coding of perception and action, that is, the same representations are used to perceive and perform an action. This explanation has a long tradition (James, 1890) and there is much research to support it. For example, perceiving an action of another can influence (i.e., facilitate or interfere with) the performance of one's own concurrent action. Kilner, Paulignan, and Blakemore (2003) had subjects make vertical or horizontal arm movements while observing congruent or incongruent movements made by another person and found that observing incongruent plane movements produced motor interference, i.e., increased motor variability in non-instructed (orthogonal) plane. Cognitive researchers argue that this interference is a consequence of simultaneous accessing of motor representations of the instructed movements by the action system and the motor representations of the non-instructed movements by the perceptual system.

Additional evidence for such a common coding of actions performed and perceived comes from discovery of mirror neurons in monkeys which "fire" both when an animal acts and when the animal observes the same action performed by another. For example, the same neurons were found to discharge when a goal-directed action was either enacted (monkey grasps an object) or observed (experimenter grasps an object). Neuronal subsystems in the premotor and parietal cortex in humans have also been found (Iacoboni et al., 1999) to have the similar ability to common code actions performed and perceived. For example, Calvo-Merino, Glaser, Grezes, Passingham, and Haggard (2005) discovered through brain imaging that there was greater mirror system activity in expert dancers and capoeira performers when they viewed videos of ballet or capoeira actions that they were trained to perform compared to actions that were in a different style. These results suggest that these "mirror" systems use an individual's personal motor repertoire in the perception of skilled performance of others. They further imply that the perceptual understanding of another's actions occurs via motor simulation of these actions.

Such mirror/common coding systems could be important mechanisms for forming simple joint actions such as those seen in imitation phenomena like when an infant sticks out his tongue in response Q3 to the mother's action (Meltzoff & Moore, 1977) or the unconscious behavioral matching that seems to increase in social interactions when two people like each other (Chartrand & Bargh, 1999). However, Sebanz and Knoblich have argued in a series of articles (Knoblich & Sebanz, 2008; Sebanz et al., 2006; Sebanz & Knoblich, 2009) that such mirror/common coding systems also help us form complex kinds of joint action because they provide a representational system for the simulating and understanding of another's actions, and consequently, can offer a basis for the prediction of the what, where, and when of others' actions (Sebanz & Knoblich, 2009). Such predictive information could then be used in producing not only imitative movements but also more complex complementary movements jointly coordinated in space/time with another person. In addition, it has been further argued that this mirror/common coding system for simulating another's actions could perhaps also provide the basis more generally of the joint intentionality or mental connectedness between the individuals engaged in a joint action (Gallese & Goldman, 1998; Knoblich & Sebanz, 2008).

Although much of this research on mirror/common coding systems is very provocative, there have been a number of concerns regarding its scope. One concern is that such systems cannot do it all, that there is more to the joint action than just these processes. Sebanz and Knoblich (2009) admit that such subsystems are necessary but not sufficient for performing a joint action – "common coding provides a representational platform for integrating the actions of self and others" but are "not sufficient to enable..... joint action (p. 364)". When joint actions are more complex they are going to require higher-level representations of the task which represent the interactive roles of both the self and the other. How these kinds of representations are represented neurally is much less clear than those of the common coding system and requiring these powerful higher-level representations seems to make the simple nature of the mirror/common coding systems explanation of joint action lose its uncomplicated appeal. Further, some researchers have argued the original findings of mirror neurons in monkeys have been inappropriately generalized to humans (to imitation, for example) without performing empirical studies that would eliminate alternative explanations (Hickok, 2009). Other researchers maintain that the organization principles by which mirror systems operate is less than clear. The "study of mirror neurons and the "human mirror system" in particular has been characterized by much speculation and relatively little hard evidence.... [we] need to establish a causal relationship between their activity and the proposed motor, cognitive, and social abilities, before such claims can definitively be accepted" (Dinstein, Thomas, Behrmann, & Heeger, 2008, p. R17). These concerns together are reminiscent of a general critique of representational explanations of behavior, namely, that instead of causal explanations that reveal the principles which allow the behavior to emerge from the CNS, nested in and constrained by a body and an environment, the cognitive theorist "puts" in the CNS powerful representations that have just the organization needed to produce the behavior (Churchland & Sejnowski, 1989). The cognitive explanation thereby does not detail the causal process by which behavior is produced but rather provides a place holder in its use of generic representations for a more general causal theory.

