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Nonlinear Interaction Decomposition (NID): A Novel Framework for Studying Cross-Frequency Coupling in Human Brain

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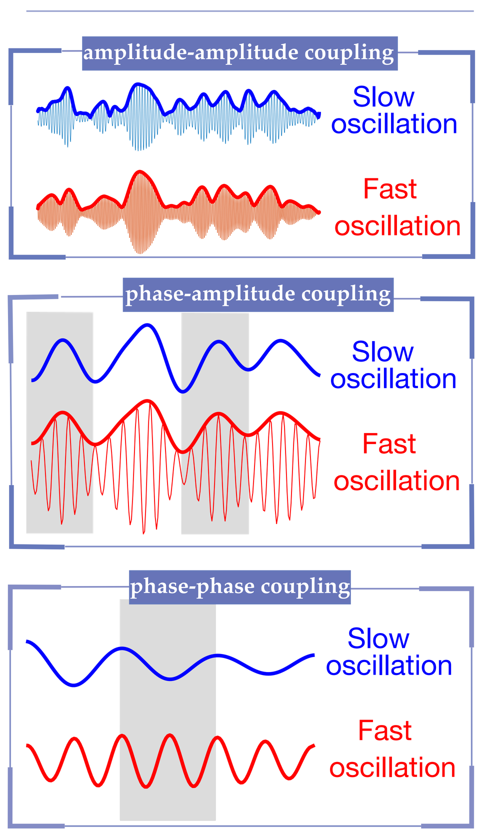
Introduction

• A group of activated neurons that synchronize rythmically produce oscillations (Singer, 1993).

• EEG/MEG record a mixture of all activities in the brain. Therefore, studying source signals from specific brain regions requires some kind of source separation method.

1 Different types of nonlinear interactions among brain oscillations.



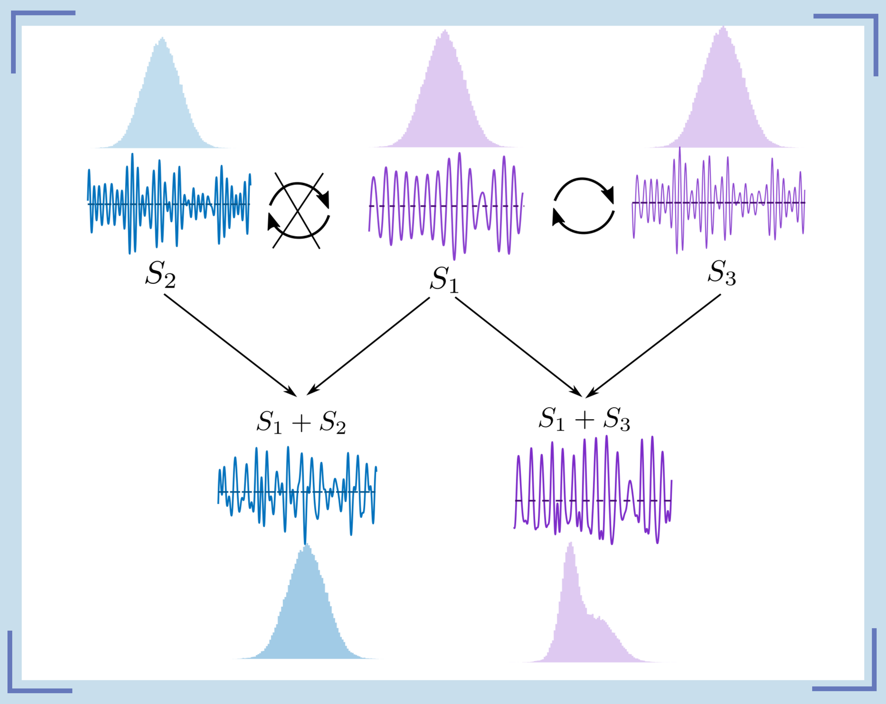
• Oscillatory neural populations interact within one frequency band (Engel and Fries, 2010), or across different frequency bands (Palva & Palva, 2018) .

• Cross-frequency coupling enables integration of spectrally distributed information processing in the brain.

•Separation of corss-frequency coupled oscillations is challenging.

• We propose a novel method for extraction of nonlinearly interacting oscillations in the brain.

NID's Main Idea



WORKING PRINCIPLES:

• Narrow-band oscillations in the brain (S_1,S_2,S_3) is approximately Gaussian distributed.

• Linear mixture of two independent narrow-band oscillations (S_1,S_2) has Gaussian distributed.

