



Phase Synchrony Neurofeedback? BEWARE!

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Background

A simple, but likely generic assumption (especially in the framework of **phase synchrony**), is to assimilate **EEG signals** to locally stationary weighted sums of sinusoids.

Methodology

We present two cases of **false synchrony**, one of **missed synchrony**, and one of **spurious synchrony**.

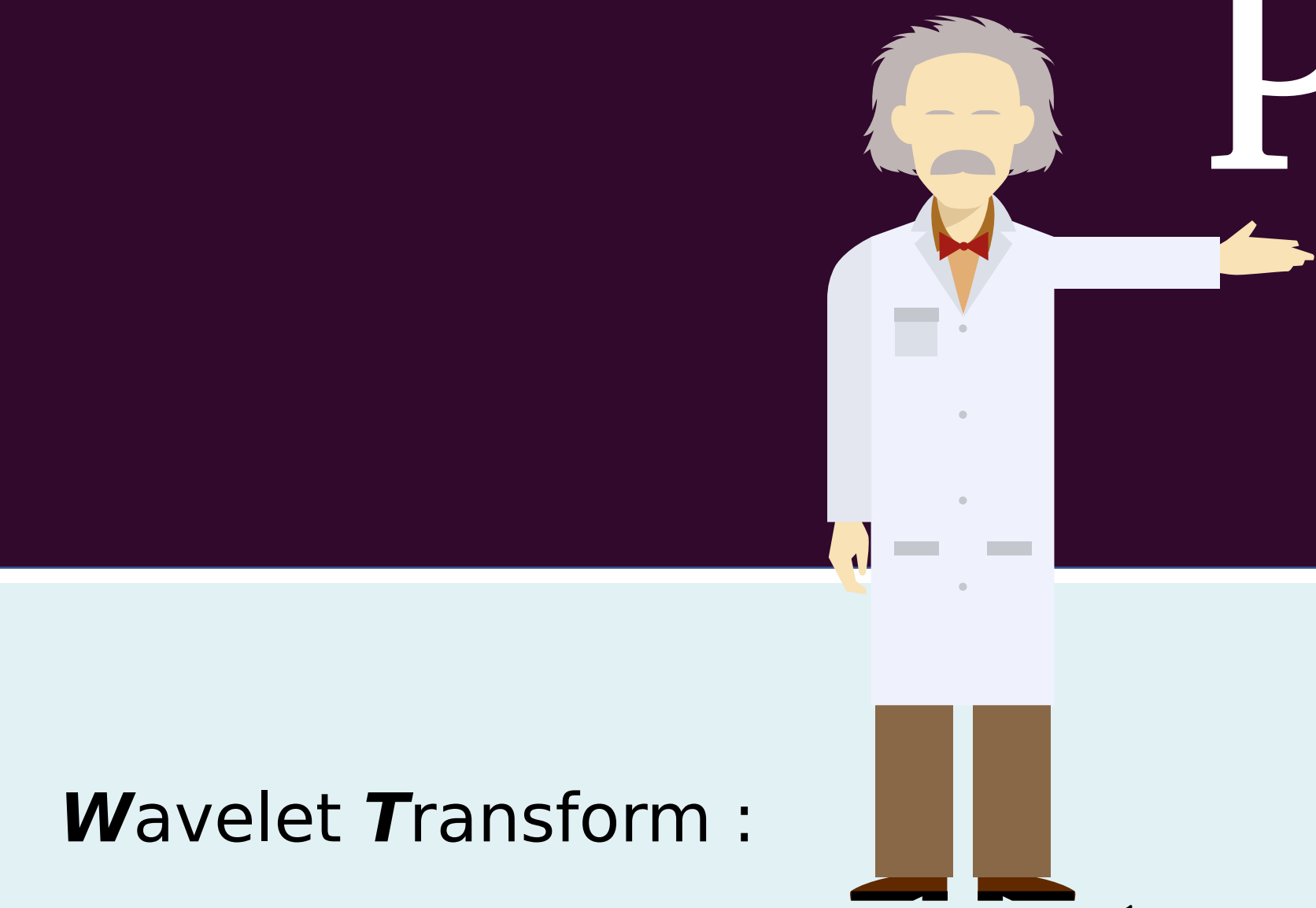
C] We set up an **experiment** to assess the correlation between common phase synchrony measures. A subject underwent 13 recordings of 275 seconds, alternating between 20s of **Eyes Open** **Fixation** of the screen (Baseline) and 20s of **Eyes Closed Relaxation**, interleaving 5 seconds of rest between each event.

