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ORIGINAL PAPER

# Measuring the Dynamics of Interactional Synchrony

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**Abstract** Past research has revealed that natural social interactions contain interactional synchrony. The present study describes new methods for measuring interactional synchrony in natural interactions and evaluates whether the behavioral synchronization involved in social interactions is similar to dynamical synchronization found generically in nature. Two methodologies, a rater-coding method and a computational video image method, were used to provide time series representations of the movements of the co-actors as they enacted a series of jokes (i.e., knock–knock jokes). Cross-spectral and relative phase analyses of these time series revealed that speakers' and listeners' movements contained rhythms that were not only correlated in time but also exhibited phase synchronization. These results suggest that computational advances in video and time series analysis have greatly enhanced our ability to measure interactional synchrony in natural interactions. Moreover, the dynamical synchronization in these natural interactions is commensurate with that found in more stereotyped tasks, suggesting that similar organizational processes constrain bodily activity in natural social interactions and, hence, have implications for the understanding of joint action generally.

**Keywords** Motor movements · Synchronization · Social interaction

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## Introduction

Social psychologists have been investigating the temporally unfolding bodily coordination that occurs in social interactions for decades (Condon and Ogston 1966, 1967; Davis 1982; Dittman and Llewellyn 1968; Kendon 1970). In contrast to research on behavioral mimicry that has dominated the study of interpersonal coordination in which people have been found to unconsciously match each other's behavior (Chartrand and Bargh 1999), other social coordination research on *interactional synchrony* has found that the bodily movements of co-actors are coordinated in time (Condon and Ogston 1966; Newtson et al. 1987). The focus of this past social psychological research, however, has been more on trying to understand the role that such interactional synchrony (Condon and Ogston 1966) plays in human communication and relationships (Kendon 1970; Tickle-Degnen 2006). Indeed, researchers studying interactional synchrony have observed that this social motor coordination increases rapport (e.g., Bernieri 1988; Hove and Risen 2009) and cooperation (Wilmermuth and Heath 2009) between individuals, and breaks down in pathologies such as premature birth (Feldman and Eidelman 2007), autism (Isenhower et al. 2012; Trevarthen and Daniel 2005), and schizophrenia (Condon and Ogston 1967; Varlet et al. 2012). In the current study, to further understand this kind of interpersonal coordination which is a bit more subtle than behavioral mimicry, we have capitalized on advances in video technology and time series analysis to develop new methods for measuring interactional synchrony in natural interactions as well as for evaluating whether the temporal coordination in interactional synchrony has properties of *dynamical synchronization*—a temporal organizational strategy found in many natural systems (Strogatz 2003)—that has been previously found in less natural interpersonal interaction tasks. To motivate the methodologies used and to understand dynamical synchronization, we will first review how interactional synchrony and the dynamics of interpersonal coordination have been previously studied.

### Studying Interactional Synchrony

Interactional synchrony, defined descriptively by Bernieri and Rosenthal (1991) as the smooth meshing in time of the simultaneous rhythmic activity of two interactors, has been investigated in a number of studies. However, the measuring (and, hence, the operational definition) of such temporal coordination in natural interactions is challenging given the complexity of whole body human movement both in terms of the number of moving components and the time-unfolding nature of its movement patterns. Initially, methods that employed the temporal coding of specific actions were used. Judges would use film or video recordings of interpersonal interactions to evaluate movement changes in the form of initiations and terminations of body part movements or vocal activity (Condon and Ogston 1966; Dittman and Llewellyn 1968) and judge whether temporal co-occurrence of actions was present. For example, researchers using such coding methods have measured postural mirroring (LaFrance 1979) and mutual eye gaze (Feldman and Eidelman 2007) to evaluate the degree of interpersonal synchrony.

These coding methods, however, in addition to being difficult to employ, provide a rather coarse grain view of interactional synchrony because they code only a few different kinds of actions in an interaction (Bernieri et al. 1994). Newtson and colleagues (Newtson 1993; Newtson et al. 1977, 1987) obviated this apparent lack of content validity by measuring the bodily activity of co-actors successively across time and then examining the relationship between the bodily activity of co-actors. To do this, they used an adaptation of the Eshkol–Wachman movement notation that was developed for dance choreography (Eshkol 1973) in which they placed a transparency over a still frame on a video screen and located 15 different body parts at 1.0 or 0.5 s intervals. Whether each of the 15 points had changed position was evaluated for adjacent frames and the number of changes per frame were then tallied yielding a measure of the amount of activity at that point in time for each actor in the interactions (see Fig. 1). This technique has the benefit of being able to measure the activity of much of the body, if not the whole body, at regular intervals, hence forming a time series of bodily activity. The time series formed could then be used to evaluate the interactional synchrony involved using time series analysis methods such as cross-spectral analysis. In spite of the promise of this method, the time intensive nature of the method has resulted in very few applications by Newtson or other researchers.

A more popular alternative to the more laborious coding procedures for evaluating interactional synchrony is a rating method developed by Bernieri (1988). This approach uses the human perceptual system to measure interpersonal synchrony. It assumes that temporal unity and harmony in social interactions has a "gestalt"-like quality (Newtson et al. 1987) to which humans are perceptually attuned. To use it, judges would watch a one-minute video of an interaction and rate the interaction for properties such as simultaneity, tempo similarity and smoothness using a nine-point Likert scale. Although this rating methodology is less laborious and has been used to investigate the relationship of interactional synchrony with the psychological aspects of an interaction (Bernieri 1988; Bernieri et al. 1994; Kimura and Daibo 2006), it does not provide as detailed a measurement of the coordination behavior as the coding methods can. For example, such ratings provide single, holistic measurement of coordination (synchrony) for an entire interaction rather than a representation of the time unfolding nature of behavioral activity (i.e., a time series) from which patterns of coordination may be evaluated. Nonetheless the use of the human perceptual system to evaluate an interaction is intriguing if it can be employed to form a time series of measurements in a more automated fashion.

