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Notes:

# The phi complex as a neuromarker of human social coordination

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**Many social interactions rely upon mutual information exchange: one member of a pair changes in response to the other while at the same time producing actions that alter the behavior of the other. However, little is known about how such social processes are integrated in the brain. Here, we used a specially designed dual-electroencephalogram system and the conceptual framework of coordination dynamics to identify neural signatures of effective, real-time coordination between people and its breakdown or absence. High-resolution spectral analysis of electrical brain activity before and during visually mediated social coordination revealed a marked depression in occipital alpha and rolandic mu rhythms during social interaction that was independent of whether behavior was coordinated or not. In contrast, a pair of oscillatory components ( $\phi_1$  and  $\phi_2$ ) located above right centro-parietal cortex distinguished effective from ineffective coordination: increase of  $\phi_1$  favored independent behavior and increase of  $\phi_2$  favored coordinated behavior. The topography of the phi complex is consistent with neuroanatomical sources within the human mirror neuron system. A plausible mechanism is that the phi complex reflects the influence of the other on a person's ongoing behavior, with  $\phi_1$  expressing the inhibition of the human mirror neuron system and  $\phi_2$  its enhancement.**

brain oscillations | electroencephalography | mirror neuron system | phi rhythm | coordination dynamics

Two anatomically overlapping yet functionally distinct systems in the brain have been identified when we interact with others. The first, historically called the motor preparation system, consists of cortical circuitry that includes the premotor cortex, the supplementary motor area, and parts of the inferior parietal cortex (1). This system is deemed responsible for implementing the intention to realize one's own actions (2, 3). The second, the mirror-neuron system (4, 5), allows for the actions of others to be perceived (6), embodied (7), understood (8, 9), and appropriated (10) by our own motor system. Its main components are the inferior parietal sulcus, the premotor cortex (5, 11, 12), and the superior temporal sulcus (STS) (although the motor properties of STS neurons coactivated during observation and execution are presently the subject of some debate; see ref. 6). In evolutionary terms, the mirror-neuron system may facilitate important functions of skill learning, language acquisition, everyday joint action, and interpersonal coordination (13). A common viewpoint (5, 14) is that the mirror-neuron system is inactive most of the time but is activated upon request. Research on pathological imitation (15) suggests a further possibility, namely, that the mirror-neuron system is constantly available for use but is actively suppressed by inhibition (16).

Neurophysiological studies of the influence of one person's actions on another have so far assessed the behavioral acts of pairs of individuals one at a time, i.e., one acts while the other observes; or one acts but only later does the other imitate (17–24). In many everyday social interactions, however, one member of a pair changes in response to the other while at the same time producing actions that alter the behavior of the other (25, 26). What neural mechanisms underlie such real-time

coordination between people, and how might they be identified? Here, we used a specially designed dual-electroencephalogram (EEG) system in an experimental paradigm (ref. 27; see also ref. 28) that allows both individual and social (interpersonal) tendencies to be quantified continuously in time. Our approach stems from coordination dynamics, an empirically based theoretical framework that aims to understand how patterns of coordination form, adapt, persist and change at multiple levels of brain and behavioral function (e.g., refs. 29–39). Such self-organized pattern formation in the brain is a subject of much active investigation in the neurosciences and expresses itself in various forms, including brain oscillations (e.g., refs. 40–42), transient phase synchrony among neural populations (30, 38, 43–47), multistability, abrupt phase transitions (“switches”) in behaviorally induced cortical activity patterns (48–53), and so forth. A positive contribution of coordination dynamics to understanding the brain-behavior relation is that it has been able (i) to identify key coordination or collective variables for complex patterns of behavior; and (ii) to derive patterns of collective behavior from the coupling among interacting components at both behavioral and brain levels (see refs. 33 and 54 for reviews).

