Characterizing high-order interactions during conflict processing in patients with epilepsy

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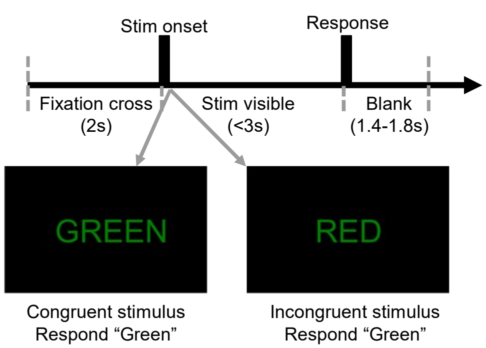
Motivation

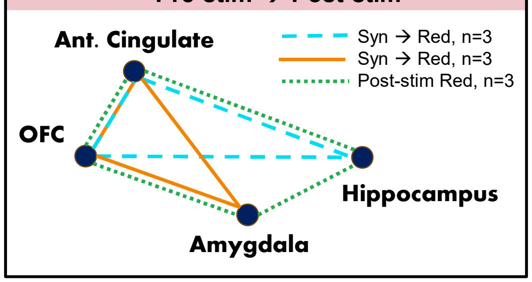
- Non-emotional conflict processing engages the anterior cingulate, orbitofrontal cortex (OFC), amygdala, and hippocampus [1]
- Stroop task on epilepsy patients implanted with stereotactic EEG depth probes
- O-Information [2] measured increased redundant information in networks
- Granger causality [4] measured *pairwise* directional coupling in theta/alpha bands, with large influence to/from hippocampus
- Results suggest an alternative perspective to the "conflict monitoring hypothesis" where cingulate modulates *multiple* areas

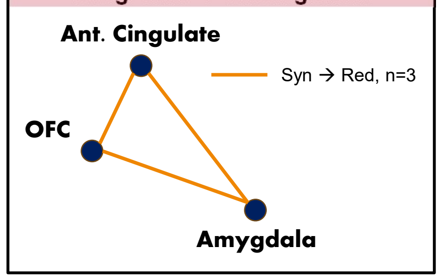
Experimental setup

- Stroop word-color task induces neural conflict with congruent and incongruent visual stimuli
- 6 right-handed epilepsy patients (1 female)
- Recordings are either all in left or right hemisphere
- 200-320 total trials in blocks of 40 trials
- 50% congruent and 50% incongruent stimuli



Redundant & Synergistic Networks



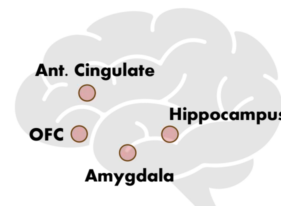


Incongruent visual stimuli may increase redundancy

- Redundancy increases after visual stim onset in two 3-area networks implicating the cingulate and OFC
- Significant redundancy in 4-area network after stim onset
- Cingulate-OFC-amygdala network sensitive to stimulus type (more redundant for incongruent)

Cingulate gamma power correlated to congruency

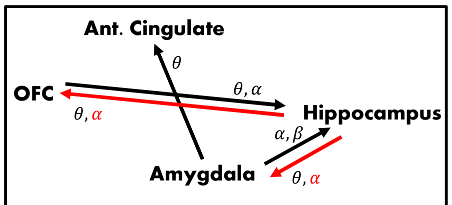
- Gamma band is most correlated with the stimulus type (i.e., incongruent vs congruent) in 4 patients
- High frequency oscillations may have a functional role in high-order, conflict-relevant interactions involving the cingulate



Cingulate and OFC may modulate multiple areas

- Cingulate and OFC are involved in all inferred high-order networks

Directional Networks



BLACK: significant in 3+ patients
RED: significant congruent-incongruent difference

Pairwise influence in theta & alpha bands

- Pairwise influence occurs in lower-frequency bands, unlike gamma correlation detected in higher-order networks

Hippocampus sensitive to congruency

- Hippocampus influence significantly varies for congruent to incongruent stimuli in alpha band

Analysis: Data are from a single channel per area. Data were bandpass filtered (0.5 to 250 Hz), downsampled from 1024 to 512 Hz, and re-referenced from unipolar to Laplacian. All analyses were locked to the stimulus at 0s. Pre-stimulus data ranged from -1 to -0.4s, post-stimulus data from 0 to 0.6s. O-information was estimated with Gaussian copulas. Iterative regression [3] identified the linear combination of congruent-relevant frequency bands. Significance by permutation test using shuffled trial orders with 500 samples. Results are based on networks with $p < 0.05$. Non-parametric Granger causality [4] estimated per frequency band with permutation testing and Bonferroni correction.

O-information

Network systems activate via:

1. **Redundancy**: information shared between brain areas
2. **Synergy**: information generated across brain areas

$$OI = Red - Syn \begin{cases} > 0 & \text{Redundancy dominant} \\ < 0 & \text{Synergy dominant} \end{cases}$$

O-Information [2] measures the overall activation of a system of *N* brain areas by comparing redundancy to synergy.

$$Syn = H(\boldsymbol{X}^N) - \Sigma_i\, H(X_i | X_{-i}^N)$$

$$Red = \underbrace{\Sigma_i\, H(X_i)}_{\text{Marginal entropy: Individual area activity}} - \underbrace{H(\boldsymbol{X}^N)}_{\text{Joint entropy: High-order activity}}$$

Conclusion

- Anterior cingulate, OFC, amygdala, and hippocampus form redundant networks following visual stimuli
- Conflict (via incongruent stimuli) may increase redundancy
- Cingulate may be involved in higher-order, conflict-related processing
- Both high and low frequency oscillations are relevant to conflict-related signals in cingulate
- Hippocampus is a hub of pairwise influence and the source of significant conflict-relevant influences

References

[1] R. S. Chung et al., Neur. Research, 2024.
[2] F. Rosas et al., Entropy, 2019.
[3] **A. Merkley** et al., ISIT, 2024.
[4] M. Dhamala et al., NeuroImage, 2008.

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