Chapter 14
Interpersonal Couplings in Human Interactions

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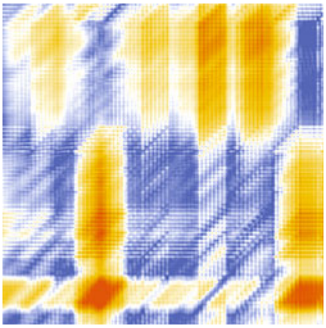

Abstract As inherently social beings people routinely interact with others. Interpersonal activities such as dancing, conversation, or team sports require people to coordinate at several different levels, ranging from the coordination of physical movements and physiological states of the body to the coordination of mental states and cognitive or linguistic activity. One of the challenges confronted by researchers in this interdisciplinary field has been to find ways to objectively quantify interpersonal coupling on the basis of brief, noisy, nonstationary, and complex time series of human behavioral sequences. Given their robustness to these challenges, recurrence-based strategies have played a very important role in the development of this field of research. This chapter provides a review of current behavioral, cognitive, and physiological research that has used recurrence methods to quantify interpersonal coupling.

14.1 Introduction

As inherently social beings people routinely interact with others, such as when navigating busy sidewalks, engaging in a friendly debate with a colleague, playing a game of pick-up basketball, or helping a friend move a heavy piece of furniture. Such interpersonal activities require people to coordinate at several different levels,

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ranging from the coordination of physical movements and physiological states of the body to the coordination of mental states and cognitive or linguistic activity. Behavioral coordination is ubiquitous and is highly likely to occur—even when people do not intend for it to occur—whenever there is present some medium of interpersonal coupling that serves to link people together, whether that medium is a physical connection between people, visual information about another person's movements, or linguistic information that is exchanged during a conversation.

Interpersonal or social coordination is very important in everyday life as well as in many practical settings such as surgical teams or military operations. There are potentially adverse consequences when breakdowns in interpersonal coupling occur. For example, if communication links among members of a firefighting team are interrupted and the firefighters' behaviors become uncoordinated, the results can be potentially very dangerous and even life-threatening. Social coordination and interpersonal coupling may also be compromised as a result of neurological deficits such as autism spectrum disorder. For these and many other reasons, interpersonal coupling is a rapidly growing field of interdisciplinary research, spanning experimental psychology, cognitive science, ergonomics, neuroscience, movement science, and sport science.

Recurrence methods (introduced conceptually by Eckmann and Kamphorst [1]) have played a very important role in the development of this field of research. One of the challenges confronted by researchers has been to find a means of objectively quantifying interpersonal coupling. Advances in motion-capture and eye-tracking technology have made it relatively easy to collect highly precise data and have rendered obsolete time-consuming and subjective methods such as qualitative hand-coding of video sequences of interpersonal interactions. But the advent of these technologies and the wealth of data they permitted introduced the new challenge of identifying metrics to quantify patterns of coordination in the data. Time series of human behavioral sequences, such as movements of the limbs during gesturing or movements of the eyes, can be noisy, nonstationary, and complex, and often the time series—particularly during real-world activity—are relatively brief. Recurrence-based methods are ideally suited to meet those challenges [2–4], and thus recurrence-based methods have advantages over many other methods. For example, simple cross-correlation in the time domain, or its equivalent in the frequency domain, spectral coherence, are both linear measures and both assume stationarity of the time series being analyzed. If the assumptions of linear interactions and stationarity are violated, the methods may give incomplete, or sometimes even misleading, results.

Interpersonal coupling has been observed and studied in a wide variety of behavioral domains. These include the coupling of movements of limbs, of overall body posture, of whole-body positions of athletes, of musical performance, of eye movements, of speech, of cognitive states such as attention, and of linguistic information. Recurrence quantification analysis (RQA; [2–4]), cross-recurrence quantification analysis (CRQA; e.g., [5–7]), and novel variations of these methods have all been utilized to study interpersonal coupling. Many important insights into interpersonal coupling have been gained from this research, yet many questions remain unanswered and many new questions have emerged. This chapter provides a review of current behavioral, cognitive, and physiological research that has used recurrence methods to quantify interpersonal coupling.

14.2 Interpersonal Rhythmic Motor Coordination

One of the most basic forms of interpersonal coupling occurs when two or more people synchronize or coordinate rhythmic movements of their bodies with each other. The coordination could be of limb segments or limbs, the head, the torso, the whole body, or even the eyes. This coordination can be intentional and is often part and parcel of the overarching behavioral goal, such as when dancing. Interpersonal rhythmic movement coordination also sometimes occurs spontaneously even when it is not intended or related in an obvious way to the behavioral goal.

Several studies have applied CRQA to a variant of a simple rhythmic coordination task that has served as a workhorse paradigm for understanding interpersonal coupling—coordinating the rhythmic movements of limb segments [8] or, more typically, hand-held pendulums (cf. [9]). As illustrated in Fig. 14.1, in the basic form of the wrist-pendulum coordination task [10] participants sit in a chair that has an armrest to support one hand and forearm. In the supported hand each participant holds a pendular object that they swing in the sagittal plane while, typically, watching the other participant swing the pendulum. The goal is to synchronize movements of the pendulum with the other person at the same frequency and at a specified phase relation—typically either 0° relative phase (pendulums are at the same points in their respective movement cycles, so that the movements are synchronous and in the same direction) or 180° relative phase (pendulums are at opposite points in their movement cycle, moving at the same frequency but in opposite directions), which are the two basic coordination patterns that are intrinsically stable (other phase relations can be learned but are unstable and difficult to produce).

The dynamics of this interpersonal rhythmic coordination task have been carefully studied, largely using measures of the average relative phase established by the interacting subjects (i.e., which coordination pattern they established) and the standard deviation (variability) of the coordination pattern, and also by identifying sudden changes (i.e., phase transitions) in the coordination pattern (see review by [11]). A very successful model of this type of coordination has also been identified, building on work in *intra*personal rhythmic coordination and the model of Haken et al. [12]. Richardson et al. [15] grounded CRQA in terms of constructs from this modeling framework, finding that *%cross-recurrence* maps onto the level of underlying noise in the coordination and that *cross-maxline* maps onto the strength of the attractors that govern stable states of interlimb coordination (see also [16]).

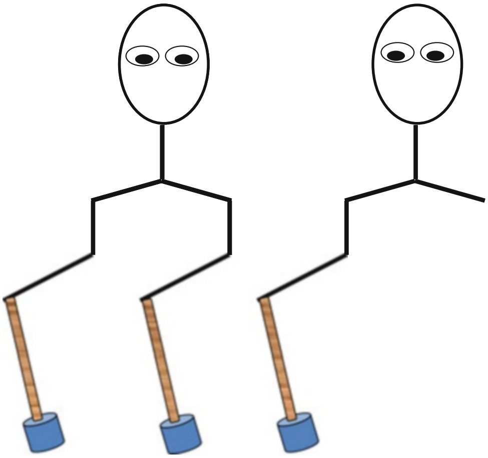

Fig. 14.1 Example of a common method used to study interpersonal interlimb coordination. Two participants swing hand-held pendula while looking at one another

Richardson et al. [17] used CRQA to compare interpersonal rhythmic coordination to *intra*personal interlimb rhythmic coordination (i.e., one person oscillates a pendulum in each hand—bimanual coordination). They found that attractor strength as indexed by *cross-maxline* was lower for interpersonal coordination than for intrapersonal coordination. *Cross-maxline* is sensitive to changes in attractor strength because *cross-maxline* refers to the duration of the longest movement sequences that the two times series being compared share with one another. Thus, when the attractor for a particular phase relation is weaker the system is unable to maintain the relation for as long as a stronger attractor. Interpersonal coupling of rhythmic movements thus differs from intrapersonal coupling in that the strength of the coupling is weaker, consistent with findings using regression-based techniques to estimate the coupling coefficients [18] and using the uncontrolled manifold approach which quantifies synergistic coupling by identifying how motor variability is structured so as to preserve the task goal (such variability can be left "uncontrolled") or not (this variability must be restricted to achieve the task goal) [19]. Richardson et al. also found that noise magnitude, as indexed by *%cross-recurrence*, was not significantly different across interpersonal and intrapersonal coordination conditions. Increasing the magnitude of noise in a system reflects an increase in random perturbations to the dynamical state of the system. Thus, the number of shared configurations (indexed by *%cross-recurrence*) will decrease proportionally with the magnitude of noise in the system (see [15, 16], for examples of independent sensitivity of cross recurrence measures to attractor strength and noise magnitude). The specific contribution of recurrence methods in the study of this type of intentional interpersonal coordination task was thus to identify the reduced strength of coupling of interpersonal coordination compared to intrapersonal coordination.