As a framework specifically geared to handle informationally coupled self-organizing systems, coordination dynamics is well suited for studying how social coordination emerges from individual behavior in real time (see, e.g., refs. 27, 55, and 56). In the present study, we employed a rhythmic task in which pairs of subjects move their fingers at their own preferred frequency and amplitude with and without vision of the other's movements. Previous behavioral studies have shown that unintended spontaneous coupling may occur (manifest in transitions from independent to phase-locking behavior) when subjects see each other's hand movements (27, 55). Here, we explored the neural underpinnings of such social coordination: along with relative phase measures to precisely quantify the informational exchange between people, we employed high-resolution spectral measures of their brain activity. As a consequence thereof, we identified three distinct EEG rhythms, one of which (located over right centro-parietal cortex) “neuromarks” the presence or absence of social coordination.

## Results

Eight pairs of participants executed self-paced rhythmic finger movements with and without vision of each other's actions. The movements and neuroelectric activity of both members of the pair were continuously monitored and recorded at a time scale

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Abbreviations: EEG, electroencephalogram; LC, liquid crystal; CV, circular variance.

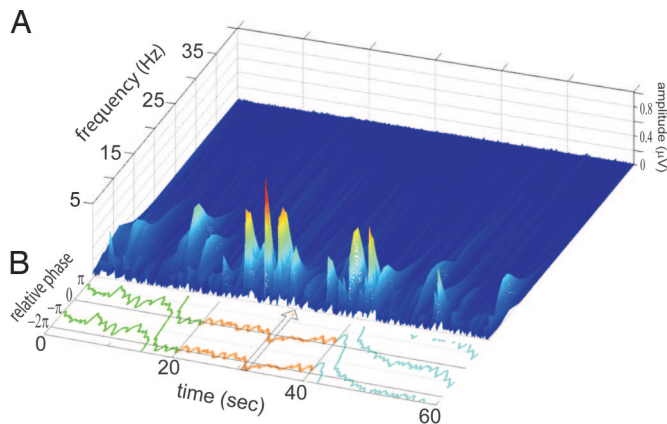
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**Fig. 5.** Relation between  $\Phi_2$  and social coordination. (A) Time-frequency spectrum for electrode CP4 from a single trial.  $\Phi_2$  is low before and after vision but increases during vision. (B) Corresponding relative phase between finger movements. Synchronized in-phase behavior is observed most of the time during visual contact. The momentary loss of coordination around  $t = 31$  s (highlighted by the arrow) is associated with the disappearance of  $\Phi_2$ , seen by the gap from time  $t = 30$  to  $t = 35$  s in the time-frequency spectra.

zation is observed during attentive vision (83, 84) whereas mu desynchronization is typically observed in a broad range of sensorimotor activities that includes execution, observation, and somatosensory stimulation (18, 20, 85–91).

Recently, the mu rhythm has been proposed as an electrophysiological correlate of mirror-neuron activity in normal (20, 87, 92) and pathological populations (88). The anatomical and functional distinction between mu and the phi complex revealed here sheds light on this hypothesis: high-resolution spectral analysis indicates that rolandic mu does not show any departure from the midline and does not engage specifically during social coordination (Fig. 2C). To the contrary, our data suggest that the mirror-neuron system effects appropriate behavioral changes by recruiting an oscillatory complex that is spatially and spectrally distinct from rolandic mu.

In short, our results suggest that mu and phi both constitute neural correlates of the human mirror-neuron system but play distinctly different roles. Whereas mu contributes to somatosensory awareness when the acting partner is perceived (85, 93), the phi complex plays the role of a gating mechanism, selectively parsing social from individual, so-called “intrinsic” behavior. Phi thus appears as a robust neuromarker or signature of social coordination, at least for the very basic forms of social interaction that emerge when people couple spontaneously with each other. Whether phi is unique and specific to social behavior or is a multifunctional mechanism shared with other forms of perceptuo-motor coupling, even with nonhuman agents (94) is, of course, open to further test. Likewise, the present approach clears the way for future investigations of a broad range of factors that may influence the tendency to coordinate, ranging from basic kinematic differences between movements of participants to high-level social factors such as trust (95). The functional dissociation among brain rhythms observed here may be important not only for the field of normal social cognition (96) but also for understanding pathologies where antagonistic results are currently translated into theories (e.g., between mu and mirror-neuron system deficits) and are on the verge of guiding therapeutic targeting.

