The Causal Structure of Band-limited Dynamics in the Human Cortex

Paul Hege[1 2 3], Markus Siegel[1 2 3]
[1]Department of Neural Dynamics and MEG, Hertie Institute for Clinical Brain Research, University of Tübingen
[2]Centre for Integrative Neuroscience, University of Tübingen, Germany
[3]MEG Center, University of Tübingen, Germany

Abstract

Measurements of the synchronous variation of neural activity in different areas of the brain provide fundamental insights into large-scale human brain function. However, research has so far largely focused on instantaneous correlations, providing little information about the causal structure of neural interactions. Here, we addressed this by systematically characterizing temporally directed interactions of band-limited neural activity across the human cortex using source-reconstructed magnetoencephalography (MEG). We found links between the structure of lagged correlations and models of large-scale brain organization, with cross-frequency lagged interactions varying along a tripolar gradient that closely resembles structural and functional MRI gradients. We also identified discrete brain networks with spatially and spectrally specific interaction profiles that were selectively modified during cognitive tasks.

Keywords: functional connectivity, magnetoencephalography, resting state networks

Introduction

The instantaneous correlation of cortical activity is an important measure of spontaneous cortical activity that reflects functional interactions between brain regions (Friston, 2011; Siegel, Donner, & Engel, 2012). But the directed, causal structure of these interactions remains unclear. To address this, we investigated the dynamics of human cortical activity using source-reconstructed magnetoencephalography (MEG) by systematically mapping lagged interactions of large-scale neural activity across different frequency bands and the full cortical space, both in the resting state and while subjects were performing a cognitive task.

Methods

We used resting state and task MEG data recorded as part of the human-connectome project (HCP), as well as data from two other MEG experiments (Van Essen et al., 2013; Radetz & Siegel, 2022) ($n_{\mathrm{HCP}} = 89$, $n_2 = 28$, $n_3 = 42$, respectively). For each recording, we reconstructed neural activity on a single-shell cortical surface using an LCMV beamformer and obtained a time-frequency representation using a continuous wavelet transform (Figure 1a). We then systematically computed the time-asymmetric lagged amplitude envelope correlation (Tewarie et al., 2023) for all pairs of frequencies and cortical locations, as well as for a wide range of time lags between 20 ms and 10 seconds. We used a new, band-specific orthogonalization method which effectively reduces effects of volume conduction.

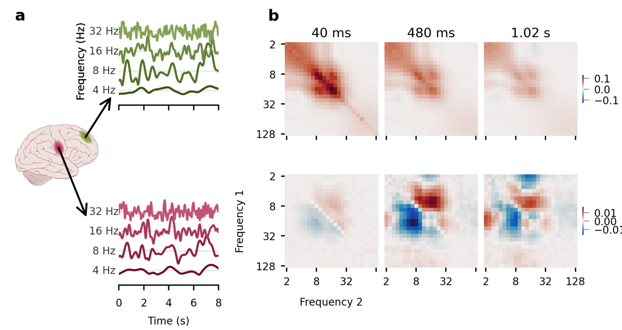

Figure 1: We computed and cross-correlated wavelet envelopes of source-reconstructed neural activity across the entire cortex (a), leading to a consistent pattern (spatial average shown) of total and time-asymmetric lagged correlations (b).

To investigate the spatial variation of cross-frequency lagged correlations, we first reduced the dimensionality of the space of lagged band-limited interaction patterns using a deep autoencoder, systematically determining the optimal latent dimension. We analyzed the geometry of the resulting latent representation, focusing on the relationship of connections sharing a single source or target, to describe the intrinsic geometry of lagged interaction patterns.

Furthermore, we extracted components with spatially specific band-limited lagged interaction profiles by applying sparse dictionary learning to the interaction patterns of different connections. We used leave-one-out cross-validation to determine the number of components in the data.

