DETECTING FREQUENCY-SPECIFIC PHASE SYNCHRONY IN BRAIN ELECTRICAL OSCILLATIONS

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Abstract

Oscillations in brain electrical activity that occur synchronously across brain regions within specific frequency bands are of great interest in neuroscience. Detecting such phase synchrony in parallel recorded oscillatory signals like EEG or MEG requires some kind of narrow-band filtering as a preliminary step for the extraction of frequency-specific phase information. We address the ensuing technical problems of phase enslaving and spurious synchrony and propose a method designed to reduce these problems. The method is detailed for application to repeated trials aligned to stimulus onset. It is going to be used in an analysis of EEG correlates of endogeneous perceptual reversals induced by ambiguous stimuli.

Synchronized neural activity is widely ascribed a major role in the functional organization of the brain. In object recognition, for example, various object features processed separately in distributed visual subsystems have to be integrated for a coherent percept to build up. According to the binding-by-synchrony hypothesis this is accomplished by a common temporal signature of all neural network nodes participating in the representation of the object, namely by synchronous oscillations at specific frequencies. Such in-phase oscillations would selectively 'tag' the involved neural structures and allow to distinguish between the representations of different objects [1]. Synchronized activity has been observed at the single cell level, where groups of neurons fire (almost) simultanously at regular strokes, up to the global level, where distant brain areas exhibit coherent oscillatory behavior. At an intermediate level of a large but localized population of neurons synchrony is reflected by enhanced amplitudes of the oscillations measurable at EEG (or MEG) electrodes [1, 8]. The focus here is on global or long range synchrony [7] as characterized by means of the oscillatory *phases* at pairs (or groups) of distant electrodes. Of primary interest are the phases of oscillations *at particular frequencies*, conceived as being embedded in the original signals. This accounts, on the one hand, for the different functional roles that have long been associated with the frequency contents of the alpha, beta, or theta bands, and more recently, in the context of the binding-by-synchrony hypothesis, with gamma band oscillations. On the other hand, it imposes the task of extracting frequency-specific phase information from the original noisy broadband signals, and condensing this information in a useful measure of phase synchrony. In our contribution we will discuss methodological problems of related standard approaches and introduce a modified synchrony measure suited to alleviate those difficulties. The proposed measure represents a compromise between pure phase correlation and coherence measures.

1. Obtaining phase information—Problems with standard approaches

This section deals with the basic situation when there is a single noisy oscillatory signal (EEG, say), and the task is to define its 'instantaneous' (time-dependent), frequency-specific phase. The idea is to conceive of the signal as consisting of a superposition of transient waves having different wavelengths. Then as a necessary step for subsequent synchronization analyses one would have to extract the phases of transient signal components oscillating at a fixed target frequency f or within some (narrow) frequency band b. A common way in neuroscience of handling the latter case [4, 6] consists in first computing a band-filtered version, $x^b(t)$, of the given signal, $x(t)$. Instantaneous, frequency band specific phases are then defined as

$$\varphi_x^{filt}(t, b) = \arctan(\mathcal{H}x^b(t)/x^b(t)), \tag{1}$$

where $\mathcal{H}x^b(t)$ denotes the Hilbert transform of $x^b(t)$ given by the (prime value) integral $\mathcal{H}x^b(t)= \frac{1}{\pi}\int \frac{x^b(u)}{t-u}\,du$. Another routine approach to phase extraction uses time-frequency transforms, which yields phases at any target frequency f as a by-product [4, 5]. The standard Morlet wavelet transform of signal $x(t)$ at time t and frequency f is given by the convolution

$$W_x(t, f) = \int x(u)\,\psi^*((u-t)f/f_0)\,\sqrt{f/f_0}\,du, \tag{2}$$

where $\psi(u) = c\,\mathrm{e}^{j2\pi f_0 u}\,\mathrm{e}^{-u^2/2}$ is a modulated Gauss curve, '*' denotes complex conjugation, and c is a normalizing constant. A typical choice of the 'central frequency' f_0, also to be used here, is $f_0 = 7/(2\pi) \approx 1.114$. Two important quantities associated with the wavelet transform are spectrogram and phase. The spectrogram is given by the squared amplitude of the wavelet transform, $|W_x(t, f)|^2$. High/low values of $|W_x(t, f)|^2$ indicate high/low oscillatory energy around the point (t, f) in time-frequency space. The (instantaneous) phase $\varphi_x^{wav}(t, f)$ at time t and target frequency f is defined as the phase angle of the complex number $W_x(t, f)$ through the equation