2. Behavioral dynamics perspective on joint action

An alternative explanation of behavior in general and joint action in particular comes from the behavioral dynamics perspective on behavior whose goal is to identify general laws of pattern formation that govern the causal unfolding of human behavior rather than searching for neurophysiological loci of behavior generation (Kelso, 1995). Or said another way, the goal of the dynamical perspective is not to provide an a priori prescription of a behavior in the form of a set of representations (i.e., program or script) which is proposed to be nested within a CNS location but to understand behavior as an a posteriori consequence of lawful principles that organize both animate and inanimate nature, namely, the principles of dynamics (Kugler & Turvey, 1987; Turvey, 2005; Turvey & Shaw, 1995). The behavioral dynamics perspective maintains that physical systems at any scale (chemical, neural, behavioral, and social) can be understood in terms of how its components *balance* to form stable patterns which can be characterized as equilibria, steady-states of change or more generically as attractor states (Kelso, 1995; Kugler, Kelso, & Turvey, 1980). As such, a dynamical theory suggests that similitude is a key property of natural systems generally: The organizational principles should be replicated at different scales of nature and similar patterns should appear although the properties being organized by these principles will be scale dependent.

Understanding joint action from the perspective of behavioral dynamics means investigating the dynamical principles that form the patterns of joint action. Following the tenets of the "new reductionism" (Koestler & Smythies, 1971), these dynamical patterns exist at the social/behavioral scale and can be understood and modeled without investigating the more microlevel of the CNS. Hence, the CNS is not viewed then as a proprietary level of explanation of behavior. Of course, the purview of a dynamical theory of joint action can be expanded to include the CNS (e.g., investigating the role of mirror systems) by studying neural dynamic patterns (Jirsa, 2004) and how these correspond to more macroscopic behavioral dynamic patterns (Kelso, 1995). However, the joint action patterns at

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the behavioral/social scale can be understood and modeled in terms of their own dynamics: The balancing of system components to form stable behavioral patterns which can be characterized as attractor states of the system's dynamics.

How one goes about determining the dynamics of joint action patterns is facilitated somewhat by the principle of similitude in that we should expect to see the same principles organize joint actions as organize actions of a person acting alone in the environment. One dynamical process that seems to be essential to the self-organization of dynamical systems across many scales of nature including single person and interpersonal systems is that of synchronization or the temporal coordination of unfolding events in a system (Strogatz, 2003). An intuitive example system that demonstrates such a dynamical process is the interaction of two clocks that share a common base of support that allows their rhythms to interact mechanically. Huygens, the father of synchronization theory, witnessed the synchronization of pendulum clocks on the same wall (Huygens, 1673/1986). The metronomes depicted in Fig. 1 (top) are an easily assembled example of such a system. The movement of the metronomes' inverted pendulums causes movement on the soda cans of the board on which they rest. A consequence of this movement is that the metronomes interact and "force" each other to adopt a common frequency and a constant relative phase angle. When their uncoupled frequencies are equal, the common relative phase angle is either inphase (0° relative phase) or antiphase (180° phase). These are the equilibrium positions or attractor states at which the components of this dynamical system (namely, the movement of metronomes' pendulums) balance. Moreover, the location of this phase balancing changes as the uncoupled frequencies of the metronomes become different (which can be affected by moving the bob on one of the pendulums to a slightly different position). Although the pendulums still become synchronized, the one with the inherently slower tempo (with the higher bob) tends to lag behind the other. Indeed, increasing the difference in the uncoupled frequencies ($\omega_1 - \omega_2 = \Delta\omega$)