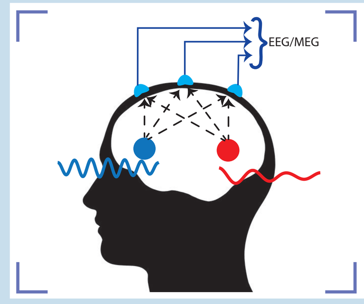
• Linear mixture of phase-phase coupled oscillations (S_1,S_3) has non-Gaussian distribution.

Method

Problem Formulation

• Source model: $\mathbf{X} = \mathbf{P}^{(n)}\mathbf{S}^{(n)} + \mathbf{P}^{(m)}\mathbf{S}^{(m)} + \xi$

($C \times T$: multi-channel observed signal; $C \times N$: N activation patterns of the oscillations at f_n; $N \times T$: N oscillations at f_n; frequency f_m)



• Goal: extraction of oscillations and activations patterns at f_n and f_m

Nonlinear Interaction Decomposition (NID)

• SSD decomposition: $\mathbf{X}^{(n)} = \mathbf{A}^{(n)}_{ssd}\mathbf{X}^{(n)}_{ssd}$

($C \times N$: N SSD activation patterns of the oscillations at f_n; $N \times T$: N SSD components at f_n)

• Concatenation: $\mathbf{X}_{Aug} = \left[\mathbf{X}^{(n)}_{ssd}; \mathbf{X}^{(m)}_{ssd}\right]$

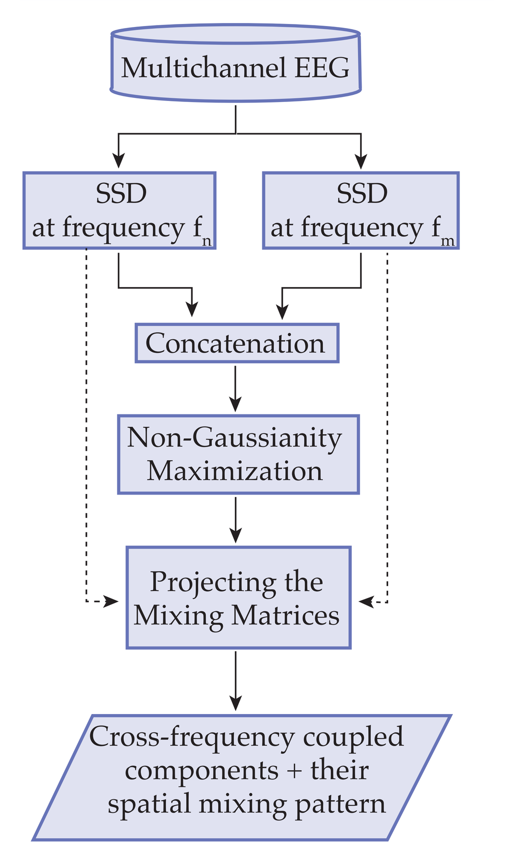
• Non-Gaussianity maximization: $\mathbf{X}_{Aug} = \mathbf{A}_{NG}\mathbf{R}$ ($2N \times T$, $2N \times N$)

$\mathbf{R} = \mathbf{W}_{NG}\mathbf{X}_{Aug}$ ($\mathbf{W}_{NG} = [\mathbf{W}^{(n)}_{NG}; \mathbf{W}^{(m)}_{NG}]$, $\mathbf{A}_{NG} = [\mathbf{A}^{(n)}_{NG}; \mathbf{A}^{(m)}_{NG}]$)

• NID activation pattern: $\mathbf{P}^{(n)}_{NID} = \mathbf{A}^{(n)}_{ssd}\mathbf{A}^{(n)}_{NG}$

• NID source signals: $\mathbf{S}^{(n)}_{NID} = \mathbf{W}^{(n)}_{NG}\mathbf{X}^{(n)}_{ssd}$

2 Block-diagram of NID



Spatio-Spectral Decomposition (SSD)

• SSD is a method for extraction of oscillations at a specific frequency band (Nikulin et al, 2011). It finds the spatial filters maximizing the SNR at a defined frequency band.

Results

Simulated Data

• Simulated data with 2 pairs of oscillations with phase-phase coupling at frequency $f_n = nf_b$ and $f_m = mf_b$ (denoted by n:m coupling).