## Materials and Methods

**Subjects.** Sixteen subjects (10 males and 6 females; aged between 22 and 41 years, mean 29 years) participated in the experiment. They constituted eight pairs: four gender-mixed; three male–

male; and one female–female. All were right-handed on the basis of self-report. They had normal or corrected-to-normal vision and reported no history of neurological disease. The protocol was approved by the Florida Atlantic University ethical board and was in agreement with the Declaration of Helsinki. Informed consent was obtained from all subjects.

**Task.** Pairs of subjects sat in front of each other while executing self-paced rhythmic finger movements during one-minute trials. An LC screen (Alumiglass, FL) with switchable opacity (switching time  $<1.2$  ms) was placed between subjects to control vision of the other’s motion. A trial consisted of three successive phases each lasting 20 s: before-vision, with the LC screen opaque (Fig. 1A), during-vision, with the LC screen transparent (Fig. 1B), and after-vision, with the screen back to opaque again (Fig. 1A). The LC screen was electronically controlled by means of a computer running the Experimental Run Time System (ERTS; Berisoft, Germany) software for optimal timing accuracy. Subjects were instructed to adopt the movement frequency that they felt most comfortable with and to maintain the fixation over a central spot on the LC screen. When the screen was transparent, the spot was in the same azimuth as the hand of the other participant. EEG artifacts induced by posture or finger movements were minimized before each trial. A trial started with two auditory cues presented in succession, one to each subject, signaling the respective recipients to commence rhythmically moving their index fingers at their preferred frequency and amplitude. The auditory warning cues were delivered through separate ear pieces 2 s ( $\pm 0.5$  s, random distribution) and 1 s ( $\pm 0.5$  s, random distribution) before the onset of the first 20-s period. The variable delay set a random initial relative phase between subjects and prevented common phase priming in the movements. The experiment consisted of 36 trials, with at least a 30-s rest between trials.

**EEG Recording.** The experiment was conducted in a sound-proof Faraday chamber. Dual-EEG was recorded by using two 60-channel EEG caps with Ag-AgCl electrodes (Falk Minow Services, Germany) arranged according to the 10% system (97) including midline and rows 1–8. The signals were fed to a single amplifier (Synamp2; Neuroscan, TX) equipped with two distinct referential montages. This specially designed dual-EEG system ensured no delays between the EEGs acquired from each subject and allowed precise analyses of cortical activity. EEG signals were measured with the respective grounds located at FPz sites and the references at the corresponding linked mastoids. Impedances were maintained below 10 k $\Omega$  (98). The signals were analog filtered (Butterworth, bandpass from 0.05 Hz ( $-12$  dB per octave) to 200 Hz ( $-24$  dB per octave), amplified (gain of 2,010) and digitized at 1,000 Hz with a 24-bit ADC in the range  $\pm 950$   $\mu$ V (vertical resolution of 0.11 nV).

**Movement Recording.** For finger movement data, angular change at the metacarpophalangeal joint was recorded by means of light single-axis goniometers (Biometrics, Ltd., U.K.) affixed to the right index finger of each subject. These signals were acquired through the high level port of the Neuroscan Synamp 2 bioamplifier, with an online bandpass filtering at a common EEG analog filter setting (0.05–200 Hz).

**Behavioral Analysis and Statistics.** Movement data were preprocessed by using a digital low-pass filter (Butterworth; 10 Hz, 24 dB) applied in a two-pass recursive manner to achieve zero-phase shift. The relative phase between the fingers was computed by using the continuous Hilbert transforms of the mean-centered time series. On the basis of the movement profiles during the visual contact period, the trials were initially classified by three experts into three categories: synchronized, transiently



synchronized, and unsynchronized trials. The classifications were further refined and numerically checked by using the synchronization index  $\gamma_{CV}$  based on the circular variance (CV) (66) of the relative phase. Note that this measure is sensitive to variations of the phase of the time series and not to the amplitudes. For  $N$  data points, the index is defined as

$$\gamma_{CV} \equiv \frac{1}{N} \left| \sum_{k=1}^N e^{i(\theta_k^{(1)} - \theta_k^{(2)})} \right| = 1 - CV, \quad [1]$$