Results

It means that the **phase is not unique** : several combinations of different frequencies produce the same phase.

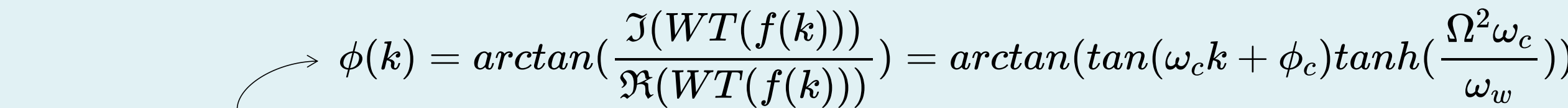
Conclusion

Before attempting to blindly use phase synchrony measures in Neurofeedback, there *a fortiori* a need for a proper and efficient estimation of the statistical significance of the measures calculated on the fly.

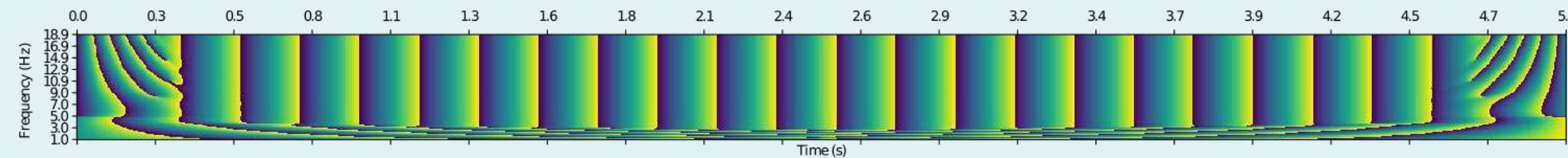


Wavelet Transform :

$$WT(f(t))(k) = \frac{1}{\sqrt{\frac{\sqrt{\pi} \Omega}{\omega_w}}} \int_{-\infty}^{\infty} f(k-t) e^{i\omega_w t} e^{-\frac{t^2 \omega_w^2}{2\Omega^2}} dt$$

$$\mathbf{f}(\mathbf{t}) = \cos(\omega_c \mathbf{t} + \phi_c) :$$


For $f(t) = \sin(2\pi\nu_s t + \phi_s)$, the argument $2\pi\nu_s t + \phi_s$ is properly recovered for ν_s close to ν_w . A deviation in the coefficient $\tanh\left(\frac{\Omega^2 2\pi\nu_s}{2\pi\nu_c}\right)$ causes the phase to warp, nonetheless the jumps occur at the frequency of the signal. The formula shows clearly why one sees on Time-Frequency planes long vertical lines and phase information far from the frequency of the signal.

