Neurobiological Approaches to Interpersonal Coordination: Achievements and Pitfalls

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Abstract Although spontaneous interpersonal coordination was originally reported in the early 1960s, the accurate measurement of this phenomenon is very recent. Sophisticated methods used by dynamic systems theory and social neuroscientific perspectives have allowed capturing and analyzing patterns of neural and bodily coordination between interactants, favoring a deeper understanding of the factors and processes involved. In the present chapter, we review neurobiological evidence on interpersonal coordination and acknowledge that, despite the use of cutting-edge technology, extant findings have not yet resulted in an understanding of real-life interpersonal coordination. Theoretical and methodological efforts in social neuroscience aimed to explore interpersonal dynamics through joint tasks have been tacitly based on an individualistic approach to social cognition that underestimates the social nature of interactional phenomena. In turn, dynamic systems theory tends to approach human interaction in the same way as any complex system, disregarding the specific features of social life. We argue instead that interpersonal coordination should be studied under the assumption that people engage in meaningful interactions, so that its study requires the design of more ecological paradigms integrating the benefits of high-precision temporal recordings and a holistic account of the brain and bodily dynamics that occur during real human interaction.

Keywords Interpersonal coordination • Interactional synchrony • Motion capture • Hyperscanning • Social cognition • Dynamic systems theory

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1 Introduction

More than 50 years of interdisciplinary research in the cognitive sciences has revealed that interpersonal coordination is a pervasive phenomenon in face-to-face human interactions. When interacting in social settings, individuals spontaneously tend to temporally synchronize their behaviors at different levels [1, 2]. For example, during a walk in the woods, it is likely that people will synchronize not only the trajectory, rhythm, and frequency of their limb movements but also their heart rhythms, breathing rhythms, speech rhythms, and even body language, gestures, and feelings. Accordingly, most research in this field has inquired into how individuals involved in social settings coordinate with each other at linguistic, psychophysiological, neurophysiological, and behavioral levels. Findings from linguistic research in conversational contexts have shown the existence of synchronization patterns at multiple scales of linguistic structure [3]. For instance, when people chat, they align their accent [4, 5], vocal intensity [6], length and placement of pauses [7, 8], descriptive schemes and utterances [9, 10], utterance length [7], response latency [8], speaking rate [11, 12], phoneme productions [13], and syntactic constructions [14, 15]. Psychophysiological studies have further revealed that people, when interacting naturally or playing together, coordinate their breathing [16], heartbeats [17–20], and galvanic skin response [21–23]. Moreover, neurophysiological evidence has allowed characterizing how neural activity becomes coupled as people solve coordination or imitation tasks in real time with another participant [24–34], with a computer program [35], or with a prerecorded video [36, 37]. Also, at a behavioral level, studies indicate that people synchronize their body movements with those of others with whom they interact in social settings [1, 38–45].

Although these phenomena have been studied from different perspectives [46], the most prolific explanations of the factors and processes involved come mainly from two research programs on interpersonal coordination: (a) the dynamical systems perspective and (b) social neuroscience. The dynamical systems approach assumes that interpersonal coordination is governed by the universal laws of self-organization of natural systems [46–50]. Therefore, much of the research in this approach has attempted to evidence whether the dynamic principles governing the coordinated movement of fireflies, schools of fish, and human limbs can also predict and explain the temporal synchronization of bodily movements among people performing joint tasks [49]. Empirical evidence reveals that, indeed, motor coordination patterns of individuals performing highly structured joint tasks are constrained by the same mechanical [51–58] and perceptual [55–60] factors that limit other movements in other natural systems via personal [45, 61–65] and contextual constraints [42, 66–69].

Using the tools and theories of cognitive neuroscience, social neuroscience seeks to understand the cognitive processes that allow people to properly understand and store personal information about each other [70]. For this approach, a truly comprehensive theory of social phenomena must consider the biological, cognitive, and social levels of organization that constitute social phenomena as well as the different relations among them [70, 71]. Consequently, neuroscientists have inquired into the cerebral structures and brain dynamics that support human social abilities. For social neuroscience, interpersonal coordination is a particular case of social cognition comprising different cognitive mechanisms that allow a person to synchronize his/her movements with some referent, in this case, another human being. In this sense, empirical evidence highlights relevant neural networks as revealed via simultaneous cerebral recordings of two subjects as they perform similar tasks or engage in social activities [72], using the same tools and techniques typically employed to describe individual brain activity—such as functional magnetic resonance imaging (fMRI) [73], electroencephalography (EEG) [28], and near-infrared spectroscopy (NIRS) [30].

In this chapter, we review empirical evidence from both perspectives and highlight a set of theoretical and methodological pitfalls that obstruct understanding of interpersonal coordination as a social and affective phenomenon occurring in naturalistic settings. Finally, we will propose that interpersonal coordination should be studied with the assumption that people engage in mutually constructed and meaningful interactions. We will thus argue that the study of interpersonal coordination should focus on emergent properties of interaction, which do not pertain to individuals, but rather emerge as a holistic organization of changes between subjects situated in a meaningful context.