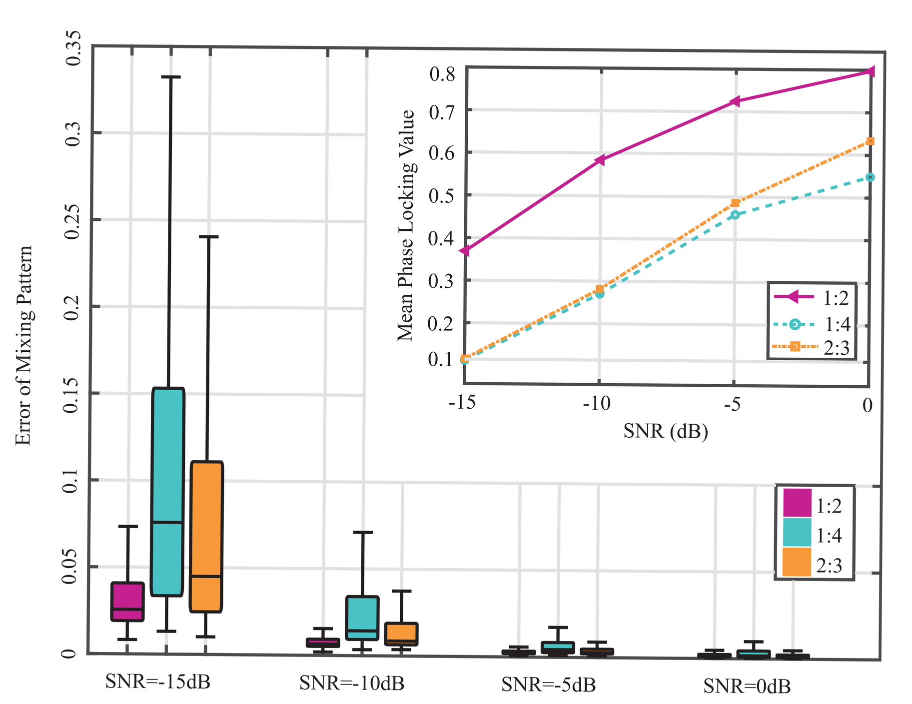
• Error of mixing pattern is the dissimilarity between the recovered and original activation patterns.

• Figure 3: The low median error of extraction of mixing patterns and the high mean PLV of the extracted oscillations show the erliability of NID.

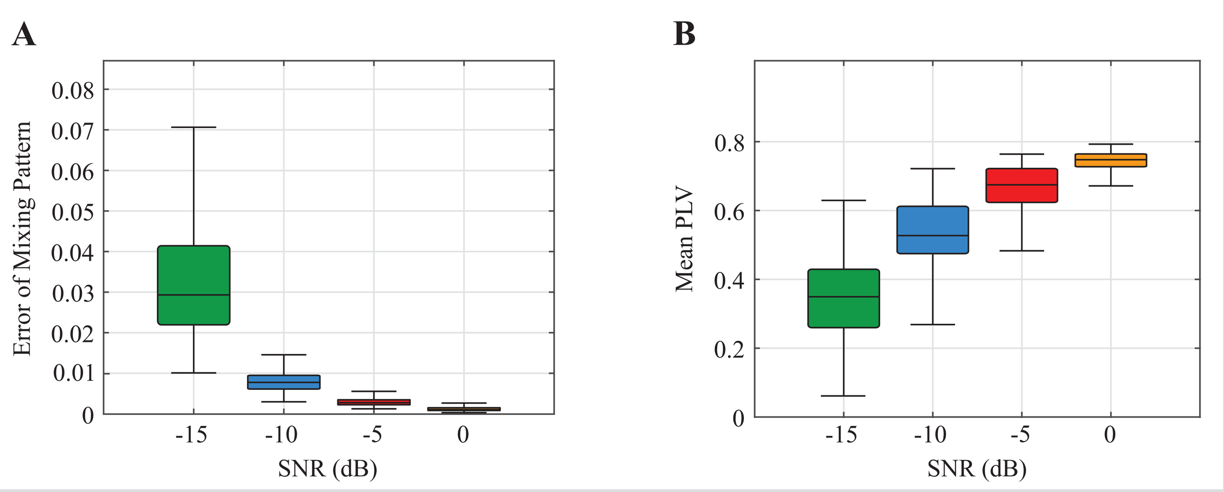
• Other additional simulations are done with 5 pairs of coupled source signals.

• We did the same simulations for extraction of amplitude-amplitude coupled oscillations and comparable results were achieved.

3 Main plot: Error of mixing pattern extraction for simulated data. Subplot: mean PLV of the extracted coupled source signals.



4 NID for extraction of triplets of coupled oscillations at 10Hz, 20Hz, and 30Hz. A: Error of mixing pattern extraction for simulated data. B: mean PLV of the extracted coupled source signals.



Extension of NID for extraction of n:m:r coupling:

• The augmented matrix is built from concatenating the SSD components of the three frequency bands.

