Why Do We Fall into Sync with Others? Interpersonal Synchronization and the Brain's Optimization Principle

Spontaneous interpersonal synchronization of rhythmic behavior such as gait or clapping is a ubiquitous phenomenon in human interactions, and is potentially important for social relationships and action understanding. Although several authors have suggested a role of the mirror neuron system in interpersonal coupling, the underlying brain mechanisms are not well understood. Here we argue that more general theories of neural computations, namely predictive coding and the Free Energy Principle, could explain interpersonal coordination dynamics. Each brain minimizes coding costs by reducing the mismatch between the representations of observed and own motor behavior. Continuous mutual prediction and alignment result in an overall minimization of free energy, thus forming a stable attractor state.

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Oxytocin improves synchronisation in leader-follower interaction

The neuropeptide oxytocin has been shown to affect social interaction. Meanwhile, the underlying mechanism remains highly debated. Using an interpersonal finger-tapping paradigm, we investigated whether oxytocin affects the ability to synchronise with and adapt to the behaviour of others. Dyads received either oxytocin or a non-active placebo, intranasally. We show that in conditions where one dyad-member was tapping to another unresponsive dyad-member - i.e. one was following another who was leading/self-pacing - dyads given oxytocin were more synchronised than dyads given placebo. However, there was no effect when following a regular metronome or when both tappers were mutually adapting to each other. Furthermore, relative to their self-paced tapping partners, oxytocin followers were less variable than placebo followers. Our data suggests that oxytocin improves synchronisation to an unresponsive partner's behaviour through a reduction in tapping-variability. Hence, oxytocin may facilitate social interaction by enhancing sensorimotor predictions supporting interpersonal synchronisation. The study thus provides novel perspectives on how neurobiological processes relate to socio-psychological behaviour and contributes to the growing evidence that synchronisation and prediction are central to social cognition.

General information
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Prediction and adaptation mechanisms facilitating interpersonal coordination

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Authors: Konvalinka, I. (Intern)
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Syncopation affects free body-movement in musical groove

One of the most immediate and overt ways in which people respond to music is by moving their bodies to the beat. However, the extent to which the rhythmic complexity of groove-specifically its syncopation-contributes to how people spontaneously move to music is largely unexplored. Here, we measured free movements in hand and torso while participants listened to drum-breaks with various degrees of syncopation. We found that drum-breaks with medium degrees of syncopation were associated with the same amount of acceleration and synchronisation as low degrees of syncopation. Participants who enjoyed dancing made more complex movements than those who did not enjoy dancing.

While for all participants hand movements accelerated more and were more complex, torso movements were more synchronised to the beat. Overall, movements were mostly synchronised to the main beat and half-beat level, depending on the body-part. We demonstrate that while people do not move or synchronise much to rhythms with high syncopation when dancing spontaneously to music, the relationship between rhythmic complexity and synchronisation is less linear than in simple finger-tapping studies.

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Synchronised and complementary coordination mechanisms in an asymmetric joint aiming task

Many forms of social interaction require that behaviour be coordinated in the here and now. Much research has been conducted on how people coordinate their actions in real time to achieve a joint goal, showing that people use both synchronised (i.e. symmetric) and complementary (i.e. asymmetric) strategies. These two mechanisms have been mostly studied independently, the former in the context of rhythmic tasks, and the latter in non-rhythmic tasks. However, people often balance these two strategies in real life social interactions, in order to achieve a joint goal more effectively. Here, our aim was to investigate how people may implicitly balance synchronisation and complementarity in a continuous joint aiming task.

We asked dyads to synchronise the timing of their clicks between targets, while changing task constraints for one member of the dyad (i.e. different task difficulties) to asymmetrically perturb the continuous interaction. This allowed us to investigate how individuals implicitly negotiate complementary leader-follower dynamics to achieve synchronisation. We found that dyads flexibly switch from mutual to asymmetric adaptation given variations in task constraints. Specifically, our results show that both members adapt equally up to a certain level of difficulty; after this point, the partner with the difficult task becomes less adaptive, and hence more of a leader, while the adaptability of the member with the easier task remains unchanged. This proves to be an effective strategy in this asymmetric task, as people synchronise better with an irregular, but adaptive partner, than with a completely predictable, but non-responsive metronome. These results show that given asymmetric task constraints, adaptability, rather than predictability facilitates coordination.
Analyzing Social Interactions: Promises and Challenges of Cross Recurrence Quantification Analysis