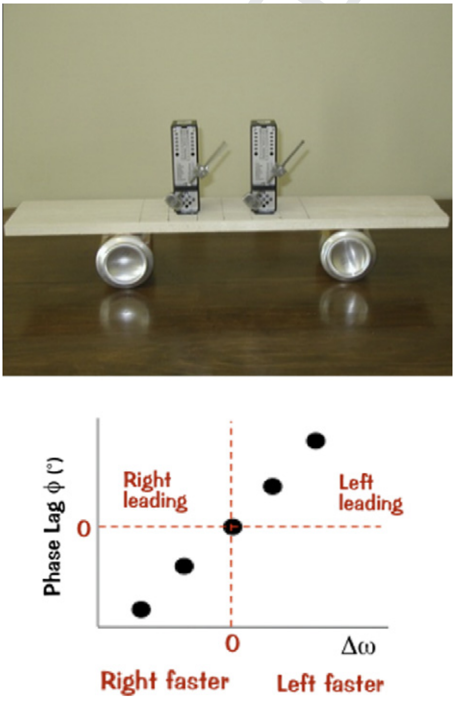

Fig. 1. (toppanel) A simple mechanical system that demonstrates the dynamics of synchronization. (bottom panel) The pattern of phase lag that emerges during synchronization during frequency detuning, i.e., when the inherent frequencies of the metronomes are made slightly unequal. $\Delta\omega$ is the difference between the pendulum bobs' uncoupled frequencies ($\omega_1 - \omega_2$).

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increases this phase lag between the two pendulums (Fig. 1, bottom). This *frequency detuning* manipulation symbolized by $\Delta\omega$ produces a phase lag that represents a new pattern of dynamical balancing.

Important for the study of the dynamics of behavioral systems in general and joint action systems in particular is the fact that this synchronization process has been found to occur between biological rhythmic units that are connected not only mechanically but also informationally. For example, much research has provided evidence for such a coupled oscillator modeling of biological rhythmic movements such as cockroach locomotion (Foth & Graham, 1983) and human bimanual coordination (Schmidt, Shaw, & Turvey, 1993; Turvey, Rosenblum, Schmidt, & Kugler, 1986). In these biological instances, the same pattern of phase lag in response to frequency detuning is found as in the physical system above (Fig. 1, bottom). However, in these biological systems the CNS is the primary vehicle for the interaction and plays the same role as the board and soda cans Fig. 1. Quite amazingly, the same synchronization dynamic unfolds in spite of the vastly different media for the interaction of the two rhythmic units.

Furthermore, other research has demonstrated how this dynamical synchronization process can operate across perceptual media to produce a coordinated timing of joint action. An example of inter-organism dynamical synchronization that has been studied for some time is the mass coordination of firefly flashing. At dusk, male fireflies of certain species in some parts of South East Asia congregate in large groups. As the night progresses, a synchronization of their flashing occurs and produces a large, light-pulsing mass of fireflies. Hanson (1978) investigated this firefly synchronization in a laboratory experiment in which he stimulated firefly flashing using an artificial light-pulsing at different frequencies. He discovered the same frequency detuning/phase lag relationship described above. Other research has shown this dynamical synchronization patterning in interpersonal bimanual coordination (Schmidt & Turvey, 1994) and interpersonal coordination of rocking chairs (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). In these examples, the only possible way that the rhythmic units could be interacting is via the information available to the visual systems of these biological agents. Consequently, the informational field of the optic array must combine with the informational fields of the two CNSs (Kugler & Turvey, 1987) to provide the media for the unfolding of the synchronization dynamic process. What is seen here is that the dynamical process involved in the synchronization of the two metronomes is quite generic in nature and can presumably operate via any media which allow two rhythmic units to interact.

