Time–Frequency Dynamics of Brain Connectivity by Stochastic Oscillator Models and Kalman Filtering

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Introduction

- Functional connectivity in functional magnetic resonance imaging (fMRI) is often estimated as the average pairwise similarity between the temporal dynamics of two regions of interests (ROIs) [5].
- In time-varying functional connectivity, where the stimulus is continuously changing, the functional connectivity is modulated in time [1–2].
- Here, we study the dynamic functional connectivity between pairs gray matter of voxels by considering the time–frequency dynamics between them.
- Each pair of time series is decomposed into oscillatory components described by a stochastic oscillator model [4].
- The oscillators are inferred from the data using optimal Bayesian filtering methods.
- The coherence between the different frequency components is converted into a time-varying functional network.

Methods

- We use a stochastic oscillator model, that is described by a second order stochastic differential equation (SDE) for each voxel i and frequency f_j:

$$\frac{\mathrm{d}\boldsymbol{x}_i(t)}{\mathrm{d}t} = \begin{pmatrix} 0 & 2\pi f_j \\ -2\pi f_j & 0 \end{pmatrix} \boldsymbol{x}_i(t) + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \xi_i(t),$$

  where $\xi_i(t)$ is a random white noise component with spectral density q_i.
- This is a linear SDE, and it can be solved for all the observations time points t_k, $k = 1, 2, \ldots$
- The discrete model can then be fitted to the fMRI data using Kalman filtering and smoothing.
- The model is based on DRIFTER — a method for removing physiological noise from fMRI data [4] — but evaluated over a set of fixed frequencies.
- Summing the cross-coherence power surface over frequencies defines the functional activation between the regions (see [1]).
- We compare the pairwise activation time series to ground truth stimuli in order to estimate connectivity maps describing the types of connections.

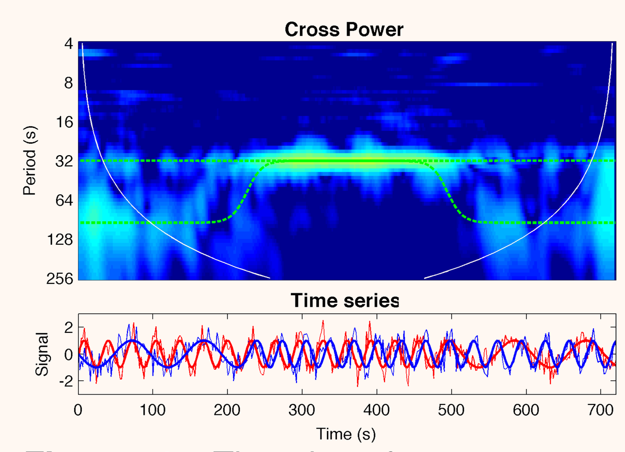

Figure 1: The time–frequency cross-power between two simulated time series.

Material

- Functional brain images together with anatomical data were acquired for 14 healthy native speakers of Finnish.
- The subjects watched 22 min 58 s of a Finnish language film in an MRI scanner (3 T GE Signa Excite, 8-channel head coil).
- The film was a shortened version of the feature film *"Match Factory Girl"* (dir. Aki Kaurismäki, 1990, original length 68 min).
- 16 visual and auditory features from the film were extracted as ground truth references (see [3] for details).
- Sequence parameters: EPI slices: 29, TR: 2 s, TE: 32 ms, matrix size: 64×64, FA: 90°, voxel size: 3.4×3.4 mm, slice thickness: 4 mm, gap size: 1 mm. Data downsampled to 6 mm isotropic voxels, and 6235 gray matter voxels chosen for study.

Results

- Figure 1 shows how the oscillator model captures the coupling of two simulated signals.
- The strongest network of intersubject consistency of connectivity time series is shown in Figure 2.
- Figures 3–5 show networks of linear regression between stimulus features (singing, head motion, hand motion) [3] and connectivity time series.
- Comparisons of intersubject consistency connectionscaptured by the wavelet approach by Chang and Glover [1]: inter-hemispheric connections between the occipital lobes appear to be less consistent across subjects when using wavelets.