The scientific investigation of social interactions presents substantial challenges: interacting agents engage each other at many different levels and timescales (motor and physiological coordination, joint attention, linguistic exchanges, etc.), often making their behaviors interdependent in non-linear ways. In this paper we review the current use of Cross Recurrence Quantification Analysis (CRQA) in the analysis of social interactions, and assess its potential and challenges. We argue that the method can sensitively grasp the dynamics of human interactions, and that it has started producing valuable knowledge about them. However, much work is still necessary: more systematic analyses and interpretation of the recurrence indexes and more consistent reporting of the results, more emphasis on theory-driven studies, exploring interactions involving more than 2 agents and multiple aspects of coordination, and assessing and quantifying complementary coordinative mechanisms. These challenges are discussed and operationalized in recommendations to further develop the field.
Frontal alpha oscillations distinguish leaders from followers: Multivariate decoding of mutually interacting brains

Successful social interactions rely upon the abilities of two or more people to mutually exchange information in real-time, while simultaneously adapting to one another. The neural basis of social cognition has mostly been investigated in isolated individuals, and more recently using two-person paradigms to quantify the neuronal dynamics underlying social interaction. While several studies have shown the relevance of understanding complementary and mutually adaptive processes, the neural mechanisms underlying such coordinative behavioral patterns during joint action remain largely unknown. Here, we employed a synchronized finger-tapping task while measuring dual-EEG from pairs of human participants who either mutually adjusted to each other in an interactive task or followed a computer metronome. Neurophysiologically, the interactive condition was characterized by a stronger suppression of alpha and low-beta oscillations over motor and frontal areas in contrast to the non-interactive computer condition. A multivariate analysis of two-brain activity to classify interactive versus non-interactive trials revealed asymmetric patterns of the frontal alpha-suppression in each pair, during both task anticipation and execution, such that only one member showed the frontal component. Analysis of the behavioral data showed that this distinction coincided with the leader-follower relationship in 8/9 pairs, with the leaders characterized by the stronger frontal alpha-suppression. This suggests that leaders invest more resources in prospective planning and control. Hence our results show that the spontaneous emergence of leader-follower relationships in dyadic interactions can be predicted from EEG recordings of brain activity prior to and during interaction. Furthermore, this emphasizes the importance of investigating complementarity in joint action.
Multivariate decoding of mutually interacting brains reveals complementary neural mechanisms in leaders and followers

General information
The Fire-Walker’s High: Affect and Physiological Responses in an Extreme Collective Ritual

How do people feel during extreme collective rituals? Despite longstanding speculation, few studies have attempted to quantify ritual experiences. Using a novel pre/post design, we quantified physiological fluctuations (heart rates) and self-reported affective states from a collective fire-walking ritual in a Mauritian Hindu community. Specifically, we compared changes in levels of happiness, fatigue, and heart rate reactivity among high-ordeal participants (fire-walkers), low-ordeal participants (non-fire-walking participants with familial bonds to fire-walkers) and spectators (unrelated/unknown to the fire-walkers). We observed that fire-walkers experienced the highest increase in heart rate and reported greater happiness post-ritual compared to low-ordeal participants and spectators. Low-ordeal participants reported increased fatigue after the ritual compared to both fire-walkers and spectators, suggesting empathetic identification effects. Thus, witnessing the ritualistic suffering of loved ones may be more exhausting than experiencing suffering oneself. The findings demonstrate that the level of ritual involvement is important for shaping affective responses to collective rituals. Enduring a ritual ordeal is associated with greater happiness, whereas observing a loved-one endure a ritual ordeal is associated with greater fatigue post-ritual.