3. Evidence of the synchronization dynamic in everyday joint actions

Although the behavioral dynamics perspective on joint action is theoretically compelling in its parsimony and has a fair amount of empirical support (see Schmidt & Richardson, 2008, for a review), critics have noted that most of the empirical examples use unnatural rhythmic tasks to demonstrate the dynamics of interpersonal synchronization. Consequently we have begun evaluating the generality of the synchronization dynamic by investigating whether it governs the temporal organization of everyday joint actions. Since one everyday domain in which temporal coordination is very important is sports or movement games, in a recent experiment, we began to investigate the temporal coordination underlying martial art interpersonal sword interactions and interpersonal hand-clapping games. Synchronization of movements is very important in martial arts to establish proper timing and spacing, often referred to as "a connectedness" with an attacker, which allows for effective execution of martial arts techniques. Formal exercises or kata are often performed in which pairs of people practice this interpersonal coordination. Hand-clapping games typically involve people performing a series of clapping patterns as they sing or chant a rhyme. Early in life, children learn to play pat-a-cake, for example. During the elementary school years, children often learn more difficult hand-clapping games on the school playground (e.g., Miss Mary Mack). Hand-clapping games with more complex sequence of hand movements are also used in young adulthood (e.g., so-called "ice breakers" at college orientations). The experiment we designed employed the interpersonal synchronization of wooden practice swords and hand-clapping to investigate the presence of the synchronization dynamic in everyday joint action.

For a preliminary study, we recruited four pairs of participants who were skilled in Aikido from the Zenshinkan Dojo in Worcester, MA and three pairs of participants who were unskilled in Aikido from

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the faculty and students at the College of the Holy Cross. The first task the participants performed was a sword "connectedness" task. The participant pairs swung wooden practice swords (also known as bokkens) in a coordinated fashion – holding the swords in front of them, raising them above their heads and then guiding them back to their original positions at a rhythmic and comfortable tempo. The natural frequency of swinging was manipulated by using three different-sized swords (0.5, 0.79, and 1.12 kg). Seven pairings of the different swords, light-heavy, light-medium, medium-light, medium-medium, medium-heavy, heavy-medium, heavy-light, were used to manipulate frequency detuning $\Delta\omega$ (see Fig. 1, bottom). The second task was a "pat-a-cake"-like hand-clapping game. The participant pairs first clapped their own hands and then clapped the two hands of the other person in front of their chests and continued this alternating pattern of clapping their own hands together and then clapping the partner's hands. The natural frequency of clapping was manipulated by attaching weights (0, 0.45, or 0.9 kg) to the wrists of the participants. Differential weighting conditions similar to those employed for the sword task were used to manipulate frequency detuning $\Delta\omega$ across trials. For both tasks, the arm movements of the participants were recorded in 40 s trials using a Polhemus Liberty system (Polhemus Corporation, Colchester, VT) with sensors attached to the participants' wrists. The recorded movement time series were subsequently analyzed to evaluate how the frequency detuning manipulation affected their relative phasing.

As can seen in Fig. 2 (top), for the sword swinging (left) and the clapping game (right) the prediction of the synchronization dynamic was upheld ($F(4, 20) = 4.45$, $p = 0.004$, $\eta_p^2 = 0.53$ and $F(4, 20) = 7.65$, $p = 0.001$, $\eta_p^2 = 0.65$, respectively): The greater the magnitude of frequency detuning $\Delta\omega$, the greater the phase lag with the faster oscillator leading in the cycle. However, we were interested in not only whether these joint rhythmic actions showed evidence of being governed by the synchronization dynamic described above but also whether such a dynamic would be more capably accessed by the skilled performers (i.e., the martial artists). As can seen in Fig. 2 (bottom), the skilled