$$\exp(j\varphi_x^{wav}(t, f)) = W_x(t, f)/|W_x(t, f)|\,. \tag{3}$$

No matter which method is applied, the extraction of frequency-dependent instantaneous phase from oscillatory signals is prone to potentially serious defects. A notorious problem is *phase enslaving:* Narrow-band filtering tends to transfer phase behaviour consistent with the target frequency (or frequency band b) from the time region where this holds to adjacent regions where corresponding oscillations are lacking. Conversely, if the signal exhibits distinct oscillations of some particular frequency $f^\star$, these may strike through to the phase course even if $f^\star$ is incompatible with the target frequency. Such tends to happen particularly in time-frequency regions where power is low. Since power in EEG signals decays rapidly with increasing frequency, phase enslaving may thus especially affect higher frequency (gamma) oscillations.

Phase enslaving is demonstrated in Fig. 1 using two test signals well-known in wavelet analysis. In the case of the 'Chirps' signal (left-hand side) the selected target frequency, $\phi = 15$ Hz, determines the phase course of the wavelet phase $\varphi_{\mathrm{Chirps}}^{wav}(t, 15)$ (top left, thin solid line) across the whole time interval of 1 s duration. Thus, looking at (wavelet) phases only one would infer that the signal includes a *continuous* 15 Hz oscillation. However, oscillations having approximately that frequency occur only in three limited time regions, roughly around $t = .1$, .5, .75, as can be seen from the corresponding spectrogram (bottom left). For comparison, phases obtained according to (1) via band-filtering (FIR filter of length 200 ms; passband $b = (14, 17)$ Hz) are included in the same plot (dashed thin lines; these phases are dilated by a factor of $4/\pi$ in order to make them better distinguishable from the wavelet phases.) The two phase courses match very well within the indicated three time regions, but differ substantially elsewhere.

Another type of phase enslaving is visible in the 'Gabor' signal (Fig. 1, right-hand side). It consists of two 'Gabor atoms', short-lived oscillatory bursts occurring around time $t = .5$ with frequency $f = 15.6$ Hz and around $t = .75$ with $f = 62.6$ Hz. The selected target frequency, $\phi = 57$ Hz, is close to the second Gabor frequency, and wavelet phase essentially adapts to the latter. (To facilitate inspection, only wavelet phase is shown in this plot.) However, it does so not only within the proper range of the Gabor atom but also in an extended neighbourhood where the actual signal vanishes entirely (is constantly zero). This region ends around $t = .6$

where the first Gabor atom starts (seen from the right). Roughly between $t = .25$ and $t = .55$, hence substantially beyond the range of that atom, the phase course again exhibits quasi-stationary behaviour suggesting that the signal contains a 27 Hz oscillation within the segment $.25 < t < .55$ (8 cycles in this interval correspond to $\approx$27 Hz)—which in fact it does not.

