Imaging and Detection of Oscillatory Activity in MEG using Time-Frequency Analysis and Permutation Tests

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Introduction

In event-related MEG studies, the standard technique for noise reduction involves averaging over stimulus-locked responses. However this also removes higher frequency components in the data that are not phase locked to the stimulus. To overcome this problem, we combine time-frequency analysis of individual epochs with minimum norm imaging to produce dynamic cortical images in multiple frequency bands. To detect statistically significant differences between two conditions, such as post-stimulus vs. baseline, we use a permutation test. By learning the null distribution of maximum signal power in each band across the cortex, we can then determine a threshold that controls the familywise error rate, i.e. the probability of one or more false positive detections across the entire cortex. Applying this test to each frequency band produces a set of cortical images showing significant event-related activity in each band of interest. We demonstrate this method in application to high density MEG studies of visual attention.

Model

- MEG data are collected as a set of \( J \) stimulus-locked event-related epochs. Each epoch consists of an array of data \( \mathbf{M} \) (\( n \times m \)) representing the measured magnetic field at each sensor as a function of time. The measurements \( \mathbf{M} \) are linearly related with the brain activation \( \mathbf{Y} \) (\( n \times m \)) as:

\[
\mathbf{M} = \mathbf{G} \mathbf{Y} + \mathbf{N}
\]

- A cortical map can be computed for each epoch by applying a min-norm Tikhonov-regularized inverse method, to produce an estimate of the temporal activity at each surface element in the cortex:

\[
\mathbf{Y} = \Sigma \mathbf{H} \mathbf{M}
\]

Wavelet Transform

- For each epoch \( j \) and each source \( i \) we obtain an estimate of the time-varying frequency components by expanding the timeseries \( \mathbf{Y}_{ij} \), using complex Morlet wavelets as basis functions:

\[
\mathbf{w}_{ijf} = (\pi \delta_0)^{-1/4} e^{i \pi \delta_0 (\mathbf{F}_{ij} + \mathbf{F}_{ij}^T)/4}
\]

\[
\mathbf{C}_{ijf} = \mathbf{Y}_{ij} \ast \mathbf{w}_{ijf}
\]

Test Statistics

- To compare two conditions on an experiment setting, such as post-stimulus vs. baseline, we need a robust test statistic

\[
E_{ijf} = \int_{\mathbf{f} \in \mathbf{F}} \mathbf{C}_{ijf} \mathbf{C}_{ijf}^* \, df
\]

- Using the notation \( k^+ \) for a post-stimulus time period \( t \in [t_i, t_f] \), and \( k^- \) for a pre-stimulus period \( t \in [-\delta, 0] \), we define the statistic:

\[
T_{ik} = \frac{E_{ik} - \bar{E}_i}{\sigma_{ik}}, \quad \sigma_{ik} = \sqrt{\text{var} \left[ E_{ik} \right] + \text{var} \left[ \bar{E}_i \right]/J}
\]

Statistical Significance

- Using permutation between pre- and post-stimulus bands, we can create \( M \) permutation samples \( \bar{T}_{ik} \).

- We summarize the information in space and bands using the maximum statistic:

\[
\tilde{T} = \max_{i,k} T_{ik}
\]

- Then we can use the empirical distribution of \( \tilde{T} \) to define a level \( \alpha \) threshold: \( \tilde{T}_{\alpha} = \tilde{T}_{\alpha} (1 - \alpha) \). A band \( k \) has statistically significant energy at source \( i \) if \( T_{ik} \) exceeds this threshold.

Experiment

- Each trial presents a central arrow cue that directs attention to the lower left or right visual field, in anticipation of a second stimulus (52), delivered 1 sec later on the left or right.

Results

- The brain regions and their timing of activity fit well with those expected from monkey recordings and functional imaging studies.

- Upper Beta (panel a) shows decreased power in what is considered to be a network for deploying attention: dorsolateral prefrontal, inferior parietal, lateral and ventral temporal areas. Note the larger decrease contralateral to the direction of attention (i.e., right hemi., for cue-left field).

- Theta (panel b) is increased in parietal and occipital areas during the early deployment stage (200-500ms), then moves to more ventral representations during the sustained stage (700-1000ms).

- Gamma (panel c) increases in areas similar to Theta. These are the brain regions considered to maintain the representations of the impending target stimulus.