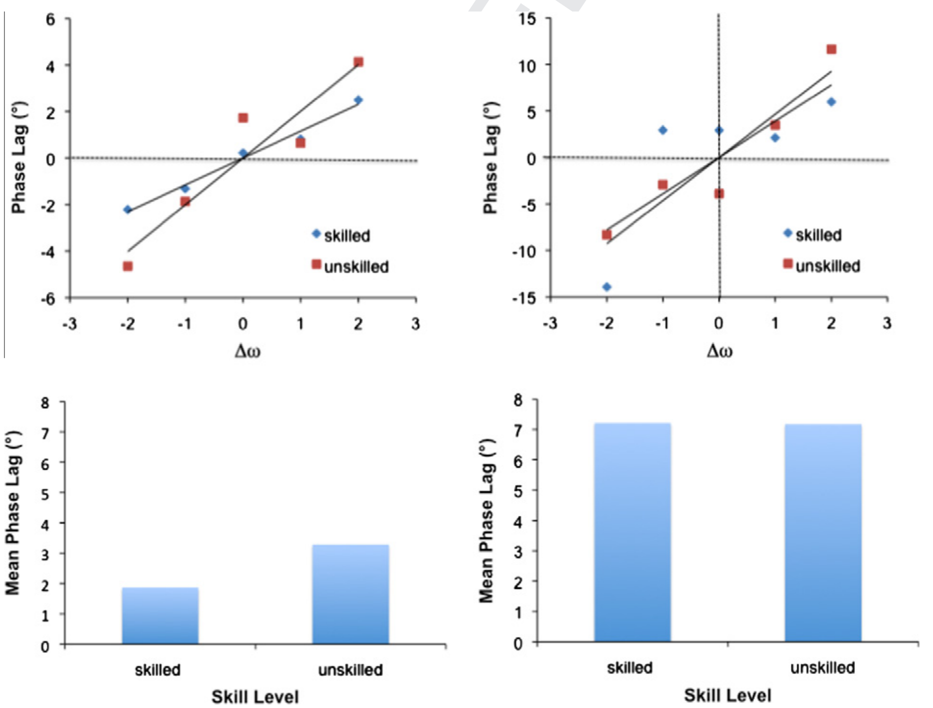

Fig. 2. (toppanels) The phase lag observed with frequency detuning in sword swinging (left) and hand-clapping (right). (bottom panels) The magnitude of the phase lag for the skilled and unskilled groups in sword swinging (left) and hand-clapping (right).

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performers tended to demonstrate less of a phase lag (which indicates a stronger assembled dynamic) than the unskilled performers in the sword task but not in the clapping task ($F(1, 5) = 4.10$, $p = 0.10$, $\eta_p^2 = 0.45$ and $F(1, 5) = 0.001$, $p = 0.98$, $\eta_p^2 = 0.00$). Additionally, the cross-spectral analysis, a technique that yields a measure of the correlation of two periodic processes in a coherence spectra (Gottman, 1981; Warner, 1998), was also performed and found that the movements of the skilled performers was significantly more correlated than that of the unskilled performers for the sword task ($F(1, 5) = 12.77$, $p = 0.004$, $\eta_p^2 = 0.72$) but not the clapping task ($F(1, 5) = 0.031$, $p = 0.87$, $\eta_p^2 = 0.006$).

These results demonstrate that a stronger synchronization dynamic was employed in skilled interpersonal performance that was specifically trained for (sword swinging by the martial artists) but did not generalize to the more ordinary hand-clapping task. However, the validity of this lack of generalization can perhaps be questioned because there was much greater variability within and across subject pairs in the hand-clapping task than the sword task. This variability could be due to the clapping task having a less constrained movement pattern, differences in perceptual information pick-up in vertical rather than horizontal movement patterns, or the influence of social factors in a task involving physical contact with the partner. Future research will evaluate these variables. The overall results of this preliminary study, however, suggest that the dynamics of synchronization apparently operate in everyday interpersonal coordination such as hand-clapping games and the martial arts: "Two become one" by virtue of dynamical synchronization principles that operate at both inanimate and animate scales of nature (Strogatz, 2003).