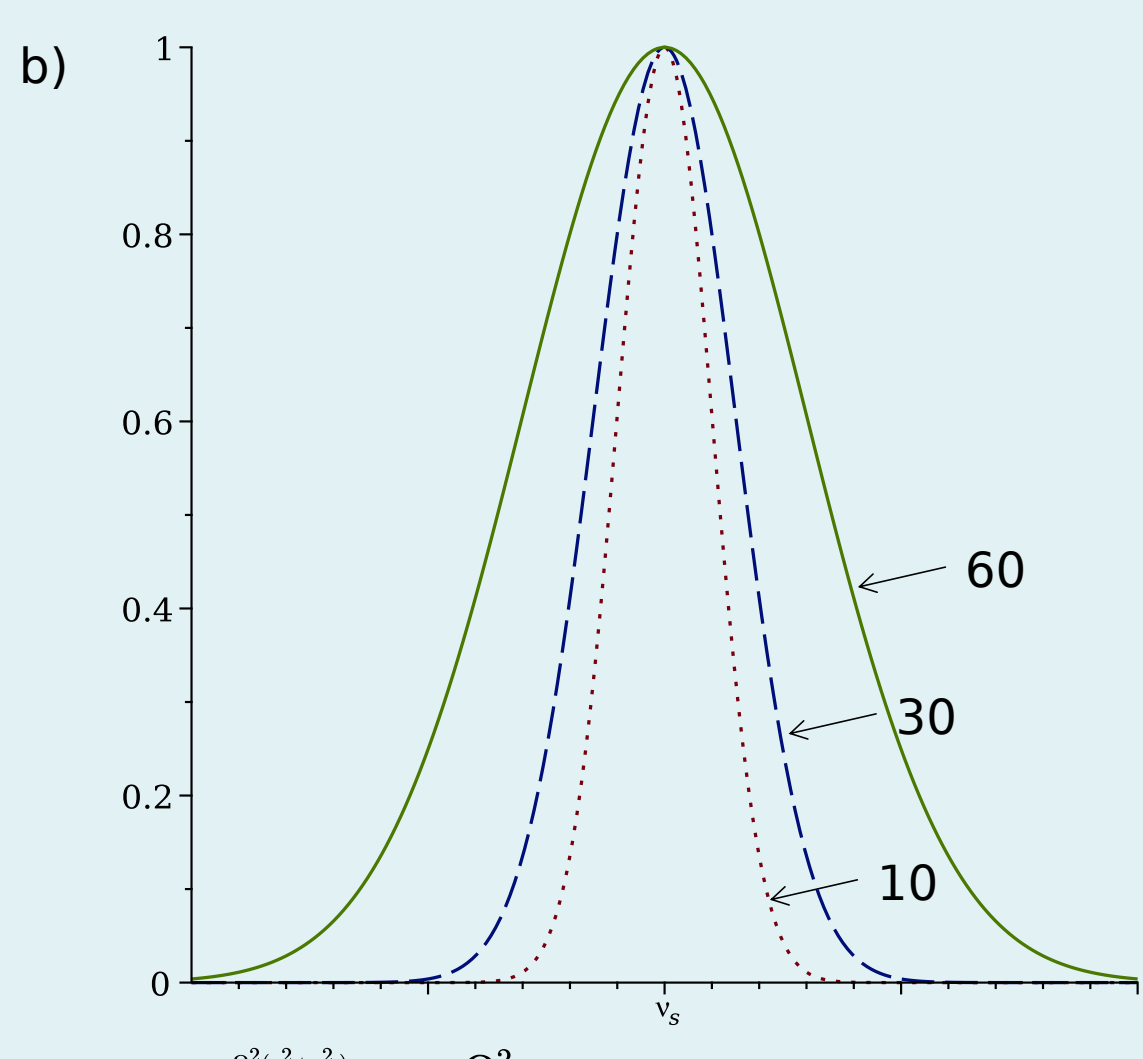