14.3 Coordination and Communication

Richardson et al. [20] studied variations on the basic interpersonal rhythmic coordination task. Coordination was not an explicit goal for the subjects—they were not instructed to adopt any particular interpersonal movement pattern. Instead, subjects were instructed to perform a simple communication task of identifying differences between two cartoon faces that were attached to the pendulums in one condition or on a stand next to the subjects in another. The participants could not see their partner's pictures—only their own—and so they had to find the differences by discussing what they saw with each. The faces on the pendulum was employed in the "visual" and "visual–verbal" conditions—subjects viewed each others' pendulum motion in each of these but talked to each other to identify differences only in the latter—while faces on the stand constituted a "verbal" condition—subjects were coupled by verbal interaction but did not watch their partner's pendulum movements. The instruction to oscillate the pendulums was described to subjects as a distractor task that served to make the puzzle task more challenging. Richardson et al. found that viewing the task partner's pendulum promoted unintentional coordination—*%cross-recurrence* and *cross-maxline* were greatest in the visual condition—but verbal coupling was insufficient to result in substantial unintentional coordination on its own nor did it enhance coordination beyond visual coupling (both measures were nominally greater in the visual than in the visual–verbal condition, in fact).

The task and the verbal condition in Richardson et al. [20] was motivated in part by an earlier study on interpersonal coupling by Shockley et al. [21]. In one of the first applications of CRQA to interpersonal coupling, Shockley et al. studied coordination of *postural sway* between two people who were engaged in a similar find-the-differences task (see Fig. 14.2, left). Postural sway is the irregular, low-amplitude, continuous, and complex fluctuation of the body's center of mass that always occurs when a person stands. Based on a large body of literature demonstrating various forms of behavioral synchrony between conversants (e.g., [22–24]), Shockley et al. [21] hypothesized that the postural sway of conversants would exhibit greater cross-recurrence and cross-maxline—i.e., greater and more stable coupling—than the postural sway of co-present but non-interacting subjects. They tracked the waist position of the participants over time as a global measure of postural sway while the participants completed the find-the-differences task. Because the waist positions embody the activity of a large number of variables (e.g., limb configurations, cardio-pulmonary dynamics, speech), the time series of waist motion was unfolded into a multidimensional space that was sufficient to capture the unfolding dynamics of movement (i.e., a reconstructed phase space; [25]) and thus each data point corresponded to a position in the multidimensional space, henceforth referred to as a (waist) configuration. Their findings confirmed this hypothesis—*%cross-recurrence* and *cross-maxline* of the waist configurations were greater for interacting than merely co-present participants (Fig. 14.2, right). In contrast to the results of Richardson et al. [20], vision of the task partner was not necessary for

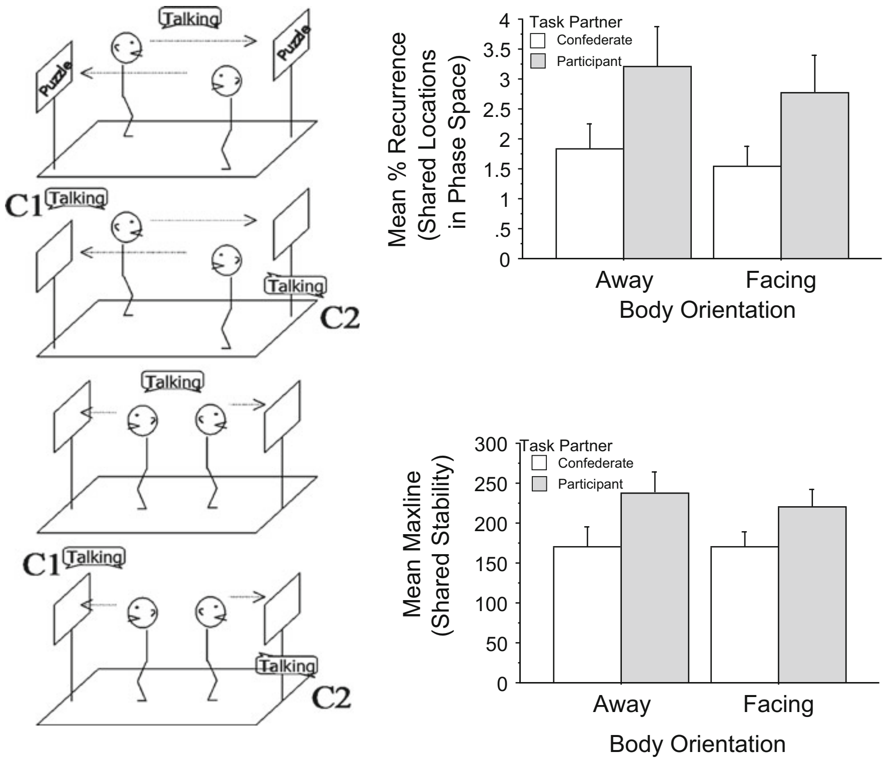

Fig. 14.2 (*Left*) Method of Shockley et al. [21]. (*Right*) Shared postural activity (*%cross_recurrence*) and coordination stability (*cross_maxline*) for the different experimental conditions. (From Shockley et al. [21], p. 329 [panel a], 330 [panel c]). Copyright 2003 by the American Psychological Association. Adapted with permission)

and did not enhance interpersonal coupling—*%cross-recurrence* and *cross-maxline* were not different between conditions in which task partners faced each other or faced away from each other while conversing to find the differences in the pictures.

Building on the understanding that conversants tend to coordinate their speech while engaging in cooperative conversation (e.g., [26–28]) and that the biomechanics of speaking influence postural sway dynamics [29–31], Shockley et al. [32] investigated whether the interpersonal postural coordination observed during cooperative conversation may simply be an artifact of how postural sway is affected similarly across members of a pair when their speech becomes coordinated. They had participants stand while uttering bisyllabic words that were presented on a computer monitor. The words were either presented simultaneously to each participant (in-phase) or in an alternating fashion (anti-phase) and the words were either the same for each participant (same word, same syllable; SS), different words with an emphasis on the same syllable (first or second) (DS), or different words with an emphasis on different syllables (i.e., one person had a word with an emphasis on the first syllable, e.g., *do*nut, while their task partner had a word with an emphasis on the second syllable, e.g., ab*out*, or vice versa) (DD). They found no influence of the phase manipulation. They did find, however, that there were greater shared postural configurations (*%cross-recurrence*) and greater coordination stability (*cross-maxline*) between members of a pair with increasing word similarity (i.e., SS > SD > DD). They also found, however, that by shuffling the pair arrangement such that postural sway of one participant is compared to a participant that completed the same task except with a different partner that there was no such increase in postural coordination with increases in word similarity. This suggested that although articulatory dynamics did influence the postural coordination patterns during conversation, there was still a social influence that impacted the interpersonal postural coordination between members of a pair (i.e., their partner had to be co-present for the enhanced coordination to occur).

Stoffregen and colleagues have further explored the spontaneous coordination that occurs during conversation that was observed by Shockley et al. [21]. In one study, Stoffregen et al. [33] investigated how the interpersonal postural coordination that occurs during conversation was influenced by the stability of the surface on which the interacting participants stood. They had pairs of participants either stand on the floor or stand on a mattress while they completed the task. They found that the enhanced coordination between members of a participant pair only occurred when they were talking to each other while standing on the floor, but not when standing on an unstable surface of support and not when talking to an experimenter. This suggested that the enhanced coordination when participant are talking to each other observed by Shockley et al. [21] is a subtle phenomenon, specifically that the constraints on postural control imposed by conversation are weaker than those imposed by the surface of support. This, again, hallmarks the sensitivity of CRQ measures to the degree of interpersonal coordination.