Results

We found that most spectrally resolved amplitude envelope interactions had clear and consistent temporal lags, both within and across frequency bands. Temporal asymmetries covered all temporal scales and decayed to zero only at lags of several seconds. We discovered a common pattern of lagged interactions between frequency bands that was ubiquitously shared across cortical connections (Fig. 1b). This pattern arises from slow, cortex-wide modulations of band-limited power that are linked to arousal as indexed by pupil dilation.

Superimposed on this cortex-wide pattern, we found highly consistent localized patterns of lagged interactions between activity in different frequency bands. Using autoencoders and other dimensionality reduction techniques, we uncovered a single, two-dimensional gradient of neural interactions. The lagged interaction profile of a given cortical connection was

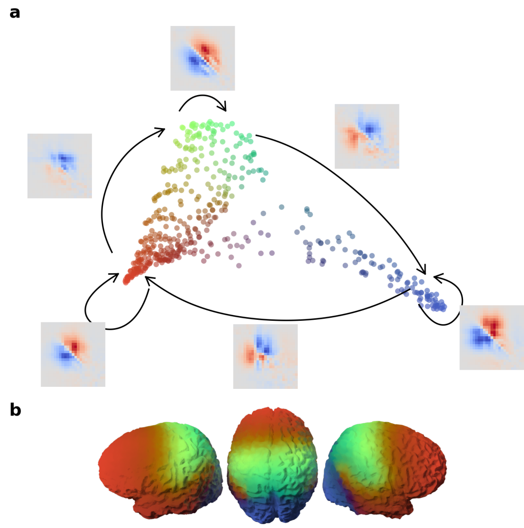

Figure 2: We identify a two-dimensional tripolar gradient across the cortex such that lagged cross-frequency interaction profiles depend to a large degree on the position of source and target along the gradient (a). The poles of the gradient correspond to visual, sensorimotor and multimodal areas (b).

determined, to good approximation, by the location of source and target regions along this gradient (Fig 2a).

We found that the gradient had a tripolar structure, with the three poles corresponding to visual, sensorimotor, and transmodal cortex, respectively (Fig 2b). This tripolar gradient fitted remarkably well with other gradient-based models of cortical organization that were derived either from structural data or from fMRI-derived functional connectivity (Mesulam, 1998; Margulies et al., 2016). We compared MEG- and fMRI-derived gradients at the single-subject level.

In addition to the gradient structure, we extracted spatially localized networks with characteristic lagged interaction patterns using a dictionary learning approach (two such networks are shown in Fig. 3a,b.) Cross-validation showed that a set of fourteen networks optimally described the observed cross-correlations. We found that most of these networks connect subareas of one or two poles of the large-scale gradient structure.

Finally, we compared lagged interactions between the resting state and different cognitive tasks. We found that dynamic patterns of spontaneous cortical activity were largely maintained during task performance, especially at faster time scales. In terms of the components identified in the resting state, we observed that task-specific changes in asymmetric cross-correlation were confined to a small subset of networks (Fig 3c). For the visual working memory task, the components in this subset reflected interactions between visual and sensorimotor areas that were directly involved in task performance.

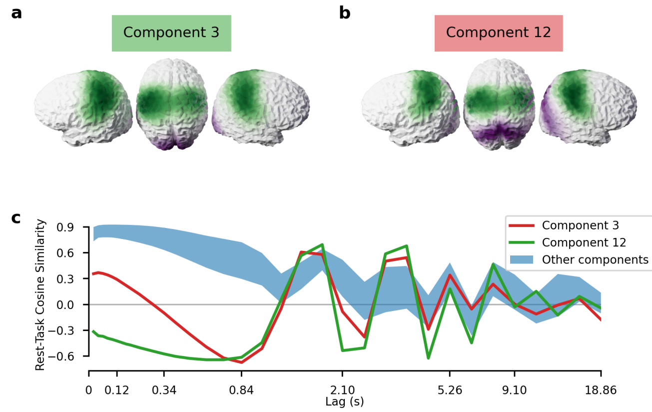

Figure 3: During a visual working memory task lagged-interactions markedly changed in two of the networks with specific lagged interaction patterns that were extracted using dictionary learning (a, b). In contrast, interaction dynamics remained similar in all other components (c; shaded area shows standard error range of 12 components)

