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Advances in Source-Space Functional Analysis
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Removal of Spurious Coherence in MEG Source-Space Coherence Analysis

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Source-space coherence analysis

Source-space coherence analysis is useful for various clinical applications, such as:

- Presurgical assessments of brain tumors

Guggisberg *et al.* "Mapping functional connectivity in patients with brain lesions," Annals of Neurology, 2007.

J. Martino *et al.* *"Resting functional connectivity in patients with brain tumors in eloquent areas,"* Annals of Neurology, 2010.

- Cognitive impairment assessments of schizophrenia patients

Hinkley et al.*"Cognitive impairments in schizophrenia as assessed through activation and connectivity measures of magnetoencephalography (MEG) data,"* Frontiers in Human Neuroscience, 2009.

- Monitoring and assessment of patients with traumatic brain injury.

Tarapore *et al.* "Resting State MEG Functional Connectivity in Traumatic Brain Injury," in press.

Recovery assessment of stroke patients

K. Westlake et al. "Resting State Alpha-band Functional Connectivity and Recovery of Upper Extremity Function after Stroke," in press.

These investigations successfully use imaginary coherence, and my talk explains why we should use imaginary coherence.

Voxel pair-wise magnitude coherence measure

The average is computed using epoch/trial averaging

voxel time course

$$\eta_{k,j}(f) = \left| \frac{\left\langle \sigma_k(f)\sigma_j(f)^* \right\rangle}{\sqrt{\left\langle \left|\sigma_k(f)\right|^2 \right\rangle \left\langle \left|\sigma_j(f)\right|^2 \right\rangle}} \right|, \quad \text{where} \quad \sigma_k(f) = \int s_k(t) e^{-2\pi i f} \, df$$

voxel spectrum

•When computing voxel coherence, a reference voxel is first determined, and coherence map is computed between this reference voxel and all other voxels.

The reference voxel is called the seed voxel.
The other voxel is called the target voxel.
Coherence computed in this manner is called the seed coherence.

Problem with Coherence Analysis

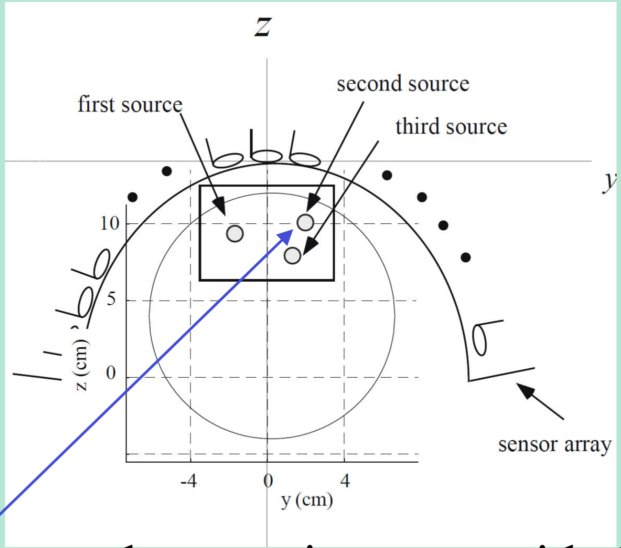
Interferences, errors, and noise that exist both in target and seed signals cause spurious (false-positive) coherence.

In source-space analysis, the leakage property of the inverse algorithm causes spurious coherence, which is typically manifested as an artificial large peak around the seed voxel.

