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Mutual Interpersonal Postural Constraints Are Involved in Cooperative Conversation

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The research was designed to evaluate interpersonal coordination during conversation with a new measurement tool. The experiment uses an analysis based on recurrence strategies, known as cross recurrence quantification, to evaluate the shared activity between 2 postural time series in reconstructed phase space. Pairs of participants were found to share more locations in phase space (greater recurrence) in conditions where they were conversing with one another to solve a puzzle task than in conditions in which they conversed with others. The trajectories of pairs of participants also showed less divergence when they conversed with each other than when they conversed with others as well. This is offered as objective evidence of interpersonal coordination of postural sway in the context of a cooperative verbal task.

> Language use is really a form of *joint action*. A joint action is one that is carried out by an ensemble of people acting in coordination with each other. (Clark, 1996, p. 3)

Clark (1996) has suggested that language use occurs prototypically in the context of cooperative activities that he calls "joint actions." These are activities in which two or more people engage to achieve mutual goals. The speech that occurs moves the activities forward toward goal achievement.

By definition, cooperative activities require interpersonal coordination. Many investigators have observed apparent indices of coordination in the context of cooperative activities that involve speech. All of the indices are examples of interpersonal imitation or entrainment. For example, individuals speaking cooperatively are found to converge in their dialect (see Giles, Coupland, & Coupland, 1991, for a review). Speakers have also been found to converge in speaking rate (Street, 1984), vocal intensity (Natale, 1975), and pausing frequency (Cappella & Planalp, 1981; see Cappella, 1981, for a review). In addition, listeners to a speaker whom they find engaging tend to mirror the postures of the speaker (LaFrance, 1982). Listeners are also reported to move in time with the rhythms of a speaker's speech (exhibiting "interactional synchrony"; Condon & Ogston, 1971; Newtson, 1994).

Findings, particularly of movement entrainment among conversational partners, are intriguing, because they appear to index the interpersonal coordination that must occur if the joint activities are to be completed. However, most findings of movement entrainment are based on fairly subjective, observational procedures. For example, Condon and Ogston (1971) assessed interactional synchrony by hand scoring videotapes of listener movements and hand marking the accompanying speech for its rhythmic properties. Although this work was painstaking and, apparently, quite carefully done, it is open to error. Speech rhythms in particular are quite difficult to document. Newtson and colleagues (see Newtson, Engquist, & Bois, 1977; Newtson, Hairfield, Bloomingdale, & Cutino, 1987) have also offered strategies for evaluating the coordination dynamics of participants engaged in various activities, including conversation. These strategies involve visual analysis of behavior sequences of recorded interactions. Stick-figure tracings are made of each actor in a sequence at specific intervals. Each successive tracing is compared for changes in joint angles. For 17 possible joint-angle changes, a value of 0 or 1 is assigned, yielding a score between 0 and 17 for each frame. This strategy yields remarkably high reliabilities and appears quite robust. The coded sequences (time series) can then be translated into spectral profiles, reflecting the periodicity of the movement sequence and also, apparently, the class of movements (e.g., throwing vs. catching a ball). Finally, the spectral profiles of two time series may be

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compared using coherence analysis. Coherence analysis is essentially the correlation between time series at the component frequencies. Similar comparisons may also be made between time series of vocal intensity and joint-angle changes either intrapersonally or interpersonally.

Newtson and colleagues (Newtson, 1994; Newtson et al., 1977, 1987) have reported coupling of these *behavior waves* between persons engaged in conversation. Specific phase relations between the spectral profiles of one person's vocal intensity with their conversational partner's joint-angle changes suggest that the activities are coordinated. These measures seem to be the most objective coding strategies currently proposed in the context of visual measurement. However, there are certain drawbacks to the procedure. Although the magnitude of change between tracings is indexed to a certain extent with this method, specific joint changes are recorded discretely. In other words, although the number of joint-angle changes is indexed, degree of joint-angle changes is not measured. Furthermore, when body segments are occluded in a video, these are not recorded. These limitations of visual recording are almost impossible to overcome, given that the viewing angle limits the degree to which joint-angle changes can be measured. Finally, although these measures are reliable, they are still subjective. We propose to look for entrainment in objective measures of postural sway.