In a different study, Stoffregen et al. [34] investigated visual influences on interpersonal postural coordination. Shockley et al. [21] did not find an influence of whether the participant could see his/her task partner. However, they did not manipulate visual aspects of the puzzle that was inspected by participants. Given that previous studies have demonstrated an influence of visual constraints on postural sway dynamics of an individual (see [35], for a review), Stoffregen et al. [34] manipulated the size and distance of the visual targets used by participants in the find-the-differences task. In the first experiment they manipulated task partner (participant or experimenter; cf. [21]) and target distance (near vs. far; e.g., [36, 37]). They found more shared head configurations (greater *%cross-recurrence*) when the targets were near as compared to far. They did not, however, find enhanced coordination between participants when they were talking to each other. In their second experiment they manipulated target size (small vs. large) and task partner. In this experiment they did find an influence of task partner, replicating Shockley et al. [21]. However, they found that the greater shared head configurations (as opposed to the shared waist configurations observed by [21]) when participants were talking to each other compared to when participants were talking to an experimenter. They also found an influence of target size for both the head and the waist. Specifically, there were greater shared head and waist configurations when participants were looking at larger targets than at smaller targets. They also found greater patterning of the coordination for head and waist (*%cross-determinism*) for larger targets than smaller targets. In a third experiment they manipulated the similarity in visual conditions between members of pair. In their first two experiments, although size and distance were manipulated, the conditions were always the same for the pair in a given trial. In their third experiment Stoffregen et al. crossed own target size (small vs. large) with partner target size (matched vs. mismatched). They found greater shared head configurations when participants' own target size was large. They also found that when the partner's target size was matched there were greater shared head configurations when the partner's target size was matched to one's own target size (i.e., when both targets were either small or large) compared to when the partner's target size was mismatched (i.e., when one target was large and the other was small or vice versa). They also found that the patterning of shared head and waist configurations were influenced by these manipulations. There was greater patterning in the shared head and waist configurations when viewing large targets as opposed to small targets. This study was the first demonstration of visual constraints on the postural coordination that occurs between conversants.

Shockley et al. [38] speculated that the coordination involved in conversation may reflect a functional organization that supports the joint goals of the individuals interacting. That is, the movement coordination observed during conversation may embody the coordinated cognition required to effectively communicate. While it is well-established that cognitive performance can interfere with concurrent motor performance, and vice versa (for a review see [39]), more recent investigations have revealed that in many cases action may not so much interfere with cognition, but instead may embody cognition. For example, the inhibition of motor activity [40] or an imposed inconsistency between motor activity and cognitive responses [41–44] can disrupt cognitive performance. In other circumstances, mental operations can be facilitated by action (e.g., [45]) and action-oriented tasks [46]. This interpretation is underscored by recent evidence that the time course of a cognitive process is reflected in the trajectory of action. For example, when moving to click 'yes' or 'no', mouse trajectories will travel directly towards 'yes' if the answer is clear (should you brush your teeth everyday?) but deviate towards no when the answer is ambiguous (is murder sometimes justified?), and the degree of motor deviation reflects the degree of cognitive certainty [47]. The discovery of the mirror neuron system (neurons that fire when observing another's actions; see reviews by [48, 49]) has underscored the growing recognition of the integral role of action in cognition, because it suggests a common neural mechanism for various forms of social perception, action, and cognition (see, e.g., [50–53]). If the movement coordination observed during communication indeed reflects the cognitive coordination required to effectively communicate, it stands to reason that constraining coordination may constrain communication. This was the focus of a recent study by [54].

Tolston et al. [54] manipulated movement coordination by restricting the movement of one or both members of a participant pair that completed the Shockley et al. [21] find-the-differences task while standing. Each pair of participants was asked to look at a pair of pictures that were very to one another but had subtle differences. They could not see one another's pictures and so had to find the differences by discussing the pictures with each other. Either both participants were free to move (F–F), Person 1 was free to move while the hand movements of Person 2 were restrained by having them place their hands in the pockets of a waist apron (F–R), or both participants' hand movement were restricted (R–R). They hypothesized the weakest coordination in the asymmetrically restrained (F–R) condition given that participants were, by design, least able to coordinate their movements. They hypothesized that cognitive performance would increase with greater freedom to move. They found movement coordination of the head and waist to be reliably lower in the asymmetric (F–R) restraint manipulation as reflected in measures including *%cross_recurrence*, *%cross_determinism*, and *cross_maxline*. They did not find a significant influence on task performance as a direct function of the manipulations. They did, however, find that overall movement of the hands of Person 1 (the one with the most freedom to move overall) significantly correlated with task performance suggesting a relation between movement and communication. In spite of the fact that movement restraint did not influence task performance in the expected fashion, CRQ was, nonetheless, sensitive to the manipulations of movement coordination at both the head and the waist.

14.4 Interpersonal Coupling During Performance of Joint Precision Motor Tasks

Ramenzoni et al. [55] studied postural and manual interpersonal coupling during performance of a simple, precision motor task. In their task one subject held a target circle and the other subject extended a pointer so as to hold it inside the target circle without touching its sides (see Fig. 14.3). The size of the target circle was varied to manipulate task difficulty. Ramenzoni et al. recorded subjects' hand movements and torso motion (i.e., postural sway) with motion-capture sensors. *%cross-recurrence* systematically increased for both hand and torso movements as task difficulty increased. *Cross-maxline* was greater in more difficult task conditions for hand but not torso movements.

Ramenzoni et al. [56] used a slightly different approach to analyze performance of a similar interpersonal precision task. They measured 3-D displacements of the torso, upper arm, forearm, and hand of each participant. Rather than analyzing coordination between body segments (e.g., between subjects' hands), they submitted each subject's 12-dimensional data set to principal component analysis (PCA). PCA is a dimensional reduction technique that identifies covariation in complex data sets and effectively "collapses" redundant data along abstract dimensions that represent the directions along which most variation in the dataset occurs (i.e., the PCs). The first PC is that which accounts for most variance in the data, and subsequent PCs account for successively less and less variance. The original time series can then

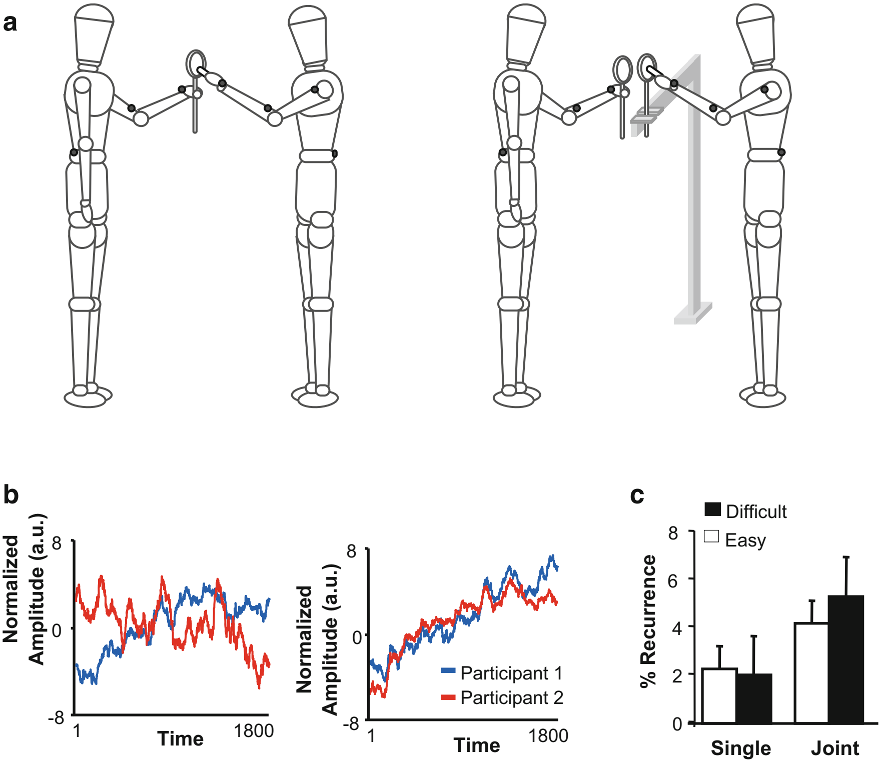

Fig. 14.3 (**a**) Depiction of the individual—(*left*) and interpersonal—(*right*) task conditions from Ramenzoni et al. [56]. (**b**) Time series of the data projected onto the intrapersonal principle components from the individual (*left*) and interpersonal-task (*right*) conditions. The striking coordination in the interpersonal-task condition was confirmed by cross-recurrence quantification analysis (**c**), which revealed a greater degree and higher stability of coupling in that condition. From Riley et al. [57]. Copyright 2011 by *Frontiers in Psychology*

be projected onto the axes of the principal components, resulting in time series that are abstract yet represent the overall or global pattern of movement—a data-driven “order parameter” [58] of sorts (see Fig. 14.3). Ramenzoni et al. then applied CRQA to analyze coupling between the time series of each subject’s first PC. Both *%cross-recurrence* (see Fig. 14.3) and *cross-maxline* were greater when subjects performed the interactive experimental task than a control task that did not require them to interact. Moreover, the CRQA measures were greater in the more difficult (smaller target) than the less difficult condition, but only during the experimental task. Interpersonal coupling occurred during performance of this task at the level of overall body movements, a level of description slightly more abstract than the movement of any individual body segment (see also, [57]).