Conclusions

- We have proposed a method for estimating coupling of oscillatory phenomena in fMRI data.
- The outcome can be used for estimating time-varying functional connectivity networks.
- This approach is related to that of [1], where a wavelet basis was used for modeling the cross-coherence.

Acknowledgements

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References

[1] Chang, C. and Glover, G.H. (2010), *'Time–frequency dynamics of resting-state brain connectivity measured with fMRI'*, NeuroImage, vol. 50, no. 1, pp. 81–98.

[2] Glerean, E., *et al.* (2012), *'Functional magnetic resonance imaging phase synchronization as a measure of dynamic functional connectivity'*, Brain Connectivity, vol. 2, no. 2, pp. 91–101.

[3] Lahnakoski, J.M., *et al.* (2012), *'Stimulus-related independent component and voxel-wise analysis of human brain activity during free viewing of a feature film'*, PloS one, vol. 7, no. 4, p. e35215.

[4] Särkkä, S., *et al.* (2012), *'Dynamical retrospective filtering of physiological noise in BOLD fMRI: DRIFTER'*, NeuroImage, vol. 60, no. 2, pp. 1517–1527.

[5] Smith, S.M., *et al.* (2011), *'Network modelling methods for fMRI'*, NeuroImage. vol. 54, no. 2, pp. 875–891.

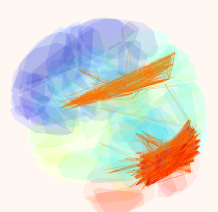
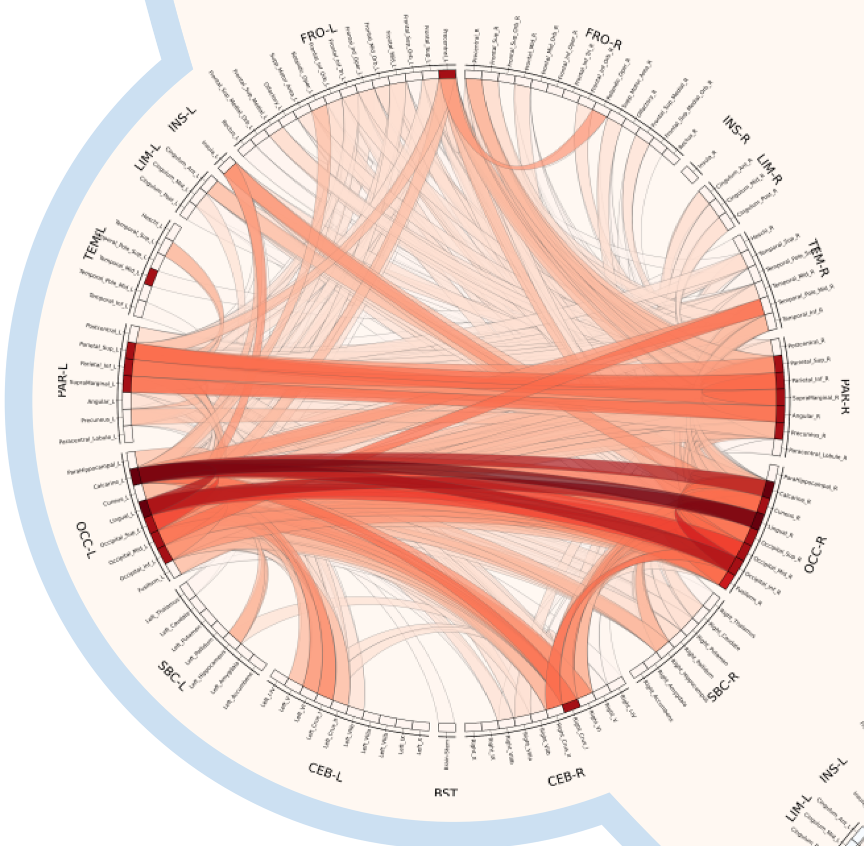

Figure 2: The network for the links returning the strongest intersubject correlations. The bilateral symmetry is strong.