2 The Dynamical Systems Perspective

Thirty years of research on the coordination of movements among people performing tasks individually or jointly has favored the emergence of the dynamical systems perspective. This framework conceptualizes interpersonal coordination as a complex, interactive, and dynamic system governed and limited by the self-organization laws of natural systems [46–50]. This approach is often referred to as "ecological and dynamical systems perspective," because it entails the recognition of reciprocal interactive effects between multiple levels of organization of perception-action systems interacting in environments.[1] This viewpoint hinges on at least four basic assumptions about interpersonal coordination. The first one is that interpersonal coordination should be understood as a complex and multilevel system. This means that it is a phenomenon composed of several elements that reciprocally interact and organize at different levels of complexity. Coordination of bodily movements involves synchronization of multiple elements that shape intra- and interindividual perception-action systems. The interacting elements begin to couple, producing temporally stable states of synchronized activity between people. Interpersonal coordination is thus conceived as a collection of patterns that emerge

[1] Note that, for the dynamic systems perspective, the concept of "ecology" is far removed from the traditional notion that denotes the study of the way human beings conceive, value, use, and impact their environment.

in the course of connection experiences between different levels of organization. This avoids the inclination to fragment the phenomenon into discrete units contained in the body (e.g., representations, neural networks, single limb movements). However, we presume that the study of bodily movement—and its coordination—in terms of the "outcome" of reciprocal interaction processes between elements of systems does not necessarily elude a solipsistic approach to the phenomenon.

The second principle assumes that interpersonal coordination emerges from reciprocal relationships among people's bodies and environments. Since "others 'moor' us in space and time" [49] p. 323, synchronization between people can be understood as part of a spontaneous tendency by which they are physically and socially pulled or attracted into the activity field of another's movements. Supposedly, this axiom highlights the relational and ecological nature of coordination phenomena between people, but it should be noted that relations are described in terms of natural laws and that the environments are devoid of meanings and values. In addition, within the framework of this principle, the perspective of dynamic systems states that the analysis unit is not the internal processes nor the movement of a particular body, but rather the reciprocal relationships between people's brains and bodies, while they interact in their environments. Therefore, the analysis unit is social in nature, as shared movement between people reveals their feelings of connection and social bond with others [48, 50]. In this respect, note that the social aspect of this perspective is reduced to the mere copresence of an interaction partner. We are sure that such a condition is necessary but not sufficient for interpersonal coordination to occur, and we are less convinced that an interaction described in such terms can account for a true social unit.

The third principle states that synchrony patterns of movements change over time, configuring temporally stable orders of motor coactivity. The spontaneous formation of these orders can occur at different time scales (e.g., milliseconds, seconds, minutes, weeks, etc.), as "time defines the frames of reference for our past, present, and future behavior" [49] p. 323. The last principle states that changes in coordinating patterns of movement can be explained by self-organization laws of natural systems [49, 50, 74]. This means that recursive interactions among the components of the system give rise to increasingly complex motor coactivity patterns (e.g., shift from no coordination to time-delay coordination or zero-lag coordination) [49, 75]. Reorganization of these temporally stable coordinated motion patterns occurs in phase transitions, that is, abrupt and nonlinear changes in the organization of the system. Thus, stability periods are followed by a phase transition that is characterized by an imbalance of the established patterns. After this period of fluctuation, the system stabilizes, giving rise to new patterns. Sensitivity to changes in the structure of coordinated patterns of movement is precisely due to multilevel relations underlying these phenomena. However, a tendency toward stabilization prevails. The degree to which movements are synchronized during a phase transition is variable, flexible, and sensitive to disturbances. However, before and after the phase transitions, the pattern is less variable, tending to remain relatively unchanged for a period of time.

Initially, the fourth of these principles led to a vast and productive line of research on the dynamics underlying intrapersonal coordination of movements. The ensuing evidence not only revealed that coordination of the limbs in a single person performing bimanual tasks is governed and limited by the self-organization laws of natural systems but also allowed the mathematical modeling of such dynamics [76–81]. Indeed, the HKB model [77] characterizes dynamical phase transitions (e.g., switching from antiphase mode to inphase mode due to an increase in movement frequency) and dynamic constraints that increase lags and variability in coordination patterns (e.g., differences in oscillator frequencies). Later, dynamic systems research concentrated its efforts on verifying whether dynamic constraints modeled by the HKB equation for intrapersonal coordination also governed coordination of movements between people [46–48, 50]. Thereby, the first studies on interpersonal coordination focused on the dynamic constraints underlying coordination of movements among people. Subsequent studies have further considered the conditions under which coordination of movements between people entails social connection. In the following subsections, we present the conceptual approaches and empirical evidence on each of these lines of research.

2.1 Dynamic Constraints of Coordinated Movement

A dynamic approach understands that coordinated movement between people is constrained by inherent dynamics at their perception-action systems [50, 82]. This principle is supported by abundant research that found the same dynamic constraints for intrapersonal and interpersonal coordination [55, 56, 82–84]. Studies in this field have traditionally used experimental tasks in which pairs of subjects, sitting side by side, are asked to swing one of their limbs at the rhythm of a metronome while trying to synchronize with symmetric or alternate movements of their interaction partner. For example, Schmidt [82] conducted frame-by-frame analyses of two subjects' leg movements in studies that manipulated the type of movement requested and the metronome oscillation frequency. In a first study, participants were asked to move the lower part of their legs at the metronome oscillation frequency while simultaneously trying to maintain the same movement (inphase mode condition) or alternate movement (antiphase mode condition) with respect to the interaction partner; participants were also asked to try to return to the initial phase after a coordination failure. The results of this study reveal less stability in the coordination of alternating movements as the metronome frequency increases, while the stability of symmetrical movement coordination remains constant. In a second study, instructions were similar to those of study 1, except that the participants were asked to maintain the new phase mode once a coordination failure occurred if this new phase mode was easier to maintain. The results of the second study revealed that as the metronome frequency increases, a phase transition occurs from the antiphase mode to the inphase mode but not the other way around. This observed phase transition possesses the physical bifurcation properties previously reported by Haken [77] and