Postural Dynamics

When people stand, they sway, most notably in the anterior–posterior direction. The movement is quite complex and can be difficult to quantify. Spontaneous fluctuation in posture often occurs independently of external perturbation (Collins & De Luca, 1994; Newell, Slobounov, Slobounova, & Molenaar, 1997). This not only is common but may be required for postural stabilization (maintaining upright stance; Balasubramaniam, Riley, & Turvey, 2000). Postural sway also exhibits nonstationarity. That is, within the boundaries of the basis of support (anterior–posterior and mediolateral extents of the feet), the fluctuations in the center of pressure[1] of the body typically drift in both the first and second moments (mean and variance; Carroll & Freedman, 1993; Collins & De Luca, 1993). These hallmarks of postural activity yield quite irregular time series, and call for analyses that do not require many assumptions regarding the structure of the data under scrutiny (such as an assumption of stationarity). The context of postural movement must also be considered when selecting an appropriate index of dynamical activity.

A number of researchers have argued that postural stabilization (maintaining upright stance) should not be regarded as an end goal, but as a facilitator of the goals of suprapostural activity (Riccio & Stoffregen, 1988, 1991; Riley, Mitra, Stoffregen, & Turvey, 1997; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). During suprapostural tasks, such as reaching (Belen'kii, Gurfinkel', & Pal'tsev, 1967; Fel'dman, 1966), visual inspection (Stoffregen et al., 2000), or even breathing (Abe, Yamada, Tomita, & Easton, 1999), maintaining a constant postural configuration is ineffective for the success of such tasks. Adjustment of the center of pressure of the body is required to compensate for changes in the center of mass that occur when suprapostural activities are performed. Thus, it would be inaccurate to consider postural stabilization successful when sway is minimized. Typical conversation is a suprapostural task that involves gesturing, listening, and visual inspection. These activities likewise require adjustments to the postural state for success.

To select an appropriate measure of interpersonal postural coordination, the complex nature of postural activity outlined above must be taken into account. An analysis that is robust in revealing structure in irregular, nonperiodic, and nonstationary time series is required. Nonstationarity violates the assumptions of many preferred analyses, including Fourier spectral analysis and correlational techniques. Nonlinear techniques that are appropriate for quantifying fine details (beyond variability measures) of postural movements have recently been pursued (Balasubramaniam et al., 2000; Riley et al., 1997; Riley, Balasubramaniam, & Turvey, 1999). These strategies capitalize on the nonlinear properties of complex systems such as posture.

Phase Space Reconstruction

In nonlinear systems, dynamical variables interact. The interplay among dynamical variables in a known system is typically captured using a *phase space*. A phase space is a plot of one dynamical degree of freedom (dimension) with respect to others. In a phase space, the preferred states of the system (its attractors) may be evaluated. Often, however, the true dynamical variables may be unknown, confounding evaluation of the system in the appropriate number of dimensions. When multiple dynamical variables are at play, distortions in the observed activity of the system result from projection of a hyperdimensional dynamical space onto the selected dimension(s) of measurement. However, a key to the investigation of dynamical systems of unknown structure is provided by the embedding theorem. According to this theorem, knowledge of the dynamics of a potentially multivariate system may be obtained through the measurement of a single scalar time series (Takens, 1981).

Given a time series of a single variable, the interactive nature of dynamical variables makes it possible to recover the dynamical structure of the system. A phase space can be constructed using time-delayed copies of the original signal as surrogate observables. The original signal is unfolded, thereby embedding it in a higher dimensional, reconstructed space (see Abarbanel, 1996, for a tutorial). The embedding theorem shows that this *reconstructed phase space* is related to the original phase space by smooth differentiable transformations. Thus, invariant features of the original phase space are preserved, allowing the system to be evaluated in the appropriate number of dimensions. Essentially, phase space reconstruction provides the multidimensional perspective that is required to reveal the contribution of multiple dynamical variables without projection distortions involved in scalar measurement.