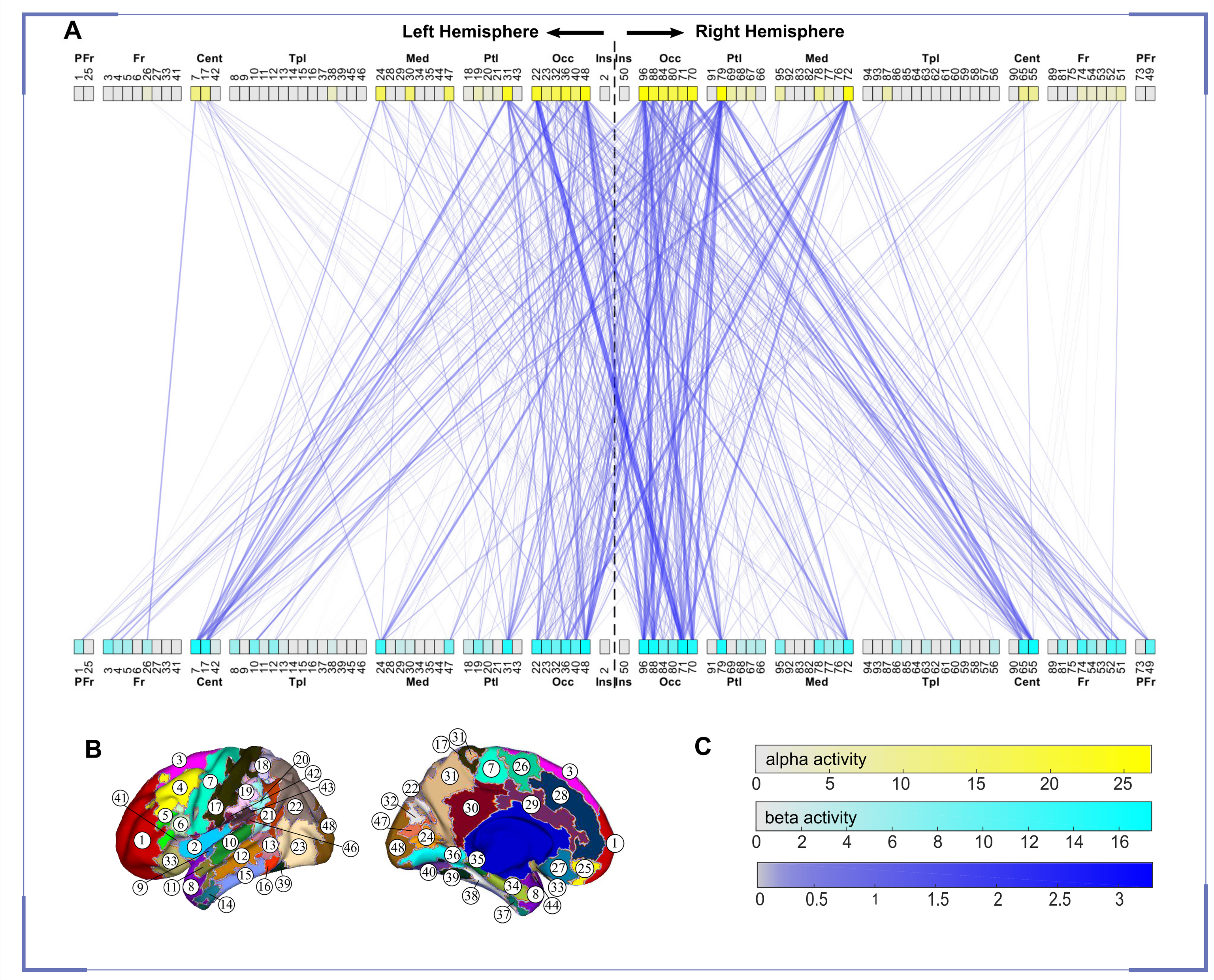
• Simulated EEG data with 2 triplets of source signals at 10Hz, 20Hz, and 30Hz.

• Figure 4: the median error of mixing patterns is small and the mean PLV is large for low SNRs.

Resting-state EEG

• Alpha-beta interaction of resting-state EEG data of 82 subjects fromLEMON dataset (Babayan et al, 2018).
• Many diverse interactions are extracted by NID. A particularly interesting coupling is between alpha activity of occipital area and beta activity of motor area.

5
• A bipartite graph (panel A) illustrating the alpha-beta interactions between ROIs of Harvard-Oxford atlas (panel B), computed for 82 subjects.
• A connection between node r1 of the upper and node r2 of the lower part indicates that alpha oscillations in ROI r1 interact with beta-oscillations in ROI r2.
• The edge weighs are proportional to the number of active voxels (across subjects) in the two ROIs. Color-codes in panel C.



Conclusion

• Former methods maximize a contrast function based on the desired coupling. NID is based on the statistical properties of the source signals.

• NID is generalizable for detection of coupling of oscillations in multiple (>2) frequency bands. No other method can be generalized in this way.

• NID can extract a subset of coupled activities in the brain that can be used for connectivity analysis.

• Future work: investigating how brain networks of resting-state EEG are predictive of task performance.

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