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Social Coordination, from the Perspective of Coordination Dynamics

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Article Outline

Glossary

Self-organization Self-organization lies behind all structure and pattern formation in nature's complex systems, including the human brain. Self-organization is a principle governing a system where no agent-like entity is ordering the elements, telling them where and what to do. In self-organizing systems, low-dimensional dynamics are revealed by changing one (or more) control parameter(s) whose role is simply to move the system through a series of state changes without prescribing its behavioral patterns.

Coordination dynamics Coordination dynamics seeks the laws, principles and mechanisms underlying the coordinated behavior of different kinds of components at multiple levels of description (molecules, cells, circuits, etc). It is an overarching conceptual framework that describes, explains and predicts how patterns of coordination form and change at multiple levels of brain and behavior. The brain, mind and behavior are linked by virtue of sharing a common underlying coordination dynamics.

Information exchange A remarkable fact is that in contrast to classical dynamics that deal with fundamental quantities such as mass, length and time and their relations, coordination dynamics is informational in nature, dealing with informational quantities of a relational kind that couple different parts of a system or different systems.

Phase transitions Phase transitions are the true illustration that a system is self-organizing. They are spontaneous qualitative pattern changes occurring as parameters are changed quantitatively. When they occur, abrupt switches from one coordinated pattern to another are observed and the dynamics of the entire self-organizing system is dominated by one or a few collective variables: the order parameters.

Stability Stability is a key concept in coordination dynamics. Here the stability is of coordination or collective variables. The (loss of) stability of a self-organizing system indicates whether a phase transition is to occur. In order to evaluate the stability of a system, one can perturb it and measure the time it takes for the system to return to its initial state, i. e. its *relaxation time*. A number of other converging measures have been used to measure stability in coordination dynamics such as *switching time* (the time it takes for the system to switch from one pattern to another when phase transitions occur) and *critical fluctuations* (the increase of variability of the collective variable in the vicinity of the phase transition).

Definition of the Subject

Social Coordination Dynamics (SCD) explores, at both behavioral and neural levels, the mechanisms mediating the formation and dissolution of bonds between individuals. SCD applies the concepts, methods and tools of informationally coupled self-organizing systems (coordination dynamics) to quantify real time social processes. Just as coordination dynamics deals with how the parts of complex systems work together in a meaningful way to achieve goals, so SCD aims to understand the interplay of forces operating at both individual and collective levels to produce effective social behavior. SCD offers a novel perspective and new metrics to explore systematically a fundamental form of human bonding (or lack thereof), and the self-organizing processes that underlie its persistence and change over space and time. SCD therefore complements recent developments in several fields such as sociology, social cognitive neuroscience, behavioral economics, game theory and neuroeconomics.

Introduction

Coordination can be broadly defined as a functional ordering among interacting components in space and time. Coming in many guises, coordination represents one of the most striking features of living organisms. The science of coordination, *Coordination Dynamics* (abbreviated CD) [36,37,38,41] stems from a complex systems framework based on the theory and methods of informationally coupled self-organizing dynamical systems (see ► Coordination Dynamics). CD explores a number of basic coordination phenomena that cut across a wide range of levels, creatures and functions. Of particular relevance to social coordination are: (i) patterned states of coordination remain stable in time despite perturbations; (ii) component parts and processes (dis)engage in a flexible fashion depending on functional demands and/or changes in environmental conditions; (iii) multiple coordination states exist rendering living things *multi-functional*, effectively satisfying the same (or different) set of circumstances; (iv) switching from partially to fully coordinated states and vice versa is commonplace; (v) selection of coordination patterns is tailored to suit the current needs of the organism; (vi) coordination patterns adapt to changing internal and external contingencies; (vii) depending on a balance between competitive and cooperative processes, learning may take the form of abrupt transitions from one coordinated pattern to another; and (viii) the system may remain in the current pattern of coordination even when conditions change thus exhibiting memory.

The foregoing list contains some of the core aspects of CD reflecting its inherently nonlinear and emergent character. Such phenomena appear so spontaneously and so consistently as to suggest the existence of an underlying lawfulness or regularity that transcends the multitude of differences between different systems and the settings in which they can be observed [41,45].

Coordination achieves its pinnacle in the vast array of cells and connections called the human brain, and in the collection of human beings we call society [41,45]. How social interactions form and change in complex systems and contexts is of great interest to many disciplines, particularly psychology, biology, physics, economics and the social sciences. The primary focus of the present article is to review recent work investigating the coordination dynamics of individuals interacting with each other in real time. At the core of all personal relationships is how the other becomes intertwined with the self. *Social coordination* is the tendency of two or more individuals to coordinate their ongoing actions with each other based on mutual information exchange. *Social Coordination Dynamics* (abbreviated SCD) is a theoretical-empirical framework that investigates the behavioral and neural dynamics of bond formation between individuals, operationalized in terms of how they spontaneously synchronize their behavioral and neural patterns [82,99].

Synchronization is a form of spontaneous pattern formation that operates according to general principles of self-organization described by nonlinear dynamics [25,26,72]. Following on Huygens's analysis of two clocks synchronizing on a wall, many studies have framed the problem of mutual synchronization in terms of a network of oscillators each of whose individual behavior is altered by nearest neighbor interaction [5,7,30,57,106,107]. Under that framework synchronization has been observed among very different entities in a broad range of physical, biological and social systems. Human brains (and behavior) have proven no exception to these principles [19,27,41,50,51,89]. Experiments have revealed that humans exchange information – whether uni- or multimodal in nature – to spontaneously adopt and switch coordination patterns (e. g. [37,53,58]).