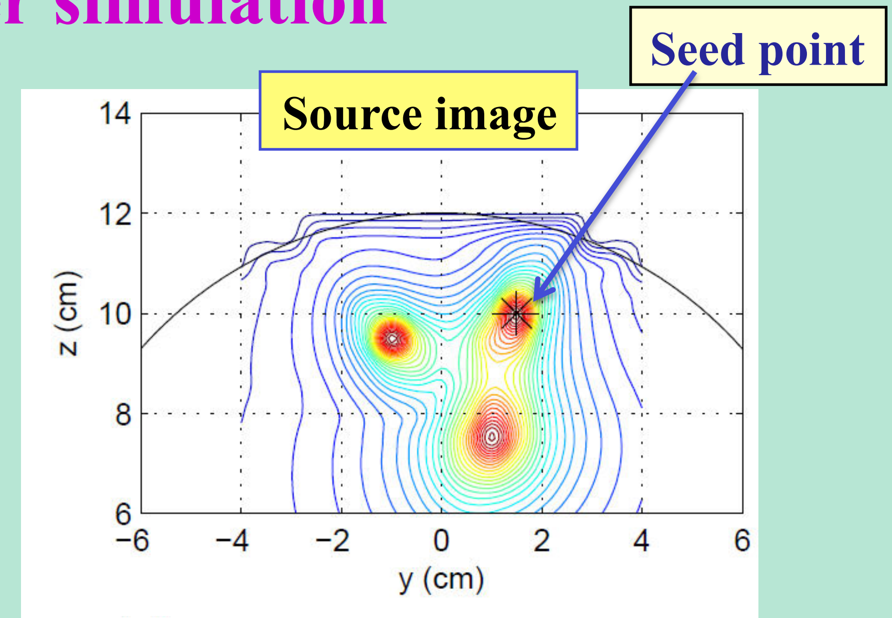
→ Called seed blur

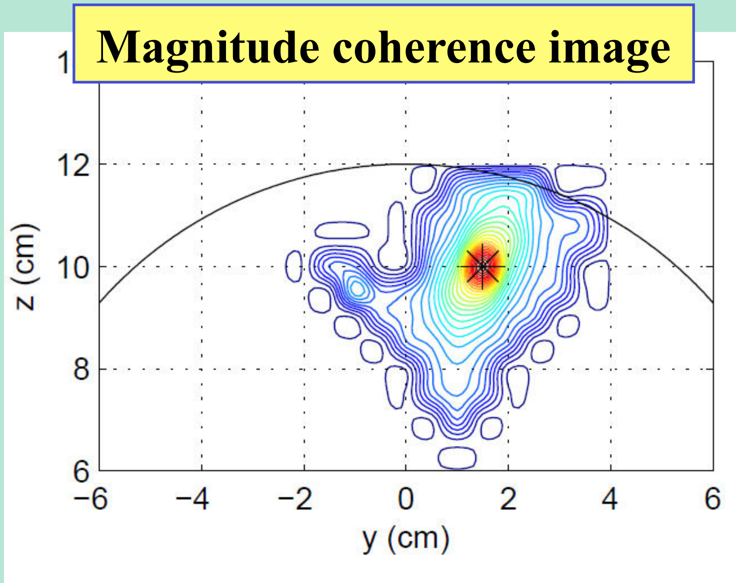
The seed blur often obscures interacting sources, as shown in the next slide.

Seed blur – computer simulation



The second source interacts with the other two sources.





- Magnitude coherence image shows the seed blur, which is a spurious coherence peak caused by the blur of imaging algorithm.
- The seed-blur peak is so high that it obscures the interacting sources.

Seed blur – analysis

Estimated seed voxel time course:

$$\hat{u}_S(t) = u_S(t) + d_1 u_T(t) + c_S(t)$$

Estimated target voxel time course:

$$\hat{u}_T(t) = u_T(t) + d_2 u_S(t) + c_T(t)$$

➡

Estimated seed voxel spectrum:

$$\hat{\sigma}_S = \sigma_S + d_1 \sigma_T + C_S$$

Estimated target voxel spectrum:

$$\hat{\sigma}_T = \sigma_T + d_2 \sigma_S + C_T$$

Neglecting C_S and C_T, estimated magnitude coherence is:

$$|\hat{\eta}| = \left|\left\langle \hat{\sigma}_T \hat{\sigma}_S^* \right\rangle\right| \Big/ \sqrt{\left\langle |\hat{\sigma}_T|^2 \right\rangle \left\langle |\hat{\sigma}_S|^2 \right\rangle}$$

$$= \frac{\left| \left\langle \sigma_T \sigma_S^* \right\rangle + d_1 \left\langle |\sigma_T|^2 \right\rangle + d_2 \left\langle |\sigma_S|^2 \right\rangle + d_1 d_2 \left\langle \sigma_S \sigma_T^* \right\rangle \right|}{\sqrt{\left[\left\langle |\sigma_T|^2 \right\rangle + d_2 \left\langle |\sigma_S|^2 \right\rangle + 2 d_2 \Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle \right) \right] \left[\left\langle |\sigma_S|^2 \right\rangle + d_1 \left\langle |\sigma_T|^2 \right\rangle + 2 d_1 \Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle \right) \right]}}$$

When no brain interaction exists, i.e., $\left\langle \sigma_T \sigma_S^* \right\rangle = 0$, $|\hat{\eta}| \neq 0$.