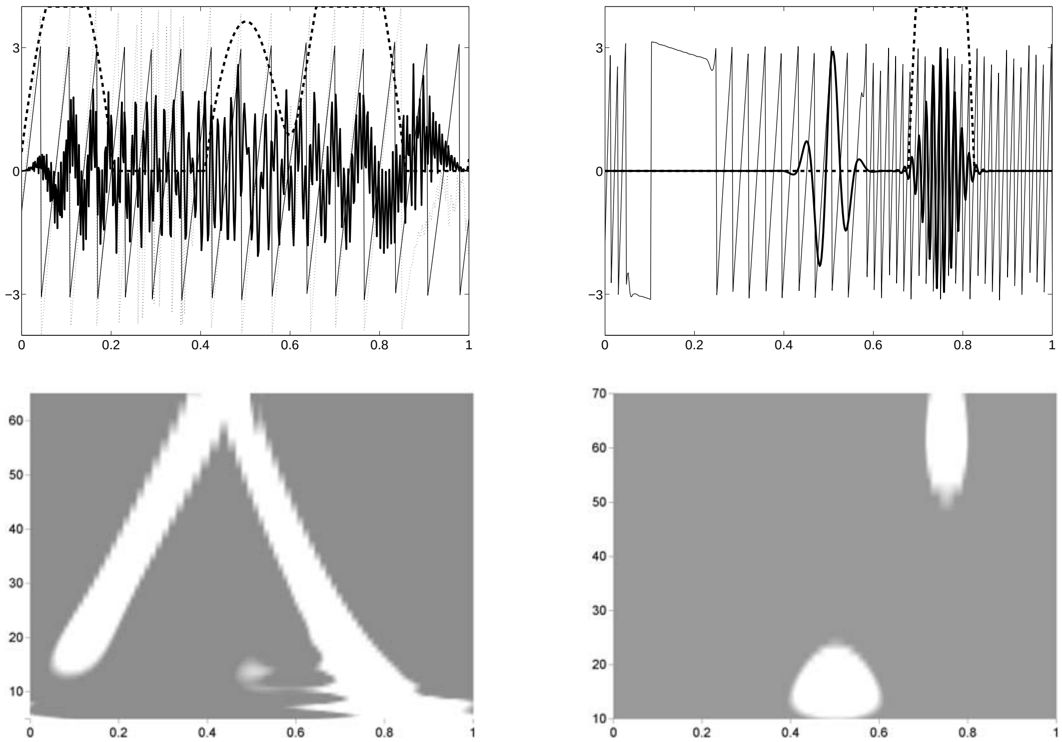

Figure 1. Phases, 'weights' (cf. Sect. 3), and spectrograms for two oscillatory signals. Left: 'Chirps'; right: 'Gabor'—cf. [5, Ch. 4]. Top: Test signals (thick lines), weights (dashed thick lines), and phases: solid thin lines are wavelet phases, cf. (3); dashed thin line (for Chirps signal only) is band-filtering phase, cf. (1). Target frequencies are 15 Hz (Chirps) and 57 Hz (Gabor). Bottom: Spectrograms; light / dark shadings indicate high / low values of $|W_x(t,f)|^2$. Ordinates represent frequency [Hz] (bottom only), abscissae represent time [s]. See also text.

The examples point to an inherent difficulty in the concept of an instantaneous, frequency-specific phase. In the first place, it should pick up the phase of an oscillatory component of the underlying signal x whenever that component's frequency matches the target frequency ϕ. However, if there is no such component, how should $\varphi_x(t,\phi)$ behave? Should it adapt to the phase of a salient oscillation with frequency different from the target frequency ϕ? If $\varphi_x(t,\phi)$ were such flexible it would, strictly speaking, be no more specific for its target frequency. If it were not, its phase course would describe a purely virtual oscillation not contained in the signal. This dichotomy is clearly overstated, 'either-or's being rare in nature. Nevertheless, it suggests that the conflict cannot be resolved at the level of the definition of phase proper.

2. Measuring phase synchrony

A phenomenon observable in many time series coupled by some underlying mechanism is the existence of transient periods of phase synchrony [6] across which the phase difference between oscillations of frequency f, or in frequency band b, remains approximately constant,

$\varphi_x(t,\alpha) - \varphi_y(t,\alpha) \approx$ const. (Here and below α may denote either a frequency f or a band b.)

Among the various proposals for quantifying phase synchrony we focus on measures usually applied in neurophysiological studies. Often there is an ensemble of N signal pairs $(x_n(t), y_n(t))$ representing, e.g., EEG traces recorded at two electrodes during repeated presentations of some stimulus ('trials'). Of interest then are time delays t (w. r. t. stimulus onset) and frequency (bands) α at which phase differences are approximately constant across trials. A corresponding measure is the *phase locking value* [4, 6]

$$\mathrm{PLV}(t,\alpha) \;=\; \left|\frac{1}{N}\sum_{n=1}^{N}\exp(j\Delta_n(t,\alpha))\right| \quad \text{where} \quad \Delta_n(t,\alpha)=\varphi_{x_n}(t,\alpha)-\varphi_{y_n}(t,\alpha). \tag{4}$$

Time segments across which $\mathrm{PLV}(t,\alpha)$ is close to 1 or 0—or is in-/decreased above/below (time) average—represent periods of (relative) synchronization or de-synchronization at frequency (band) α; see Fig. 2.

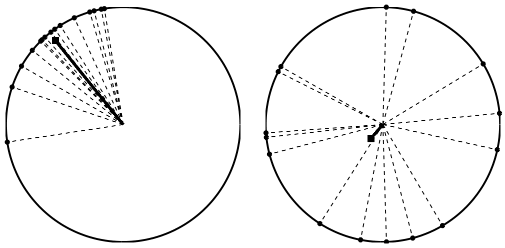

Figure 2.
PLV measuring phase difference consistency across trials:
PLV (= length of solid line) is ≈ 1 if complex phase differences (endpoints of dashed lines) point in similar directions (left).
PLV ≈ 0 if there is no 'preferred' direction (right).