Applications of Recurrence Strategies to Posture

Recurrence strategies involve the determination of recurrent values in a reconstructed phase space (Webber & Zbilut, 1994).

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[1] The forces acting between the feet and the ground can be summed to yield a single ground reaction force vector (**F**) and a free torque vector ($\mathbf{T}_z$). The point of application of the ground reaction force on a force plate is the center of pressure. Center of pressure data was not used in the present research because kinematic displacement rather than force distributions were recorded.

Points in a phase space are considered recurrent if they fall within some Euclidean distance (radius) of one another. The primary advantage of using a recurrence strategy in the context of postural sway is that it requires no assumptions regarding the size, structure, or stationarity of the data under scrutiny. Recurrence strategies have been applied successfully to the evaluation of postural fluctuations of an individual (Balasubramaniam et al., 2000; Riley et al., 1999). These techniques may also be used to quantify shared activity between two time series (Shockley, Butwill, Zbilut, & Webber, 2002; Webber, Shockley, Zbilut, & Butwill, 2001).

A qualitative picture of the shared structure between two time series becomes evident by indexing $x(i)$ along the abscissa and $y(j)$ along the ordinate, such that a point is plotted when $x(i) = y(j)$ within some radius (a recurrence plot; see Figure 1A). Cross recurrence quantification (CRQ) involves plotting only recurrent values of two different time series, x and y, in reconstructed phase space (Zbilut, Giuliani, & Webber, 1998). Thus, recurrence in CRQ reflects an overlap of trajectories $[x(i) = y(j)]$, within some radius, in reconstructed phase space. The percentage of values that recur (%RECUR) can be quantified as the ratio of the number of recurrent points to the number of possible recurrent points. Consecutive strings of recurrent points (diagonal lines in a recurrence plot) provide an index of the deterministic structure (%DETER) that is shared between the two time series. %DETER (shared regions in phase space) is quantified as the ratio of the number of recurrent points that form diagonal lines (in the recurrence plot) to the total number of recurrent points. The longest diagonal line segment (MAXLINE) in a recurrence plot has been shown to be inversely proportional to the largest positive Lyapunov exponent[2] (Eckmann, Kamphorst, & Ruelle, 1987). Thus, MAXLINE provides an index of the degree of convergence of the unfolded time series over time. ENTROPY is calculated as the Shannon entropy of a histogram of diagonal line segment lengths and is accordingly an index of the complexity of the shared activity.

Experiment

Our research was designed to buttress earlier findings of interpersonal coordination during conversation with new measurement tools. We have asked whether participants in a joint activity show convergence in their postural sway. We pursued the investigation in the context of postural activity measured during conversation. CRQ was applied as an index of the shared activity between the postural dynamics of two persons. Accordingly, %RECUR (shared locations between participants in phase space) was expected to be greater in conditions where participants are conversing with each other than conditions in which participants were conversing with confederates. In this way, we held constant that participants were speaking in a cooperative task. We varied only whether they were or were not speaking cooperatively with one another.

Method

Participants. Twenty-six undergraduate or graduate students (13 pairs) at the University of Connecticut provided informed consent and participated in partial fulfillment of a course requirement or on a voluntary basis.

Apparatus. Twelve pairs of cartoon pictures (8 × 11 in. [20.32 × 27.94 cm]) were used as stimulus cards. These cards were individually displayed at approximately eye level and were supported by wooden stands that could be moved during the course of the experiment.