Use of imaginary part of coherence

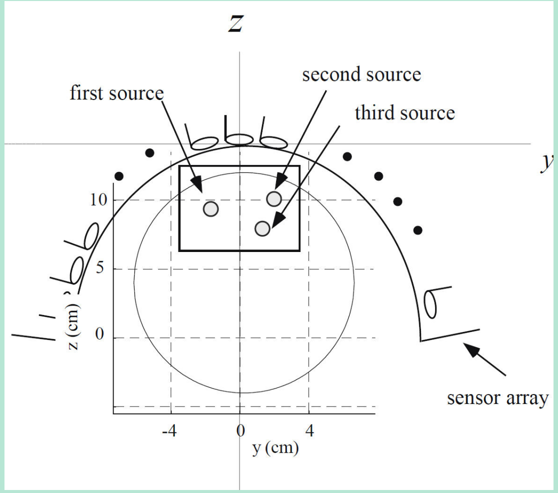
$$\Im\left(\hat{\eta}\right) = \frac{\Im\left(\left\langle \hat{\sigma}_T \hat{\sigma}_S^* \right\rangle\right)}{\sqrt{\left\langle \left|\hat{\sigma}_T\right|^2 \right\rangle \left\langle \left|\hat{\sigma}_S\right|^2 \right\rangle}}$$

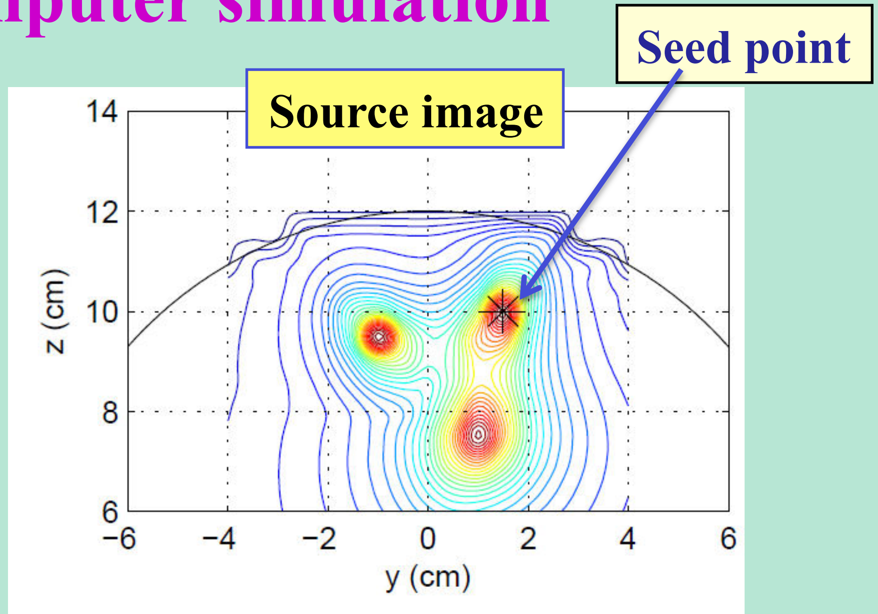
$$= \frac{\left(1 - d_1 d_2\right)}{\sqrt{\left[1 + d_2 \dfrac{\left\langle \left|\sigma_S\right|^2 \right\rangle}{\left\langle \left|\sigma_T\right|^2 \right\rangle} + 2 d_2 \dfrac{\Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right)}{\left\langle \left|\sigma_T\right|^2 \right\rangle}\right]\left[1 + d_1 \dfrac{\left\langle \left|\sigma_T\right|^2 \right\rangle}{\left\langle \left|\sigma_S\right|^2 \right\rangle} + 2 d_1 \dfrac{\Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right)}{\left\langle \left|\sigma_S\right|^2 \right\rangle}\right]}} \Im\left(\eta\right)$$