14.5 Verbal Coordination

While there are many instances summarized above where speech and communication influence interpersonal motor coordination, communication itself has also become an object of inquiry using recurrence methods. Orsucci et al. [59] made an initial foray into quantifying conversational interaction by analyzing the transcriptions of conversations between two friends and between a therapist and client in order to illustrate the different dynamics of the these two different types of verbal interaction. The transcribed text can be coded, letter by letter into numbers (e.g., $a = 1$, $b = 2$, etc.) yielding a numeric time series that represents the speech vector of each person involved in the conversation. Unlike the movement time series described above, however, the magnitude of the numbers in the time series have no significance. In other words, a value of 2 is not twice the value of 1 as it would be in ratio data. Rather, the data set is strictly nominal. When CRQA is used on this type of data it is referred to as *categorical* CRQA. As described in previous chapters of this book, the primary difference between continuous CRQA and categorical CRQA is that continuous CRQA typically involves time-delayed embedding of the two continuous time series into a reconstructed phase space and using a radius of inclusion that is greater than zero (i.e., the value in question must match the value to which it is compared within some radius in reconstructed phase space). Categorical CRQA, on the other hand, generally does not involve embedding, typically involves *data* series rather than *time* series (i.e., although the data are sequential, the spacing between observations is not necessarily equivalent across observations, and uses a radius of zero (i.e., the value in question must exactly match the value to which it is compared)). Orsucci et al. elected to use paired three-letter patterns (i.e., when both time series exhibited the same three letter sequence) as evidence of a recurring value between the two times series. They found that friends' conversational interaction exhibited greater synchrony between participants as indicated by greater shared sequences of utterances (i.e., greater *%cross_determinism*) as compared to the clinical interaction. This suggests that recurrence methods are sufficiently sensitive to pick up variations in the form of conversation.

Dale and Spivey [60] took recurrence-based investigations into speech coordination a step further by studying the similarity in word-class n-gram (bigram, trigram, quadrigram) sequences from three CHILDES corpora [61]. They performed categorical cross-recurrence of children and their caregivers. Dale and Spivey [60] explored both synchronous verbal coordination as well as leader–follower relationships. Synchronous coordination was evaluated by quantifying recurrence along the central diagonal region of the cross-recurrence plot (CRP), which corresponds to temporal coincidence between the two data series. Leader–follower relationships can be quantified by evaluating the upper and lower triangular regions separately. If time series A serves as the abscissa of a CRP and time series B serves as the ordinate, then recurrence in the upper triangular region refers to values in time series B that occurred in time series A at an earlier time (i.e., X led Y) and vice versa for the lower triangular regions (i.e., Y led X; Fig. 14.4, bottom). This is because, by definition, any index above the diagonal corresponds to an index of Y that is greater than the index of X (Fig. 14.4, top). Dale and Spivey demonstrated that there was indeed coordination between syntactic sequences of child and caregiver that was greater than chance (i.e., as compared to the coordination observed between pairs of randomly shuffled time series) suggesting that CRQA is a useful tool for capturing this type of verbal coordination. They also demonstrated that the leader–follower relationship between child and caregiver seemed to change over the course of development and that different children exhibit different lead–follower relations with their caregivers. This finding suggests that CRQA may be useful in differentiating different conversational interaction styles across interlocutors.

Warlaumont et al. [62] further explored verbal coordination between children and adults in a study investigating both autistic and typical control groups. They coded their data differently than in the previously described studies. They simply determined at a given time segment whether the child or adult was speaking. If one person was speaking that person received a 1 for the segment and the other received a null value. In a similar fashion to Richardson et al. [13], they found that using a 30-s window on either side of the central diagonal (i.e., coincidence in time) of the cross recurrence plot that autistic children tended to follow adults more and lead adults less than the control group.

Angus et al. ([63]; see also [64]) also investigated the similarity between utterances of dyads. However, rather than analyzing textual data (i.e., syntactic strings) as Dale and Spivey [60] did, they instead analyzed the conceptual similarity of the text samples in question. They used Salton's [65] strategy of building a semantic similarity model of the transcribed discourse under scrutiny based on the probability of the co-occurrence of terms in the text. Thus, the similarity of any two utterances can be assigned a number. The conceptual similarity of every utterance to every other utterance is determined yielding a matrix of similarity values. The strategy for quantifying the similarity in the discourse is a bit different than that used by Dale and Spivey [60]. Angus et al. created a single trajectory of utterances that included both interlocutors (i.e., a single vector of semantic similarity values). Because CRQA involves comparing two vectors, a semantic vector was the submitted to auto-recurrence quantification analysis (i.e., RQA) rather than CRQA. However, recurrence in this case reflects conceptual similarity between conversants rather than within a single speaker's utterance (see Fig. 14.6).

Angus et al. [66] used the same basic strategy. However, the investigators demonstrated the utility of their approach for quantifying multi-participant recurrence (i.e., more than two interacting individuals rather than the more conventional dyadic comparison) in the context of linguistic interaction. In this study they introduced new metrics for quantifying the recurrence in communication such as immediate topic repetition, topic consistency, and topic novelty based on what they referred to as utterance primitives including time scale (near, middle, and far from present utterance), direction (utterances forward or backward in time from the present utterance), and type of utterance (self or other). These metrics may be more meaningful to the study of conceptual similarity in the context of communication

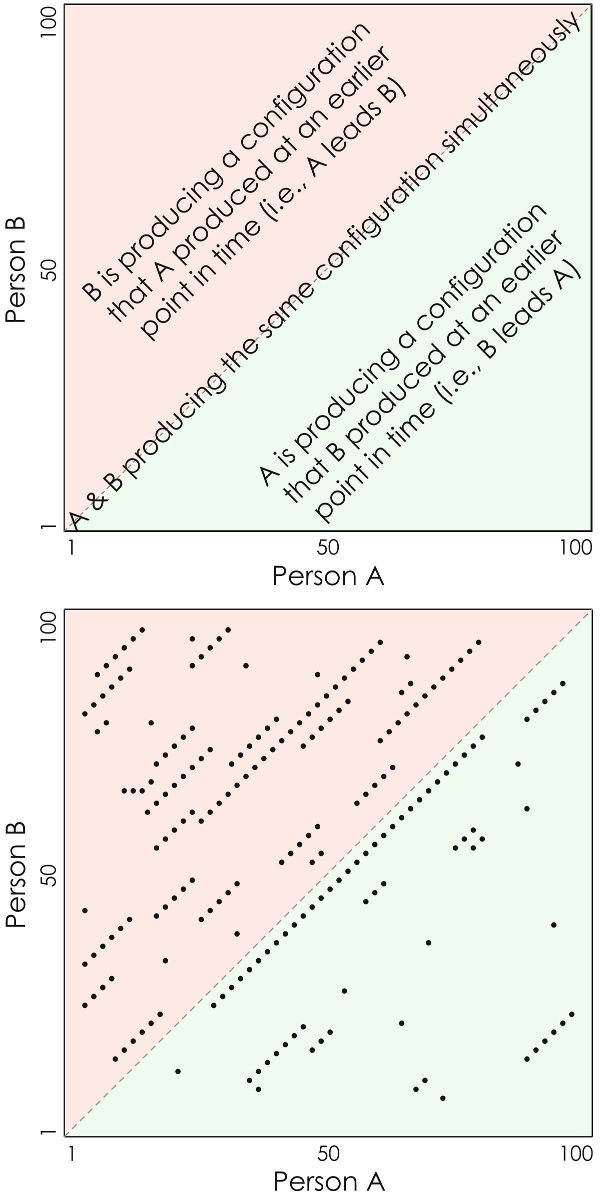

Fig. 14.4 (*Top*) Illustration of how upper and lower triangular regions of a cross recurrence plot can capture leader–follower relationships in interpersonal interactions. By aligning any index on the abscissa with any index on the ordinate that is above the central diagonal (upper [*red*] triangular region) corresponds to an earlier point in time for Person A than Person B. (*Bottom*) Illustration of greater recurrence in upper triangular region than in lower triangular region indicating that, in general, B is following A

than the more conventional metrics used in recurrence-based analyses (e.g., *%cross-recurrence*, *%cross-determinism*, *cross-maxline*).