Discussion

Patterns of lagged correlation have previously been studied in fMRI (Mitra, Snyder, Hacker, & Raichle, 2014; Mitra, Snyder, Blazey, & Raichle, 2015) and the irreversibility of lagged amplitude envelope correlation has been quantified in MEEG recordings (Tewarie et al., 2023) and shown to be an important marker of brain dynamics across species (Deco, Sanz Perl, Bocaccio, Tagliazucchi, & Kringelbach, 2022; Idesis et al., 2024).

Here, we extended this work by providing a systematic characterization of lagged interaction patterns within and between cortical areas and frequency bands in spontaneous and task-driven human cortical dynamics. We found a spatially ubiquitous pattern of lagged cross-frequency interaction driven by slow cortex-wide power modulations, and described the spatial variation in interaction profiles using a two-dimensional cortical gradient. The gradient we obtained has a tripolar structure and resembles known models and gradients of large-scale cortical organization. This provides an important link between measures of structure and symmetric functional connectivity on the one hand and the fast, time-irreversible dynamics of spontaneous brain activity on the other. Furthermore, we identified cortical networks with specific lagged interaction patterns and showed that during cognitive tasks, these patterns are modulated in a task-specific subset of networks.

Acknowledgements

We thank Marcus Siems and Andrea Ibarra-Chaoul for valuable discussions. This research is supported by the European Research Council (ERC CoG 864491).

References

Deco, G., Sanz Perl, Y., Bocaccio, H., Tagliazucchi, E., & Kringelbach, M. L. (2022). The insideout framework provides precise signatures of the balance of intrinsic and extrinsic dynamics in brain states. *Communications Biology*, *5*(1), 572.

Friston, K. J. (2011). Functional and effective connectivity: a review. *Brain connectivity*, *1*(1), 13–36.

Idesis, S., Geli, S., Faskowitz, J., Vohryzek, J., Sanz Perl, Y., Pieper, F., ... Deco, G. (2024). Functional hierarchies in brain dynamics characterized by signal reversibility in ferret cortex. *PLOS Computational Biology*, *20*(1), e1011818.

Margulies, D. S., Ghosh, S. S., Goulas, A., Falkiewicz, M., Huntenburg, J. M., Langs, G., ... Smallwood, J. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences*, *113*(44), 12574–12579.

Mesulam, M. (1998). From sensation to cognition. *Brain*, *121*(6), 1013–1052.

Mitra, A., Snyder, A. Z., Blazey, T., & Raichle, M. E. (2015, mar). Lag threads organize the brain's intrinsic activity. *Proceedings of the National Academy of Sciences*, *112*(17).

Mitra, A., Snyder, A. Z., Hacker, C. D., & Raichle, M. E. (2014). Lag structure in resting-state fmri. *Journal of Neurophysiology*, *111*(11), 2374–2391.

Radetz, A., & Siegel, M. (2022). Spectral fingerprints of cortical neuromodulation. *Journal of Neuroscience*, *42*(18), 3836–3846.

Siegel, M., Donner, T. H., & Engel, A. K. (2012). Spectral fingerprints of large-scale neuronal interactions. *Nature Reviews Neuroscience*, *13*(2), 121–134.

Tewarie, P. K. B., Hindriks, R., Lai, Y. M., Sotiropoulos, S. N., Kringelbach, M., & Deco, G. (2023). Non-reversibility outperforms functional connectivity in characterisation of brain states in MEG data. *NeuroImage*, *276*, 120186.

Van Essen, D. C., Smith, S. M., Barch, D. M., Behrens, T. E., Yacoub, E., Ugurbil, K., ... others (2013). The wu-minn human connectome project: an overview. *Neuroimage*, *80*, 62–79.