Machine Learning and Neuroscience

Biological neural networks are characterized by a widespread connectivity at multiple scales. From this structure emerge transient cooperative phenomena giving rise to coherent behaviors and percepts. These phenomena manifest themselves in multivariate brain signals recorded with various techniques. Our research aims at designing better methods for the analysis of these phenomena and their relationship to brain function.

In our first contribution, we developed Bayesian Generalized Linear Models for the system identification of networks of spiking neurons. Using sparse priors on the potential connections, this approach was very efficient for capturing key model parameters [1].

Oscillations are widespread indicators of collective dynamics and provide useful features for Brain Computer Interfaces (BCI) [1]. In particular, the statistical dependency between oscillations in different frequency bands currently raises considerable interest. These relationships fail to be captured by classical cross-spectral analysis, which can only account for second order statistics. We extended this technique to the non-linear case by using an implicit mapping of the time-series in a Reproducing Kernel Hilbert Space [6]. We showed this Kernel Cross Spectral Density measure asymptotically detects any pairwise dependency between two time series. Unlike linear techniques, this method can detect non-linear dependencies in extracellular signals between high and low frequency bands (Figure).

Beyond their mere statistical dependency, a key issue is how brain rhythms influence each other. Causal inference is used to address this question because it can ideally quantify directed interactions between variables. In a first project, we detected non-linear causal interactions using an information theoretic generalization of Granger causality, Transfer Entropy (TE). We defined a methodology to efficiently estimate TE between oscillations of multichannel electrophysiological recordings [2] and quantified their hierarchical organization. Gamma oscillations (40-90Hz) played an increased role in this hierarchy during sensory stimulation, supporting their putative role in distributed information processing.

Causal inference techniques can also be used to assess which aspect of brain activity affects the outcome of an experiment across different trials or subjects. Within the framework of causal graphical models, we established the relation of gamma oscillations to the sensorimotor rhythm (SMR) in healthy human subjects using electroencephalography [3]. We demonstrated that the inferred causal structure entails an influence of gamma oscillations on the SMR. This finding is of particular interest for BCI research, as it suggests gamma oscillations have an influence on a subject's capability to utilize a SMR-based communication system.

We recently started to develop unsupervised techniques to identify transient collective events in highly multivariate neural recordings, ranging from high density electrode arrays[2] to brain wide functional magnetic resonance signals. One of our contributions, based on non-negative matrix factorization, participated in a high impact publication showing the relationship of electrophysiological events originating from the hippocampus to large scale brain activity [4].

Besides advanced data analysis, an interesting link of our field with neuroscience is learning. Although training biologically inspired neural networks such as the perceptron is well-studied, understanding plasticity mechanisms of cortical spiking neurons with learning theory concepts has not been addressed so far. In a recent paper [5], we investigated spike-timing dependent plasticity (STDP) from this point of view. We showed that STDP-equipped neurons can be seen as implementing stochastic gradient descent on an objective function, and that the generalization error of such neurons is controlled by a margin depending on an l_1-regularizer. This work provides the first steps towards a theoretical framework for learning in biological neurons.

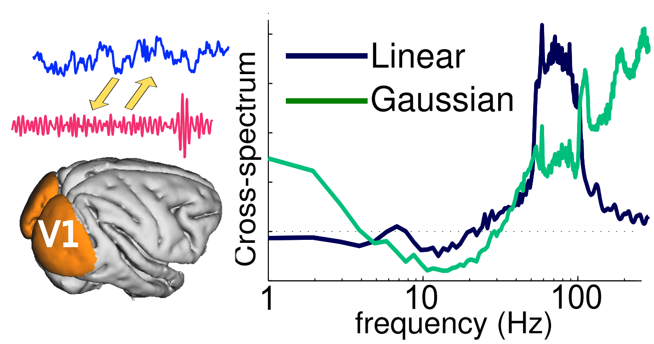

Figure 0.1: Cross-spectral density between two neural signals using linear and Gaussian kernel

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[3] M Grosse-Wentrup, B Schölkopf, and J Hill. Causal influence of gamma oscillations on the sensorimotor rhythm. *NeuroImage*, 56(2):837–842, 5 2011. 1

[4] NK Logothetis, O Eschenko, Y Murayama, M Augath, T Steudel, HC Evrard, M Besserve, and A Oeltermann. Hippocampal-cortical interaction during periods of subcortical silence. *Nature*, 491:547–553, 11 2012. 1

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