Of course this experiment demonstrates that dynamical principles of organization constrain social actions when people consciously try to coordinate with one another. But many joint actions occur spontaneously or automatically without the participants being consciously aware of their coordination with each other. The question is whether synchronization dynamic also constrains the temporal coordination within social interactions which do not have such bodily coordination as an explicit goal. A number of past studies have adapted laboratory tasks to investigate whether dynamical synchronization of two people's rhythmic movements would occur automatically if they were focusing on performing some cognitive task (e.g., performing a dyadic problem solving task such as finding the differences between two cartoon faces). Richardson et al. (2007) found that two people rocking in rocking chairs spontaneously harnessed the dynamic, synchronized in inphase and at a strength that was dependent upon how much information the two people had of one another's rocking movements. These results and those of a number of studies (e.g., Issartel, Marin, & Cadopi, 2007; Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008) suggest that dynamical synchronization processes can organize joint actions even when joint coordination is unintended and occurs spontaneously. Note, however, that all these past studies employed laboratory joint action tasks that were comprised of prescribed, stereotyped rhythmic movements and such simple movements are not often part of joint actions naturally occurring in social interaction. The question still remains of whether the synchronization dynamic constrains the temporal coordination in more complex, natural joint actions. Social psychologists studying social interactions have observed such interactional synchrony, namely, people's bodily activity tends to be entrained in time (Bernieri & Rosenthal, 1991; Condon & Ogston, 1966). Indeed, Newtson some time ago suggested a coupled oscillator explanation of interactional synchrony but his argument was purely theoretical and was not empirically investigated (Newtson et al., 1987).

Recently, we performed a study whose goal was to assess Newtson's hypothesis – to determine whether the interpersonal coordination of the generalized body activity (i.e., interactional synchrony) seen in natural interactions has the criterial properties of dynamical synchronization. To evaluate this, a structured interaction task was used in which pairs of participants stood facing one another and told each other a series of jokes that required the response of the other person. Although the participants were told that the experiment was investigating the psychology of humor, the true aim was to study the amount of spontaneous synchrony exhibited between the participants' movements during the joke telling interaction. For the interactions, participants stood facing one another and took turns being the joke teller and joke listener in enacting a series of four "knock-knock" jokes. Here is an example of such a joke:

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Teller: Knock, Knock.
Listener: Who's there?
Teller: Pecan.
Listener: Pecan who?
Teller: Pecan someone your own size!

Video recordings were made of the interactions. Using computer software, four raters viewed the still frames 0.5 s apart and estimated the amount each person moved from one frame to another using a 9-point rating scale, where 1 = no movement and 9 = the most movement possible. The series of estimations averaged over the four raters resulted in perceived activity time series for each participant in each interaction sampled at 2 Hz. Note that these time series (Fig. 3, top) make clear that the bodily activity during the interaction was rhythmic for both participants but not simply sinusoidal as in pendulum swinging or rocking in a rocking chair.

Of interest is whether these perceived activity time series of a pair of interactors would provide evidence for dynamical interactional synchronization in spite of the fact that they had neither goal nor explicit intention to jointly adjust the timing of their movements. A few measures were used to evaluate this. A cross-spectral analysis (Gottman, 1981; Warner, 1998) was performed and the average coherence at the peak frequencies (i.e., which measures the correlation of the dominant rhythms of the two time series; see Schmidt & O'Brien, 1997) was calculated to evaluate the coordination between the activity of the two participants. Additionally, the distributions of relative phase angles formed between the two activity time series were calculated. These distributions across nine 20° regions of relative phase between 0° and 180° were determined by calculating the instantaneous relative phase (Pikovsky, Rosenblum, & Kurths, 2001) for each trial and calculating the frequency of occurrence of the relative phase angles in each of the nine relative phase regions (Richardson et al., 2005; Schmidt & O'Brien, 1997). Spontaneous dynamical entrainment would be indicated by a concentration of relative phase angles near the synchronization dynamic attractors of 0° or 180°. To determine whether