Schöner [85] in intrapersonal coordination: coordination of alternating movements gradually weakens, goes through a period of critical fluctuations, and finally arrives at a new state characterized by symmetrical coordination of movements. Another dynamic constraint of intrapersonal coordination was evidenced by Schmidt and Turvey [84] with pairs of participants who swung pendulums of different length under conditions of uncoupled or coordinated movements. They found greater decoupling in participants' movements as the difference in the lengths of the pendulums increased. Schmidt and O'Brien [83] corroborated previous findings during unintentional interpersonal coordination. These authors found that when pairs of subjects were asked to move the pendulums to their preferred frequency, a phase transition occurred toward a state of greater symmetry in the coordination of movements, but this coordination was never absolute. They also found greater stability in coordination when couples moved pendulums of similar length.

Findings on dynamic constraints have allowed a more complete understanding of mechanistic conditions favoring the emergence of temporally stable patterns of coordinated movement between people. However, the highly structured nature of the tasks calls into question the ecological validity of such findings [50, 86]. In real life, coordinated movements occur in situations that surpass the complexity involved in laboratory tasks requiring couples to stereotypically move at metronome rhythm while attempting to synchronize (inphase or antiphase) with specific limb movements by their interaction partner. This lack of naturalness in experimental environments is also characteristic of studies on dynamic constraints underlying unintentional interpersonal coordination. Although these studies allow subjects to move at their preferred frequency [55, 56, 87], the type of activities requested and the number of repetitions are distant from the conditions under which coordinated movements typically occur in real social interactions [88].

2.2 Socio-environmental Constraints of Coordinated Movement

The socio-environmental approach not only assumes that interpersonal coordination can be predicted by dynamic laws of individual perception-action systems; it also claims that interpersonal coordination can be predicted from constraints resulting from situated interaction between multiple perception-action systems. According to this view, interpersonal coordination is more than simple mechanical coordination of movements. It configures a "social unit" in which patterns of synchronized movements describe the linkages between people [48, 50]. As long as the phenomenon emerges from interactions with others, it cannot be studied independently of the set of exchanges in which patterns of coordinating activity emerge, organize, and reorganize. Studies in this area have explored at least three types of socio-environmental factors as predictors of interpersonal coordination: (1) perceptual access to the interaction partner, (2) personal characteristics of the interaction partner, and (3) features of the interactional situation. Mainly, the experimental settings of such studies include the use of joint action paradigms in which pairs of participants are asked to perform simple limb movements (such as finger tapping, rocking in a rocking chair, postural swaying, swinging pendulums, walking, jumping, dancing, climbing stairs), play a musical instrument, play a video game, or, to a lesser extent, engage in conversations. In general, movements of individual limbs or displacements of objects by joint task participants are recorded through motion-tracking devices such as accelerometers, potentiometers, electrogoniometers, and optical and magnetic capture systems. Such devices yield time-series measurements of movement variation in space (e.g., angles, velocity, acceleration, and distance) and allow implementing linear and nonlinear analysis methods (e.g., cross-recurrence quantification analysis, circular variance of the relative phase, cross-correlations, cross-spectral coherence, and distribution of relative phase angles).

Concerning the effects of perceptual constraints on interpersonal coordination, the movement of pairs of subjects participating in joint tasks is usually compared under conditions in which they have and do not have visual, auditory, or haptic access to their interaction partner [55–60, 83, 89, 90]. For instance, Oullier [90] studied the influence of visual coupling on spontaneous social coordination in pairs of people participating in a finger-tapping task under conditions in which they could or could not see each other's fingers. The results revealed that finger coordination between pairs occurs as soon as they exchange visual information. Richardson [55] contrasted the movement of dyads rocking in rocking chairs under conditions in which they could see the total or peripheral movement of their partner. Their results suggest a major stability of unintentional interpersonal coordination when an individual focuses visual attention directly on the partner's movement, compared to instances in which individuals have peripheral access to that information. Using the same paradigm, but this time contrasting visual and verbal constraints, Richardson [56] found greater unintended interpersonal coordination when participants had access to visual information compared to the condition where they only had access to verbal information from the partner. Demos [59] compared visual (vision, no vision) and auditory (no sound, rocking sound, music) conditions between dyads rocking in rocking chairs. Their results suggest that spontaneous coordination occurs under conditions of both seeing and hearing the other person rocking, but "coupling with the music was weaker than with the partner, and the music competed with the partner's influence, reducing coordination" [59] p. 49. The impact of access to peer visual information on interpersonal coordination and its prevalence compared with other types of perceptual information has been reported in other studies [87, 89, 91, 92]. However, in the case of people with musical training, Nowicki [60] found greater interpersonal coordination under conditions in which they had access to auditory feedback on the partner's musical performance, compared to a condition in which they had access to visual feedback. Other studies also highlight the relevance of access to haptic information in the consolidation of coordinated movement patterns between dyads swaying rhythmically [57, 58]. Taken together, these studies have made it possible to understand the impact of informational dynamic constraints on interpersonal synchronization. However, it is noteworthy that in these studies, the social and environmental aspects are reduced to the exchange of perceptual information between the interactants. Similar to studies of dynamic constraints, studies of informational constraints do not pay much attention to the truly social aspects underlying coordinated patterns of movement, that is, the values and meanings involved in synchronized motor actions.