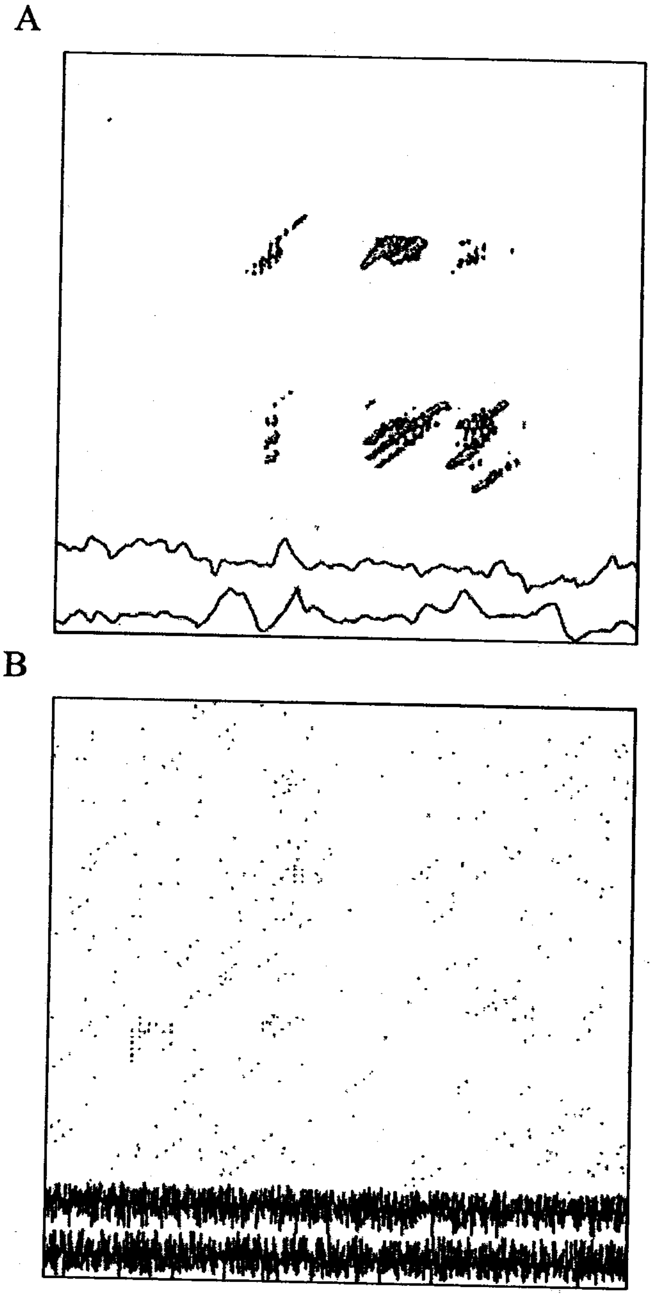

Figure 1. (A) A sample cross-recurrence plot of 2 participants facing each other and conversing with each other. Time series for the 2 participants are plotted at the bottom of the figure. (B) A sample cross-recurrence plot of the same data set in Panel A, randomly shuffled.

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[2] A Lyapunov exponent λ is an index of the exponential temporal divergence of two nearby points in phase space. If $x(t)$ is a point in phase space at time t, then a nearby point is $x(t) + \delta(t)$, where δ is a small separation vector in phase space of initial length δ_0. Separation of these two points at any given time is $\|\delta(t)\| \sim \|\delta_0\|e^{\lambda t}$ (Strogatz, 1994). Positive and negative exponents thereby reflect divergence and convergence of trajectories, respectively. Thus, MAXLINE, which has been shown to be inversely proportional to the largest positive Lyapunov exponent, provides an index of convergence.

Movement data were collected using a magnetic tracking system (Polhemus Fastrak, Polhemus Corporation, Colchester, VT) and 6-D Research System software (Skill Technologies, Inc., Phoenix, AZ). Movement data (displacement in centimeters) were recorded at 60 Hz.