The aim of the current study is to demonstrate that current digital video technology allows us to evaluate the activity, and hence, synchrony of co-actors in a fairly non-

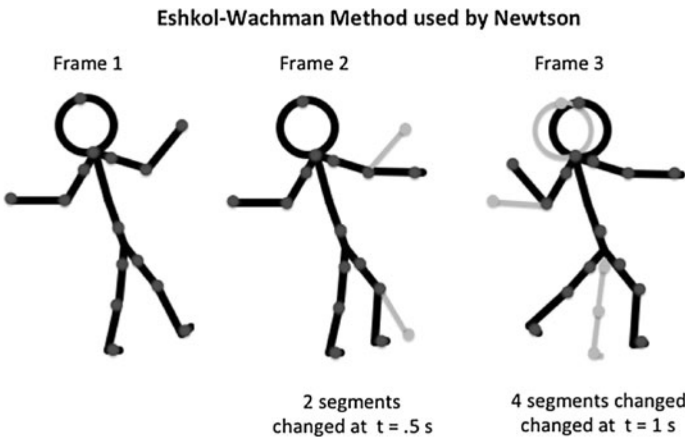


**Fig. 1** Newtson used Eshkol–Wachman dance notation to point locate 15 different body parts for video frames 0.5 s apart. By counting the number of segments that changed for each point in time it was possible to create an activity time series for each person in an interaction. The time series formed could then be used to evaluate the interpersonal coordination (e.g., synchrony) involved

invasive and naturalistic way. We employed two methods, a perceived activity measure (inspired by Bernieri's work) that uses human raters to assess the moment to moment degree of activity and an automated image change measure (inspired by Newtson's work) that uses computer calculated frame to frame pixel change information to assess the moment to moment degree of activity. The use of these two measures not only provides continuity with those previously used in the literature but also allowed us to evaluate the convergent validity of the methods as well. The outcome of each is a time series of activity for each participant sampled at short time intervals (2 times a second or at 2 Hz). These time series can then be submitted to various synchronization analyses that have been used in other disciplines such as in interlimb motor coordination studies where such time series are used to evaluate and mathematically model the limb synchronization underlying bimanual and locomotory rhythmic movements of a single person as well as limb coordination between two people. It is this latter domain of inquiry that we now turn to see how these new perceived activity and image change measures can be evaluated for both the degree and kind of synchronization demonstrated.

## Studying the Dynamics of Interpersonal Limb Coordination

Researchers interested in the coordination of movement have employed other methods to study the phenomenon of interpersonal synchronization. While social psychologists have been interested in interpersonal synchrony's role in the psychological aspects of social interactions (e.g., rapport), human movement scientists have been investigating the processes that underlie interpersonal synchronization and whether interpersonal bodily synchronization is an extension of and follows the same principles as single-person bodily (motor) coordination (Newtson et al. 1987; Schmidt and Richardson 2008). Much research has found that coordinated rhythmic limb movements of a single person are synchronized in a way that can be mathematically modeled as a coupled oscillator system (Kugler et al. 1980; Turvey et al. 1986). From this perspective on coordinated rhythmic movements such as the rhythmic coordination of the legs in locomotion, each limb is considered an oscillator swinging in a gravitational field like a pendulum while the nervous system is modeled as a coupling function for the oscillators. Research investigating the rhythmic coordination patterns observed (Kelso 1995; Kugler and Turvey 1987) indicates that the nervous system employs the dynamics of synchronization—an organizational strategy found in the physical rather than biological or psychological world—to create such coordinated rhythmic movements.

An intuitive example system that demonstrates such a dynamical synchronization 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). Two metronomes placed on a board that rests on soda cans is an easily assembled example of such a system (see Schmidt et al. 2011). 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: Such systems become phase synchronized at either 0° or 180° where 0° relative phase represents when the movements are inphase (i.e., in the same part of their cycles at a given time) and 180° relative phase represents when the movements are in antiphase (i.e., in the opposite part of their cycles at a given time). These relative phase angles are the equilibrium positions or attractor states at which the components of this dynamical system (e.g., the movement of metronomes' pendulums) "balance". This dynamical process of synchronization is well known and has been mathematically modeled extensively for many animate and inanimate systems (Haken et al. 1985; Strogatz 1994; Winfree 1980).

Interpersonal human movement studies have found just this kind of dynamical synchronization in tasks where two people sitting side by side are moving rhythmically. Just seeing another person's movements (for example, seeing another person rocking in a rocking chair as in Richardson et al. (2007)), is sufficient for a person to synchronize their own movements with the other person: The dynamical synchronization to another's rhythmic movement occurs *spontaneously* without conscious awareness (Miles et al. 2010; Oullier et al. 2008; Richardson et al. 2005; Schmidt and O'Brien 1997; Shockley et al. 2003; van Ulzen et al. 2008) and is nearly impossible to prevent from occurring (Issartel et al. 2007).