The validity of the measures and constructs from coordination dynamics are worth mentioning because they speak to the appropriateness of a dynamical framework for investigating social situations. Whereas it is easy to justify the physical existence of linkages between components in the coordinated behavior of a single entity, no such linkage typically exists between people. *Social coordination occurs via information exchange*, typically through vision, touch and sound. Emotional interactions may also be involved. A natural measure that describes this informational exchange is the relative phase between coordinating behaviors. The relative phase is an informational variable whose dynamics and has been shown to capture quantitatively coordinated patterns of brain and behavior among different kinds of components, events and processes (see ► Coordination Dynamics [26,40,41]). For coupled rhythmic behaviors, the relative phase dynamics is often adequate not only for uncovering basic mechanisms underlying synergy formation and behavioral change but also the strength and directionality of influences during social interaction ([82,99]; see also [62,87]) for recent reviews.

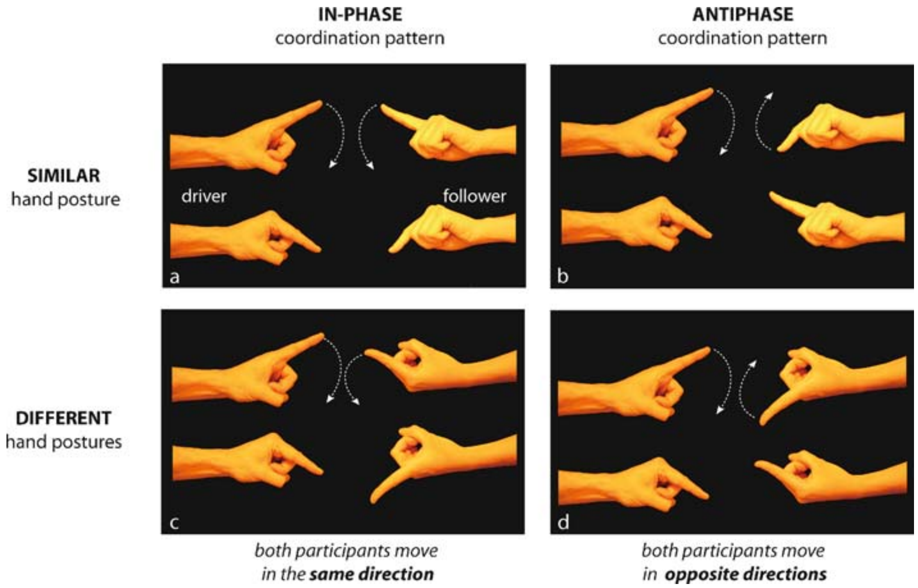
Intentional Interpersonal Coordination

Among the many phenomena of human social coordination, one that most of us have experienced is the synchronized clapping of an audience. Néda and colleagues [70,71] have investigated why applause occurs in unison, with individual "clappers" sometimes acting as a single synchronized ensemble. Although synchronized clapping may vary little from one situation to another, the mechanisms governing the phenomenon are nuanced and context-dependent, even within the same audience. An illustration of this context-dependence comes from the world-famous *New Year's Concert* given every year by the Vienna Philarmonic Orchestra in Austria. Traditionally the concert ends with the Radetzky March by Johann Strauss Jr. This piece of classical music is performed in quite an unusual way. For instance, the conductor leads not only the orchestra but also the audience. Upon a visual cue from the maestro, the audience claps in synchrony with the music. The collective clapping is synchronized both with the music and the visual signals given by the conductor. The reader who is not really into classical music might prefer the example of the song *'We will rock you'* by Queen. Except for a final and unique guitar solo, this song is constituted by a powerful rhythm and a poignant vocal performance by lead singer Freddie Mercury. When this very rhythmic song was performed live, the audience intentionally coordinated its movements with the sound of the drums and the pattern of movements visually provided by the singer. People were therefore intentionally clapping their hands on the first two beats and extending their arms on the third. In the coordination dynamics literature, this is referred to as *intentional sensorimotor coordination* of individuals with external events.

Several studies have employed the sensorimotor coordination tasks to investigate interpersonal coordination dynamics for the case when a person intentionally synchronizes her movements with another by means of visual information exchange see [62] for a review. Following the bimanual and sensorimotor paradigms introduced by Kelso and colleagues [36,37,46,48], Schmidt, Carello and Turvey [88] asked two individuals sitting next to each other to swing their legs in an in-phase or antiphase fashion with respect to the leg movements of the other member of the dyad. As movement frequency was increased (or decreased) by means of an auditory metronome, they found many of the predicted features of nonequilibrium phase transitions [27,47,89]: (i) *differential stability* between the two coordination patterns; (ii) *phase transitions* from the less stable coordination pattern (antiphase) to the more stable one (in-phase); (iii) *critical fluctuations* (i. e. increase in coordination variability) in the vicinity of the transition region and (iv) *hysteresis* (i. e. a sensitivity to the history of the system). All such hallmarks of coordination dynamics (and others such as *critical slowing down* in the vicinity of transitions) have been repeatedly found in a huge number of studies covering various experimental settings. Those settings include, but are not restricted to inter- (e. g. [36,37]) and intra-limb coordination (e. g. [9]) and coordination beween a limb and its uni- (e. g. [3,9,48]) or multi-modal environment [58] to name only a few. The main contribution of Schmidt and colleagues' research was to demonstrate that coordination phenomena found within a person's brain or body, extend to the interactions between people. It is noteworthy that the observed effects extend outside the typical laboratory setting to include coordination phenomena between an individual and an animal as in Lagarde and colleagues' investigation of the coordination dynamics of the horse–rider system [59]. In this unique experiment horses were ridden while walking, trotting and running on a treadmill. The movement dynamics of the horse, the rider and the horse–rider pair were recorded and analyzed revealing that the human–animal dyad exhibits similar coordination dynamics to human interpersonal coordination [59]. In this respect, it cannot be overemphasized that coordination dynamics deals with emergent cooperative effects across very different coordinating elements from neurons to muscles to limbs to people and across the animal–environment divide ([41,42]; for an excellent discussion, see Turvey [100] and commentaries in Vallacher and Nowak [101]). Both the 'intrinsic dynamics' of the individual elements and the nature of the coupling between different elements must be identified for a full account of the phenomena observed.

