

Functional connectivity of fractal and oscillatory cortical activity is distinct

Andrea Ibarra Chaoul (andrea.ibarra-chaoul@cin.uni-tuebingen.de)

Hertie-Institute for Clinical Brain Research, Centre for Integrative Neuroscience & MEG Center,
Otfried-Mueller-Str. 25, 72076 Tuebingen, Germany

Markus Siegel (markus.siegel@uni-tuebingen.de)

Hertie-Institute for Clinical Brain Research, Centre for Integrative Neuroscience & MEG Center,
Otfried-Mueller-Str. 25, 72076 Tuebingen, Germany

Abstract:

Electrophysiological signals of cortical population activity contain oscillatory and fractal (1/frequency) components. However, the relationship between these components is unclear. To address this, we investigated human resting-state MEG recordings. We applied combined source-analysis, signal orthogonalization and irregular-resampling auto-spectral analysis (IRASA) to separate oscillatory and fractal components of the MEG signals at the cortical source-level. We then compared the spatial correlation structure of fractal and oscillatory components across the human cortex. We found that these correlation structures differed, which suggests different mechanisms underlying fractal and oscillatory population signal components.

Keywords: scale free; 1/f; functional connectivity; MEG; resting state

Introduction

Neuronal population activity, as measured with EEG, MEG or LFPs, can be separated into oscillatory and the fractal components. While oscillations have been implicated in various functions (Buzsáki & Draguhn, 2004), it is not until recently that the broadband, or 1/frequency, part of the spectrum became itself a focus of study (He, 2014). Broadband activity has been related to neural noise (Voytek, Kramer, Case, Lepage, Tempesta, Knight & Gazzaley, 2015), self-organized criticality, long range temporal correlations, and excitation-inhibition balance. However, it remains unclear how oscillatory and fractal signal components are related.

To address this, we systematically compared the functional connectivity, i.e. spatial correlation structure, of fractal and oscillatory components of human cortical population activity using resting-state MEG recordings.

Methods

We analyzed data from 112 healthy subjects recorded either at the MEG Center, Tuebingen or as part of the Human Connectome Project (HCP).

We adapted the minimally preprocessed pipeline of the HCP (Larson-Prior, Oostenveld, Della Penna, Michalareas, Prior, Babajani-Feremi, ... Snyder, 2013) and the same artifact rejection to both data sets.

Clean data was high-pass filtered at 0.1 Hz using a 4th order Butterworth filter. We removed line noise artifacts and resampled the data to 1000 Hz.

We used linearly constrained minimum variance (LCMV) beamforming (Van Veen, van Drongelen, Yuchtman & Suzuki, 1997) to project the sensor-level MEG data into source space using a single-shell head-model leadfield (Nolte, 2003) based on each individual subject's MRI.

We analyzed the source-level data in non-overlapping 3 s sliding windows. For each time-window and source-location, we applied time-domain orthogonalization to discount volume conduction effects (Hipp, Hawellek, Corbetta, Siegel & Engel, 2012). We then performed irregular-resampling auto-spectral analysis (IRASA) (Wen & Liu, 2016) on the orthogonalized signal to split the signal into oscillatory and fractal components.

For each time-window and source-location, we fitted a power law to the fractal spectrum. We compared a simple linear model, a continuous linear model with a knee at 15 Hz, and a model that



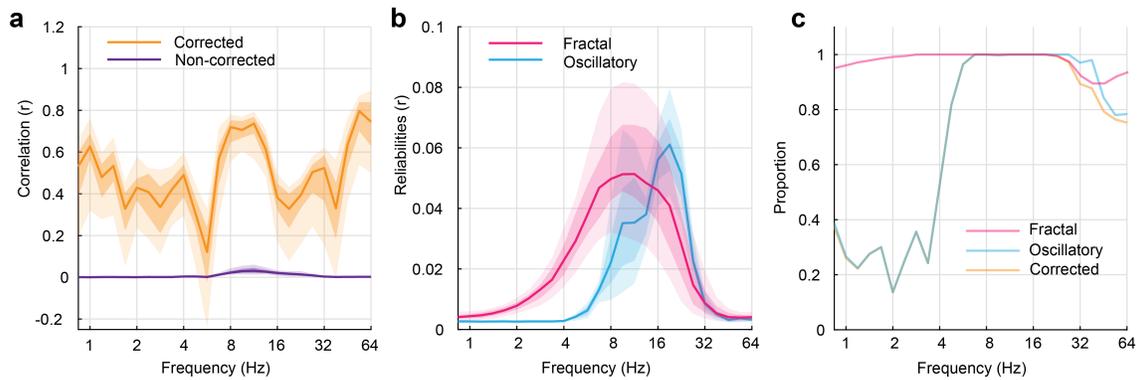


Figure 1: Attenuation corrected correlation between cortex-wide correlation patterns of fractal and oscillatory neuronal activity: a) Attenuation corrected and non-corrected correlation between correlation patterns of fractal and oscillatory activity, b) inter-subject reliabilities of correlation patterns of fractal and oscillatory activity, c), proportion of reliable patterns. Shaded regions in a) and b) indicate 5-95% and 25-75% percentiles across the cortex.

takes into account the effect of the ambient noise. We assessed model fits using the Akaike information criterion (AIC).