Procedure. A pair of students participated in four trials for each of four experimental conditions. Tracking system receivers were attached with velcro straps around the head and around the waist of participants. A single trial consisted of a 2-min data collection session. During each trial, 2 participants stood upright in a specific location of a 17- × 23-ft (5.18- × 7.01-m) room while discussing with each other or someone else the subtle differences between two similar cartoon pictures. Each member of a discussion pair was instructed to find the differences between his or her picture and the picture of the other member of the discussion pair. During the 2-min session, neither participant in a discussion pair was able to see the other picture. Therefore, verbal cooperation was required between members of a discussion pair to solve the task. Different pairs of pictures were used for each trial. During the course of a trial, each participant in a discussion pair was allowed to move his or her body freely, while keeping his or her feet in the specified location. To manipulate visual coupling between participants and constraints of the task itself (interactive speaking while standing), independent variables of body orientation and task partner were factorially combined to yield the four testing conditions (see Figure 2). Body orientation refers to whether the 2 participants faced one another and, therefore, could see one another. Task partner refers to whether the 2 participants performed the task with one another or each with a confederate whose postural sway was not tracked. In all conditions, the confederates were seated outside of the magnetic motion-capture region. The confederates were positioned to the side of the participants and, therefore, were not in direct visual contact with them. This configuration eliminated visual influences of the confederates on the participants while still allowing verbal communication. The confederate conditions were conducted with both participants simultaneously. Thus, for all trials, movement of the 2 participants was tracked, while the conversational partner of the participants depended on the trial condition.

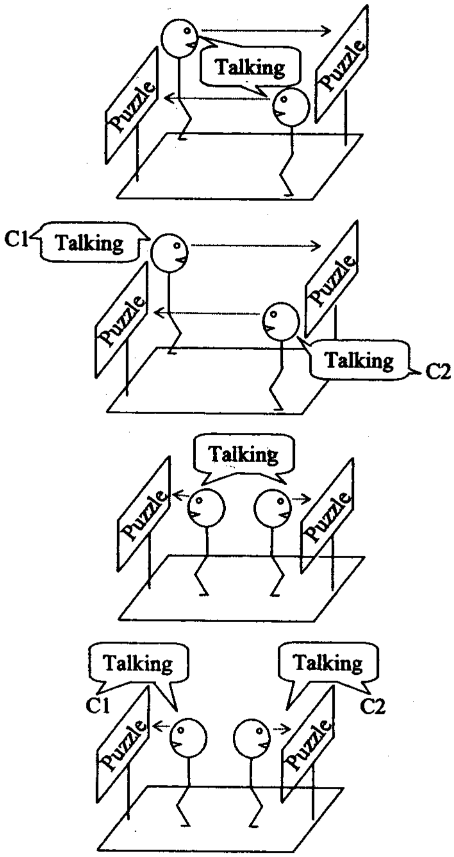

Figure 2. Method of evaluating interpersonal postural constraints involved in cooperative conversation. Participants faced toward or away from each other and conversed with either each other or a confederate (C).

Data analysis. Displacement (measured in centimeters) of each participant in the anterior–posterior direction at the forehead and hip were selected for analysis. These time series were converted into standard (z) scores to achieve a common scale without influencing the distribution of scores within each time series. The first step in recurrence analysis procedures is to determine the appropriate values for the following input parameters: time delay, embedding dimensions, radius, and line length.

The time delay refers to the temporal offset between copies of the time series that are used as surrogate dimensions in reconstructed space. Ideally, a time delay should yield the minimum of correlated activity between points in the time series separated by that difference. The correlated activity can be determined using the first zero crossing of the autocorrelation function, or the first minimum of the average mutual information function (Abarbanel, 1996). Because of the nature of postural data (nonstationary, irregular, and nonperiodic), these functions tend to be quite noisy, and neither measure offers a clear landmark. However, in recurrence quantification, the choice of a time delay is not critical and can be determined from the output measures themselves (Riley et al., 1999; Zbilut & Webber, 1992). Recurrence measures may be computed for a range of input parameters. Ranges for which small changes in parameter settings yield smooth (i.e., not large or discontinuous) changes in recurrence output measures should suffice. To guard against possible artifactual results, output measures may be compared against randomly shuffled data under the same input parameter settings. Because the random shuffling will destroy time-correlated information, the magnitude of recurrence measures should decrease accordingly. If substantial changes in recurrence measures do not result, then the input parameter selection should be more closely evaluated. Our choice of temporal separation (25 data points or 0.42 s) satisfied the above requirements (compare Figure 1A with the randomly shuffled data in Figure 1B for an illustration).