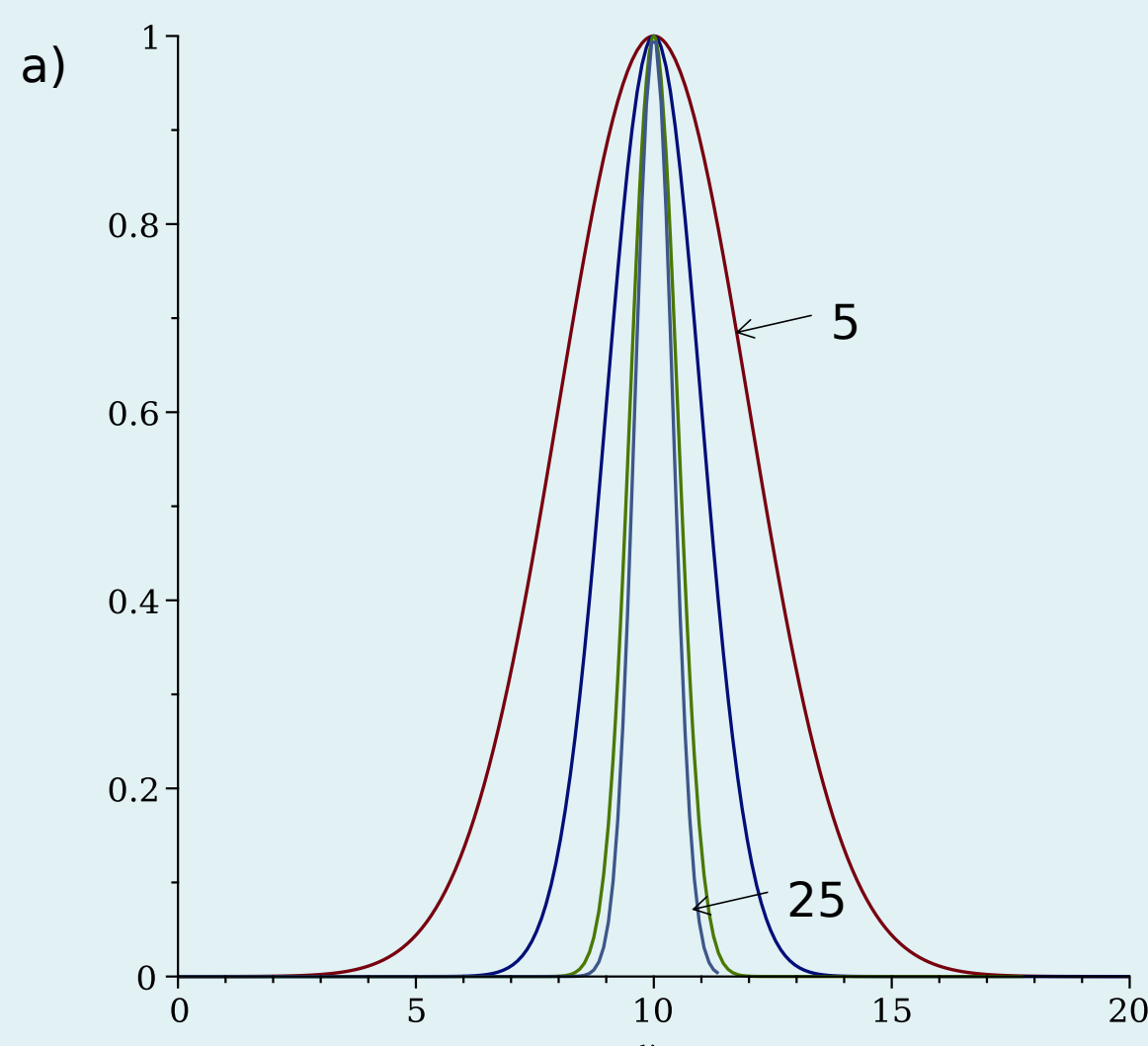