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Autobiographical Memory in a Fire-Walking Ritual
Abstract Anthropological theories have discussed the effects of participation in high-arousal rituals in the formation of autobiographical memory; however, precise measurements for such effects are lacking. In this study, we examined episodic recall among participants in a highly arousing fire-walking ritual. To assess arousal, we used heart rate measurements. To assess the dynamics of episodic memories, we obtained reports immediately after the event and two months later. We evaluated memory accuracy from video footage. Immediately after the event, participants’ reports revealed limited recall, low confidence and high accuracy. Two months later we found more inaccurate memories and higher confidence. Whereas cognitive theories of ritual have predicted flashbulb memories for highly arousing rituals, we found that memories were strongly suppressed immediately after the event and only later evolved confidence and detail. Physiological measurements revealed a spectacular discrepancy between actual heart rates and self-reported arousal. This dissociation between subjective reports and objective measurements of arousal is consistent with a cognitive resource depletion model. We argue that expressive suppression may provide a link between individual memories and cultural understandings of high-arousal rituals.

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Believing versus interacting: Behavioural and neural mechanisms underlying interpersonal coordination

When two people engage in a bidirectional interaction with each other, they use both bottom-up sensorimotor mechanisms such as monitoring and adapting to the behaviour of the other, as well as top-down cognitive processes, modulating their beliefs and allowing them to make decisions. Most research in joint action has investigated only one of these mechanisms at a time – low-level processes underlying joint coordination, or high-level cognitive mechanisms that give insight into how people think about another. In real interactions, interplay between these two mechanisms modulates how we interact with others. In order to tease these apart in a mutual interaction, we conducted a synchronization-tapping experiment using a 2x2 factorial design, where one factor was the auditory feedback (hearing other or computer), and the other was the belief of what they were hearing (other or computer). MEG was measured from one co-actor, with the other co-actor seated outside the scanner. Our findings show frontal alpha suppression during anticipation of the task with a person vs. a computer, and frontal-sensorimotor suppression during task execution with the person vs. computer. This provides insight into neural mechanisms underlying belief of interacting with another person as well as engaging in interaction with the responsive other.
Complementary coordination strategies in a joint Fitts' reciprocal aiming task

How do dyads coordinate their actions to achieve a common goal when one person has the more difficult task? In the present study, dyads were instructed to engage in a Fitts's reciprocal aiming task as accurately as possible, and at a given tempo sent through their headphones. They were in conditions where they either received auditory feedback of 1) SELF-generated taps, 2) taps generated by the OTHER co-actor, or 3) regular, COMPUTER-generated taps. In conditions 2) and 3), they were also instructed to synchronize with their feedback as best as possible. In each trial, each participant was assigned to either the target's role – with varying target width, and hence task difficulty – or the reference role – with the widest (easiest) target. Results show that when the task was performed interactively with the other person, they were most synchronized, and also used the target most similarly, while compromising rhythmic accuracy. In addition, as task difficulty increased for the member with the target's role, the participant with the reference role became more adaptive to her tempo. This suggests that interacting members of a dyad optimally negotiate coordination strategies to achieve a joint goal, by taking on leader-follower roles.

Images from a jointly-arousing collective ritual reveal affective polarization

Collective rituals are biologically ancient and culturally pervasive, yet few studies have quantified their effects on participants. We assessed two plausible models from qualitative anthropology: ritual empathy predicts affective convergence among all ritual participants irrespective of ritual role; rite-of-passage predicts emotional differences, specifically that ritual initiates will express relatively negative valence when compared with non-initiates. To evaluate model predictions, images of participants in a Spanish fire-walking ritual were extracted from video footage and assessed by nine Spanish raters for arousal and valence. Consistent with rite-of-passage predictions, we found that arousal jointly increased for all participants but that valence differed by ritual role: fire-walkers exhibited increasingly positive arousal and increasingly negative valence when compared with passengers. This result offers the first quantified evidence for rite of passage dynamics within a highly arousing collective ritual. Methodologically, we show that surprisingly simple and non-invasive data structures (rated video images) may be combined with methods from evolutionary ecology (Bayesian Generalized Linear Mixed Effects models) to clarify poorly understood dimensions of the human condition.
Dual-EEG of joint finger tapping: what can two interacting brains teach us about social interaction?