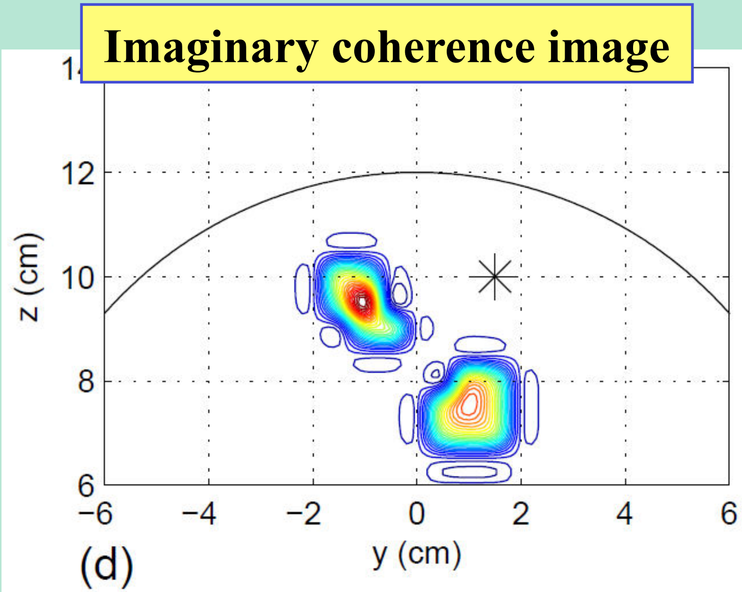
When no brain interaction exists, i.e., $\eta = 0$, $\Im\left(\hat{\eta}\right) = 0$.

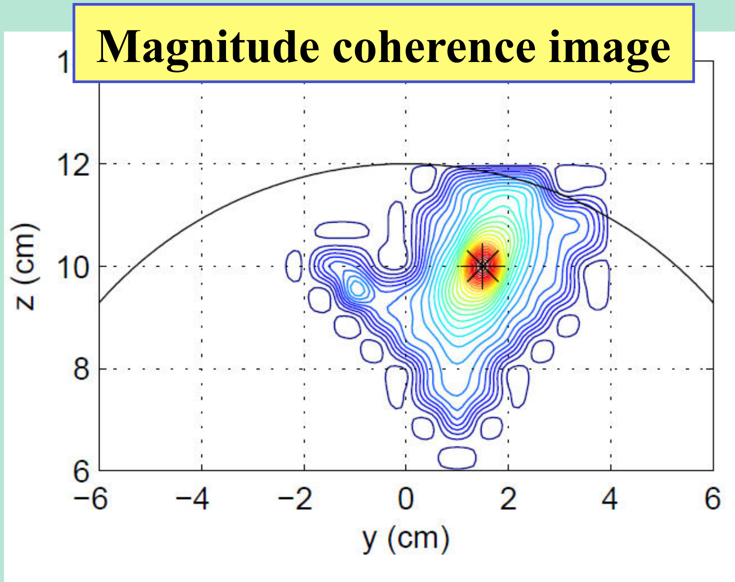
G. Nolte *et al.* *"Identifying true brain interaction from EEG data using the imaginary part of coherency," Clin. Neurophysiol.*