Other studies have been conducted to ascertain the effect of personal characteristics on interpersonal coordination. For example, to study the influence of prosocial and pro-self orientation on interpersonal coordination, Lumsden [61] executed a study with individuals participating in an arm curl coordination task (to the rhythm of a metronome) with a virtual confederate (a prerecorded video). The results revealed that participants with a pro-social orientation were more coordinated with the virtual confederate than those with a pro-self orientation. In another study, Schmidt [93] found higher levels of synchronization in pendulum swinging tasks performed by dyads with heterogeneity in their social competence (high-low), compared to couples with homogeneity in their social competence (high-high and low-low). Recently, Zhao [65] reported higher levels of synchronization in individuals who believed they were performing a motor coordination task with a physically attractive virtual confederate, in contrast to individuals who believed they were interacting with a less attractive virtual confederate.

Research has also been conducted on personal characteristics that reduce the probability of consolidating patterns of coordinated movement with others. Marsh [62] reported a lower degree of motor coordination between the rocking of children diagnosed with autism spectrum disorders and an adult (both sitting on rocking chairs side by side during story reading) in comparison with typically developing children in the same experimental situation. Similar results were found by Varlet [94] in adults diagnosed with social anxiety disorder. Patients presented less motor coordination with their interaction partner in a pendulum oscillation task than the healthy control group. This line of research has allowed a broader understanding of personal factors that promote or inhibit coordination between people. However, this approach still neglects the study of the social and environmental nature of the phenomenon to the extent that the emphasis is on how individual variables impact or determine patterns of coordination between people.

Another group of studies has demonstrated that some characteristics of social contexts differentially impact coordination levels among interactants. Experimental studies via classic paradigms involving the movement of objects or individual limbs of joint task participants have shown that interpersonal coordination occurs in competitive, collaborative, and recreational contexts [66, 95, 96]. Such studies have also shown that engaging in emotionally negative contexts could decrease or extinguish coordinated behavior. For example, Miles [42] asked individuals to partake in a stepping task with a female confederate, who half of the times arrived 15 min late. The results evidence that inphase synchrony was significantly reduced when participants interacted with the confederate who arrived late. These results are consistent with evidence from more naturalistic studies that highlight higher levels of interpersonal coordination in affiliative conversational contexts than in argumentative conversational contexts [68, 70]. However, the scope of these studies' conclusions is limited by the lack of accurate and fine measurements of the movements of participants in naturalistic conversations; these studies typically use automated video analysis techniques, such as frame differencing, motion energy analysis, and correlation map analysis. Although research on interpersonal coordination in conversational contexts has opened up a promising outlook for understanding the socio-environmental nature of this phenomenon, studies that accurately measure movements in more naturalistic contexts are urgently needed.

3 Social Neuroscience

With the emergence of the so-called interactive turn in cognitive science [97], social neuroscience has begun to study the dynamics of interpersonal coordination. This pursuit has been undertaken with the tools and theories offered by studies of social cognition. Empirical evidence from a wide variety of studies on social cognition has illuminated the roles of specific brain regions in social cognition tasks. For example, different neural networks that operate during social cognition tasks have been identified. Kennedy and Adolphs [72] highlight four core neural networks that can be described in the brain when it engages in social activities: (1) the amygdala network, (2) the mentalizing network, (3) the empathy network, and (4) the mirror-simulation network.

With the goal of generating a comprehensive account of social phenomena, Cacioppo and Berntson [71] have outlined several principles that should guide the empirical and theoretical aspects of social neuroscience. The first principle is multilevel determinism, which specifies that behaviors can have multiple antecedents across various levels of organization. This principle highlights that a truly comprehensive theory of social phenomena requires consideration of multiple levels of organization underlying social cognition phenomena and that the mappings among elements across proximal levels of organization become more complex as the number of intervening levels increases [70]. The second principle is nonadditive determinism, which specifies that the properties of the whole are not always predictable by the sum of the recognized properties of the individual levels. The last principle is reciprocal determinism, which highlights the mutual influences between biological and social factors in explaining behavior [71]. A consequence of the above-outlined principles is that a comprehensive account of human social behavior cannot be achieved taking into account only the biological, cognitive, or social level. To give a fully comprehensive and non-reductive view of the social cognition, multiple levels (personal, biological, cognitive, and social) should be addressed assuming their nonadditive, mutually influencing, and multi-layered nature.

Nevertheless, in spite of the integrative approach, social neuroscience has seen interpersonal coordination as a particular case of social cognition. Social cognition approaches different social phenomena as cognitive processes that occur within the mind of an individual, who constructs models of other people's mental states and who uses these models to predict and explain others' behaviors and intentions (see [98]).

Under this assumption, interpersonal coordination is understood as the set of internal mechanisms that allows a person to synchronize his/her movements with some referent who, in the particular case of interpersonal coordination, happens to be another human being. In what follows, we will present the two main conceptual approaches that have been proposed to understand this phenomenon: representationalism and interactivism.

3.1 Representationalist Approaches to Interpersonal Coordination

A representationalist theory conceives social cognition as a cognitive process that occurs within the mind of an individual, who constructs models of other people's mental states. This approach assumes that the cognitive processes necessary for social interaction are internal and individual, such that one can understand social life by studying individual minds in isolation. A large amount of research in social neuroscience has embraced this view. Common experimental paradigms in social neuroscience typically place human participants in fMRI scanners, devices that constrain the natural movement of the subjects. Once in the scanners, participants are asked to respond to "social" stimuli by observing pictures or videos of other people. These studies have identified several brain areas that respond in social settings, such as the amygdala, the orbitofrontal cortex, the temporal cortex, and the medial prefrontal cortex [17].