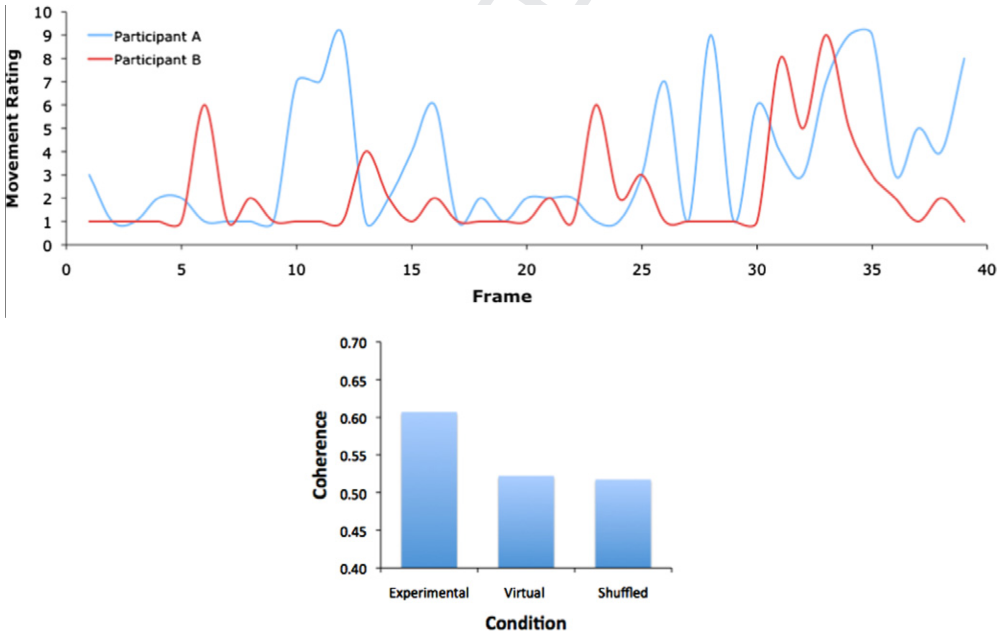

Fig. 3. (toppanel) An example of the perceived activity time series of a pair of subjects enacting knock-knock jokes. (bottom panel) The cross-spectral correlations of activity time series during the joke interactions (experimental) versus two estimates of chance correlation of those time series, virtual pairs and time-shuffled.

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the synchronization of these time series is different from chance synchronization, two kinds of surrogate time series were used as control conditions. A virtual pairs surrogate was obtained by pairing the time series of one person in a pair with the times series of the five other participants who stood in the spatial location of their partner. A shuffled surrogate was obtained through a random time-shuffling of the time series of the virtual pairs.

A preliminary analysis of the cross-spectral coherence indicated that the perceived activity of the participants tended to be more correlated than expected by chance ($F(2, 10) = 3.71$, $p = 0.06$, $\eta_p^2 = 0.43$). This suggests that indeed the joint action in these joke interactions did evince interactional synchrony. Furthermore, the strength of the movement correlation between the two participants was dependent on how quickly they executed the four jokes: The magnitude of the cross-spectral coherence increased as the length of the time to enact the four jokes increased (Fig. 4, top). Given that jokes told more quickly will result in faster speech and associated gesturing, this result suggests that the strength of synchronization as measured by coherence is dependent on the tempo of the rhythmic participants' behavioral rhythms. This relationship between frequency and coupling strength is just what is predicted from the Haken, Kelso, and Bunz (1985) synchronization equation that has been used to model both intrapersonal (Kelso, Scholz, & Schöner, 1986) and interpersonal (Schmidt et al., 1990) coordinated rhythmic movements. Finally, an analysis of the relative phasing of bodily activity indicated that there was a tendency for the activity of the interactors to show greater than chance in-phase behavior and less than chance antiphase behavior, $F(2, 10) = 6.68$, $p = 0.01$, $\eta_p^2 = 0.57$. As seen in Fig. 4 (bottom), this result suggests that the participants tended to start their movements together in time and, in spite of the fact that they were taking turns speaking, they tended not to alternate their movements.