Imaginary coherence– computer simulation









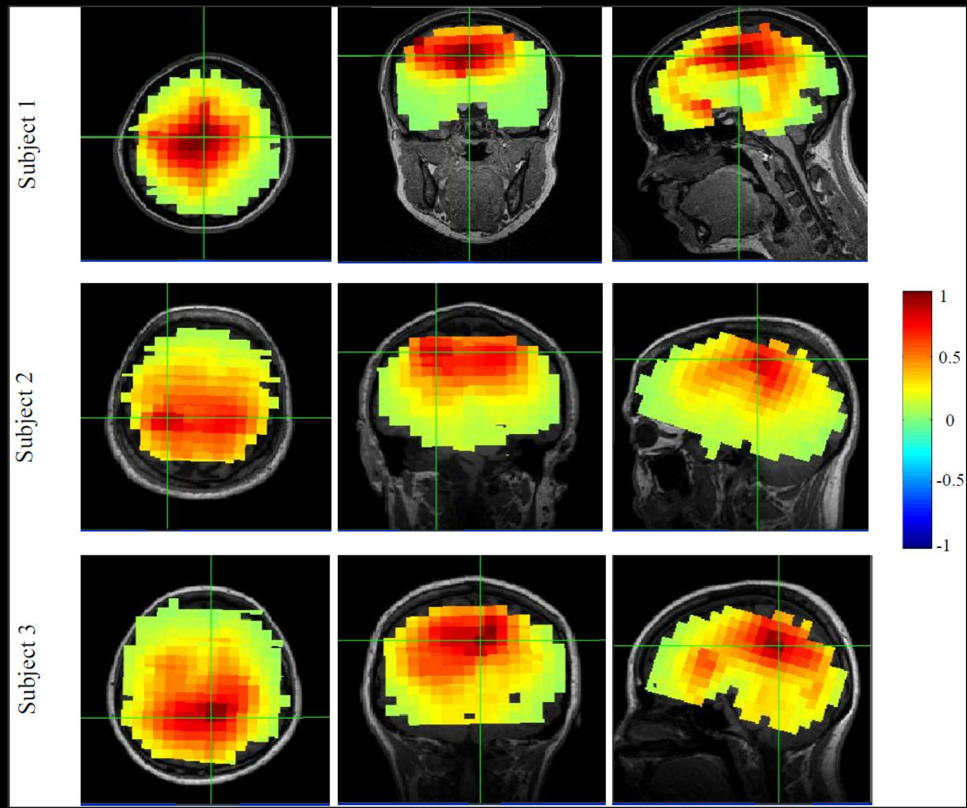
Surrogate-data method is used to derive a proper thresholding value.

Experiments with Resting state MEG data

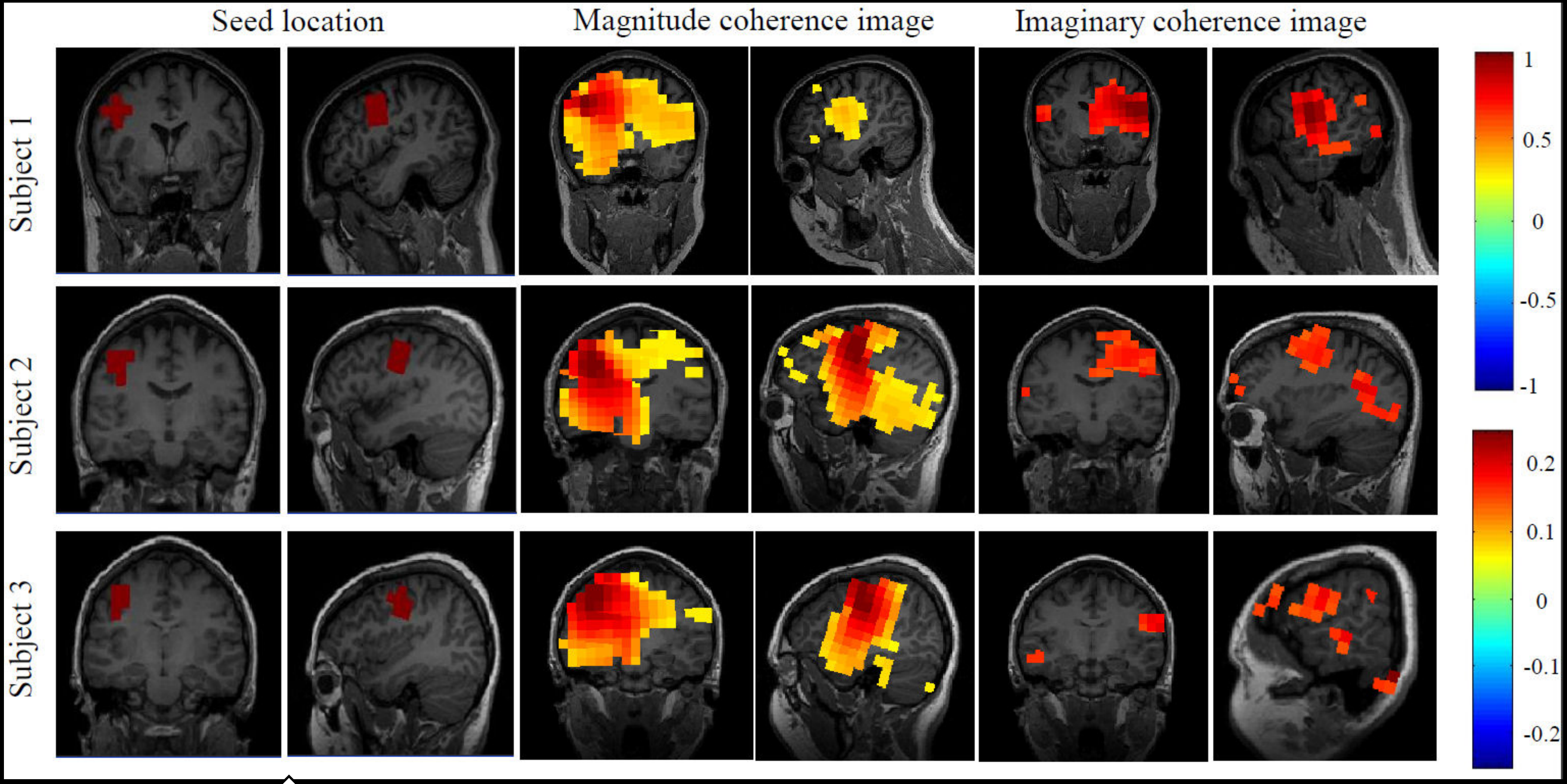
Resting state MEG was measured from three subjects:

Source power image

- **275-channel CTF system used.**
- **60-sec-long continuous data with 1200Hz sampling rate.**
- **Source reconstruction using narrow-band adaptive spatial filter with the beta (14-27 Hz) frequency band**



Results of Coherence Imaging



Voxels located within the left pre-central gyrus (left primary motor area) were selected as seed voxels.

The surrogate data method was applied to select voxels with statistically significant values of coherence (α=0.99).

Intensity bias of imaginary coherence

The blur of imaging algorithms also causes bias in the coherence value.

$$\Im(\hat{\eta}) = \frac{\Im\left(\left\langle \hat{\sigma}_T \hat{\sigma}_S^* \right\rangle\right)}{\sqrt{\left\langle \left|\hat{\sigma}_T\right|^2 \right\rangle \left\langle \left|\hat{\sigma}_S\right|^2 \right\rangle}}$$

$$= \frac{\left(1 - d_1 d_2\right)}{\sqrt{\left[1 + d_2 \frac{\left\langle \left|\sigma_S\right|^2 \right\rangle}{\left\langle \left|\sigma_T\right|^2 \right\rangle} + 2 d_2 \frac{\Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right)}{\left\langle \left|\sigma_T\right|^2 \right\rangle}\right]\left[1 + d_1 \frac{\left\langle \left|\sigma_T\right|^2 \right\rangle}{\left\langle \left|\sigma_S\right|^2 \right\rangle} + 2 d_1 \frac{\Re\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right)}{\left\langle \left|\sigma_S\right|^2 \right\rangle}\right]}} \Im(\eta)$$

$$= \Omega \, \Im(\eta)$$

Intensity bias: *Ω*

Assuming $d_1 = d_2 = d$, and $\left|\sigma_T\right|^2 \approx \left|\sigma_S\right|^2$, we have $\frac{1+|d|}{1-|d|} \geq \Omega \geq \frac{1-|d|}{1+|d|}$

When $d < 0.1$, $1.2 > \Omega > 0.75$ and the maximum intensity bias is 25%.

Residual Coherence

We propose a new way of computing coherence.

Regress the target spectrum with the seed spectrum:

$$\sigma_T = \alpha\sigma_S + v \quad (\alpha : \text{real-valued constant})$$

$$\alpha = \arg\min_{\alpha} \left\langle \left| \sigma(f) - \alpha\sigma_S(f) \right|^2 \right\rangle_{\text{trial}}$$