The underlying neural mechanisms of real-time social interactions remain largely unknown. Only a small number of recent studies have explored what goes on in brains of two people simultaneously as they interact. The question still remains whether such quantification can better reveal the neural signatures of social cognition. In our study, we wanted to address this question by quantifying whether we gain more information about the interaction from the two brains. We measured dual-EEG from pairs of participants as they engaged in an interactive finger-tapping task. They were asked to synchronize with an auditory signal coming from the other member of the pair or the computer. They experienced two conditions: an interactive ‘coupled’ condition, each receiving feedback of the other person’s tapping; and an ‘uncoupled’ computer-control condition, each receiving feedback from a non-responsive computer. Time-frequency analysis revealed a left-motor and right-frontal suppression at 10 Hz during task execution, when carrying the task out interactively in contrast with the uncoupled computer-driven task. We used machine-learning approaches to identify the brain signals driving the interaction. The raw-power at 10 Hz during tapping emanating from electrodes of member one and member two were used as features. We combined data from both participants in each pair, and applied logistic regression using feature selection in order to classify the two conditions. The first seven (frontal) electrodes consistently emerged as good classifiers, with 85-99% accuracy. There was a tendency for one member’s frontal electrodes to drive the classifier over the other’s, which predicted the leader of the interaction in 8/9 pairs. This study reveals new neural mechanisms underlying two-person interactions. It also shows how analyzing two interacting brains can give better classification of behaviour; and hence that the whole of two brains is indeed better than the sum of its parts, at disentangling neural signatures of interaction.
Dual EEG of social interaction: a machine learning approach to the two-brain problem

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The two-brain approach: how can mutually interacting brains teach us something about social interaction?
Measuring brain activity simultaneously from two people interacting is intuitively appealing if one is interested in putative neural markers of social interaction. However, given the complex nature of interactions, it has proven difficult to carry out two-person brain imaging experiments in a methodologically feasible and conceptually relevant way. Only a small number of recent studies have put this into practice, using fMRI, EEG, or NIRS. Here, we review two main two-brain methodological approaches, each with two conceptual strategies. The first group has employed two-brain fMRI recordings, studying (1) turn-based interactions on the order of seconds, or (2) pseudo-interactive scenarios, where only one person is scanned at a time, investigating the flow of information between brains. The second group of studies has recorded dual EEG/NIRS from two people interacting, in (1) face-to-face turn-based interactions, investigating functional connectivity between theory-of-mind regions of interacting partners, or in (2) continuous mutual interactions on millisecond timescales, to measure coupling between the activity in one person's brain and the activity in the other's brain. We discuss the questions these approaches have addressed and consider scenarios when simultaneous two-brain recordings are needed. Furthermore, we suggest that (1) quantification of inter-personal neural effects via measures of emergence, and (2) multivariate decoding models that generalize source-specific features of interaction, may provide novel tools to study brains in interaction. This may allow for a better understanding of social cognition as both representation and participation.

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Neural oscillations of interpersonal coordination: an MEG study of interactive tapping

Quantifying collective effervescence: Heart-rate dynamics at a fire-walking ritual
Synchronized arousal between performers and related spectators in a fire-walking ritual

Collective rituals are present in all known societies, but their function is a matter of long-standing debates. Field observations suggest that they may enhance social cohesion and that their effects are not limited to those actively performing but affect the audience as well. Here we show physiological effects of synchronized arousal in a Spanish fire-walking ritual, between active participants and related spectators, but not participants and other members of the audience. We assessed arousal by heart rate dynamics and applied nonlinear mathematical analysis to heart rate data obtained from 38 participants. We compared synchronized arousal between fire-walkers and spectators. For this comparison, we used recurrence quantification analysis on individual data and cross-recurrence quantification analysis on pairs of participants' data. These methods identified fine-grained commonalities of arousal during the 30-min ritual between fire-walkers and related spectators but not unrelated spectators. This indicates that the mediating mechanism may be informational, because participants and related observers had very different bodily behavior. This study demonstrates that a collective ritual may evoke synchronized arousal over time between active participants and bystanders. It links field observations to a physiological basis and offers a unique approach for the quantification of social effects on human physiology during real-world interactions.
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Web of Science (2003): Indexed yes
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Follow you, follow me: Continuous mutual prediction and adaptation in joint tapping

To study the mechanisms of coordination that are fundamental to successful interactions we carried out a joint finger tapping experiment in which pairs of participants were asked to maintain a given beat while synchronizing to an auditory signal coming from the other person or the computer. When both were hearing each other, the pair became a coupled, mutually and continuously adaptive unit of two ohyper-followerso, with their intertap intervals (ITIs) oscillating in opposite directions on a tap-to-tap basis. There was thus no evidence for the emergence of a leader-follower strategy. We also found that dyads were equally good at synchronizing with the irregular, but responsive other as with the predictable, unresponsive computer. However, they performed worse when the oothero was both irregular and unresponsive. We thus propose that interpersonal coordination is facilitated by the mutual abilities to (a) predict the other's subsequent action and (b) adapt accordingly on a millisecond timescale.