TF plane of $\sin(10.2\pi t)$, t varies from 0 to 5 seconds. The signal is decomposed on frequencies varying from 1 to 19 with wavelets composed of 7 oscillations (Q). The plot is obtained by numerical convolution (solved with multiplication in the Fourier domain of the Fourier Transform of the signal and the Fourier Transform of the wavelet followed by Fourier Inverse Transform of the product).

Effect on the phase of varying the frequency ratio
(signal vs wavelet) up to high values

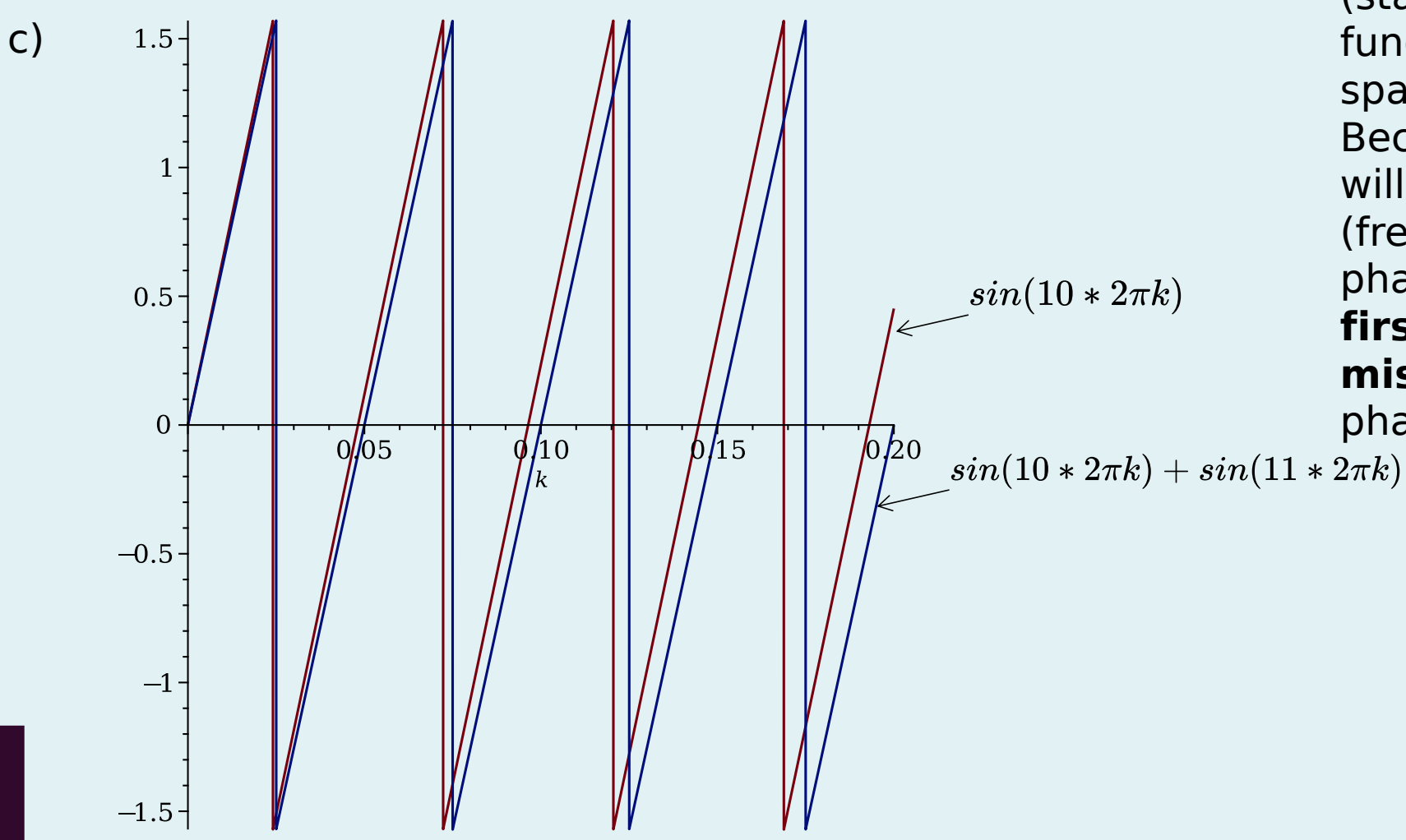
$$\mathbf{f}(\mathbf{t}) = \sum \alpha_i \cos(\omega_i \mathbf{t} + \phi_i) : \quad \phi(k) = \arctan\left(\frac{\Im(WT(f(k)))}{\Re(WT(f(k)))}\right) = \arctan\left(\frac{\sum \alpha_i e^{-\frac{\Omega^2(\omega_i^2 + \omega_0^2)}{2\omega_0^2}} \frac{\sinh(\frac{\Omega^2 \omega_i}{\omega_0})}{\cosh(\frac{\Omega^2 \omega_i}{\omega_0})} \sin(\omega_i k + \phi_i)}{\sum \alpha_i e^{-\frac{\Omega^2(\omega_i^2 + \omega_0^2)}{2\omega_0^2}} \frac{\sinh(\frac{\Omega^2 \omega_i}{\omega_0})}{\cosh(\frac{\Omega^2 \omega_i}{\omega_0})} \cos(\omega_i k + \phi_i)}\right) \approx \arctan\left(\frac{\sum \alpha_i e^{-\frac{\Omega^2(\omega_i^2 + \omega_0^2)}{2\omega_0^2}} \sin(\omega_i k + \phi_i)}{\sum \alpha_i e^{-\frac{\Omega^2(\omega_i^2 + \omega_0^2)}{2\omega_0^2}} \cos(\omega_i k + \phi_i)}\right)$$