where  $\theta_k^{(1)}$  and  $\theta_k^{(2)}$  are the Hilbert phases for the subject pair at time  $k$  and  $CV$  is the circular variance of the differences  $\theta_k^{(1)} - \theta_k^{(2)}$ . If the phases follow each other closely at all times (highly synchronized),  $\theta_k^{(1)} - \theta_k^{(2)} \approx \delta$  for some constant  $\delta$ , and  $\gamma_{CV}$  is close to one. For fully unsynchronized and uncoupled systems,  $\gamma_{CV}$  tends to 0. A lower bound and an upper bound for  $\gamma_{CV}$  were used to discriminate between synchronized and unsynchronized trials, respectively. Note that the index is a measure of the net strength of the interaction arising from the individual intrinsic dynamics (reflected in the frequency and amplitude of movement chosen before visual contact) and the mutual coupling.

**EEG Spectral Analysis.** Classical studies of EEG oscillations are often performed (i) at low spectral resolutions by using fast Fourier transform (FFT) on samples of a few hundreds of milliseconds; (ii) within large frequency bands (typically 2–3 Hz in the alpha range); and (iii) without access to the inter-individual variability in the frequency of the rhythms. Our paradigm allowed us to investigate rhythms over a period of 16.5 s from each 20-s segment of a trial (a 3-s transient at the onset and a 0.5-s transient at the end were removed as the brain activity was expected to be nonstationary near these boundaries), resulting in a spectral resolution of 0.06 Hz. Single trials were tapered with a Tukey window (10%), and discrete Fourier transforms (DFT) were used to estimate amplitude spectra. For display purposes, the spectra were smoothed with a 5-point Bartlett filter. Oscillatory processes in the brain were isolated on a subject-by-subject basis by using the following procedures.

**Power asymmetry.** The difference in the spectral amplitudes between the interhemispheric pairs of electrodes in rows 3 and 4 of the 10%-montage (97) (e.g., difference C3–C4 over the central sulcus) was computed. Symmetrical rhythms canceled out, and the phi complex was isolated because of its asymmetry. Active phi components (components increasing their amplitude during visual contact in synchronized or unsynchronized behaviors) were identified, and their changes in power, event-related desynchronization (ERD) and event-related synchronization (ERS) (99), were examined further.

**Occipital and central rhythms.** Waking EEG is characterized by a  $1/f^\alpha$  spectrum (100), over which a few peaks appear. Those peaks express the underlying presence of a specific functional network operating at defined frequencies. We defined spectral peaks as maxima in the spectrum in excess of the  $1/f^\alpha$  trend. The presence of the occipital/rolandic maxima in the range 7.5–13 Hz was determined by visual inspection, and their boundaries/amplitude were extracted.

**EEG Time-Frequency Analysis.** The spectral density over the time course of individual trials was also investigated. The spectral amplitude in the time-frequency plane was computed by using a continuous wavelet transform (CWT). For the mother function of the transform, we chose the complex Morlet wavelet  $\psi(x)$

$$\psi(x) = \sqrt{\pi f_b} e^{2i\pi f_c x} e^{-\frac{x^2}{f_b}}, \quad [2]$$

where  $f_c$  is the center frequency and  $f_b$  is frequency bandwidth. The Morlet wavelet is a complex sinusoidal function tapered with a Gaussian window and is optimal for sinusoidal-shaped oscillations such as alpha. It can also detect periodic signals of different morphologies such as mu but with lower spectral definition and leakage of parts of the power into additional/other components.

**EEG Artifacts.** Eye blinks are large-amplitude EEG components whose waveshapes resemble positively skewed Gaussians, sometimes associated with final undershoots. The typical duration of an eye blink is 200–400 ms, and its spectral signature spans the delta and theta range (101, 102), with most of the energy residing below 5 Hz. Muscle artifacts arise from the fluttering of the electrodes in the vicinity of active neck and face muscle groups and span the frequency range from the beta band up to  $\approx 500$  Hz (103, 104). The spectral characteristics of these two contaminants (eye blinks and muscle artifacts) have no overlap with the frequency bands investigated here. In agreement with Wallstrom's report (105) of induced second-order artifacts when correcting for primary contaminants (and especially in the alpha band), we did not employ correction techniques (e.g., regression, filtering, and decomposition) on the data.

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