How one goes about evaluating the dynamics of synchronization is depicted in Fig. 2. In this experiment (Schmidt and O'Brien 1997), two people sitting side by side swung hand-held pendulums from the wrist and were instructed to look straight ahead for the first part of the trial and then to look at each other's pendulum in the second part of the trial while maintaining their original tempo. The occurrence of synchronization was examined two ways. The *strength* of synchronization was determined by evaluating how much the two time series correlate over time by finding the cross-spectral coherence (Gottman 1981; Warner 1998) at the dominant frequency. The *pattern* of synchronization was evaluated by calculating the continuous relative phase angle between the two movements at each point in time (Schmidt et al. 1993) and seeing how the relative phase angles of the two movements through the course of the trials were distributed over the range of possible angles between inphase (0°) and antiphase (180°). The results indicated that when the individuals were looking at each other's movements, their movements became unconsciously entrained: The movements were more

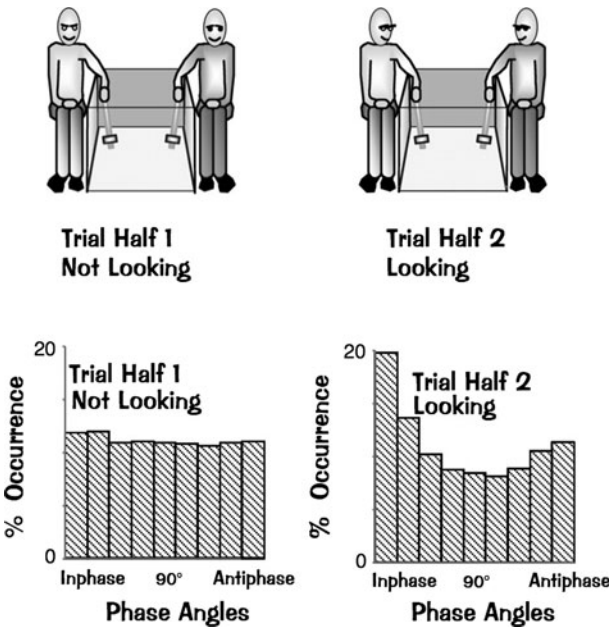


**Fig. 2** The methodology used to evaluate spontaneous interpersonal synchronization by Schmidt and O'Brien (1997). The *top panel* illustrates the interpersonal wrist-pendulum task while the *bottom panel* depicts the distribution of relative phase angles when there is synchronization (*right*) and when there is not (*left*). See text for fuller explanation

correlated and had a greater inphase and antiphase patterning than in the first part of the trials when no visual information about the other person's movements was available (Fig. 2, bottom). The concentration of phase angles near 0° and 180° is evidence that the relative phasing of the two people's movements were attracted to the equilibrium points of a weakly coupled oscillator system and, consequently, that a dynamical synchronization process of coupled oscillators is constraining the coordination of rhythmic movements of the two participants (Richardson et al. 2005, 2007; Schmidt and O'Brien 1997). Moreover, the results support the idea that the nervous systems of the two individuals can mutually harness such oscillatory dynamics to create coordinated movements and that perceptual information is sufficient to dynamically couple people's movements to those of others and to the environment in general (Schmidt and Richardson 2008).

These laboratory interpersonal synchronization studies speak to the generality of the dynamical processes in interpersonal coordination and provide support for the hypothesis that such dynamical processes guide interactional synchrony seen in everyday interactions. By specifically recording rhythmic movements of limbs, they were able to bring to bear rich time series analyses to determine whether dynamical processes of synchronization are involved in interpersonal coordination. However, the disadvantage of these studies is that the interactions between participants were not very natural. All the tasks involved having the subjects produce stereotyped rhythmic movements, which are obviously not present in everyday interactions. Moreover, the social interactions prescribed in the tasks were artificial. For example, Schmidt and O'Brien (1997) instructed the participants "look at the other person's movements but maintain your own tempo". Although Richardson et al. (2005) combined wrist-pendulum swinging with a dyadic picture discrimination task that was more natural and had fewer task demands, such an interaction task is still quite artificial. Consequently, these past studies still leave unanswered the question of whether dynamical processes of synchronization present in these laboratory tasks underlie natural interactional synchrony observed outside the laboratory.

The current study was designed to provide a methodology that bridges the gap between natural social interactions used to study interactional synchrony and the laboratory tasks used to evaluate the dynamics of interpersonal coordination. Here we use a structured conversation task in which two standing participants enacted a series of jokes that required questions and answers by both participants (i.e., knock–knock jokes). A knock–knock joke interaction was chosen because it is a structured conversation interaction: What gets said during the interaction is rigorously controlled but participants are totally free to move in a self-chosen and communicative fashion. As noted above, we used digital video processing technology to acquire two activity measures inspired by the work of Bernieri (e.g., Bernieri 1988) and Newtson (e.g., Newtson 1993; Newtson et al. 1987) that yield time series of whole body activity. We used analytic methods that have been used to evaluate the dynamics of interpersonal limb coordination to measure the degree of synchronization that occurs in the structured conversation interactions as well as determine whether the pattern of phase synchronization that occurs in the interactions is specific to that found in dynamical synchronization models.

## Method

### Participants

Twelve undergraduate students from the College of the Holy Cross ranging in age from 18 to 21 years participated in this study for either a small stipend or partial course credit. They were combined to form six participant pairs. Two of the pairs were female pairs, two were male pairs, and two were mixed gender pairs. In three of the pairs, the participants were friends whereas in the other three pairs, the participants were unacquainted.