Several experiments by Schmidt and co-workers, as well as by other groups, have explored the effects on interpersonal coordination of variables such as the manipulation of objects (e. g. hand-held pendulums) or visual surroundings ([74,86]; see [87] for a recent review). Incorporating both aspects de Rugy and colleagues developed a neuro-mechanical model of visually mediated intentional interpersonal coordination [16]. Their model consists of two cross-coupled neuro-mechanical units, each composed of a neural oscillator driving a wrist-pendulum system moved by a different person. Taken individually, each unit reproduces the natural tendency of the participants to freely oscillate close to resonance frequency. When cross-coupled through the vision of movements of the other individual, each person entrains the other as they adopt a common frequency influenced by their own mechanical properties. Although important, neuromechanical properties are not the only factors that determine the stability of coordination patterns between individuals: attentional load and egocentric constraints also influence interpersonal coordination dynamics [96,97].

A series of experiments has investigated whether the motoric and perceptual constraints that shape the dynamics of inter- and intra-limb coordination play a similar role in the coordination between people (e. g. [12,13,53,58,66,78]). In intrapersonal bimanual coordination the preference for co-activation of homologous muscles appears to be mediated by general principles of symmetry in neural organization such as reciprocal connectivity between homologous brain areas. In a study by Oullier and colleagues [76] investigating the relative role of visual/directional and motor (a) symmetries in interpersonal coordination, two participants made index finger flexions while seated facing each other. One acted as a driver (D) by synchronizing to a metronome that systematically increased in rate. The second participant, or follower (F), was required to coordinate finger movements with D via visual coupling only. F participated in four conditions (Fig. 1) determined by a combination of coordination pattern (in-phase or antiphase) and hand posture (supination or pronation). The relative phase requirement was defined by the spatial configuration (i. e. the position of the endpoint of the finger). In this way, co-activation of homologous muscles (finger flexion by F and D) produced both an in-phase and antiphase relationship between the effector endpoints depending on the experimental condition. If purely directional constraints [92] determine the stability of interpersonal coordination, and D functions only as a generic rhythmic stimulus, perceptual antiphase coordination should display decreased stability regardless of the relative hand position of the participants. Contrary to this hypothesis, a strong role was found for interpersonal homologous muscle co-activation. Coordination between individuals was most stable when they were activating similar muscle groups such that co-flexion was always more stable regardless of the resulting spatial pattern. Directional constraints played only a modulatory role. These initial results are at odds with the concept of social coordination as a form of simple perceptual-motor coupling. Rather, it appears that perception of homologous muscular activation acts as a constraint on coordinative stability, creating a "functional homology" to bimanual coordination. Thus, social coordination may be differentiated from



Social Coordination, from the Perspective of Coordination Dynamics, Figure 1

Participants show a preference for homologous muscular activation, irrespective of the visuospatial congruency of their movement. Each column describes a possible configuration of interpersonal coordination. The left participant is paced with a metronome whose frequency increases (driver). Oullier and colleagues [76] studied the frequency at which the right subject (follower) loses stability in each condition. In columns a and b, both subjects are in the same hand position. The pattern a (both flex then both extend: in-phase coordination) is more stable than the pattern b (when one extends the other flexes: anti-phase coordination). In columns c and d, the participants adopt a different hand posture. The pattern d (both flex then both extend: anti-phase coordination) is more stable than the pattern c (where both subjects move in the same direction). These results suggest that coordinative stability is not purely governed by visuospatial congruency (cf. [67]). Rather, the embodiment of the other's movement leads the follower to adopt an anatomically homologous movement. This pattern of behavior is unique to the fact that the follower and the entity with which he/she coordinates are both humans [76]

simple perceptual-motor coupling by virtue of the biological and functional relevance provided when viewing another person.

Although all these studies have employed comparable experimental settings and the common theoretical framework of coordination dynamics with the aim of better understanding intentional interpersonal coordination, it is not yet clear whether spontaneous mutual entrainment actually occurs in a true two-way interaction, or whether one individual simply acts as a pacing stimulus or 'driver' for the other (e. g. [48]). A similar concern can be raised regarding the behavior of the audience during the Radetzky March at the New Year's Concert in Vienna. It seems unlikely that audience members spontaneously synchronized with each other while music was played, since their primary intent was to respond by clapping in rhythm with the music and with the visual cues coming from the stage. This process has been well described in human movement (neuro)science and coordination dynamics and occurs when an individual intentionally coordinates his movements with external physical stimuli [3,41,48]. A sensorimotor interpretation of audience participation is strengthened by results of an experiment in which the auditory metronome used to pace the interpersonal coordination was silenced at times [76]. The study revealed that the presence of an external pacing stimulus (an auditory metronome in that case) actually reduced interpersonal coordinative stability regardless of the adopted directional or muscular pattern adopted. Oullier and colleagues [76] provided evidence for stronger mutual entrainment when no external information could perturb the dyadic interactions, analogous to what the music and the conductor would do during a concert. Hence, from an experimental perspective, this phenomenon is not social interaction per se but rather sensorimotor coordination to an external event. In the case of the "observed" audience clapping in unison *during* the performance, one could argue that the audience is constituted by a collection of individuals coordinating mainly with the music and the conductor with little contribution from neighbor-to-neighbor interactions, (A similar concern can be raised in the study by Schmidt and co-workers [88] as participants were instructed to intentionally coordinate with each other *and* with an auditory metronome. Hence, one participant could serve as a visual metronome to the other (and reciprocally) and/or the phase transitions observed could either be interpersonal in nature (from interpersonal antiphase to in-phase) or from syncopation to synchronization as in a single individual coordinating with an auditory metronome (cf. [48]).