“phase”

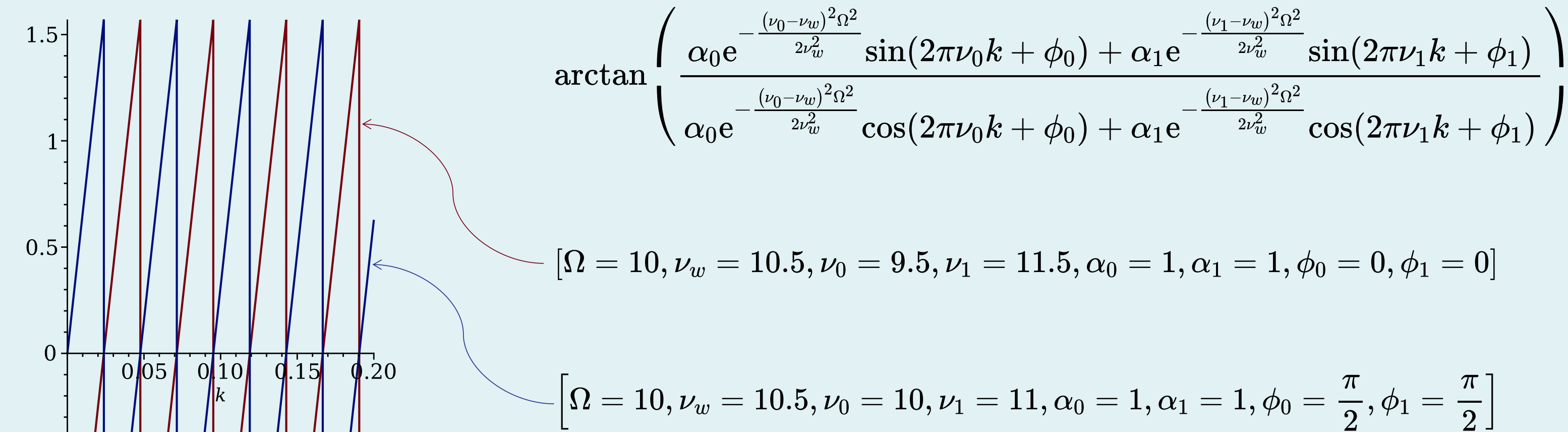


Both are in accordance with the uncertainty principle, that compromise should be made on temporal resolution to increase frequency resolution.

c) This figure illustrates the **importance in phase synchrony estimation of frequency mixing**. We imagine two oscillators (10 Hz) that are in phase (stable 0° difference for illustration purpose) due to functional coupling and a third oscillator oscillating spatially close to the second. Because scalp EEG combination the 11 Hz oscillator will completely perturbate the phase at 10Hz (frequency of the wavelet used to extract the phase), and the **phase synchrony between the first and second oscillators is completely missed**. If the third oscillates at 14 Hz, then the phase synchrony is restored for a wavelet at 10Hz.