Many fMRI paradigms have employed this kind of pseudo-interactive setting. In these cases, the experimental situation relies on scanning one person at a time or on telling participants that they are interacting with a real person, while they are actually interacting with a computer. In a study conducted by Earls [36], Caucasians showed higher peak activation while observing (via a recorded video) and imitating the hand movements of Caucasian actors, relative to observing and imitating the hand movements of African–American actors, in key areas of the previously defined action simulation network: the inferior frontal gyrus, the inferior parietal lobule, the superior parietal lobule, and the superior temporal sulcus. In a study conducted by Cacioppo [35], participants inside a fMRI scanner played a game called "bexting" (beat-texting), which consisted of simple back-and-forth keyboard tapping as if two people were texting each other. Participants were told that they were exchanging texts with another person in the room, whereas they were really interacting with a computer programmed to respond synchronously (in the same rhythm) or asynchronously (in a different rhythm) to the player tapping. The synchronous tapping condition was characterized by greater response in the left inferior parietal lobule, the parahippocampal gyrus extending to the amygdala, the ventromedial prefrontal cortex, and the anterior cingulate cortex.

In sum, the major achievement of individualistic approaches is that they have identified those brain areas that regularly become more active with social stimuli, such as the left inferior parietal lobule, the parahippocampal gyrus, the amygdala, the ventromedial prefrontal cortex, the inferior frontal gyrus, and the inferior parietal lobule [35, 36]. Nevertheless, the representationalist approach to social interaction and interpersonal coordination has been criticized, as the studied social situation does not consist of a true and ecologically valid interaction with another person. Such experimental paradigms severely constrain mutual information exchange and continuous adaptation among interacting participants. Social interaction seems to be substantially different in situations wherein people are engaged in a social unit, compared with situations in which people are acting alone [99, 100].

3.2 Interactivist Approaches to Interpersonal Coordination

Claims about ecological validity have led to an alternative approach to understand social interaction. This perspective considers social cognition as a process that occurs between dyads or among people interacting together, coordinating their actions in a common space and time. Real-life social cognition requires two or more subjects in live interaction [17]. This "interactivist" view has moved away from studying brains in isolation, toward the study of more than one brain in live interaction. Empirically, this perspective implies the study of people during coordinative actions, which requires measuring brain dynamics during live interaction.

Accordingly, social neuroscience has recently examined interpersonal coordination processes under constructs such as "brain coherence" [30], "brain activity coupling" [37], "interbrain coupling" [28], "interbrain synchronization" [26], and "inter-subject neural synchronization" [31]. Researchers have used the term "hyperscanning" when any fMRI, electroencephalography (EEG), or near-infrared spectrometry (NIRS) setup is used to simultaneously track two or more brains [29, 73, 101]. The goal of hyperscanning techniques is to provide simultaneous recordings of brain activity in interactional settings that involve two or more subjects [101].

The first hyperscanning of cerebral activity during interactions between subjects was reported by Montague [73]. In their work, two participants were scanned using two different fMRI devices during a simple game. One participant was assigned to the role of sender; the other, to the role of receiver. Black or white stimuli were presented on the screen of the sender, who could decide which color to transmit to the receiver through a computer screen. The receiver had to determine whether the sender was sharing the true color presented on her screen. Montague et al. [73] observed common activity in the supplementary motor areas of both the sender and the receiver.

In recent times, EEG and NIRS have also been used to study the neuronal dynamics of more than one brain, while different participants perform a given activity [27, 28, 102]. For example, Astolfi et al. [26] obtained EEG recordings from two pairs of subjects playing a card game to measure the neural dynamics of cooperation during face-to-face interaction. They found functional connectivity in the alpha, beta, and gamma bands between the cooperating pairs but not the competing pairs, showing different patterns of cortical activity in different interactional situations. Konvalinka et al. [28] conducted an EEG hyperscan to explore the neural mechanism underlying coordinative and complementary behavioral patterns during joint action. They had participants (seated with their backs to one another) tap together synchronously or to follow a computer metronome in the control condition. The degree of tapping coordination between participants was used to measure leader-follower behavior in each pair. They assessed the adaptability of one member in relation to the other; for example, if member A was leading, member B would change the speed of his/her movements to adapt to A's rhythm. When participants interacted with another person, but not with the computer metronome, the researchers found suppression of alpha and low-beta oscillations over motor and frontal areas. They also found asymmetric brain-coupling patterns or complementary patterns of individual brain mechanisms. Specifically, they found frontal alpha-suppression, especially for the leader, during the anticipation and execution of the task. Their results suggest that leader-follower behavior can emerge spontaneously in dyadic interactions and that leaders invest more resources in prospective planning and control.

In a NIRS study performed by Cui et al. [30], participants sat side by side and played a computer game in which they had to either cooperate or compete. Each trial began with a hollow gray circle at the center of the screen, visible for a random interval between 0.6 and 1.5 s. Subsequently, a green cue signaled participants to press keys simultaneously using the index or middle finger of their right hands. If the difference between their response times was smaller than a threshold, both participants were rewarded with one point; otherwise, both participants lost one point. The competition task was similar to the cooperation task, except that each participant was rewarded for responding faster than his/her partner. The authors found interbrain coherence in the frequency band between 3.2 and 12.8 or between 0.3 and 0.08 Hz in the superior frontal cortex during cooperation but not in the competition condition.