## Materials and Procedure

Participant pairs enacted a series of four knock–knock jokes while their interactions were recorded using a digital video recorder. For three of the pairs, the movement of their dominant wrists and movement of their heads were simultaneously recorded using a magnetic motion tracking system (Polhemus Liberty system; Polhemus Inc., Colchester, VT). The Polhemus sensors were attached using Velcro to the participants' dominant wrist using a wristband and to the top of their head using a cap worn by the participants.

Participants were told that the experiment was investigating the psychology of humor. The true aim of the study was to investigate the amount of spontaneous temporal coordination (i.e., synchrony) exhibited between the movements of the pairs of participants while they enacted the knock–knock jokes. At the beginning of the experimental session, participants were asked to read and familiarize themselves with the jokes so that their enacting of the jokes was more natural. Then they were instructed to recite four knock–knock jokes switching roles as the teller or the responder for each joke. Here is an example of one such joke:

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

For the conditions being analyzed in this report, the participants were told to "move freely, using the body and hand gestures" while they enacted the joke. One trial was performed for each sequence of four jokes. Participants stood on marks approximately 3 ft. apart facing one another. The digital video recorder was placed on a tripod at eye level and positioned 14 ft. away from the participants facing their sides. This allowed a sagittal view of both participants' whole bodies.

## Analyses

The video recordings of the joke telling interactions were down sampled from 30 to 2 Hz and analyzed in two ways to obtain *activity* time series (i.e., measurement of activity every 0.5 s) for each of the participants. First, the perceived amount of activity of each participant from frame to frame was evaluated. Four raters viewed the adjacent still frames using computer software that allowed them to toggle back and forth between frames and estimated the amount of movement produced by a given participant using a 9-point Likert rating scale, where 1 = *no movement* and 9 = *the most movement possible*. The raters were undergraduate psychology students who did not participate in the experiment as subjects. They received modest training in applying the rating scale to assess the degree of activity and assessed the movements of one participant for the full length of a trial and then the movements of the other participant for the full length of a trial. (Although both participants were in full view on each frame, the raters found it easy to attend to the changes occurring for a given subject and ignore the changes of the other.) The result was a pair of perceived movement time series sampled at 2 Hz (Fig. 3, top).

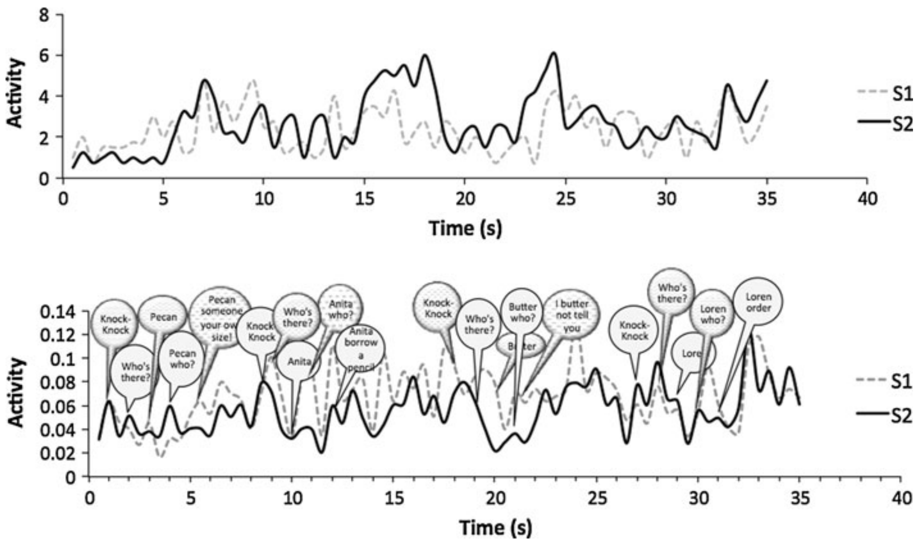


**Fig. 3** Activity time series for a representative joke telling trial using the perceived activity (*top panel*) and image change (*bottom panel*) methodologies

The second way that the activity time series were acquired was using video analysis routines written in Matlab (Mathworks, Inc., Natick, MA) that in a more automated fashion evaluate the amount of pixel change between adjacent video frames which corresponds to the amount of activity of a participant when nothing else is moving in that part of the frame beside the participant (see Kupper et al. 2010). After down sampling, the video frames were cropped to include the movements of only one person (i.e., the left half or right half of the screen) and the absolute difference of pixel change between the adjacent frames of the video was calculated to form an image change time series for each participant in the interaction also sampled at 2 Hz (Fig. 3, bottom).

Different dependent measures were used to evaluate the strength and the pattern of synchronization in the activity time series. First, a spectral analysis, a technique used to decompose a complex time series into its component frequencies (rhythms), was performed to determine whether there were indeed periodicities apparent in the activity of the two individuals. A spectral analysis partitions variance of a time series into the amounts accounted for by rhythms of different cycle lengths. The process is much like a best-fitting regression line but fits data to sinusoids of different frequencies/cycle lengths. In the top left of Fig. 4, the x-axis represents the frequencies of the candidate sinusoids whereas the spectral power on the y-axis represents how well the given sinusoids fit the data (see Warner 1998).