Gorman et al. [67] extended the analysis of discourse to three-member teams who were controlling an uninhabited air vehicle (UAV). They used categorical CRQA to evaluate communication data (i.e., the data were coded in terms of which team member was speaking) under conditions where the team either changed composition or stayed the same following a retention interval. They found that after three missions the *%cross-determinism* of the mixed teams' communication interaction sequences did not change across three successive missions. The intact teams, however, exhibited greater *%cross-determinism* in their communication interaction sequences by the third mission. The found a similar pattern of results for pattern information as measured by mutual information. Intact teams exhibited greater pattern information by the third mission, whereas mixed teams did not show such an increase (and even showed a decrease in the second mission). They interpreted this enhanced patterning of interactions of intact teams as potentially reflecting a rigidity that may not be desirable given that control of UAVs may require adaptability and flexibility given the unpredictable dynamics of the task environment [68]. They argued that for a system to be flexible, it requires a mix of determinism and randomness that unchanging teams may move away from over time.

14.6 Interpersonal Coupling During Sport Performance

In many sports coupling of whole-body activity is a major component of the game. In American football, defensive backs must closely cover receivers to prevent them from catching a pass, which requires coupling to the receiver's movement across the field of play. In basketball, a defender must similarly couple to the movements of the player with the ball. Recurrence strategies have recently been applied to whole-body interpersonal coupling in sports environments such as these. Esteves and Araújo [69] found that CRQA can distinguish successful from unsuccessful performance (i.e., scoring a basket vs. not) during one-on-one scenarios in basketball. *%cross-recurrence* between the positions of the attacker and the defender is lower but *cross-maxline* is greater during successful attacker actions compared to unsuccessful ones.

Carvalho et al. [70] applied RQA to quantify coupling of opponents' movements during rallies in professional tennis matches. They focused on comparing opponent coupling as captured by time series of relative positional advantage. Positional advantage is determined by each player's position relative to the central line and to the net. Relative positional advantage is the difference between this quantity defined for each player. A player is considered to have greater positional advantage the closer the player is to the central line or to the net, relative to an opponent. The authors examined positional advantage before versus after a "break shot" (a critical shot that determined the outcome of a point). Prior to the break shot, *%recurrence* was lower and *maxline* was higher than after the break shot. These results are similar to the basketball findings presented above, suggesting that certain patterns of interpersonal coupling (a reduced overall likelihood of opponents sharing the same position, but at the same time exhibiting more stable patterns of coordination) characterize decisive moments related to scoring.

14.7 Interpersonal Coupling During Musical Performance

Music is a rhythmic means of communicating and conveying emotion, and as such might provide a natural medium for coupling rhythmic activities between individuals. Studies have used recurrence methods to describe coordination between time series of the music itself and movements of the musicians [71, 72] or have investigated the use of music sonification as a coupling medium during active listening to help people synchronize their movements when synchrony is an explicit task goal [73, 74]. Other studies described below have used recurrence methods to identify interpersonal coupling between musicians during musical performance, but in general very little work has been done in this area.

Gill et al. [75] used CRQA to quantify coordination of postural sway between participants who performed musical improvisations with shakers (percussion instruments consisting of tubes with objects inside them that make noise when they collide with each other or the tubular container). Similar to the findings of Shockley et al. [21], interpersonal coupling during this musical production task did not require that participants could see each other. This confirms the above intuition that music might serve as a medium for coupling musicians' actions.

Varni et al. [76] used a recurrence-based phase synchrony measure [77] to quantify interpersonal coupling of the head movements of two violinists performing a musical piece live with instructions given to one of the performers to accentuate different emotional states (anger, sadness, joy, or serenity) in the performance on a given trial (the same music was always used). The performances also occurred under conditions of visual plus musical (auditory) coupling or musical coupling alone. They were interested in the phase synchronization of the head movement involved in the two performances—the degree to which the time scales of the head movement of each the two musicians were related to one another. Varni et al. evaluated the probability distributions of distances between recurrence points for each of the head movements being compared to one another. Because the distances between recurrent points reflects the time scale of the system in question (e.g., the system revisits the same states every so often), then if another system conforms to a similar time scale (even if the particular states [e.g., head configurations] of one time series are entirely different than the states of the time series to which it is compared). Phase synchronization values were, overall, rather low and did not seem to depend on emotion or feedback conditions. However, Camurri et al. [78] reported that inducing positive emotions in one musician tended to increase head movement synchrony among groups of violinists compared to a no-emotional-induction control condition.

14.8 Interpersonal Cognitive Coordination

Many of the instances of movement coordination above imply some degree of cognitive coordination and it has even been suggested that the coordination of eye and body movements may reflect the cognitive coordination required to effectively communicate [38]. However, cognitive coordination, in the sense of joint attention, has been explicitly studied in recent years. In a series of studies, Richardson et al. quantified joint attention by measuring the eye movements of two people discussing a common visual scene. This is particularly interesting from a cognitive standpoint because they demonstrated that gaze coordination reflects the shared knowledge of interacting dyads, their beliefs about each other, and the success of their communication. For example, Richardson and Dale [79] asked participants to talk about a television show while they tracked the gaze of the speaker who was looking at an array of characters' faces from the show in question. They then played back the recorded speech for a listener and tracked the listeners' eye movements toward the array of faces in the same fashion. They then evaluated the comprehension of the listener. They used CRQA to quantify the degree to which speaker and listener gaze coordinates overlapped at successive time lags (see Fig. 14.5). They found that two seconds after a speaker looked at a particular image, the listener was more likely than chance to be looking at that same image. They also found that the *%cross-recurrence* between the gaze positions of speaker–listener pairs was correlated with the listeners' comprehension of what the speakers said. Further, when the pictures at which a speaker was looking were flashed before the listener, this resulted in the listeners' gaze trajectories to look more similar to the speakers' and improved the listeners' comprehension, suggesting that gaze coordination is causally related to comprehension. In a different study, the gaze was tracked for pairs of conversants engaged in live dialogue while they discussed TV shows and paintings [13]. Conversants' eye movements were coupled as they looked at a shared display, peaking at a lag of 0 ms—the conversants were most likely to be looking at the same thing at the same point in time. They also found that when provided with the same background information about what they were looking at their gaze was more coupled. In other words, they demonstrated that shared knowledge enhanced joint attention. These studies demonstrate how CRQ of joint attention can be used to index shared knowledge in everyday verbal interchanges (see also [13]).

Jermann and Nüssli [80] investigated joint attention in a similar fashion to Richardson and Dale's studies, by having pairs of engineering students complete program understanding tasks while their gaze was recorded. They had pairs of participants jointly study code for a simple arithmetic game and their task was to explain the rules of the game based on their understanding of the code that was studied. The authors rated pairs on the interaction quality (e.g., collaboration flow, efforts to sustain mutual understanding, degree of division of labor) as well as level of understanding of the code following their interaction. They manipulated whether selection sharing (i.e., where one programmer can highlight text for the other programmer with which she is working) permitted (selection sharing and dual-selection sharing [i.e., where both programmers can select text that the other can see]) compared to an individual (i.e., no-sharing) condition. They found that within 200 ms of one programmer selecting text, the other programmer was more likely to look at the text selection during that time than if the pair was in the no-sharing condition. There was also an increase in speech when a selection was made.