PLV depends solely on phases φ, which above have been shown to behave strangely particularly when power is low. This raises concerns about the reliability of PLV as a measure of phase consistency. A less fragile such measure is classical 'coherence', a time-resolved version of which is given by the (trialwise) *wavelet coherence* [3]

$$\mathrm{WC}(t,\alpha) \;=\; \left|\frac{1}{N}\sum_n W_{x_n}(t,\alpha)\,W^*_{y_n}(t,\alpha)\right| \bigg/ \sqrt{\frac{1}{N}\sum_n |W_{x_n}(t,\alpha)|^2\,\frac{1}{N}\sum_n |W_{y_n}(t,\alpha)|^2}. \tag{5}$$

Since by (3), (4) we have $W_{x_n}(t,\alpha)\,W^*_{y_n}(t,\alpha)=\exp(j\Delta_n(t,\alpha))\,|W_{x_n}(t,\alpha)||W_{y_n}(t,\alpha)|$, putting

$$\lambda_n(t,\alpha)=|W_{x_n}(t,\alpha)||W_{y_n}(t,\alpha)| \bigg/ \sqrt{\frac{1}{N}\sum_n |W_{x_n}(t,\alpha)|^2\,\frac{1}{N}\sum_n |W_{y_n}(t,\alpha)|^2} \tag{6}$$

allows us to express WC as a *weighted* variant of PLV,

$$\mathrm{WC}(t,\alpha) \;=\; \left|\frac{1}{N}\sum_n \exp(j\Delta_n(t,\alpha))\;\lambda_n(t,\alpha)\right|. \tag{7}$$

The contribution of the complex phase differences $\exp(j\Delta_n(t,\alpha))$ to $\mathrm{WC}(t,\alpha)$ is diminished where wavelet amplitudes are low, due to multiplication by $\lambda_n(t,\alpha)$. This clearly reduces the potential consequences of phase enslaving. On the other hand, wavelet coherence has been criticized precisely for its amplitude dependence. As argued in [3], WC "does not separate the effects of amplitude and phase in the interrelations between signals;" moreover, since "phase locking is [hypothesized to be] the relevant biological mechanism of brain integration, [wavelet] coherence provides only an indirect measure."

The situation amounts to a conflict between two important requirements: A suitable synchrony measure should truly reflect *phase* rather than amplitude relations; at the same time it should be immune to meaningless phase determinations occurring particularly when amplitudes are small. At this stage it is natural to look for a compromise: our proposal is to replace PLV by a *weighted phase locking value* $\omega\mathrm{PLV}$ similar to (7),

$$\omega\mathrm{PLV}(t,\alpha) \;=\; \left|\frac{1}{N}\sum_n \exp(j\Delta_n(t,\alpha))\;\omega_{x_n}(t,\alpha)\,\omega_{y_n}(t,\alpha)\right|, \tag{8}$$

with weights ω that are not proportional to amplitudes, as in (6), but differ from 1—which value would yield PLV—only when amplitudes are not large enough. What is considered 'not large enough' should depend on the respective spectral characteristics, because otherwise higher (e.g. gamma) frequencies of interest might be completely cut off due to too low power.

3. Selection of weights (and phases)

To concretize ω, let us first consider the case of a single signal, $x(t)$. For definiteness, suppose that α stands for a frequency band $b = (b_1, b_2)$. Let $P_x(t, b)$ denote the mean wavelet power in band b at time t, and $P_x(b)$ the time average of $P_x(t, b)$ across the relevant epoch T,

$$P_x(t,b) = \frac{1}{b_2 - b_1} \int_{b_1}^{b_2} |W_x(t,f)|^2 \, df, \quad P_x(b) = \frac{1}{|T|} \int_T P_x(t,b) \, dt \,. \tag{9}$$

We consider the time-resolved power $P_x(t, b)$ as 'large enough', and set $\omega_x(t, b) = 1$, if it exceeds the average band power $P_x(b)$ by at least 50 %; we consider it as 'too small', and set $\omega_x(t, b) = 0$, if $P_x(t, b) \leq \frac{3}{10} P_x(b)$. For values in between, $\frac{3}{10} P_x(b) < P_x(t, b) < \frac{3}{2} P_x(b)$, weights are interpolated on a logarithmically linear scale,

$$\omega_x(t,b) = \frac{\log P_x(t,b) - \log(0.3 P_x(b))}{\log(1.5 P_x(b)) - \log(0.3 P_x(b))} = \frac{\log(P_x(t,b)/P_x(b)) - \log(3/10)}{\log 5} \,. \tag{10}$$