Then a cross-spectral analysis, which allows one to determine the relationship between two time series at each component frequency, was performed and the average coherence at the dominant rhythms (peak frequencies) of the two participants was calculated to measure the strength of synchronization between the activity of the two participants. This average coherence is a measure of the correlation (actually an $r^2$ value) at the dominant frequencies (i.e., of the dominant rhythms) of the two time series (see Fig. 4, top right) and ranges on a scale from 0 to 1. A coherence of 1 reflects perfect correlation of the movements (absolute

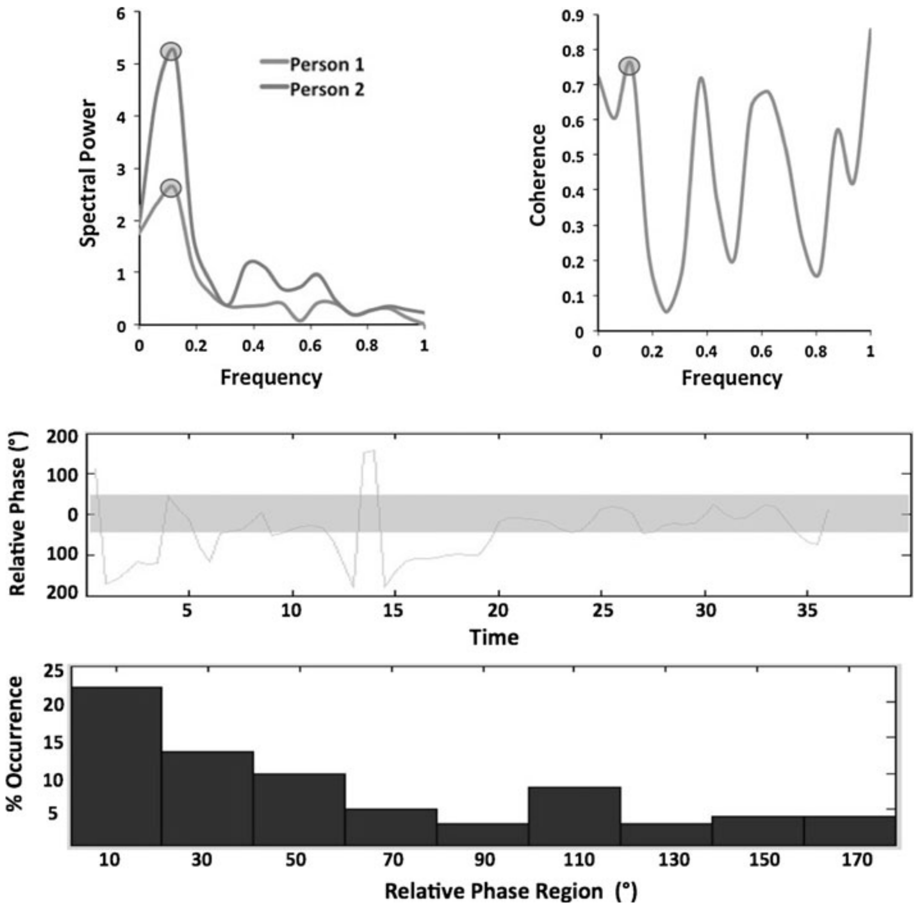


**Fig. 4** Spectral (*top left*), cross-spectral (*top right*) and relative phase (*middle* and *bottom*) analyses of the activity time series of a representative pair of participants. See text for fuller explanation

synchrony) and 0 reflects no correlation (no synchrony) (Richardson et al. 2005; Schmidt and O'Brien 1997). Coherence values were standardized using a Fisher-z transformation before statistical analyses were performed.

Additionally, to assess the pattern of synchronization and determine whether it was indeed dynamical synchronization, the relative phasing of the two activity time series was evaluated. Relative phase is an angle that measures where one rhythm is in its cycle (i.e., its phase) with respect to where another rhythm is in its cycle. If two rhythms are in identical parts of their cycles, they have a relative phase of 0° and are inphase. If two rhythms are in opposite parts of their cycles, they have a relative phase of 180° and are in antiphase. Since we were evaluating the relative phasing of activity time series, inphase indicates that the two people were moving at the same time whereas antiphase indicates two people were moving in an alternating fashion. To measure the relative phasing, an instantaneous relative phase algorithm (Pikovsky et al. 2001) was employed that calculated the relative phase angle for each sample of the time series (i.e., every 0.5 s). The calculated relative phase time series (Fig. 4, middle) were then analyzed for the degree of attraction to the equilibrium points of a coupled oscillator model (i.e., 0° and 180°) by finding the frequency of occurrence of the relative phase angles in each of nine 20° relative phase regions between 0° and 180° (Richardson et al. 2005; Schmidt and O'Brien 1997). The resultant distributions of relative phase (Fig. 4, bottom as well as Fig. 2, bottom) could then be used to evaluate whether dynamical phase entrainment occurred by determining whether there were concentrations of relative phase angles near the coupled oscillator system's equilibrium points of 0° or 180° (i.e., inphase and antiphase modes).

Finally, to evaluate whether the degree and pattern of synchronization of these activity time series was different from the degree and pattern expected by chance synchronization, surrogate time series were created to form control conditions. Virtual pair time series were obtained by pairing the time series of one person in a pair with the times series of the five other participants who they did not interact with but who stood in the spatial location of their partner while participating with someone else. The average coherence and the relative phase distributions were calculated for these five virtual pairs. The average of these values provided estimates of chance coordination that may occur between individuals even if they were not affecting one another's movements but just saying four jokes in sequence. To be able to use this virtual pairs control condition, the time series needed to be of equal lengths; consequently, analyses were performed on time series that were 31 s in length.