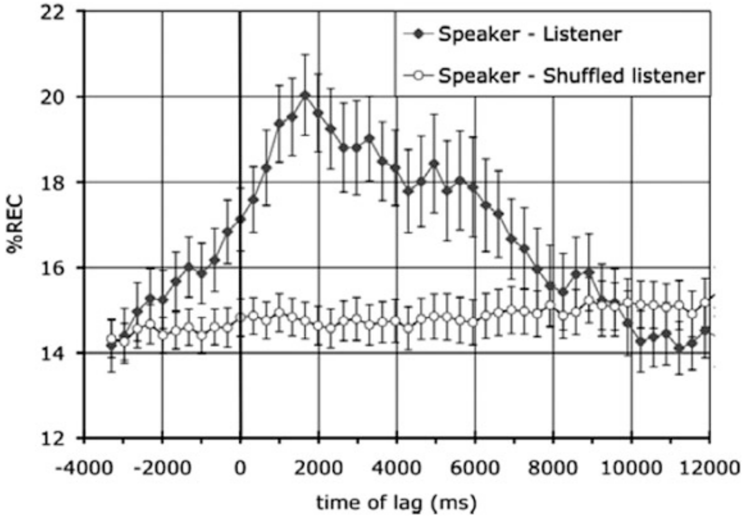

Fig. 14.5 *%cross_recurrence* of gaze coordinates as a function of the lag between speakers' and listeners' gaze. From Richardson and Dale [79]. Copyright 2005 by the Cognitive Science Society, Inc. Adapted with permission

Interestingly, this increase in speech was greater for the individual condition than for the sharing conditions. They found that both selection and speech increased gaze *%cross-recurrence* and that these also had an additive effect such that when selection was accompanied by speech this further increased *%cross-recurrence* of gaze. They also found that when the interaction quality was higher, gaze *%cross-recurrence* was also higher, but gaze *%cross-recurrence* did not vary with the level of understanding of the code. The relationship between gaze coordination and interaction quality echoes the findings of Richardson and Dale [79] who found that when interlocutors shared gaze more their comprehension of what the other person said increased (see Fig. 14.6).

14.9 Interpersonal Physiological Coordination

To our knowledge only one study to date has explored interpersonal physiological coordination using recurrence-based methods. Konvalinka et al. [81] investigated how synchronized the arousal was between performers of a fire-walking ritual and the related spectators of the ritual. Their study was motivated by previous studies that have shown synchronized behavior to enhance cooperation within groups [82, 83] and lead to increased rapport between group members [84, 85]. Konvalinka et al. speculated that enhanced group cohesion may emerge from the shared emotion that accompanies rituals rather than just from synchronized movements that may occur

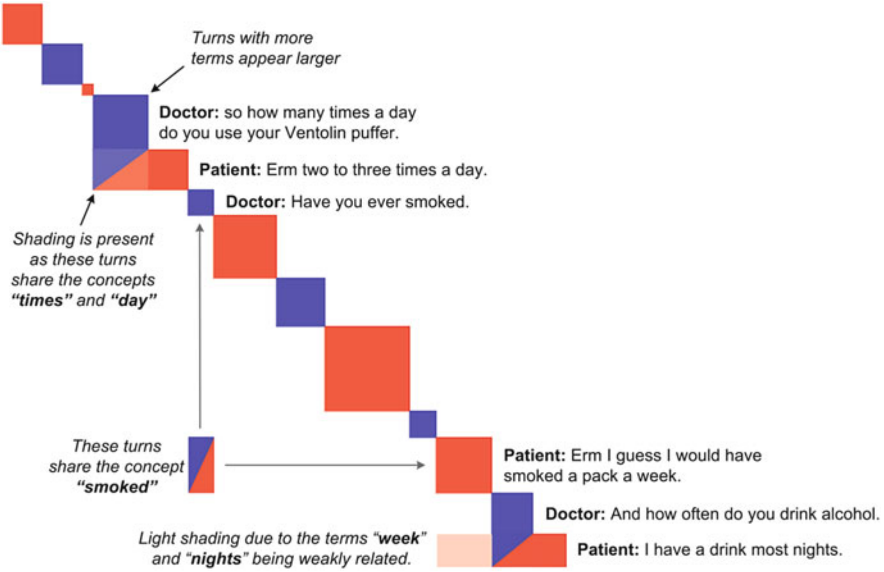

Fig. 14.6 Conceptual Recurrence Plot of 13 utterances and 4 corresponding recurrence elements from a Doctor/Patient consultation. The Patient is coloured *red* and the Doctor is coloured *blue*. Conceptual recurrence between the Patient and the Doctor is indicated by a half/half coloured *square*, and self-recurrence is in the speaker's own colour From Angus et al. [63]

during rituals. They measured the heart rate of performers as well as spectators (both those related to the performers as well as general audience members). Konvalinka et al. found that all of the firewalkers had a distinctive signature to their heart rate dynamics, with a peak in heart rate around the firewalk itself. This same pattern was found for relatives of the fire walker. CRQA demonstrated that performers and those spectators to whom they were related or tangentially related maintained common heart rate trajectories longer (i.e., *cross-maxline*) than performers and those spectators to whom they were unrelated compared to a baseline level of arousal (i.e., heart rate when not observing the ritual). They proposed that this quantitative evidence of emotional synchrony (even in the absence of movement synchrony) may reflect the type of affective empathy that accompanies such rituals.

14.10 Conclusions

We have presented an overview of much of the work on interpersonal coordination that has quantified coordination using recurrence-based methods. Although this strategy for studying interpersonal coordination originated in movement coordination research, it is clear that it has made its way beyond the study of movement into a broad range of domains that continues to grow as research involving these methods becomes more widely disseminated. It is also important to point out that the recurrence-based measures that have most commonly been used for quantifying coordination (e.g., *%cross-recurrence*, *%cross-determinism*, *cross-maxline*) are only a subset of the potential measures that could be developed. A number of researchers have branched out using new measures that may prove sensitive to different types of influences on interpersonal coordination. Angus et al. [63, 66], for example, have introduced a variety of new measures as described above. Lancia and Tiede [86] have likewise developed new strategies for quantifying deterministic structure in multi-signal CRPs (particularly in speech articulators) that avoid some of the assumptions of existing quantification tools. These also capture less conventional types of structure in CRPs, namely bowed diagonal lines that occur when two signals may not unfold on the same time scales (a form of non-stationarity). They applied an algorithm, based on a skeletonizing strategy often proposed by [87], which they use to calculate what Lancia and colleagues have subsequently referred to as *elastic determinism* [88, 89]. While their study did not explore interpersonal coupling, there is no barrier to using their strategy for doing so. The study of interpersonal coupling will continue to inform the development of recurrence strategies, just as recurrence strategies will continue to inform the theoretical and applied understanding of interpersonal coupling.

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References

1. J.P. Eckmann, S.O. Kamphorst, D. Ruelle, Recurrence plots of dynamical systems. Eur. Lett. **4**, 973–977 (1987)
2. C.L. Webber Jr., Rhythmogenesis of deterministic breathing patterns, in *Rhythms in Physiological Systems*, ed. by H. Haken, H.-P. Koepchen (Springer, Berlin, 1991), pp. 171–191
3. C.L. Webber Jr., J.P. Zbilut, Dynamical assessment of physiological systems and states using recurrence plot strategies. J. Appl. Physiol. **76**, 965–973 (1994)
4. C.L. Webber Jr., J.P. Zbilut, Assessing deterministic structures, in *physiological systems using recurrence plot strategies, in Bioengineering Approaches to Pulmonary Physiology and Medicine*, ed. by M.C.K. Khoo (Plenum Press, New York, 1996), pp. 137–148. Chapter 8
5. N. Marwan, J. Kurths, Phys. Lett. A **302**(5–6), 299 (2002)
6. K. Shockley, M. Butwill, J. Zbilut, C. Webber, Cross recurrence quantification of coupled oscillators. Phys. Lett. A **305**, 59–69 (2002)
7. J.P. Zbilut, A. Giuliani, C.L. Webber Jr., Phys. Lett. A **246**, 122 (1998)