Both "isolated brain" experiments [35, 36] and "interactional experiments" [26, 28, 30] explore the mechanisms underlying interpersonal coordination. Nevertheless, they explore different aspects. The isolated brain approach inquiries into individual processes involved in processing social stimuli, exploring which brain areas or neuronal networks became active during observation of (or judgment about) others or during pseudo-interactions in which there is no real-time feedback between the interactants [37]. In turn, the interactive approach explores the mechanisms needed to interact with another person, during task of mutual coordination. The two perspectives complement each other in quantifying different properties of social interactions [17]. These approaches have allowed the scientific community to achieve a better grasp of the neuronal level of interpersonal coordination processes.

3.3 Psychophysiological Measures of Interpersonal Coordination

In the study of interpersonal coordination, brain activity corresponds to one important level of a phenomenon that involves the whole person—an important level, yet not the only one. Psychophysiological measures of interpersonal coordination have also been used since the 1980s [103], revealing the centrality of the affective dimension involved in social interactions. For example, heart rate and galvanic skin response are relatively unobtrusive methods that have been used to capture the bodily dynamics that occur among people in different kinds of interactions, on time scales as short as minutes or even seconds. Synchrony of involuntary and automatic psychophysiological responses has been found across a broad range of contexts. For instance, Levenson and Gottman [103] evidenced heart rate synchrony between spouses engaged in conversation. More recently, Chatel-Goldman [22] observed that touching each other increases skin conductance synchrony in couples. Additionally, Mønster [23] found evidence of skin conductance synchrony among team members during a cooperative task.

Heart rate and skin conductance have also been used to address interpersonal coordination in groups. Strang [21] aimed to identify the relationship between physio-behavioral coupling and team performance. Dyads played cooperatively and were assigned to the roles of rotator or locator in a variant of the Tetris video game. The researchers measured physio-behavioral coupling by means of the coupling strength between cardiac inter-beat intervals and used a self-report questionnaire that assessed group cohesion, team trust, effectiveness of team communication, and collective efficacy. They found that physio-behavioral coupling exhibited negative relationships with team performance and team attributes, such as cohesion, team trust, and effectiveness of team communication. These findings imply that team attributes generally increased with decreases in physio-behavioral coupling, reflecting a complementary process of coordination (as opposed to mirroring coordination) during task performance, potentially due to different team roles, such as rotator or locator.

3.4 Common Coding Theory

Even though there are many empirical findings about neuronal correlates of interpersonal coordination, there has been little theoretical or conceptual consideration of this phenomenon [17, 101]. One main conceptual approach that has been used in the study of interpersonal coordination holds that coordination is based on a “common coding mechanism” [104–106]. From this perspective, successful interactions between people depend on their capacity to attribute mental states to others.

Because of the centrality of the mirror neuron network in this theoretical approach, here we briefly review its central aspects and address its relevance for research on interpersonal coordination. Mirror neurons, first discovered in nonhuman primates in the premotor cortex, are said to be activated when subjects engage in instrumental actions and when one participant sees another person engage in those actions [107, 108]. The activation of this neuron assembly is related to grasping the intention of the acting individual (thus supporting a form of mind reading). Different studies note that this system discriminates among physically identical movements according to the pragmatic contexts in which these movements occur [109–111]. The evidence that links the mirror neuron system with interpersonal coordination is the finding that people rely on their own motor system when perceiving and predicting others' actions [112].

According to common coding theory [105], the links between mirror neurons and interpersonal coordination explain how interpersonal coordination occurs among people. More precisely, it explains how people predict the action of others to allow a successful pattern of coordinated behaviors. The discovery of the mirror neuron system is said to provide a neural substrate for interpersonal coordination. Coordination processes would be based on the coding and integration of the outcomes of the actions of others and one's own actions. To engage in coordinated behaviors with others, we must understand what others are doing and predict what they will do [105]. For interpersonal coordination to happen, people must predict three aspects of the behavior of others. First, predictions must indicate what kind of action the other will perform as well as the intention that drives the action. Second, predictions should provide information about the temporal unfolding of the action to allow swift, effective interpersonal coordination of actions. Finally, predictions should provide information about the spatial unfolding of the actions of others to effectively distribute a common space to avoid collisions and optimize movement.

In making these predictions, the brain is theorized to rely on the mechanisms of its own motor system. These mechanisms are supported by feed-forward models of sensory feedback in various modalities [105, 113]. Thus, the prediction models are based on the internal motor commands that the observer would use for performing the action himself [113, 114]. Therefore, the same processes underlying individual action planning are involved in predicting the actions of the other person.

4 A Critique of the Theoretical Models of Interpersonal Coordination

Even though interpersonal coordination was initially documented more than 50 years ago at behavioral level [2], the first report of interbrain synchrony appeared only in the last decade [73]. This delay is due partially to the considerable technical difficulties that needed to be overcome to enable recording and analysis of the brain activity of two (or more) interacting people. If the mathematical processing of the brain activity of one individual is complex, the task of identifying synchrony between two or more brains is doubtlessly more difficult. However, it is worth noting that cognitive neuroscience faced questions of similar mathematical difficulty years ago, such as olfactory bulb modeling [115] and intrabrain synchrony [116]. Thus, the main factor to explain such a delay should be sought at a conceptual rather than a methodological level.

Since cognitive neuroscience inherits the same philosophy of mind that originally inspired the cognitive revolution, some of its substantive assumptions continue in contemporary neuroscience. One of these is the idea that the cognizing agent operates while radically isolated from others. Knowledge is originated and stored in individual entities, which encounter the environment isolated from their fellows. Even more, the others like me are in principle another kind of things, whose specific features (e.g., having minds) must first be proven. Thus, the fact that other persons are mind-endowed entities is not a starting point but rather the result of a calculation occurring over the first years of life, from which the cognizing entity infers that the complexity of the other's behavior cannot be explained unless proper desires, intentions, and beliefs are ascribed. Considering this inherited view of mind, it is not difficult to understand why the study of socio-interactional phenomena, such as interpersonal coordination, took time to enter the focus of cognitive neuroscience.