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A Coupled Oscillator Model of Interactive Tapping

Background: Synchronization in music has been a popular experimental basis for studying social interactions, as musicians are required to synchronize to each other's beats and integrate abstract social information in order to coordinate their actions as part of a non-verbal communication process. A finger-tapping paradigm has been used in studies of sensorimotor synchronization as well as coordination dynamics within and between people (Repp 2005). Recent models of tapping dynamics have included two error-correction mechanisms: phase and period correction (Repp & Keller). They have generally been linear models, which are oversimplifications of these dynamics.

Aims: To model the dynamics capturing entrainment between pairs in a finger-tapping paradigm.

Method: Pairs of subjects were asked to tap on their respective keyboards following an 8-beat auditory stimulus sent through their headphones. Subjects were instructed to keep the given beat as precisely as possible as well as synchronize with the 'other'. They were in scenarios where they received auditory feedback of themselves tapping, the other, or the computer metronome.

Results: A dynamical systems approach was taken to model the tapping dynamics, using a system of two oscillators coupled in both phase and frequency, corresponding to phase and period correction. The model demonstrated that the tapping dynamics depend on the four coupling constants (phase and frequency for each oscillator), and are highly sensitive to noise.

Conclusions: Both phase and frequency coupling is required to capture the tapping dynamics of dyads. Coupling constants can be used to capture the degree of interaction.

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Synchronization in joint action: from tapping to fire-walking

Synchronization of actions, goals, and intentions among people is an important phenomenon in successful social interactions, which has been studied in both intentional and unintentional scenarios. It has been observed in coordination tasks requiring mutual information exchange between individuals, as well as scenarios of unidirectional coupling whereby one individual aligns with another through mimicking or simulation. In order to explore the dynamics and mechanisms involved in entrainment, a finger tapping experiment was carried out. Pairs of subjects were asked to tap on their respective keyboards following an 8-beat stimulus. They were instructed to keep the given beat as precisely as possible as well as synchronize with the 'other', while they received auditory feedback of themselves tapping, the other, or the computer metronome. Analysis of their inter-tap intervals showed that dyads were unable to achieve full synchrony but rather in the attempt to lock in phase with each other, they corrected their tapping onsets in opposite directions. Windowed cross-correlations revealed high correlation in both lag +1 and -1 in the interactive condition, suggesting a shared continuous adaptation to the other's output. Unintentional synchronization was also considered through a second study, looking at heart rates of spectators and participants during a fire-walking ritual. Preliminary analysis revealed high synchronization among family members. Dynamical systems analysis showed that both types of interactions may be represented through varying degrees of coupling strengths between people, possibly correlated with their affinity to one another; however, even through indirect contact with each other, people do not adopt leader/follower positions.

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Synchronized tapping as a model of minimal social interaction

Human beings have an extraordinary ability to synchronize their actions, goals, and intentions in order to accomplish goal-directed tasks. In order to study the dynamics and mechanisms involved in entrainment in social interaction, a finger tapping experiment was carried out, where pairs of subjects were asked to tap on their respective keyboards following an 8-beat stimulus sent through their headphones. The subjects were instructed to keep the given beat as well as synchronize with the ‘other’. They were in scenarios where they could either hear themselves tapping, the other, or the computer metronome. Analysis of their inter-tap intervals (ITI) suggests that dyads are unable to achieve full synchrony but rather adopt oscillatory behaviour, such that each member attempts to lock in phase with the other, thereby error-correcting their tapping onsets in opposite directions. Windowed cross-correlograms showed that there was no leader/follower in the interactive condition, revealing high correlation in both lag +1 and -1, which suggested shared continuous adaptation to the other’s output. A dynamical systems approach was taken to model this behaviour, using a system of two oscillators coupled in both phase and frequency, corresponding to phase and period error correction.