8. R.C. Schmidt, C. Carello, M.T. Turvey, Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. J. Exp. Psychol. Hum. Percept. Perform. **16**, 227–247 (1990)
9. P.N. Kugler, M.T. Turvey, *Information, Natural Law and the Self-Assembly of Rhythmic Movement* (Erlbaum, Hillsdale, 1987)
10. R.C. Schmidt, M.T. Turvey, Phase-entrainment dynamics of visually coupled rhythmic movements. Biol. Cybern. **70**, 369–376 (1994)
11. R.C. Schmidt, M.J. Richardson, Dynamics of interpersonal coordination, in *Coordination: Neural, Behavioral and Social Dynamics* (Springer, Berlin, 2008) pp. 281–308
12. H. Haken, J.A.S. Kelso, H. Bunz, A theoretical model of phase transitions in human hand movements. Biol. Cybern. **51**, 347–356 (1985)
13. D. Richardson, R. Dale, N.Z. Kirkham, The art of conversation is coordination: common ground and the coupling of eye movements during dialogue. Psychol. Sci. **18**, 407–413 (2007)
14. D.C. Richardson, R. Dale, M.J. Spivey, Eye movements in language and cognition, in *Empirical Methods in Cognitive Linguistics*, ed. by M.J. Spivey, M. Gonzalez-Marquez, I. Mittelberg, S. Coulson (John Benjamins, Amsterdam, 2007), pp. 323–344
15. M.J. Richardson, R.C. Schmidt, B.A. Kay, Distinguishing the noise and attractor strength of coordinated limb movements using recurrence analysis. Biol. Cybern. **96**(1), 59–78 (2007)
16. G.L. Pellecchia, K. Shockley, M.T. Turvey, Concurrent cognitive task modulates coordination dynamics. Cognit. Sci. **29**(4), 531–557 (2005)
17. M.J. Richardson, S. Lopresti-Goodman, M. Mancini, B. Kay, R.C. Schmidt, Comparing the attractor strength of intra-and interpersonal interlimb coordination using cross-recurrence analysis. Neurosci. Lett. **438**(3), 340–345 (2008)
18. R.C. Schmidt, M. Bienvenu, P.A. Fitzpatrick, P.G. Amazeen, A comparison of intra- and interpersonal interlimb coordination: coordination breakdowns and coupling strength. J. Exp. Psychol. Hum. Percept. Perform. **24**, 884–900 (1998)
19. D.P. Black, M.A. Riley, C.K. McCord, Synergies in intra-and interpersonal interlimb rhythmic coordination. Motor Control **11**, 348–373 (2007)
20. M.J. Richardson, K.L. Marsh, R.C. Schmidt, Effects of visual and verbal interaction on unintentional interpersonal coordination. J. Exp. Psychol. Hum. Percept. Perform. **31**, 62–79 (2005)
21. K. Shockley, M.V. Santana, C.A. Fowler, Mutual interpersonal postural constraints are involved in cooperative conversation. J. Exp. Psychol. Hum. Percept. Perform. **29**, 326–332 (2003)
22. W. Condon, W. Ogston, Speech and body motion synchrony of the speaker–hearer, in *The Perception of Language*, ed. by D. Horton, J. Jenkins (Charles E. Merrill, Columbus, 1971), pp. 150–184
23. M. LaFrance, Posture mirroring and rapport, in *Interaction Rhythms: Periodicity in Communicative Behavior*, ed. by M. Davis (Human Sciences Press, New York, 1982), pp. 279–298
24. D. Newtson, The perception and coupling of behavior waves, in *Dynamical Systems in Social Psychology*, ed. by R.R. Vallacher, A. Nowak (Academic, San Diego, 1994), pp. 139–167
25. H.D.I. Abarbanel, *Analysis of Observed Chaotic Data* (Springer, New York, 1996)
26. J. Cappella, S. Planalp, Talk and silence sequences in informal conversations: III. Interspeaker influence. Hum. Commun. Res. **7**, 117–132 (1981)
27. M. Natale, Social desirability as related to convergence of temporal speech patterns. Percept. Mot. Skills **40**, 827–830 (1975)
28. R.L. Street Jr., Speech convergence and speech evaluation in fact-finding interviews. Hum. Commun. Res. **11**, 139–169 (1984)
29. B. Conrad, P. Schonle, Speech and respiration. Arch. Psychiatr. Nervenkr. **226**, 251–268 (1979)
30. M.C. Dault, L. Yardley, J.S. Frank, Does articulation contribute to modifications of postural control during dual-task performance? Cogn. Brain Res. **16**, 434–440 (2003)
31. L. Yardley, M. Gardner, A. Leadbetter, N. Lavie, Effect of articulation and mental tasks on postural control. Neuroreport **10**, 215–219 (1999)
32. K. Shockley, A.A. Baker, M.J. Richardson, C.A. Fowler, Articulatory constraints on interpersonal postural coordination. J. Exp. Psychol. Hum. Percept. Perform. **33**, 201–208 (2007)

33. T.A. Stoffregen, M.R. Giveans, S. Villard, J. Yank, K. Shockley, Interpersonal postural coordination on rigid and non-rigid surfaces. Motor Control **13**, 471–483 (2009)
34. T.A. Stoffregen, M.R. Giveans, S.J. Villard, K. Shockley, Effects of visual tasks and conversational partner on personal and interpersonal postural activity. Ecol. Psychol. **25**, 103–130 (2013)
35. M. Woollacott, A. Shumway-Cook, Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture **16**, 1–14 (2002)
36. T.A. Stoffregen, L.J. Smart, B.G. Bardy, R.J. Pagulayan, Postural stabilization of looking. J. Exp. Psychol. Hum. Percept. Perform. **25**, 1641–1658 (1999)
37. T.A. Stoffregen, R.J. Pagulayan, B.G. Bardy, L.J. Hettinger, Modulating postural control to facilitate visual performance. Hum. Mov. Sci. **19**, 203–220 (2000)
38. K. Shockley, D.C. Richardson, R. Dale, Conversation and coordinative structures. Top. Cogn. Sci. **1**, 305–319 (2009)
39. L.W. Barsalou, W.K. Simmons, A.K. Barbey, C.D. Wilson, Grounding conceptual knowledge in modality-specific systems. Trends Cogn. Sci. **7**(2), 84–91 (2003)
40. D. Frick-Horbury, R.E. Guttentag, The effects of restricting hand gesture production on lexical retrieval and free recall. Am. J. Psychol. **111**, 43–62 (1998)
41. C. de'Sperati, N. Stucchi, Motor imagery and visual event recognition. Exp. Brain Res. **133**(2), 273–278 (2000)
42. R. Ellis, M. Tucker, Micro-affordance: the potentiation of components of action by seen objects. Br. J. Psychol. **91**(4), 451–471 (2000)
43. A.M. Glenberg, M.P. Kaschak, Grounding language in action. Psychon. Bull. Rev. **9**, 558–565 (2001)
44. M. Wexler, S.M. Kosslyn, A. Berthoz, Motor processes in mental rotation. Cognition **68**, 77–94 (1998)
45. D. Kirsh, P. Maglio, Some epistemic benefits of action: Tetris a case study, in *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society* (Morgan Kaufmann, New York, 1992)
46. D.H. Ballard, M.M. Hayhoe, J.B. Pelz, Memory representations in natural tasks. Cogn. Neurosci. **7**, 66–80 (1995)
47. C. McKinstry, R. Dale, M.J. Spivey, Action dynamics reveal parallel competition in decision making. Psychol. Sci. **19**, 22–24 (2008)
48. L. Fogassi, L. Simone, The mirror system in monkeys and humans and its possible motor-based functions, in *Progress in Motor Control: Neural, Computational, and Dynamic Approaches*, ed. by M.J. Richardson, M.A. Riley, K. Shockley (Springer, New York, 2013)
49. G. Rizzolatti, L. Craighero, The mirror-neuron system. Annu. Rev. Neurosci. **27**, 169–192 (2004)
50. V. Gallese, C. Keysers, G. Rizzolatti, A unifying view of the basis of social cognition. Trends Cogn. Sci. **8**, 396–403 (2004)
51. B. Hommel, J. Müsseler, G. Aschersleben, W. Prinz, The theory of event coding (TEC): a framework for perception and action planning. Behav. Brain Sci. **24**, 849–878 (2001)
52. P.L. Jackson, J. Decety, Motor cognition: a new paradigm to study self-other interactions. Curr. Opin. Neurobiol. **14**, 259–263 (2004)
53. W. Prinz, B. Hommel (eds.), *Common Mechanisms in Perception and Action: Attention and Performance XIV* (Oxford Press, Oxford, 2002)
54. M.T. Tolston, K. Shockley, M.A. Riley, M.J. Richardson, Movement constraints on interpersonal coordination and communication. J. Exp. Psychol. Hum. Percept. Perform. (in press)
55. V.C. Ramenzoni, T.J. Davis, M.A. Riley, K. Shockley, A.A. Baker, Joint action in a cooperative precision task: nested processes of intrapersonal and interpersonal coordination. Exp. Brain Res. **211**, 447–457 (2011)
56. V.C. Ramenzoni, M.A. Riley, K. Shockley, A. Baker, Interpersonal and intrapersonal coordinative modes for joint and single task performance. Hum. Mov. Sci. **31**, 1253–1267 (2012)
57. M.A. Riley, M.J. Richardson, K. Shockley, V.C. Ramenzoni, Interpersonal synergies. Front. Psychol. **2**, 1–7 (2011)