## Results

The enacting of the four jokes took on average 37.8 s for the six pairs of participants. Because there were four jokes that each had five lines, this length of time corresponded to on average one joke every 9.4 s and one line of a joke every 1.9 s. Importantly, spectral analyses performed on each interaction using both the perceived synchrony and the image change measures demonstrated spectral peaks indicative of nested periodicities at the time scale of the joke ($\sim$0.1 Hz) and near the time scale of the utterance ($\sim$0.5 Hz). Figure 4 (top) has an example spectrum for the image change activity of a representative participant pair. There were large spectral peaks at a frequency of 0.125 Hz indicating a rhythm of behavior once every 8 s or so representing the frequency of the joke. There were also smaller spectral peaks for both participants in the range of 0.5 Hz indicating a rhythm of behavior every 2 s or so representing the frequency of the phrase. In summary, the bodily activity of the two participants moved rhythmically at the tempos of their verbal gestures. Of interest in the analyses below is whether these activity rhythms were synchronized.

### Perceived Activity Measure of Synchrony

Four raters judged the amount of perceived movement of each participant from frame to frame (Fig. 3, top). On average, 74 perceived movement ratings were performed for each of the 12 participants. The average range on the 9-point scale was 4.7 units. The consistency (inter-rater reliability) across the judgments of the four raters was found to be 0.85 using Cronbach's $\alpha$. The average convergent validity of the perceived movement time series when compared with those of the Polhemus Liberty system was $r^2 = 0.67$. Such a correlation is quite good considering that the Polhemus time series represented the summed activity of only two points on the participants' bodies, their dominant wrist and head.

To determine whether the activity waves of the two individuals were coordinated, the average coherence estimates of the experimental participant pairs were compared to those of the virtual pairs. The mean average coherence demonstrated greater coordination for the experimental interactions (0.74) than expected by chance (0.54). However, two-tailed paired $t$ tests revealed a marginally significant effect ($t(5) = 2.21$, $p = .07$, $r^2 = 0.50$). The analysis of the relative phasing of interpersonal activity specifically addresses whether the movements of the two participants exemplify patterns of phase synchronization while telling each other the jokes. A 2 (condition: experimental pairs, virtual pairs) × 9 (relative phase region: 0–20, 21–40 …, 161–180) repeated measures ANOVA revealed a significant interaction between condition and relative phase region, $F(8, 40) = 4.08$, $p = .001$, $\eta_p^2 = 0.45$. As can be seen in Fig. 5 (top), there was a tendency for the activity waves of the co-actors to show greater than chance inphase behavior and less than chance antiphase behavior. Since these are activity time series, the concentration of inphase relative angles near 0° indicates that the two people were predominantly moving at the same time and tended to not move in an alternating (antiphase) manner. Follow-up $t$ tests evaluating the relative phasing of activity near inphase and antiphase revealed marginal effects for both patterns (0°: $t(5) = 2.02$, $p = .10$, $r^2 = 0.45$, 180°: $t(5) = 2.43$, $p = .06$, $r^2 = 0.54$).

In summary, using the perceived activity measure of activity, the pattern of results suggest that the activity of the two individuals were correlated and synchronized in a relative phasing pattern specific to a coupled oscillator dynamics, although the statistical

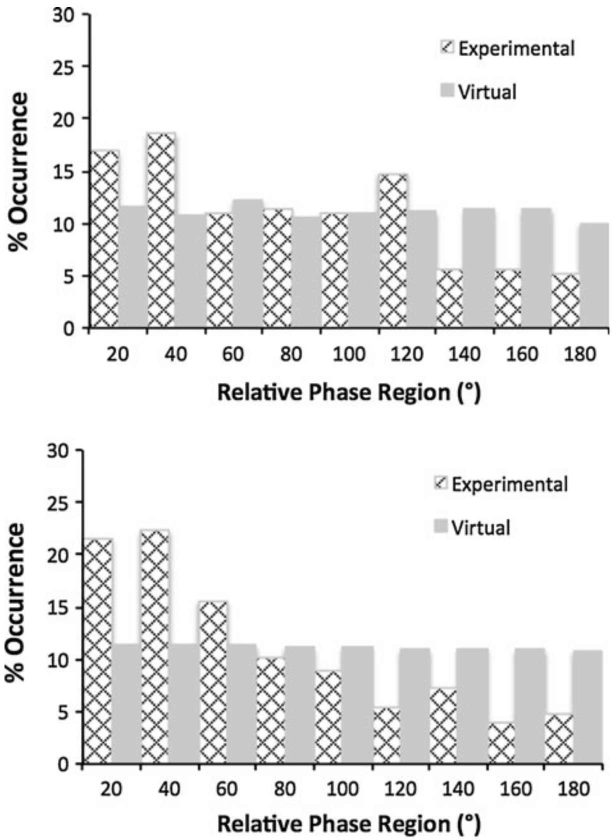


**Fig. 5** Distributions of the relative phasing of activity during joke telling for the perceived activity (*top panel*) and image change (*bottom panel*) time series

tests revealed only marginal significance. However, one has to note the large effect sizes associated with all the tests performed. They range between 0.45 and 0.54, with a large effect size typically defined by a value of $r^2 = 0.25$ (Cohen 1988). Consequently, the magnitude of the effect sizes observed in these tests suggest that failing to reject $H_0$ may in fact be a Type II error. The image change activity measure which we turn to next, given its automated and less subjective nature, may provide a more objective evaluation of participant activity, a less variable index of the participants coordination, and consequently, a more powerful basis for these statistical comparisons.