A different scenario, however, is characteristic of the end of the performance, when the audience expresses its approval of the orchestra and conductor through applause. At this moment each person applauds according to her preferred/intrinsic pace with no driving stimuli – whether visual or auditory – coming from the stage. In spite of the absence of pacing information, the audience quickly and spontaneously entrains to a common rhythm such that everyone is clapping in unison. Note that at this moment, the only information that can alter an individual's behavior is the sound (and possibly the vision) of the movements made by their neighbors [70,71]. Thus, we have units involved in individual rhythmic behaviors communicating via, at least, one means of information exchange. According to Winfree [108], this is a minimum requirement for self-organized spontaneous synchronization to emerge (see also [41]). In that case, any collective pattern that emerges is more likely to be unintentional compared to situations where the audience follows the conductor and the music.

Issues in Quantifying Spontaneous Interpersonal Coordination

An abundant literature exists addressing unintentional interpersonal coordination in experimental paradigms ranging from people swinging pendulums [86], dancing [33], walking [102] or rocking chairs [84] to performing joint Fitts' tasks [69], talking to each other [83,91] or even boxing [60]. However, many questions remain regarding the nature of the behavioral and neural processes mediating the formation and dissolution of unintended synchronous behavior between individuals and how such processes may be quantified [2,55].

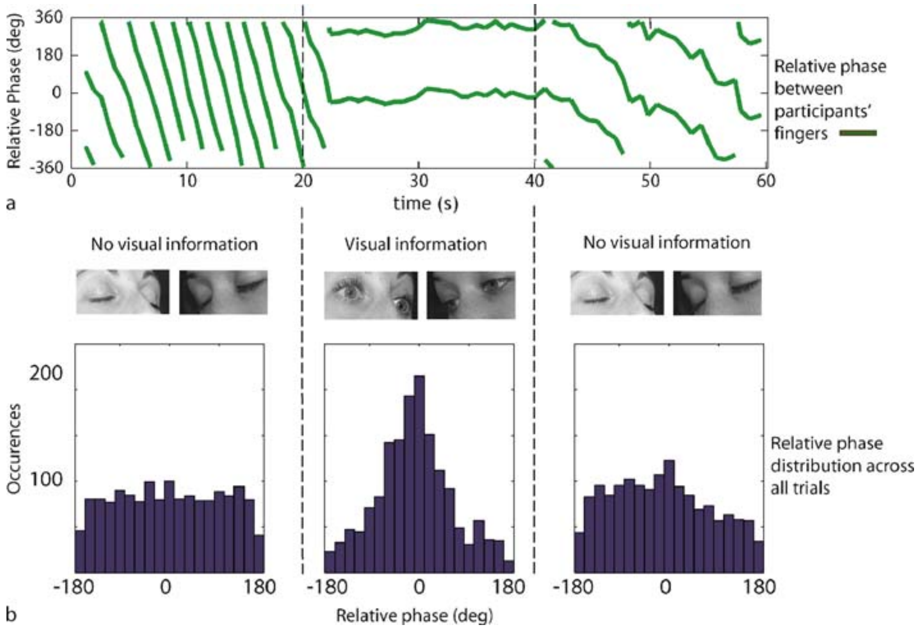
Oullier and colleagues [82] have identified three major problems in investigating spontaneous synchronization in social settings. First, even when the source and nature of the coupling has been identified, it is difficult to manipulate experimentally relevant variables such as the coupling strength (e. g. [71]). Almost by definition, spontaneous behavior is not externally goal directed or explicitly controlled. Most of the results reporting unintentional synchronization in humans are based on observation and categorization methods that rely primarily on the experimenter's appreciation of a given exemplar behavior rather than a quantitative measure of coupling and individual behavior (e. g. [4,14]).

A second problem is the challenge of complexity, both in terms of the large number of units to analyze (e. g. thousands of pairs of clapping hands [71]) and the complexity of the behavior itself (e. g. mother-infant synchronization [14]). Such compositional and behavioral complexity has hindered experimental attempts to record and quantify both the individual and social dynamics. Even the reduction in dimensional complexity afforded in coordinated behavior can only go so far in elucidating the relationship between group behavior and the individual units of which it is composed.

A third problem comes from the possibility that any change in a person's behavior induced by interacting with another may persist even after the encounter is over. So far, there has been very little precise quantification of the mutual influence people have on each other's behavior a posteriori, i. e. how individual behavior is affected after the social encounter when people no longer exchange information (but see Sect. "Social Memory and the Dependence on Initial Conditions").

Human Spontaneous Synchronization

In behavioral experiments that revealed spontaneous interpersonal synchronization, Oullier and colleagues [77,80,82] explored coordinative patterns that emerge only as a function of visual information exchange. The main hypothesis was that even without instructions to do so, spontaneous synchronization between partners would occur as soon as they coupled visually while moving in front of each other. On the other hand, spontaneous interpersonal coordination should disappear whenever exchange of information is no longer possible. In Oullier et al.'s behavioral experiments, pairs of participants executed movements while in full view (or not) of each other's ongoing actions as well as their own [77,80,82]. Each member of the dyad executed movements at their own preferred frequency and amplitude without any external pacing from a metronome or any other sort. Movements were required to be as smooth and continuous as possible throughout an experimental trial. What is important here is that participants were not given any instructions regarding the way to move with respect to each other. The experimental protocol consisted of participants moving with no vision of the other's movements before being allowed to see their own actions at the same time as they saw the other person's. Finally, visual information was removed again. Experi-



Social Coordination, from the Perspective of Coordination Dynamics, Figure 2
Relative phase between the movements of two individuals. a This panel illustrates the evolution of the relative phase as a function of time in a representative trial of the SCD paradigm. *Left column* No visual information exchange, each individual moves independently, movements are uncoordinated. *Middle column* as soon as people exchange visual information, they spontaneously couple. Their relative phase is therefore close to 0° . *Right column* When visual information is removed, they are no longer synchronized. b This panel represents distributions of relative phase for all the subjects and all the trials (adapted from [82])

mental trials were therefore equally partitioned into three contiguous segments each of equal duration within which both subjects either were allowed to exchange information with each other or not. When visual information was available, participants looked at each other's finger motion and were also able to see their own finger [77,80,82].