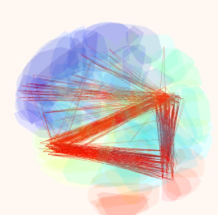
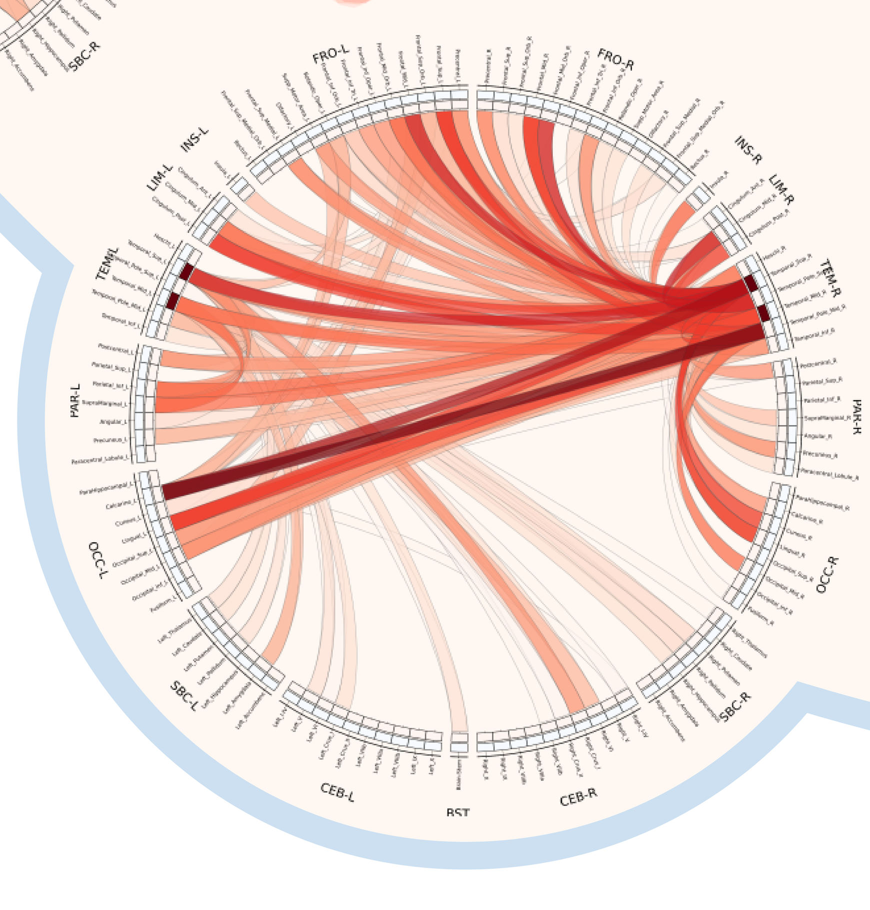

Figure 3: The connectivity map correlated with singing in the movie. Lateralization over right temporal areas for melody/pitch processing.