### Image Change Activity Measure of Synchrony

A spectral analysis of the image change time series for the six interactions revealed spectral peaks similar to those of the perceived activity measure, that is, nested periodicities at the time scale of the joke and near that of the utterance. To evaluate whether the image change activity waves of the two individuals were coordinated more than expected by chance, a cross-spectral measure of temporal correlation was again used. The mean average coherence was greater coordination for the experimental interactions (0.69) than expected by chance (0.50). A two-tailed paired *t* test now revealed a significant effect for average coherence ($t(5) = 4.53$, $p = .006$, $r^2 = 0.80$). Consequently, these results now allow us to conclude that the movements of the two participants were indeed significantly correlated, and hence, synchronized in time.

To evaluate whether phase entrainment of activity occurred as predicted by dynamical processes of synchronization, an ANOVA performed on the relative phasing of the image change time series revealed a significant interaction between condition and relative phase region, $F(8, 40) = 11.73$, $p = .001$, $\eta_p^2 = 0.70$. As was found for the perceived activity measure above, the activity waves tended to show a greater than chance inphase behavior and less than chance antiphase behavior (Fig. 5, bottom). Follow-up *t* tests evaluating the relative phasing of activity near inphase and antiphase now revealed significant effects for both patterns (0°: $t(5) = 5.11$, $p = .004$, $r^2 = 0.84$, 180°: $t(5) = 3.52$, $p = .02$, $r^2 = 0.71$). These results allow us to conclude that the two co-actors were synchronized in phase and in particular that they tended to move in an inphase pattern (i.e., at the same time) but also tended not to move in antiphase pattern (i.e., alternating their activity in time).

## Discussion

Past research has noted how interpersonal interactions have the psychological connectedness of the two co-actors complemented by two forms of bodily social coordination, behavioral mimicry and interactional synchrony. The goal of this study was to present new methods for measuring interactional synchrony in social interactions as well as to evaluate the synchronization that occurred. The initial question was whether the methods introduced allow us to conclude that the bodily movements of the participants during the joke telling task exhibited interactional synchrony, that is, whether they allow us to determine that the bodily movements had the properties which Bernieri and Rosenthal (1991) used to define interactional synchrony: The movements need to be simultaneous, rhythmic, and smoothly meshed in time. As can be observed in the activity time series in Fig. 3, the bodily movement of the participants exhibited movement simultaneity in that their activity overlapped in time. Moreover, the spectral analysis of the movements, as exemplified in

Fig. 4, demonstrates that the participants' movements contained rhythmic "waves" (e.g., represented by the spectral peaks) that correspond to the periodic joke telling component events (e.g., time of the joke and time of an utterance). Finally, the analysis of average coherence from cross-spectrum demonstrates that the activity time series of the two participants when telling the jokes were correlated in time which indeed suggests that the movements of the co-actors were smoothly meshed. Hence, these results allow us to verify that the methods introduced can resolve the criterial properties of interactional synchrony.

Although both the perceived activity and the image change activity measures demonstrated properties of simultaneity and rhythmic "waves", only the image change measure yielded significant correlations in time as well as significant inphase synchronization. However, the pattern of effects is identical for the perceived activity and the image change activity measures. Additionally, even though the statistical tests were not significant, their $r^2$s suggest effect sizes that are quite large (Cohen 1988). Increasing the number of pairs tested of course would have increased the power of our statistical tests; however, the laborious nature of the perceived activity measure undermines the practicality of analyzing too many pairs using this measure. The image change measure seems to be the preferred measure of activity for evaluating interactional synchrony. Not only is it an objective measure of the participant movement (i.e., numbers of pixels that change from frame to frame) that seems to yield more accurate measures of activity but also it is an automated method that can be applied more efficiently in the lab.

It is important to note that our use of virtual pairs provides a strong test of objective synchronization. There existed a certain healthy skepticism about the initial interactional synchrony research that the observed synchrony was real because the appropriate statistical controls for chance synchrony had not been applied (Cappella 1981; McDowall 1978). Indeed, the chance for spurious chance correlations between the movements of participants while telling the jokes is quite high: The rhythmic movements generated by the structure of the joke telling might create an apparent synchronization of participant movements not because they are mutually influencing one another but because the rhythm of telling the jokes is similar for the two participants. If that were the case then a given participant's movements during the joke telling would be correlated equally with his real partner's movements as with those of other participants with whom he/she did not interact (i.e., virtual partners). However, that was not the case. Although there were fairly high coherence magnitudes for the virtual pairs (which is evidence for some spurious coordination), the coherence magnitudes of the real pairs were always greater. This indicates that there was a mutual influence of the participants' movements on each other and the synchrony observed was beyond that imposed by the structure of the joke telling task.

The use of these methods have allowed us to provide not only objective evidence for existence of interactional synchrony in this structured conversation task but also provide support for the ideas of Newtson (1993) who argued that activity in social interactions can be understood as correlated behavioral waves. What needs to be underscored about the activity measures used here is that they are time series measures of the movement of the whole body, and consequently, allow us to capture behavioral waves of the participants rather than just motor movements (e.g., the movement of particular effectors). Such a generalized measure of movement may have great utility for investigating the structure of action and interaction (e.g., Ramseyer and Tschachter 2011) for a couple of reasons. First, because it is hard to know for a particular joint action which effectors to measure and what their qualitative coordinative pattern should be, often such decisions in past research have been made rather arbitrary. Second, an activity measure is a measure of whole body movement, a summary measure of all activity of all effectors. Although one might assume that neural control structures govern the movements of specific effectors, the control of general activity may be important when performed in the context of social goals. That is, it may not be important when interacting with someone to move a particular effector in a particular direction with respect to the movement of their particular effector. What may instead be important to build a social rapport (for example) is to move in a generally correlated fashion when the other person is moving.