In SCD, following theories of cooperative phenomena in open systems [25,26] a central idea is that the behavior of a complex dyadic system may be captured by the value of a low-dimensional collective variable known as the *order parameter*. In the vicinity of critical points, emergent behavior is governed by the dynamics of this collective variable e. g. [25,41]. In experimental cases the order parameters are not known in advance but have to be discovered. For the situation of social coordination as in many other cases treated by CD, an appropriate order parameter describing the system dynamics is the relative phase ϕ between the movements of each member of the pair [80,82]. The relative phase measure allows for a reduction of a potentially very high dimensional system (e. g. where one has to consider, among other components, the neurons, joints and muscles of both individuals) as it captures the macroscopic spatio-temporal behavioral pattern (see Fig. 2). Even at an overt behavioral level, four degrees of freedom (position and velocity of each component) may be compressed onto a single relative phase value that summarizes the organization of the dyadic system. Quantitative evaluation of spontaneous synchrony is also provided by the FFT power spectrum overlap between the movements of each person. The spectrum overlap measures the percentage of movement frequencies common to both partners in a pair [82]. Defined as the area of intersection between each participant's normalized spectral plots, it serves an indicator of the strength of the frequency entrainment between the two participants (see Fig. 4).

When no visual exchange was allowed, each subject produced movements independently at their own frequency. As a result, the relative phase ϕ between the subjects' finger motions exhibited phase wrapping (Fig. 2, left column). However, following a simple auditory cue to open their eyes, subjects spontaneously adopted in-phase motion, ϕ stabilizing around 0° (Fig. 2, middle column). On a signal to close the eyes again, the individual movement frequencies diverged and ϕ fell back into phase wrapping (Fig. 2, right column). These initial results were corroborated by a subsequent more extensive study, in which the order of the vision and no-vision segments was changed. Once again, spontaneous synchronization emerged as soon as vision of the other's movements was allowed [82]. Overall, results reveal that with visual information exchange, participants tend to mutually couple at a common phase and frequency, whereas in the absence of vision, participants' movement trajectories diverge and behave independently. Such emergent mutual coupling is truly a result of spontaneous social interaction and may be distinguished from previous dyadic studies in which one person may simply be intentionally tracking (or driving) the other [16,77,88,97] or maintaining their own rhythm [86].

Why does spontaneous interpersonal coordination occur at all? Compelling examples stretching from human evolution through religious ritual and sports to political, war and economical strategy suggest that *keeping together in time* is one of the most powerful ways to create and sustain communities and communication [65]. Moreover, *not* moving in synchrony may be too costly for the dyad see, (e. g., [56]).

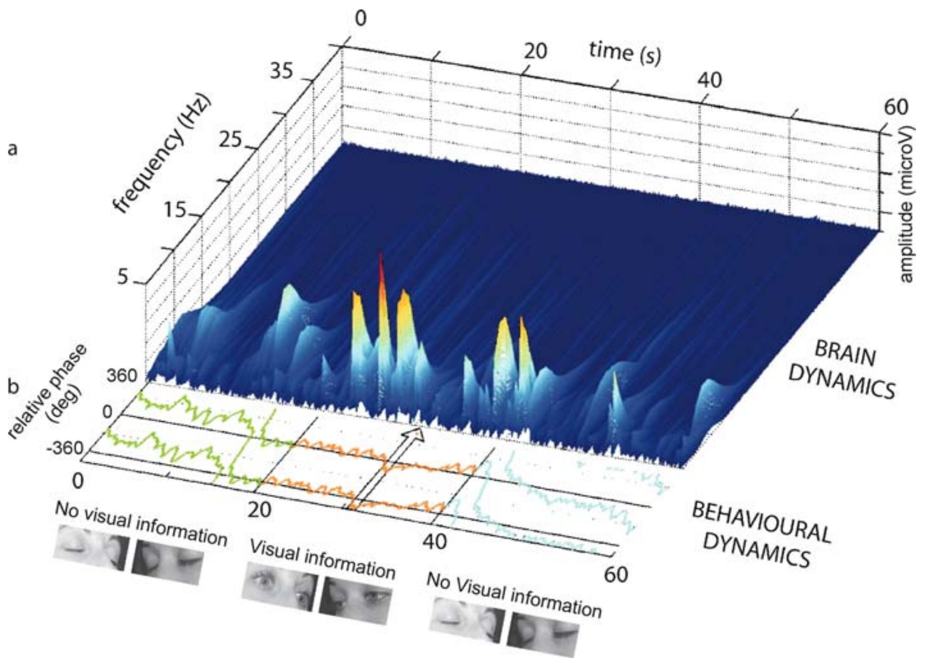
In order to better understand which features of visual information exchange may facilitate spontaneous social coordination one has to bear in mind that human movements can be unintentionally affected by the vision of an object oscillating in the environment. This is illustrated by experiments using the moving-room paradigm in which the walls of the room move but not the floor (e. g. [61,75,78]). Body sway of the observer's couples in time spontaneously with small oscillatory motions of the room. In addition, experimental data show that the mere observation of the movements of another person interferes with one's execution of a similar action [54]. Interestingly, such interference is less noticeable when the movements observed are not generated by humans [15]. In the latter work, one of the members of the dyad was replaced by a computer-generated moving hand, the trajectory of which was driven either by a sinusoidal function or a pre-recorded real finger trajectory. The stimulus movement frequency in the study by de Guzman and coworkers [15] was fixed at either 10% below or 10% above the subject's self-paced rate as determined at the start of the experiment. Results revealed that the human–avatar coordination was strongest when the latter was an image of a hand driven by real movement data. The weakest coupling occurred when the visual stimulus followed a sinusoidal trajectory. Unlike the interpersonal situation [82], spontaneous synchronization was not found for all trials and, when it happened, was supported by a significantly lower frequency overlap [15]. One may invoke a one-way coupling to explain these findings, since the motion of the computer generated hand could not be influenced by the movement of the participant. Taken together, the foregoing results support the hypothesis that biological relevance in general, and biological motion in particular – including its natural variation– play a key role in social coordination.