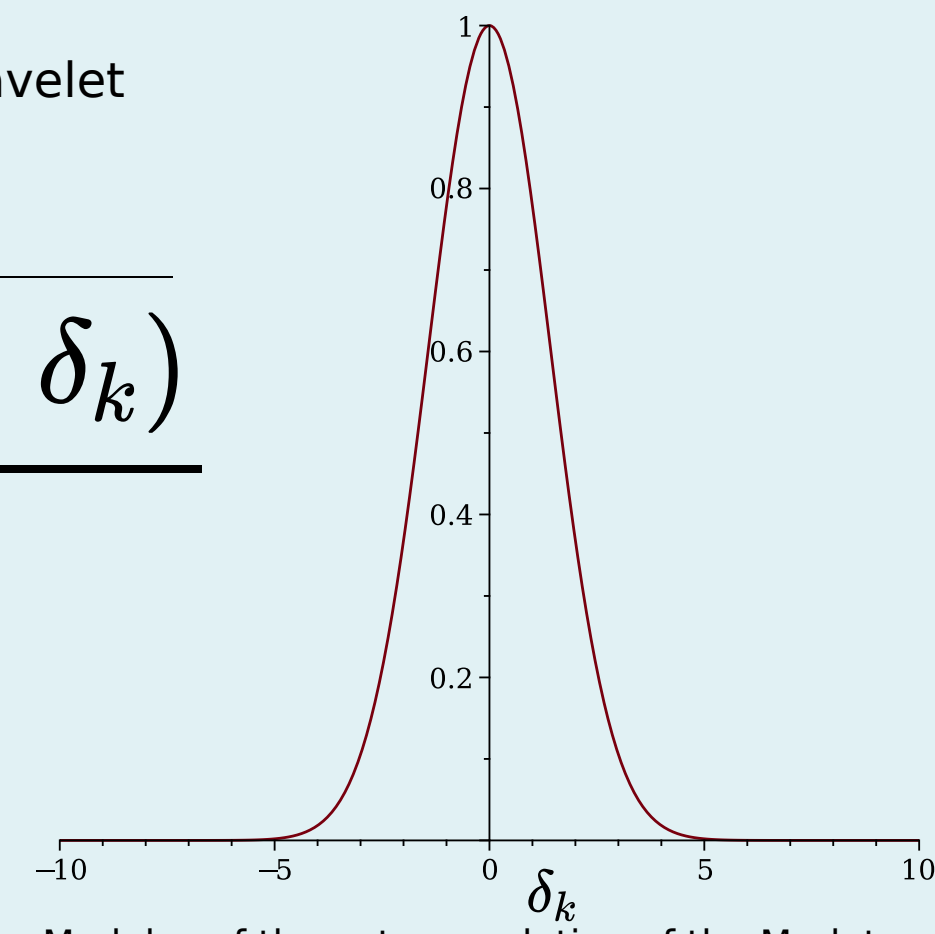


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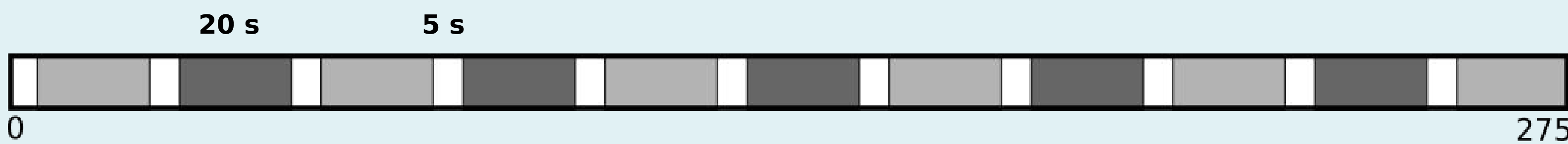
The **phase difference** between **two different combinations** of sinusoids oscillating at different frequencies **can be constant** ($\frac{\pi}{2}$). It means that perfect synchrony can be completely **spurious**. It's nonetheless an edge case, since it requires a symmetry with respect to the wavelet frequency, and be close enough (in the width of the wavelet).

$$\rho(WT(k), WT(k + \delta_k)) = \frac{\sum_{t=-\Gamma}^{\Gamma} W(t)W(t - \delta_k)}{\sum_{t=-\Gamma}^{\Gamma} W(t)^2}$$