Moreover, in addition to verifying the presence and objective measurement of interactional synchrony in a structured conversation task, this study also investigated whether *interactional* synchrony is *dynamical* synchrony. Interactional synchrony is periodic temporal coordination between bodily movements of people in social interactions. Dynamical synchrony is the kind of periodic temporal coordination that occurs in physical coupled oscillator systems that have been extensively studied and mathematically modeled in the biological and physical sciences. The question of whether interactional synchrony is dynamical synchrony is important because it asks whether dynamical synchrony models are general enough to explain social as well as physical synchronization. The key property that identifies dynamical synchrony is in the relative phasing of the coordinated movements, in particular whether the movements tend to an inphase (0°) or antiphase (180°) pattern (Haken et al. 1985). Although evidence for dynamical synchronization in interpersonal coordination has been found in laboratory tasks (see Schmidt and Richardson 2008 for a review), whether such dynamical synchronization is present in whole body movements in more naturally occurring interactions has yet to be determined. Spontaneous phase entrainment of the participants' bodily activity in the joke task was evaluated by calculating the relative phasing of their activity time series. Dynamical models of synchronization predict relative phasing near 0° or 180° (the model's equilibrium or attractor states) for weaker states of synchronization and such intermittent entrainment has been found in spontaneous interpersonal coordination (Schmidt and O'Brien 1997, see Fig. 2) in more stereotyped movement tasks.

The results in Fig. 5 demonstrate that relative phasing near inphase occurs at a frequency greater than expected by chance while relative phasing near antiphase occurs at a frequency less than expected by chance. These results indicate that the two co-actors tend to move at the same time (inphase). Of course, because we were measuring the relative phasing of the *magnitude of activity* this interpretation of relative phase is different from how it is typically interpreted in past human movement science literature (Schmidt et al. 2011): Relative phase here does not indicate inphase or antiphase in terms of the relative spatial directions which the participants were moving but rather the relative timing of activity. Such a finding is somewhat surprising given the alternating nature of the knock–knock joke sequence. This result is not an artifact of the video methodology: Recent research using it to investigate movement coordination in imitation found significant antiphase patterning when the movements of the two individuals were alternating in a stereotyped fashion as seen in imitation tasks (Schmidt 2010). The inphase nature of the activity seems to indicate that the speaking actions of the participants (in that these were alternating) were not wholly structuring their activity. This finding suggests that one way of maintaining social connection during turn-taking exchanges is to move in a coordinated fashion with your partner during "their" turn. This embodied action may facilitate social rapport by signaling to the other person that we are engaged in the joint social exchange (Bernieri et al. 1994).

The observed dynamical structure of interactional synchrony in these joke interactions has implications generally for researchers interested in social coordination (Schmidt et al. 2011). First, it demonstrates that coupled oscillatory processes that are found in the rest of nature (Strogatz 2003) provide a deep structure for temporal coordination in joint actions.

The dynamical connection between the rhythms (i.e., meter or beat pattern) of the interactors may provide a means for the interactors to predict or anticipate each other's actions that may facilitate (or even obviate the need for) mental simulation processes proposed for this function (Sebanz and Knoblich 2009) which have been hypothesized by some to be instantiated in the mirror systems of the brain (Newman-Norlund et al. 2007). The results further demonstrate that dynamical processes can coordinate more complex human actions than simple sinusoidal rhythmic movements that have been investigate in previous research (Schmidt and Richardson 2008). Consequently, the current findings are relevant for researchers investigating interpersonal interactions as found in conversations (Garrod and Pickering 2004; McGarva and Warner 2003) and sports (Passos et al. 2009). Indeed, one reason why the coordination in conversation and sport interactions seem so 'easy' may be that a combination of complex rhythmic activity and their interpersonal synchronization provides a basis for two individuals to become a single dynamical system, an interpersonal coordinative synergy, that functions outside of their awareness.

In summary, the present study also provides some methodological innovation with its two computer-based methods for analyzing social activity from video. These methods are essentially automated versions of the Eshkol–Wachman inspired procedure used by Newtson and produces time series representing similar what he called behavioral 'waves' (Newtson 1993). Although both methods are fairly easy to perform compared to those used previously (Newtson et al. 1977), the image change methodology seems to not only have the benefit of being automated but also stronger statistical results. A similar method has been used to evaluate the degree of synchrony in the social interactions of schizophrenics (Kupper et al. 2010; Ramseyer and Tschachter 2011). Importantly though, performing the rating method allowed us to establish the validity of the image change measure: The similarity of the results from the two methods removes any doubt that the pixel change measure is estimating the magnitude of bodily change from frame to frame.

The implication of being able to easily acquire these "behavioral waves" using this video method is that it allows social (Bernieri et al. 1994; Miles et al. 2010) and developmental (Feldman 2007) psychologists who are interested in the rhythmic nature of unfolding interactions an automated method for investigating social coordination. Not only are the resulting time series much more representative of the structure of behavior across time than coding punctate properties such as head nods or gestalt-like qualities such as interaction smoothness, but also the quantitative nature of the time series allows the whole battery of techniques from time series analysis and nonlinear dynamics to be brought to bear on their analysis. Additionally, the methods may also be useful to the many researchers interested in the phenomenon of behavioral mimicry as well as its personality or social correlates (e.g., Chartrand and Bargh 1999; Rogers et al. 2003). The coordination of activity in mimicry tasks has not previously been studied and may allow such phenomena to be understood not just in action-reaction terms but more in terms of their time unfolding structure (Schmidt 2010).

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