Similarly, there are prescriptions for choosing the number of embedding dimensions (Abarbanel, 1996). Again, because of the inherent noisiness of postural data, such prescriptions are not practical. Because determination of the embedding dimensions is not the goal of this procedure, the same output measure strategy as above may be used for the selection of embedding dimensions. It is most important to select enough embedding dimensions to allow for the interplay of a reasonable number of dynamical variables. Webber (1997) suggested beginning with an embedding dimension in the range of 10 to 20 and working downward. Our choice of 10 embedding dimensions corresponded to the choice of Riley et al. (1999) in a study applying phase space reconstruction strategies to postural data.

The radius is an inclusion criterion for recurrence. That is, it defines a distance around a point of the first trajectory that, if another point of the second trajectory falls within, will be considered a recurrent point. Selection of radius is crucial in successful application of recurrence quantification. It is necessary to select a radius large enough that it will capture recurrence that is above the resolution threshold of the measurement instruments. Furthermore, the radius needs to be small enough to avoid global recurrence (e.g., all points recurrent). Using the output measure strategy from above, it is advisable to use a radius that allows a reasonable amount of variability in these measures (i.e., %RECUR and %DETER do not saturate at the floor of 0% or the ceiling of 100%). One may further constrain the choice by plotting in log–log coordinates the obtained %RECUR values for a range of radius values for a fixed time delay and embedding dimension. An appropriate range should be roughly linear in these coordinates. When multiple samples are to be analyzed, a certain percentage of the mean distance by which points are separated in the reconstructed phase space is advisable. On the basis of these criteria, our selection was radius of 30% of the mean distance separating points in reconstructed space for a given trial.

The number of consecutive recurrent points required to define a line segment should be at least two. The more points required reflect increasingly conservative estimates of the deterministic structure in the system. This may be appropriate if contamination of data is suspected. A line segment in this study was considered to be two consecutive recurrent points.

Results

The nature of the puzzle task yielded very natural conversation during the course of the 2-min trials. The goal of the task was to find as many differences as possible between the two similar pictures of a given pair of conversers. This encouraged a lively interchange of inquiries and descriptions. As expected, gesturing was common, and conversation generally had to be halted by the experimenter when the 2-min period had ended. Genuine interest in the task was illustrated by the typical requests of participants to inspect their partner's picture at the end of the data collection sessions.

The mean results for cross recurrence measures of %RECUR and MAXLINE calculated between displacements of the hips are presented in Figure 3. In support of our hypothesis, a two-factor analysis of variance found a main effect of task partner on %RECUR. For a given pair, there was greater overlap of trajectories in phase space when participants were conversing with each other (112,065 recurrent points on average) than when participants were conversing with the confederates (63,352 recurrent points on average), $F(1, 12) = 7.83, p < .05$. There was no significant effect of body orientation on %RECUR (the percent of recurrent points divided by the possible recurrent points ×100), and no significant interaction ($Fs < 1$). Similarly, there was a main effect of task partner on MAXLINE (longest diagonal line segment) at the hip, $F(1, 12) = 21.80, p < .01$, with no significant effect of body orientation and no interaction ($F < 1$). Postural trajectories of a given pair of participants diverged less over time when they were conversing with each other than when they were conversing with confederates. No other recurrence measures that were calculated on hip movements yielded significant differences between conditions. No significant effects of any recurrence measures were observed when they were calculated on movements of the head.