The solipsist bias is still recognizable in several socio-neuroscientific approaches to interactional phenomena. For example, despite its focus on joint actions, common coding theory, paradoxically enough, assumes an individualistic approach to social cognition. From a philosophical perspective, the emphasis on predicting the mental states of others has been put into question [117, 118]. Common coding theory holds several assumptions about social interaction. The clearest one is the mentalizing supposition, which assumes that to understand and coordinate with others, we must infer their mental states and future actions. This assumption entails that people must be observers and adopt a third-person attitude toward other people as a condition to explain and predict their behavior.

By denying access to other minds, common coding theory assumes a priori the opacity of others. It is precisely because of the alleged absence of experiential access to other minds that we need to rely on and employ internal simulations. Hidden mental entities should be inferred to predict the actions of others [105] from the actions of publicly observable bodies. Nevertheless, there is a difference between arguing that the mental models are a way to understand the experience of others and claiming that mental models are the only way for understanding the experience of others [117]. This difference is disregarded in common coding theory, which assumes that social cognition processes occur in the isolated minds of people by generating feed-forward models.

Furthermore, there are empirical facts on interpersonal coordination that can hardly be explained if one assumes that the core of social understanding lies in predicting the future actions of others. In particular, evidence shows that people synchronize their movements simultaneously when interacting socially. Cornejo et al. [86] studied interpersonal coordination through an experimental paradigm in which people talked and moved rather spontaneously. Bodily movements were tracked by an optical motion capture system. They conducted two studies aiming to describe patterns of interpersonal coordination in situations of trust and distrust. The results of both studies show a simultaneous coordination of the participants' movements during the conversations. This strongly suggests the presence of a kind of interpersonal coordination that occurs with no time delay between the participants' movements. These findings highlight that zero-lag coordination occurs on a faster time scale than simple human reaction times, which implies that it cannot be interpreted as an imitative movement by one participant with respect to the other. The findings of Cornejo et al. [86] also reveal that speakers coordinate their movements with listeners' movements—both simultaneously and with a delay. Speakers also react to their listeners in a chain of dynamic coordination patterns affected by interactants' immediate disposition and long-term relationship. Thus, interaction dynamics implies complex processes of coupling and mutual adaptation. It is not clear how common coding theory [105], whose explanatory factor resides on predictive mechanisms, can explain zero-lag coordination, in which coordinative movements among interactants are perfectly simultaneous.

Dynamic systems approaches are possibly in a better position to overcome the solipsistic bias still present in social neuroscience. As described above, this set of theories overcomes the inherited idea that a social interaction is no more than the encounter of two encapsulated, mutually inaccessible individualities. On the contrary, they propose as a unit of analysis the complex system that emerges from the interaction among the individuals: interacting people would constantly and unintentionally configure a "coupled system" [68]. As long as the coupled system existed, the rules for dynamic complex systems would apply. Although this approach succeeds in dealing with the individualistic bias of traditional cognitive neuroscience by avoiding the burden of the concept of representation, it falls into another pitfall of a different sort. By modeling human interaction as another type of dynamic complex system, it blurs the substantive differences between human social life and any other complex system in the physical world. From the fact that the atmospheric movement of gases, the stock market, and the immune system exhibit complex behavior, it does not follow that these entities are ontologically the same. From the fact that a certain explanans (in this case, a certain mathematical model) is helpful to describe a certain explanandum (in this case, human interaction), it does not follow that both are the same thing. Human interaction is not a dynamic complex system, just because nothing is per se a dynamic system. Rather, certain phenomena can be described as such. It may well be the case that human interaction displays features described through nonlinear mathematics—as do several other, quite different phenomena of the natural world. If this is the case, dynamic system theories are necessary but not sufficient to explain human interaction. The task remains to explain what distinguishes this complex system from other (perhaps physical) complex systems.

Unfortunately, the specificity of human interaction is conspicuously absent in dynamic system approaches to social coordination. Most of the specifically human features of interpersonal coordination are omitted from such conceptualizations. We know, for example, that interpersonal coordination is particularly sensitive to social factors: interpersonal coordination will be stronger or more stable if interactants perceive themselves as similar [40], if they share the same social membership, or if they are cooperating rather than competing [31]. There are essential, substantive insights to be drawn from the empirical evidence thus far collected that are risk of being overlooked because they need a specifically human vocabulary—distant from the allegedly neutral vocabulary of dynamical systems theory.

In brief, the theoretical advances of the last few decades on interpersonal coordination give us two important lessons for the future. First, we need to overcome the inherited assumption that social interaction implies an encounter with opaque entities whose mentality the individual must decipher. Second, social interaction has human-specific traits whose understanding should be undertaken to capture a faithful description of human interaction.

5 Recovering the Meaning of Human Interaction

Extant evidence on interpersonal coordination underlines important features of human interaction that have been overlooked by individualistic and dynamical perspectives. One of these facts is that interpersonal coordination, far from being a brain phenomenon, involves the whole bodies of the interactants. Psychophysiological evidence is quite expressive in this respect. As presented above, we know that there is coordination of heart rates between spouses [103] as well as of skin conductance in dyads during cooperative tasks [23]. Moreover, mothers and infants coordinate their ECGs in moments of affective synchrony [119]. There is also evidence of higher heart rate synchrony in trust interactions [20]. Finally, evidence from motion capture devices shows that interpersonal coordination not only involves the whole bodies of participants in a social interaction but also, crucially, that they can be perfectly simultaneous [27, 86].