Shared Behavioral and Neural Social Coordination Dynamics

One explanation for the emergence of spontaneous social coordination may be found at the neurophysiological level. For instance, some areas of the brain are known to be associated with the perception (but not the execution) of biological motion including the posterior superior temporal sulcus (abbreviated STS) [1,23,24,31]. STS is known to be a major source of visual information for the so-called *human mirror system* (abbreviated HMS) [85]. Originally identified in monkeys, *mirror neurons* are (sensori)motor neurons discharging both when one performs a given action and sees the same action performed by someone else. They have been identified primarily in the ventral premotor cortex and the rostral region of the inferior parietal lobule [20]. The HMS constitutes a neural mechanism that is automatically activated by the sight of somebody else's actions, even when the observer does not make overt movements. The main idea is that during observation the HMS provides a simulation of the actions of other people potentially providing a basis for understanding the intentions of others [31].

Since the foregoing behavioral experiments allow participants to both produce and observe movement at the same time it seems possible that the HMS is at least partially involved in the spontaneous coordination observed. In order to investigate this question, Tognoli and colleagues [99] recorded brain activity of each member of the dyad using a specially designed dual-electroencephalography (EEG) system. Each participant wore a 60-electrode EEG-cap that enabled simultaneous recording of their brains to accompany kinematic measurements of their behavior.

To grasp the significance of the work by Tognoli and colleagues, we need to revert to earlier studies conducted within the framework of Coordination Dynamics have employed instabilities in coordination as a means to uncover the link between the dynamics of behavior and the dynamics of the brain [39,42], with the goal of relating levels by virtue of their *shared dynamical properties* (e. g. [19,39,49,50,52]). In such research, the high temporal resolution of electroencephalography (EEG) and magnetoencephalography (MEG) was exploited to quantify the relationship between the large scale neural dynamics emerging from billions of interconnected neurons and the behavioral dynamics revealed in experiments on coordi-



Social Coordination, from the Perspective of Coordination Dynamics, Figure 3

Relation between Phi$_2$ and social coordination. a Time-frequency spectrum from electrode CP4 (located over parietal brain regions) from a single trial. Phi$_2$ is low before and after vision but increases during vision. b Corresponding relative phase between finger movements. Synchronized in-phase behavior is observed during visual contact. Notice the temporary disengagement of the rhythm when coordination is lost briefly (adapted from [99])

nation [41]. Observed features of the dynamics expressed at both levels of description such as multistability and phase transitions (i. e. the spontaneous switch from one pattern to another due to loss of stability), were taken as evidence that principles of self-organization govern pattern formation in both brain and behavior [26,41]. Of particular initial interest was the identification of qualitative changes in the pattern of neural activity that occurred simultaneously with transitions between behavioral patterns [19,49,50,63,104]. On the basis of this work, an exciting hypothesis is that the transitions from uncoordinated to spontaneous coordination observed in the SCD paradigm may be accompanied by similar events at the brain level.

In an effort to shed new light on how social processes are integrated in the brain, Tognoli and colleagues [99] identified several neural mechanisms or *neuromarkers* that appear and disappear with the emergence and dissolution of coordinated behavior between two people. Interestingly, these social neuromarkers consist of brain rhythms in the 10 Hz frequency range located over right centro-parietal areas of the cerebral cortex. In particular, a social brain rhythm termed the *Phi Complex* consists of two components: the first, Phi$_1$, increases during independent behavior i. e. before information exchange between members of the dyad. When subjects saw each other's finger movements and coordinated together, Phi$_1$ disappeared and Phi$_2$, a different rhythm within the same frequency band appeared (Fig. 3) [99].

In a subsequent study, Tognoli and colleagues [98] explored the dynamics of the *Phi Complex* by instructing participants to *intentionally* synchronize when visual information exchange was allowed. In this case, participants interact to accomplish a shared goal. Again, Phi$_1$ appeared during uncoordinated behavior and Phi$_2$ when social coordination occurred. Analysis of dyads who participated in both experiments [98,99] revealed that the amplitude of Phi$_2$ was higher during intentional than spontaneous coordination. Thus, Phi$_2$ appears to be a neural signature of social coordination whether it emerges spontaneously or not.

The cortical location of the *Phi Complex* appears to be consistent with neuro-anatomical sources within the human mirror system. One of the conclusions drawn by Tognoli and colleagues is that Phi$_1$ might have an inhibiting role on the mirror system. Previous claims by Brass and Heyes [8] have argued that the mirror system is always active by default and thus must be inhibited in non-social contexts. Hence Phi$_1$ could inhibit Phi$_2$, the latter being seen as a facilitator of social coordination that participates in information exchange between the motor cortex and the mirror system [98,99].

In summary, experiments using dual high density electrode arrays to record and measure brain activity from two persons in conjunction with motion capture technology, have allowed an exploration of shared behavioral and neural social coordination dynamics [98,99]. Transitions from uncoordinated dyadic behavior to interpersonal synchronization have been demonstrated to accompany the emergence of a new brain rhythm – the Phi complex – located in the human mirror system. Such work suggests that SCD may serve as a novel framework for identifying behavioral and neural signatures in reciprocal interactions and allows for a more dynamical approach to the study of the mirror neuron system.