In summary, this experiment demonstrates a number of things. First, it demonstrates a methodology that allows interactional synchrony to be quantitatively evaluated in natural interactions using video records. Second, it demonstrates that the nature of full bodily activity during social action is rhythmic and wave-like (Newtson, 1993). Finally, the analyses of the body activity records of these

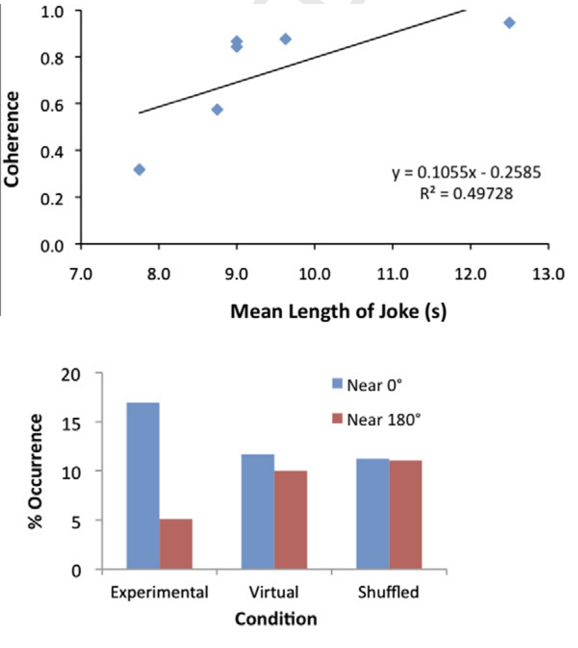

Fig. 4. (toppanel) The relationship between the magnitude of the cross-spectral correlations of activity time series and the mean length of a joke as derived from the total length of the interaction. (bottom panel) The relative phasing of bodily activity of the two interactors near inphase (0°) and antiphase (180°) for the experimental and two control surrogate conditions.

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joke telling interactions suggest that the joint action in natural interactions is constrained by processes of dynamical synchronization and are commensurate with past analyses of more stereotyped joint rhythmic tasks. Taken in total, the research reported in this section makes clear the ubiquitous nature of synchronization in everyday joint action.

4. Caring about synchronization

Why should a cognitive theorist investigating mirror/common coding explanations of joint action care about synchronization dynamics? The point is this: even if perception and action coding occurs in mirror systems as argued by cognitive theorists and such a representational system is the mechanism that allows us to understand another's actions, we still need to understand how joint actions are coordinated in time. The deep structure of temporal coordination in joint action seems to be the same as that found in the rest of nature, namely the result of dynamical synchronization processes. But importantly, as the research discussed above makes clear, these synchronization processes in joint action have some fairly novel properties in that they can function across informational linkages and can coordinate temporally more complex behavioral waves than simple sinusoidal rhythms.

In closing, two other recent developments in joint action behavioral dynamics that may help establish further linkages with the cognitive theorists interests are important to mention. First, Tognoli, Lagarde, DeGuzman, and Kelso (2007) in a recent EEG experiment on interpersonal finger tapping provided evidence that the mirror systems may be the specific neural medium for the unfolding of the synchronization dynamic. Specifically, they discovered that activity in the mirror neurons is enhanced during synchronous but not asynchronous joint action. Such research is again demonstrating the similitude of the dynamics of self-organization as an explanation of nature by demonstrating the importance of dynamics in general and synchronization in particular in neural information processing (Jirsa, 2004). Other research (Richardson, Campbell, & Schmidt, 2009) has revealed that the movement interference that occurs when concurrently observing and executing incompatible actions which has previously been given a mirror/common coding interpretation (Kilner et al., 2003) is not noise variability but rather rhythmically patterned variability that can be modeled by interpersonal synchronization processes. Under an entrainment explanation, what was previously considered noise interference can be understood as due to an additional control process that emerges as a consequence of increased task difficulty.

Of course, synchronization processes are not the whole story for joint action just as they are not the whole story for perceiving and acting in general. The synchronization explanation needs to be broadened to address discrete (e.g., mimicry) and object-directed (e.g., constructing a tower) joint actions in addition to simply rhythmic ones (Sebanz & Knoblich, 2009). Additionally, understanding the "what" and the "where" of joint action (Sebanz & Knoblich, 2009) will require the investigation of interpersonal spatial and semantic behavioral dynamics. Just how this is to be accomplished is less clear although there are some good hints in the current literature (Araújo, Davids, & Hristovski, 2006; Spivey, 2007; Warren, 2006). However, what remains clear is the importance of dynamical principles of organization in accounts of behavior as a whole and social motor coordination specifically.

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