To assess functional connectivity, we took the logarithm of oscillatory and fractal power spectra and binned them into logarithmically spaced bins. (Hipp, Hawellek, Corbetta, Siegel & Engel, 2012). Then, we computed the Pearson correlation between each pair of orthogonalized seeds.

To compare the correlation structures of fractal and oscillatory components, we performed a correlation with attenuation correction (Siems, Pape, Hipp, & Siegel, 2016). Attenuation correction takes into account each signal's reliability (SNR) and computes correlations corrected for finite SNR.

Results

We source-reconstructed cortical activity from the MEG, discounted volume conduction by means of signal orthogonalization and separated fractal and oscillatory components using IRASA. We fitted and compared different signal models of the fractal power spectra. From the tested models, the optimal model (minimum AIC) included a knee at 15 Hz and included the (non-flat) shape of the power spectrum during empty-room MEG measurements (Bedard, Gomes, Bal & Destexhe, 2017; Dehghani, Bédard, Cash, Halgren, & Destexhe, 2010).

We then computed the attenuation corrected correlation between the brain-wide correlation patterns of oscillatory and fractal signal components (Figure 1). Across the entire

investigated frequency range, attenuation corrected correlations were substantially larger than 0 but significantly smaller than 1. Thus, the functional connectivity patterns of oscillatory and fractal components were distinct. At 5.5 Hz the difference between connectivity patterns was most pronounced. For frequencies around 10 Hz and 64 Hz connectivity patterns were most similar.

Conclusions

Our results show that fractal and oscillatory signal components provide different information about the temporal correlation, i.e. functional connectivity, of different cortical regions. This raises the question, which processes may be reflected by the functional connectivity of fractal signal components?

Broadband activity is correlated with neuronal firing rates in intracortical recordings. Thus, the connectivity patterns of fractal activity measured with MEG may provide a window into the spatial structure of co-fluctuations of broadband or spiking activity.

Independent of the specific underlying mechanisms, the observed differences in connectivity patterns of oscillatory and fractal activity indicate that oscillatory and fractal signals components are, at least partially, independent. This suggests different neuronal mechanisms underlying fractal and oscillatory components of human cortical population signals.

Acknowledgements

This work was supported by the European Research Council (ERC) StG335880 and the Centre for Integrative Neuroscience (DFG) EXC 307. The authors acknowledge support by the state of Baden-Württemberg through bwHPC and the German Research Foundation (DFG) through grant no INST 39/963-1 FUGG (bwForCluster NEMO).

References

- Bedard, C., Gomes, J. M., Bal, T., & Destexhe, A. (2017). A framework to reconcile frequency scaling measurements, from intracellular recordings, local-field potentials, up to EEG and MEG signals. *Journal of Integrative Neuroscience*, 16(1), 3–18.
- Buzsáki, G., & Draguhn, A. (2004). Neuronal Oscillations in Cortical Networks. *Science*, 304(June), 1926–1929
- Dehghani, N., Bédard, C., Cash, S. S., Halgren, E., & Destexhe, A. (2010). Comparative power spectral analysis of simultaneous electroencephalographic and magnetoencephalographic recordings in humans suggests non-resistive extracellular media. *Journal of Computational Neuroscience*, 29(3), 405–421
- He, B. J. (2014). Scale-free brain activity: past, present, and future. *Trends in Cognitive Sciences*, 18(9), 480–487
- Hipp, J. F., Hawellek, D. J., Corbetta, M., Siegel, M., & Engel, A. K. (2012). Large-scale cortical correlation structure of spontaneous oscillatory activity. *Nature Neuroscience*, 15(6), 884–890.
- Larson-Prior, L. J., Oostenveld, R., Della Penna, S., Michalareas, G., Prior, F., Babajani-Feremi, A., ... Snyder, A. Z. (2013). Adding dynamics to the Human Connectome Project with MEG. *NeuroImage*, 80, 190–201.
- Nolte, G. (2003). The magnetic lead field theorem in the quasi-static approximation and its use for magnetoencephalography forward calculation in realistic volume conductors. *Physics in Medicine and Biology*, 48(22), 3637–3652.
- Siems, M., Pape, A. A., Hipp, J. F., & Siegel, M. (2016). Measuring the cortical correlation structure of spontaneous oscillatory activity with EEG and MEG. *NeuroImage*, 129, 345–355.
- Van Veen, B., van Drongelen, W., Yuchtman, M., & Suzuki, A. (1997). Localization of brain electrical activity via linearly constrained minimum variance spatial filtering. *IEEE Transactions on Biomedical Engineering*, 44(9), 867–880.
- Voytek, X. B., Kramer, M. A., Case, J., Lepage, K. Q., Tempesta, Z. R., Knight, R. T., & Gazzaley, A.
- Wen, H., & Liu, Z. (2016). Separating Fractal and Oscillatory Components in the Power Spectrum of Neurophysiological Signal. *Brain Topography*, 29(1), 13–26.