(Other choices of the thresholds may turn out better.) Since with this definition the wavelet transform has to be computed anyway, we suggest to use it also for the definition of the phases. Precisely, we propose to determine wavelet phases for frequency bands similarly to (3) as the phase angle of the band-averaged complex wavelet coefficients, i.e., through the equation

$$\exp(j\varphi_x^{wav}(t,b)) = \frac{\overline{W}_x(t,b)}{|\overline{W}_x(t,b)|} \quad \text{where} \quad \overline{W}_x(t,b) = \frac{1}{b_2 - b_1} \int_{b_1}^{b_2} W_x(t,f) \, df \,. \tag{11}$$

With these specifications the definition of the weights (and phases) is completed—in the case of a single signal and a frequency *band* ($\alpha = b$). The case where frequency is fixed precisely ($\alpha = f$) is handled in the obvious way: one skips the averaging across b in (9) and sets $P_x(t, f) = |W_x(t, f)|^2$. Before proceeding to the multiple signals case let us yet complete the legend of Fig. 1: Weights and phases for the two test signals were computed as described above, using frequency bands $b_{\text{Chirps}} = (14, 17)$ Hz and $b_{\text{Gabor}} = (53, 59)$ Hz. (These bands are borrowed from a yet unfinished study. Besides, ωs were multiplied by 4 in order to improve legibility.)

Now, suppose we are given an *ensemble* of N single trials $x_n(t)$. One could define weights ω_n (brief for ω_{x_n}) 'individualistically', just as above. It appears more appropriate, however, to take average characteristics as well as fluctuations into account. A concrete proposal is as follows. At first, average band power $P_n(b)$ for each single trial x_n is calculated as in (9). The average of these standard (i.e., not time-resolved) spectra across trials indicates which amplitude may typically be expected at which frequency. Fluctuation occurs both across trials and time. For example, some typical oscillation may be completely missing in some trial, or occur with different amplitudes at different time delays in different trials. To account for this variability, and avoid robustness problems with statistical outliers, we define upper and lower thresholds by means of quantiles of the $P_n(b)$s. Specifically, let $U(b)$ denote the median of the set of all numbers $1.5\, P_n(b)$ ($n \leq N$), and let $L(b)$ denote the (lower) 5% quantile of that set. Given these thresholds, ensemble-adapted weights $\widetilde{\omega}_n$ are then defined analogously to (10): $\widetilde{\omega}_n(t, b) = 1$ if $P_n(t, b) \geq U(b)$, $\widetilde{\omega}_n(t, b) = 0$ if $P_n(t, b) \leq L(b)$, and

$$\widetilde{\omega}_n(t,b) = \frac{\log P_n(t,b) - \log L(b)}{\log U(b) - \log L(b)} \tag{12}$$

for values in between. Substituting these weights into (8) yields the phase synchrony measure finally proposed here for application with pairs of stimulus-aligned EEG (or MEG) signals.

4. Concluding remarks

In this purely methodological contribution we have introduced weighted variants ωPLV of the phase locking value [3, 4] often used in studies of brain oscillatory activity focussing on long-range phase synchrony. The synchrony measure ωPLV is designed to reduce possibly detrimental effects incurred in the extraction of frequency-specific phase such as phase enslaving and ensuing spurious synchrony. The basic idea is that phase may be meaningless where power is low. Accordingly, ωPLV is constructed as a compromise between a pure phase synchrony measure such as PLV and (time-resolved) coherence, which latter depends also on power, albeit too strongly to count as a true measure of phase synchrony.—The proposed construction pertains to synchrony across trials. Alternatively, synchrony can also be defined on a single-trial basis, as constancy of phase differences across small time intervals [3]. It seems possible to adapt the present approach to the single trial case, too. (By the way, the wavelet coherence measure WCo in [3] covered in fact the single trial case. In (5), the time average of [3] has been replaced by an average across trials.)— One may argue that phase enslaving should be a less serious problem with EEG signals than with our test signals, which have a sharply defined spectrum. This is probably true, as well as averaging across trials tends to dilute spurious synchrony occurring unsystematically dispersed in time. Still, we expect that with the weighted version ωPLV considerable noise reduction can be achieved compared to PLV, making (de-)synchronization phenomena better detectable in noisy signals. Also, in earlier attempts with a less elaborate version of ωPLV we found substantial differences between weighted and unweighted phase locking measures in genuine EEG data. In future work we intend to apply the proposed approach to a phase synchrony analysis of EEG recordings during endogeneous perceptual reversals of ambiguous stimuli. For related ERP results see [2].

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