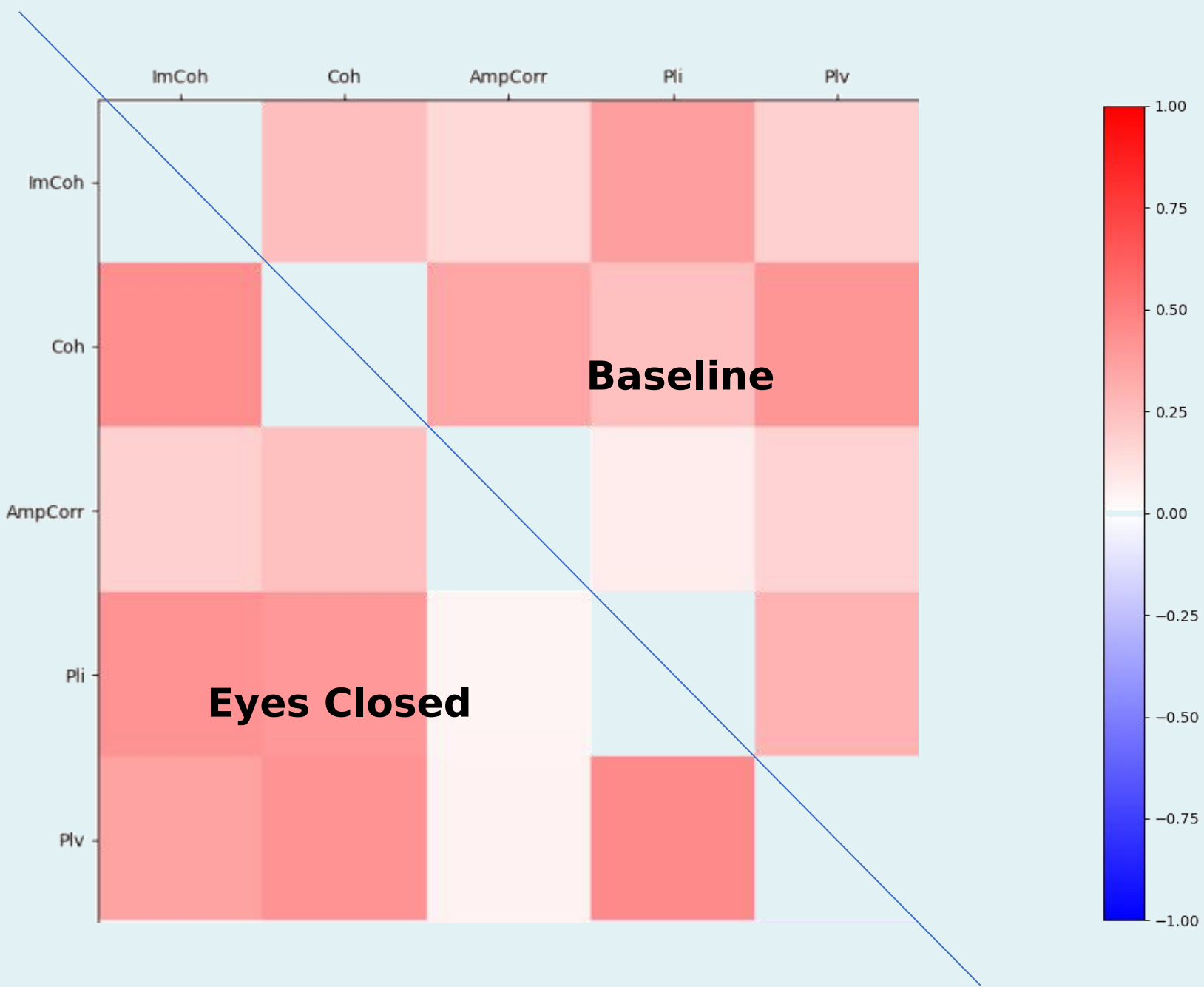


Though, EEG signals **are not strictly non auto-correlated** as we hypothesize, their auto correlation should be integrated in statistical tests.

This correlation coefficient can be used to sub sample the wavelet coefficients in order to minimize their correlation. In turn, this correlation must be introduced in statistical significance testing.



Baseline **Eyes Closed**



For instance, **strong PLV and PLI values occurring simultaneously would encourage the assessment of a strong synchrony** between electrodes of a given pair.

ImCoh: Imaginary Coherence; Coherence : Coherence;
AmpCorr : Correlation between amplitudes envelopes;
Pli : Phase Lag Index; Plv : Phase Locking Value

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