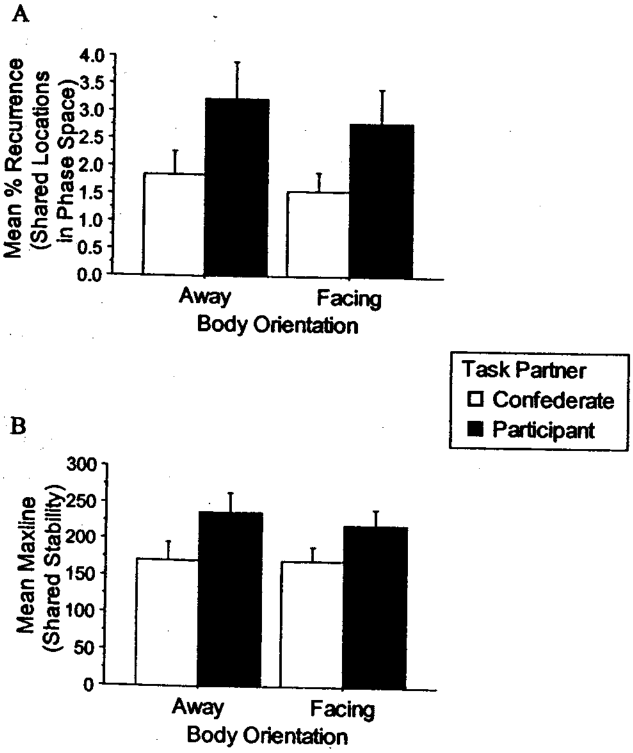

Figure 3. (A) Results for %RECUR (the percentage of values that recur) calculated at the hip. Recurrence corresponds to overlap of the two postural trajectories in reconstructed phase space. (B) MAXLINE results calculated at the hip. MAXLINE refers to the longest diagonal line segment in a cross-recurrence plot, which is an index of the stability of the system. Error bars represent standard errors of the means.

Comparison of Figure 1A with Figure 1B illustrates that randomly shuffled data increased the homogeneity of the cross recurrence plot, thereby reducing the percent recurrence for the data set. This supports our selection of input parameters for the analysis.

Discussion

The implication of this experiment is two-fold. First, we have established a paradigm to evaluate interpersonal constraints on posture in a rigorous and nonsubjective manner. Second, our findings provide objective evidence of the underlying cooperative nature of verbal communication. The fact that the postural dynamics of one person can significantly constrain the postural dynamics of another through verbal communication, independently of visual influence, is remarkable. It is not surprising that the control of posture must accommodate the many requirements for conversation, including gesturing, listening, and visual inspection. However, the fact that successful conversation results in the coordination of such postural compensation has implications regarding the nature of communication.

Cooperation in communication: Our current understanding and future directions. Characteristic real-world events in which language is used involve two or more people. Often, participants in such events have shared or complementary goals. Goals are shared when, for example, two individuals maneuver a large piece of furniture through a doorway in the course of a move. Goals are complementary when, for example, a cashier sells an item to a customer.

In the context of such activities, Clark (1996) suggested that language, among other tools, can serve as a coordination device—that is, as a way of fostering successful coordinations that help to achieve shared or complementary goals. So, for example, language serves as a coordination device when one mover suggests to another a way to rotate a box spring so that it will fit through a doorway. Language also serves as a coordination device if, in Clark's (1996) example, a cashier working on an inventory catches a waiting customer's eye and says "I'll be right there."

Our research suggests a very basic way that language, or perhaps especially speech, can serve as a coordination device. It can serve to foster entrainment among initially autonomous individuals who then constitute an ensemble organized to achieve shared or complementary goals.

The major finding of our research will require further study before we can understand it on a deeper level than this. We obtained clear evidence of an effect of cooperative speaking on movement entrainment. However, it is not yet at all evident how cooperative speaking can, by itself, have had the effects we observed. In particular, it is doubtful that the content of our participants' exchanges can have affected postural trajectories. Only slightly more likely is that the cooperative nature of the task as it was revealed to participants during their spoken interaction fostered an implicit search for entrainments that facilitated task execution. Although entrainment in postural sway itself may not facilitate task execution, it is necessary to keep in mind that entrainment in that domain may not be the only coupling that occurred. It was the one we chose to measure.

Perhaps the relevant coupling occurred in the speech domain itself, and entrainment of postural trajectories was mediated by that. We listed some of the vocal attunements that have been found to occur during cooperative speech. An especially likely source of entrainment in other domains may be speaking rhythms. Historically, many phoneticians suggested that speech is rhythmical (e.g., Abercrombie, 1967; Classe, 1939; Pike, 1945), although no satisfactory way of verifying the proposal has been developed (see, e.g., Fowler, 1977, for a review). English, the language of our participants, is said to be stress-timed such that stressed syllables approximately alternate with unstressed syllables, generating a speech rhythm. Couper-Kuhlen (1993) has proposed that interlocutors entrain in their speaking rhythms even to the extent that, in turn-taking, the new speaker picks up on the beat of the earlier speaker's rhythm. Perhaps postural sway entrains to speaking rhythms. This interpretation is consistent with Newtson's (1994) findings of joint-angle changes occurring with specific phase relations to conversational partner's vocal intensity.