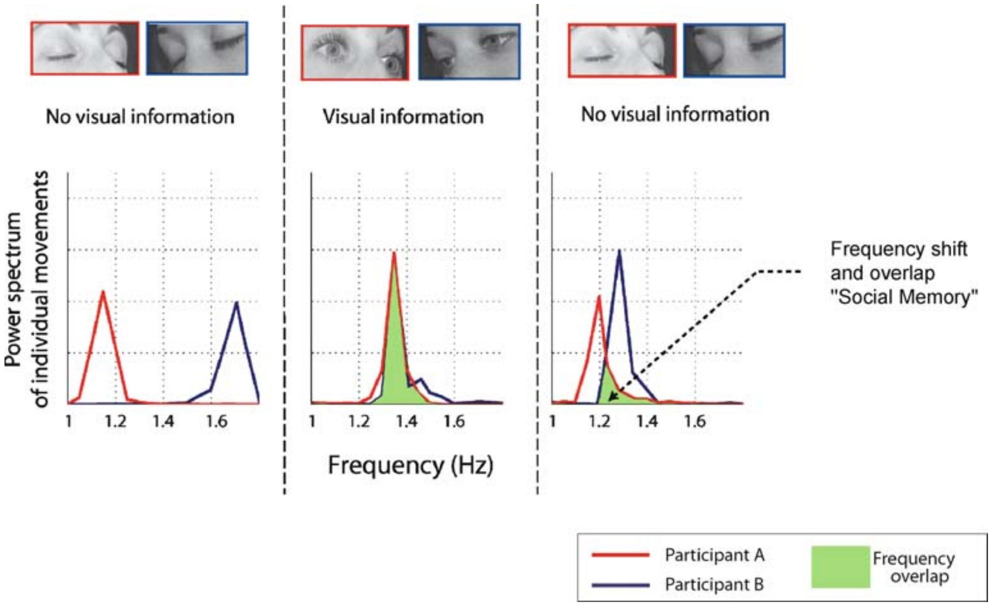
Social Memory and the Dependence on Initial Conditions

At first blush, the emergence of spontaneous coordination between individuals [77,80,82,99] might be seen as an instantiation of mutual entrainment that entails nothing more than a couple of oscillators and a medium of information exchange [41,108]. In such generic cases, once the coupling is removed, each oscillator should return to its own intrinsic frequency, that is, any influence of the interaction should disappear. However, the situation between two people is different (see Fig. 4). Theoretically, in a typical coupled clocks scenario, there should be no difference between the movement periods of the 'clocks' before or after coupling-induced synchronization. However, a serendipitous experimental finding [82] was the consistent and persistent influence of the social interaction on subsequent rhythmic behavior despite the absence of information exchange between the pair (Fig. 4). This remnant of a prior social interaction may qualify as a kind of *social memory* [82].

Social memory is thought to play an important role in human actions, and, to a larger extent, on the way we live [32]. In the context of SCD, social memory implies that the intrinsic parameters of the individual components have been altered by virtue of the social interaction. Mathematically [42], one may represent the situation before the interaction as follows:

$$\begin{aligned}\ddot{x}_1 + i_1(x_1, \dot{x}_1, a_1) + \omega_1^2 x_1 &= 0\\ \ddot{x}_2 + i_2(x_2, \dot{x}_2, a_2) + \omega_2^2 x_2 &= 0\,.\end{aligned} \quad (1)$$

Where x_1 and x_2 represent the coordinating components,



Social Coordination, from the Perspective of Coordination Dynamics, Figure 4

Evidence for social memory. Illustrated is an example of frequency overlap between the movements of both subjects in a representative trial of the SCD paradigm. *Left column* no vision of each other's movements; each individual moves at their own intrinsic frequency so there is no frequency overlap. *Middle column* visual information is exchanged between participants, causing spontaneous synchronization to occur at a common frequency (and phase, see Fig. 2). *Right column* visual information is no longer exchanged but individuals do not revert back to their initial intrinsic frequency. This remnant of frequency overlap as a result of prior social interaction suggests a kind of 'social memory' (adapted from [82])

$i_{1,2}$, $a_{1,2}$ and $\omega_{1,2}$ refer to individually chosen intrinsic parameters such as the chosen frequency and amplitude.

During the interaction, the system is visually coupled, F_1 and F_2 representing a coupling function such as the well-known HKB-coupling [27,44]:

$$\begin{aligned} \ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 &= \mathrm{F}_1(x_1, \dot{x}_1, x_2, \dot{x}_2) \\ \ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 &= \mathrm{F}_2(x_2, \dot{x}_2, x_1, \dot{x}_1) \, . \end{aligned} \tag{2}$$

Now notice that the interactive context has formed a coupling (the right hand side of Eq. (2)) but also led of a modification of the individual component parameters, I and A (on the left hand side of Eq. (2)). One may say that the boundary conditions of Eq. (1) have been altered by the social interaction.

After the interaction, the coupling function disappears (F_1 and F_2 terms on the right hand side are zero) and the system is "uncoupled" (cf. Fig. 1):

$$\begin{aligned} \ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 &= 0 \\ \ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 &= 0 \, . \end{aligned} \tag{3}$$

However, notice in Eq. (3) the individual intrinsic parameters of the system which were modified by the interaction are still in place. Though uncoupled, the individual components are still affected by the interaction. How this internalization process occurs remains open to empirical investigation.

A benefit of the SCD paradigm is that one is able to quantify the strength and persistence of prior social influences on an individual's behavior. The finding that the modification of the neural network depends on which modality is engaged during the mutual encounter suggests that additional cortical areas may have been recruited and included into the initial global neural assembly due to social context [32]. However, beyond the Phi complex, and perhaps due to inherent limitations in spatial resolution, examination of the dual EEG data showed no evidence of further cortical engagement. Another possibility (in line with the foregoing mathematical analysis) is that the connectivity and dynamics of the initial network is modified by social interaction, and the new organization retained after the interaction is over. Recent evidence in support of this hypothesis suggests that two people engaging in a common task share a representation of each other's movement dynamics, including trajectory amplitude and frequency [6,17]. Such a (shared) representation may persist when vision is removed, i. e. when information exchange is no longer possible [21]. Moreover, representations at the neural level have been shown to be highly flexible and context-dependent [34,35], influenced both by environmental [105] and task demands [79].