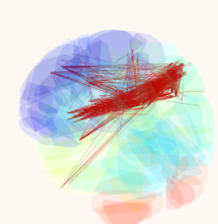
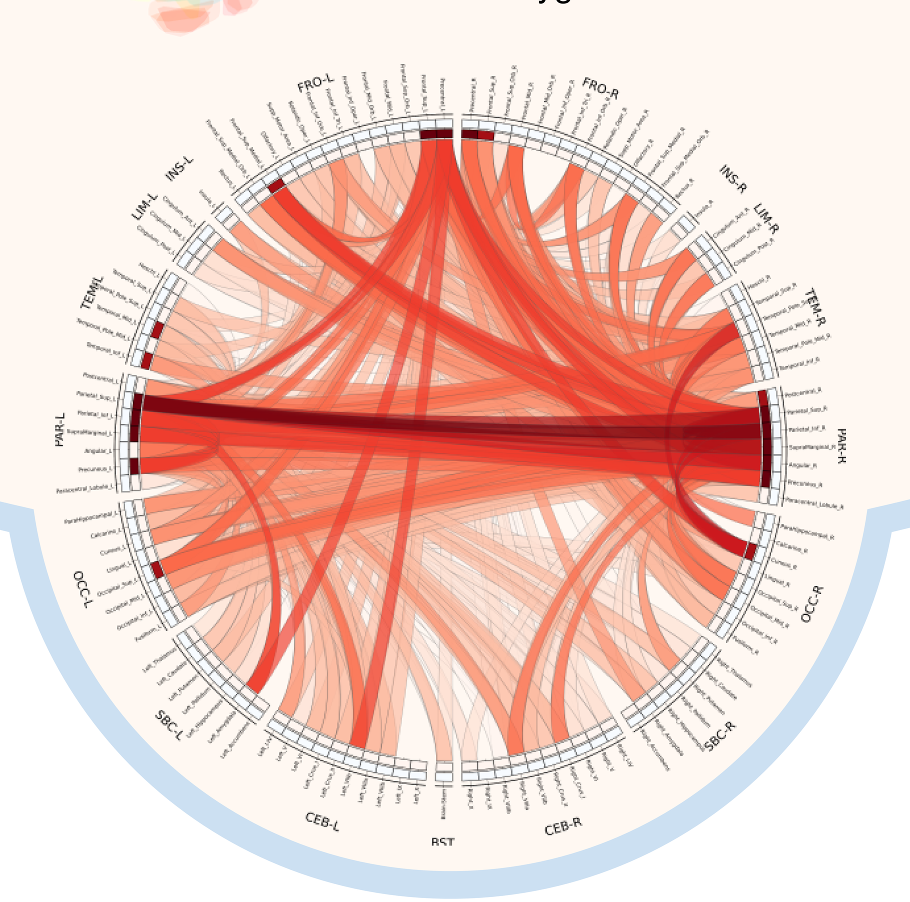

Figure 4: Network for head motion in the film. Strong parietal regions, bits of fusiform face area, frontal areas and amygdala.

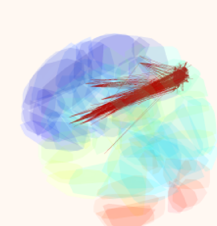
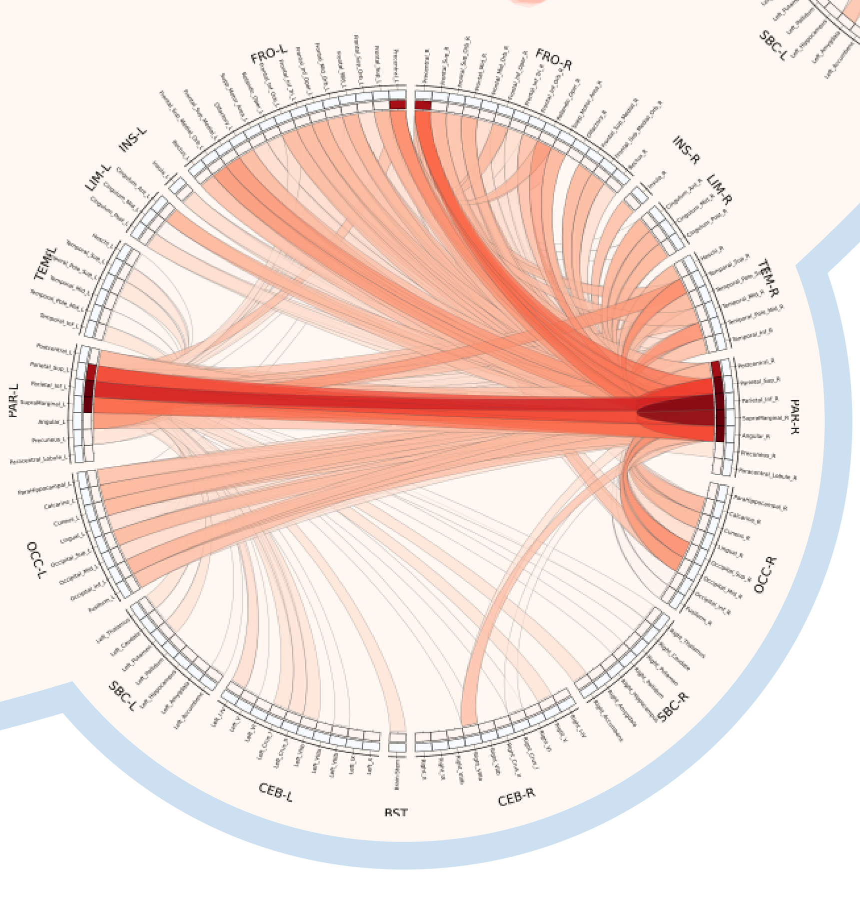