A second claim robustly supported by empirical evidence is that interpersonal coordination appears and becomes stronger whenever an activity is performed together with others [24]. Interpersonal coordination is stronger when interactants are hearing the same music [120, 121] and when they are performing a task directed toward a common goal [122]. It is relevant to note that everyday joint actions are not equivalent to coordinated movements: in social life, joint actions are deployed when the interactants understand what the common goal is. Human actions are always socially embedded; thus, interpersonal coordination never occurs in a social vacuum. In everyday life, people share an ample base of background knowledge, which makes social interactions always meaningful [123]: the individual understands others' movements not like the movements of objects but rather as actions, i.e., as meaningful movements. This social background provides a substratum that cuts across sensorial, motor, and cognitive processes. In our view, this is the fact that explains the constant result that interpersonal coordination becomes enhanced when interactants have visual contact [59, 60, 89, 91, 94].

A third systematic observation is the tight relation between interpersonal coordination and positive affect. We know that interpersonal coordination is strongly associated with empathy [40, 124] and with the perception of pro-social disposition in the other [61]. Interpersonal coordination is particularly enhanced whenever interactants trust each other [20, 125] or whenever interactants perceive themselves as belonging to the same reference group [36]. Finally, there is ample evidence that interpersonal coordination is higher in cooperative interactions than competitive ones [23, 27, 30, 31, 34].

From a broader viewpoint, interpersonal coordination corresponds to a basic anthropological phenomenon (behaviorally and neurophysiologically measurable) that is tightly associated with the establishment and maintenance of social bonds. It emerges with positive affect (trust, empathy, and collaboration) and tends to disappear when this affective matrix is broken. Interpersonal coordination emerges also when interactants are embedded in a "co-phenomenology" [123]—also called "we-mode" [126] or "we-relationship" [127]. It is not something that occurs in the mind of an observer but something that emerges as in an intersubjectively shared space [97, 123]. This most natural and pre-reflexive kind of interaction allows people to share a common sense within which movements are meaningful actions. It is this tacit background that makes people coordinate permanently and simultaneously and even anticipate others' movements. Its automatic, nonreflexive character is also supported by empirical evidence: interpersonal coordination tends to be higher when it is unintentional than when it is intentional [39, 45, 55, 56, 83, 128]. In addition, Konvalinka et al. [28] showed that whenever interactants are asked to lead an interaction, the symmetric brain coupling changes its dynamics, possibly due to the leader undertaking a planning process that puts her outside the natural attitude.

One aspect that should be underlined is that this interpretation of interpersonal coordination assumes that the most natural way to interact with others is not solipsistically but intersubjectively. Schütz [127] notes that in social relations our consciousness is interlocked, with each person's mental states immediately affecting the other, and in such situations, there is a form of immediate interpersonal understanding. In the most basic way to interact, we do not approach them from a third-person perspective. People are primordially not things for us. They can, under certain circumstances, become like things, when we are forced to abandon the we-relationship and theorize about their real intentions. In those circumstances, we are reflecting on the other individual's behavior, and it is likely that no interpersonal coordination will be perceptible anymore.

6 Conclusion

Given the wide availability of brain-imaging techniques and methods to measure interpersonal coordination, perhaps the most important challenge in this area is to build a coherent theoretical framework for integrating the existing results. Here, we proposed that instead of assuming that interpersonal coordination requires prediction mechanisms or that it is another physical-like dynamical system, a theoretical framework should focus on the construction of a common social and affective space.

We stated that the study of interpersonal coordination has been advanced basically by the dynamical systems perspective and by social neuroscience. However, despite the use of sophisticated methods to capture and analyze neural and bodily synchrony, the methodological efforts of both perspectives were still detached from real-life human interactions. In most studies, emphasis is placed on the accurate measurement of dyads' actions (movements or neural activity) but only during highly structured tasks, focusing on the individual brain/mind or paying little attention to the affective and social nature of face-to-face encounters. This bias is particularly strong in social neuroscience, since it inherits the axiom that social interaction can be explained as the encounter of two individual minds attempting to decipher each other's mentality: first comes the individual mind, then social life. This axiom produces several anomalies, such as simultaneous coordination, that social neuroscience is in no condition to adequately explain. On the other hand, dynamic systems theory, while avoiding the problems of solipsism, dismisses the specificities of human interaction in favor of understanding it as any other dynamic complex system—including physical ones. The consequence of the complexity approach is neglect for the meaning of social life.

We advanced a theoretical alternative that satisfies both necessities: (1) studying interactions as such (and not as individual mental puzzles) and (2) recovering the meaning in social interaction. In this framework, interpersonal coordination is the behavioral/neurophysiological correlate of the most basic form of interaction, the we-relationship, in which an authentic co-phenomenology is felt and lived. This is the reason why interpersonal coordination is unintentional, strongly affective, bodily, and highly sensitive to a sense of common belonging.

Certainly, findings on interpersonal coordination have opened a new space to study the interactional context in which human actions occur. Future research needs to focus on integrating the different levels of analysis at which this phenomenon occurs while respecting the ecology of social life. The challenge is to build paradigms that reproduce real-life situations as much as possible, integrating the benefits of high-precision temporal recordings and a whole-body account of the brain and bodily dynamics that occur during a real human interaction.

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