The extent and duration of the carryover or remnant effects observed in behavioral experiments may reflect many factors, including the strength of the bond that is formed between people, place in the social hierarchy, the willingness of each participant to cooperate, gender differences, personality characteristics and the significance each participant attaches to the social encounter [32]. An additional finding from our work favors a motor contribution to social memory as well: the persistence effect was found to be independent of the duration of movement that followed the social encounter [82]. This hypothesis is strengthened by results showing that observation of another person performing movements generates a kinematically specific memory of the observed motions in primary motor cortex [95].

The systematic directionality effect observed in the SCD paradigm is revealing also [82]: the extent to which one member of the dyad is influenced by the other was shown to depend on initial conditions. Obviously for synchronization to occur, the person moving with the lowest/highest intrinsic movement frequency must speed up/slow down during information exchange. A surprising result is that the difference between the initial and the final intrinsic movement frequencies (vision absent) was always greater for the person starting with the higher compared to the lower movement frequency [82]. The extent to which initial, so-called 'intrinsic dynamics' determine behavior after the social encounter is over may be of great interest to understanding social interactions in more complex settings where hierarchical relations are involved.

An important problem in human social behavior concerns understanding the degree to which an individual influences the actions of a group (e. g. peer group, family, class) he/she is in. Due to several factors (personality, situational), a person (the leader) may affect the behavior of others more than the others affect her or him. The concept of leadership is commonly associated with interactions taking place in hierarchical settings such as typical organizations, but is actually broader than that. Strength of behavioral influence is overlooked because behavioral interactions have not been systematically studied. Contemporary complex systems approaches (e. g. [28]) view the formation of leader-follower roles as interactive and emergent but in so doing may have undermined the significance of individual dimensions. The approach of SCD is rather to ask: *What makes two people behave independently and what makes them behave as a unit?* The paradigm of social coordination dynamics exploits inherent asymmetry between two people during behavioral interactions and gauges, e. g. using directional coupling measures, which of the two has a stronger influence.

Future Directions

Human beings are social by nature, and interactions with others represent a substantial portion of their many daily activities. A common and well described consequence of interpersonal activity is that an individual's behavior, whether intentional or not, is modified by interactions with others [32]. Alterations of individual and collective behaviors range from imitation and mimicry to spontaneous synchronization, and have been observed in groups varying in size from dyads to thousands of individuals e. g. [4,68].

Social Coordination Dynamics investigates how the natural (uninstructed) social influence of one person on another evolves in real time and has led to a number of new findings. The first is that humans immediately and spontaneously coordinate their actions with each other when provided vision of the movements of the other together with their own. The second is that a specific brain rhythm underlies social coordination. Transitions from individual to coordinated social behavior are observed at both behavioral and brain levels.

The third finding is that an individual's intrinsic behavior is altered by social interaction: the effect of the previous social encounter persists when vision of the other's movements is no longer available. A fourth and final finding is that social coordination is affected by initial conditions, enabling one to predict which individual is most affected by the social encounter.

Insights into elementary forms of social interaction have been obtained by applying the concepts, methods and tools of coordination dynamics. A notable feature of coordination dynamics is its ability to uncover mechanisms and principles common to different kinds of complex systems at different levels of observation and to relate them by virtue of shared behavioral and neural dynamics [41]. SCD and its dynamical measures have proven to provide adequate quantification of the spontaneous coupling between individuals, the transition to loss of entrainment and the effect of the social encounter at both behavioral and brain levels. The same basic patterns of coordinated behavior and pattern dynamics (multistability, critical fluctuations accompanied by a temporary loss of stability, phase transitions, hysteresis and critical slowing down) have been observed within an individual, between an individual and the environment, and between individuals. In this respect SCD complements recent developments in social cognitive neuroscience, behavioral economics, game theory, socio-economics and neuroeconomics (e. g. [10,11,18,73,81,94,103]).

The field of *social neuroeconomics* serves to illustrate the benefits of considering SCD in contexts other than interpersonal sensorimotor interaction. Social neuroeconomics investigates the neural correlates of economical decision making [18]. One particular feature of this nascent field is that decision making processes are always studied in a body- and movement-independent fashion. Why is that? After all, from the very first months of life, individuals live vicariously through one another adopting, if only temporarily, a similar posture or tempo during interactions with a peer, or yawning [4,64,90]. As Henry Greely [22] recently reminded the readership of Science Magazine *"Human society is the society of human brains. Of course those brains are encased in, affected by, and dependent on the rest of the body, but our most important interactions are with other people's brains, as manifested through their bodies."* Although this statement sounds like common sense, thus far the coordination dynamics between bodies has remained unexplored in the field of social neuroeconomics. Yet how many times have we experienced the feeling that trusting someone will be difficult even before talking to them? Whether it was the way she moved or some other factor, body-related cues play a key role in modulating economic decisions (e. g. [93]). A scientific approach to "body language" might aim to understand how perceived actions of others affect the cognitive and emotional processes involved in economical decision-making. For instance, a finding such as the Phi Complex – especially the modulation of Phi_2 when individuals intentionally coordinate [98,99] – could turn to be crucial to better competition–cooperation mechanisms underlying decision in economic contexts such as public coordination games [29]. In sum, as a conceptual framework that encompasses the dynamics of both neural and behavioral levels, SCD promises to bridge the gaps between levels of analysis [41,81] and clear a path for new multi-level, interdisciplinary investigations of social interactions. Like synchronization itself, the function of SCD is to facilitate communication across heretofore unrelated fields.

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