This possibility can be tested, but not yet by measuring the rhythms of speech directly. If only speech rhythms, and not the cooperativity that they generally signal, underlie our findings, interpersonal entrainment of postural rhythms should be evident in a less social, less cooperative setting in which rhythmic speaking is enforced. For example, if pairs of speakers simultaneously read alternating stress words (e.g., *baby, tunic, dollar*) presented on a computer screen in time to a metronome beat, would entrainment of postural sway occur? Alternatively, if entrainment of speech rhythms mediates the postural attunement that we have seen, but when the entrainment arises naturally it itself is an index of cooperativity, our metronome-timed reading task should not give rise to the same magnitude of cross recurrence that we have found in the present study.

Aside from its promise to help track down how the cooperative speaking in our task might underlie entrainment of postural trajectories, there is another reason why it will be useful to consider further the settings in which speech or language may foster interpersonal coordination. We deliberately chose to look at language use in the service of a cooperative task. For our purposes, our comparison condition provided a useful baseline. Participants performed the same task and so produced similar kinds of utterances, but to a confederate; accordingly, the utterances were not mutual coordination devices for the 2 participants. However, in future research, the extent to which cooperation is the crucial variable underlying entrainment needs to be considered. That can be addressed in one way in an experiment such as our metronome experiment above, but the issue can be addressed in a different way as well. Giles (1973) found dialect convergence among interlocutors communicating in a cooperative, friendly setting, but dialect divergence in a less cooperative, more hostile setting. If our task is changed so that participants are competing to reach mutually incompatible goals, will they exhibit less postural entrainment than what we saw in the current task? They may or may not. Even a competitive task is cooperative to a degree; participants perform the task together and must do so to achieve their own goals; of course, in addition, they speak the same language to each other in a language known to both. Will the degree of shared postural activity be influenced by the degree of cooperation demanded by the task? We leave this question for future investigation.

Although we found evidence of entrainment of the hip movements of pairs of participants engaged in conversation, no significant evidence of entrainment was observed when calculations were based on displacement of the head. We ascribe this lack of effect to the disruption of head movements resulting from speaking. Were entrainment to persist at the level of head movements, vocal gesturing involved in conversational discourse could mask any subtle entrainment that may be present.

Recurrence strategies and posture. Recurrence strategies continue to prove their usefulness in quantification of postural constraints. As discussed above, the mutual constraints imposed on persons engaged in cooperative conversation are particularly challenging to quantify. One of the most compelling aspects of our design is the lack of constraints imposed on both the participants and the data. Participants' movements were not restricted beyond the necessity of the motion-capture equipment. They were allowed to gesture freely and adjust their posture as desired throughout the course of the experiment. This likely provided very naturalistic evolution of the time series. Consequently, this design also provided complex time series to be evaluated. As discussed above, traditional time series analyses, such as Fourier spectral analysis, cross correlation, and coherence, are not appropriate for a fine-grain evaluation of postural data. In addition to any influence of drift in the mean state of the system, these linear methods are not sensitive to distortions of projection from multidimensional control spaces to single dimensional (time series) measurement (i.e., dynamical properties of a system that are only observable in multidimensional space may be masked when using linear methods of analysis). Furthermore, to capture any mutual constraints that complex physiological systems (e.g., postural systems) impose on one another, a very sensitive measure is likely to be required. Using a recurrence strategy simplified these major challenges by requiring no assumptions about the structure, stationarity, or size of the time series under scrutiny. Furthermore, by avoiding data transformations such as detrending, the data were allowed to evolve naturally. Cross recurrence provided measures of both the time-dependent (MAXLINE—convergence of trajectories over time) and time-independent (recurrence—shared regions of phase space) aspects without the contamination that may occur using linear methods.

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