Figure 5: Network for hand motion in the film. Strong parietal regions and parieto–occipital connections.

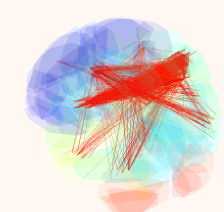
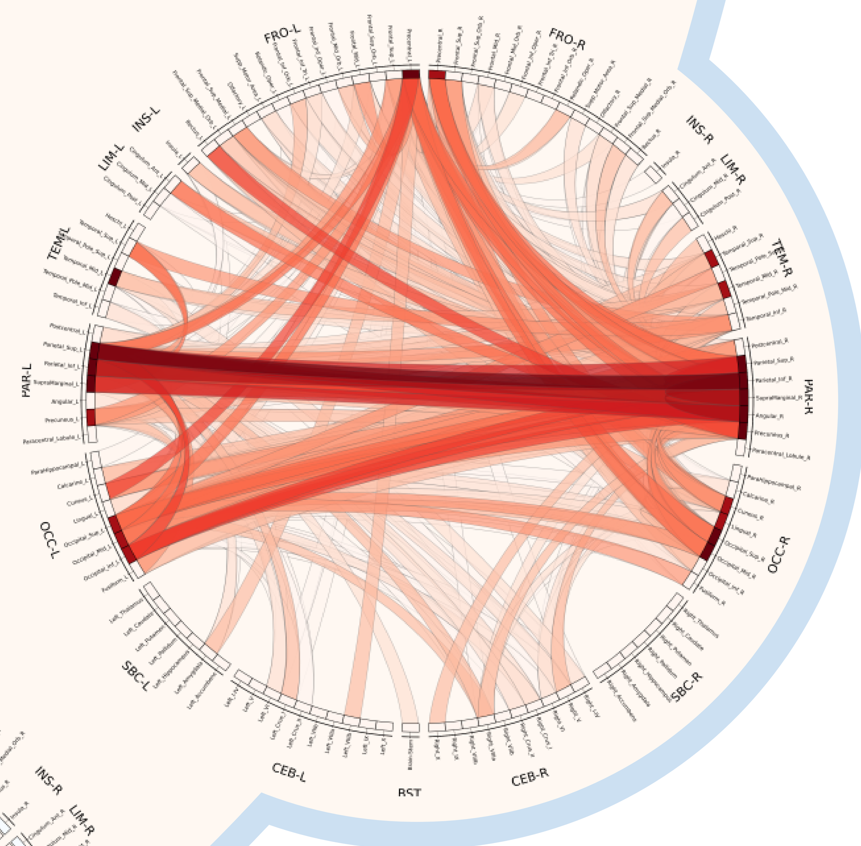

Figure 6: The same network as in Fig. 2, but calculated by the wavelet method by Chang and Glover [1].

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