58. H. Haken, *Synergetics: An Introduction* (Springer, Berlin, 1977)
59. F. Orsucci, A. Giuliani, C. Webber Jr., J. Zbilut, P. Fonagy, M. Mazza, Combinatorics and synchronization in natural semiotics. Phys. A Stat. Mech. Appl. **361**(2), 665–676 (2006)
60. R. Dale, M.J. Spivey, Unraveling the dyad: using recurrence analysis to explore patterns of syntactic coordination between children and caregivers in conversation. Lang. Learn. **56**, 391–430 (2006)
61. B. MacWhinney, *The CHILDES Project: Tools for Analyzing Talk* (Erlbaum, Mahwah, 2000)
62. A.S. Warlaumont, D.K. Oller, R. Dale, J.A. Richards, J. Gilkerson, D. Xu, Vocal interaction dynamics of children with and without autism, in *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 121–126). Cognitive Science Society, Austin (2010)
63. D. Angus, B. Watson, A. Smith, C. Gallois, J. Wiles, Visualising conversation structure across time: insights into effective doctor–patient consultations. PLoS One **7**(6), e38014 (2012). doi:10.1371/journal.pone.0038014
64. D. Angus, A. Smith, J. Wiles, Human communication as coupled time series: quantifying multi-participant recurrence. IEEE Trans. Vis. Comput. Graph. **20**, 1795–1807 (2012)
65. G. Salton, *Automatic Text Processing: The Transformation, Analysis, and Retrieval of Information by Computer* (Addison-Wesley, Reading, 1989)
66. D. Angus, A. Smith, J. Wiles, Conceptual recurrence plots: revealing patterns in human discourse. IEEE Trans. Vis. Comput. Graph. **18**, 988–997 (2012)
67. J.C. Gorman, N.J. Cooke, P.G. Amazeen, S. Fouse, Measuring patterns in team interaction sequences using a discrete recurrence approach. Hum. Factors: J. Hum. Factors Ergon. Soc. **54**(4), 503–517 (2012)
68. J.C. Gorman, P.G. Amazeen, N.J. Cooke, Team coordination dynamics. Nonlinear Dynamics Psychol. Life Sci. **14**, 265–289 (2010)
69. P.T. Esteves, D. Araújo, Aplicação da cross recurrence quantification ao estudo da coordenação interpessoal no basquetebol. Paper presented at the 2nd international symposium on sports performance. CIDESD, Covilhã, Portugal, 2011
70. J. Carvalho, D. Araújo, B. Travassos, P. Esteves, L. Pessanha, F. Pereira, K. Davids, Dynamics of players' relative positioning during baseline rallies in tennis. J. Sports Sci. **31**(14), 1596–1605 (2013)
71. A. Demos, T. Frank, R. Chaffin, Understanding movement during performance: a recurrence quantization approach in *International Symposium on Performance Science* (2011)
72. A.P. Demos, T.D. Frank, T. Logan, Movement during performance: a hunt for musical structure in postural sway. Poster presented at the society for musical perception and cognition (SMPC), Rochester, New York, August 2011
73. G. Varni, M. Mancini, G. Volpe, A. Camurri, A system for mobile active music listening based on social interaction and embodiment. Mobile Netw. Appl. **16**(3), 375–384 (2011)
74. G. Varni, G. Dubus, S. Oksanen, G. Volpe, M. Fabiani, R. Bresin et al., Interactive sonification of synchronisation of motoric behaviour in social active listening to music with mobile devices. J. Multimodal User Interf. **5**(3–4), 157–173 (2012)
75. S. Gill, M.R. Thompson, T. Himberg, Body rhythmic entrainment and pragmatics in musical and linguistic improvisation tasks, in *Proceedings of the 12th International Conference on Music Perception and Cognition and the 8th Triennial Conference of the European Society for the Cognitive Sciences of Music* ed. by E. Cambouropoulos, C. Tsougras, P. Mavromatis, K. Pastiadis (2012)
76. G. Varni, A. Camurri, P. Coletta, G. Volpe Emotional entrainment in music performance, in *Automatic Face & Gesture Recognition*: *Proceedings of the 8th IEEE International Conference* (IEEE, 2008) pp. 1–5
77. N. Marwan, M.C. Romano, M. Thiel, J. Kurths, Recurrence plots for the analysis of complex systems. Phys. Rep. **438**, 237–329 (2007)
78. A. Camurri, G. Varni, G. Volpe, Towards analysis of expressive gesture in groups of users: computational models of expressive social interaction, in *Lecture Notes in Computer Science*, vol. 5934, 122–133 (2010)

79. D. Richardson, R. Dale, Looking to understand: the coupling between speakers' and listeners' eye movements and its relationship to discourse comprehension. Cognit. Sci. **29**, 1045–1060 (2005)
80. P. Jermann, M.A. Nüssli, Effects of sharing text selections on gaze cross-recurrence and interaction quality in a pair programming task, in *Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work* (ACM, 2012), pp. 1125–1134
81. I. Konvalinka, D. Xygalatas, J. Bulbulia, U. Schjødt, E.M. Jegindø, S. Wallot et al., Synchronized arousal between performers and related spectators in a fire-walking ritual. Proc. Natl. Acad. Sci. **108**(20), 8514–8519 (2011)
82. R.B. Van Baaren, R.W. Holland, K. Kawakami, A. Van Knippenberg, Mimicry and prosocial behavior. Psychol. Sci. **15**(1), 71–74 (2004)
83. S.S. Wiltermuth, C. Heath, Synchrony and cooperation. Psychol. Sci. **20**(1), 1–5 (2009)
84. E.E. Cohen, R. Ejsmond-Frey, N. Knight, R.I.M. Dunbar, Rowers' high: behavioural synchrony is correlated with elevated pain thresholds. Biol. Lett. **6**(1), 106–108 (2010)
85. M.J. Hove, J.L. Risen, It's all in the timing: interpersonal synchrony increases affiliation. Soc. Cogn. **27**(6), 949–960 (2009)
86. L. Lancia, M. Tiede, A survey of methods for the analysis of the temporal evolution of speech articulator trajectories, in *Speech Planning and Dynamics*, ed. by S. Fuchs, P. Perrier (Peter Lang, Frankfurt am Main, 2012), pp. 233–271
87. N. Marwan, M. Thiel, N. Nowaczyk, Cross recurrence plot based synchronization of time series. Nonlinear Processes Geophys. **9**(3–4), 325–331 (2002)
88. L. Lancia, H. Avelino, D. Voigt, Measuring laryngealization in running speech: interaction with contrastive tones in Yálalag Zapotec. Poster presented at 14th Annual Conference of the International Speech Communication Association Interspeech, Lyon (2013)
89. L. Lancia, S. Fuchs, M. Tiede, Application of concepts from cross-recurrence analysis in speech production: an overview and a comparison to other nonlinear methods. J. Speech Lang. Hear. Res. doi:10.1044/1092-4388(2013/12-0223)