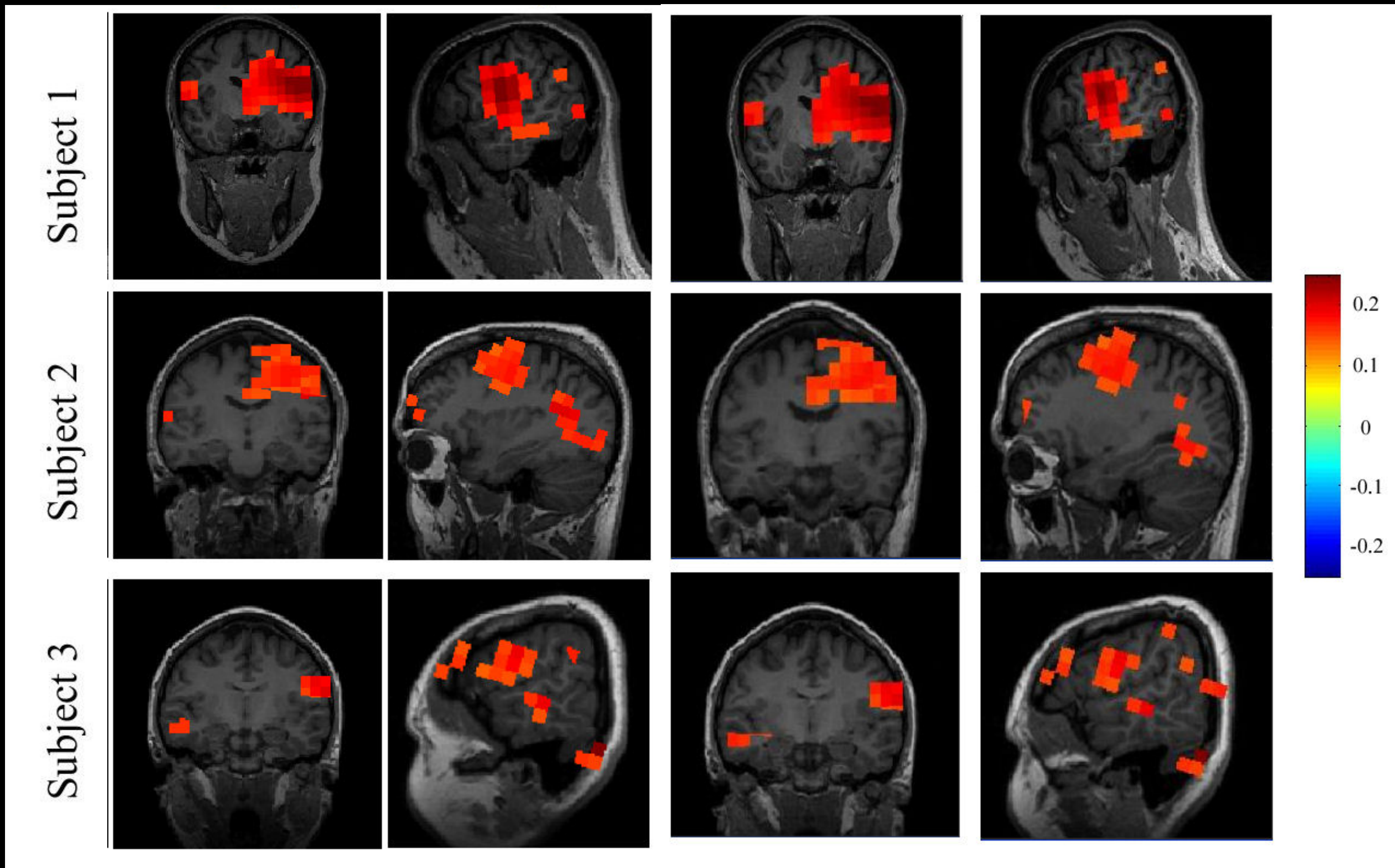
Compute coherence between σ_S and the residual v

$$\tilde{\eta} = \frac{\left\langle v\hat{\sigma}_S^* \right\rangle}{\sqrt{\left\langle |v|^2 \right\rangle \left\langle |\hat{\sigma}_S|^2 \right\rangle}} = \frac{\Im(\eta)}{\sqrt{\left[1 - \Re(\eta)\right]}}$$

$\tilde{\eta}$ does not depend on the leakage property d_1 and d_2 and generally has a small intensity bias, unless $\Re(\eta)$ is very large.

Imaginary coherence: $\Im\left(\hat{\eta}\right)$

Residual coherence: $\tilde{\eta}$



Effects of interference terms

Seed voxel spectrum:

$$\hat{\sigma}_S = \sigma_S + C_S$$

Target voxel spectrum:

$$\hat{\sigma}_T = \sigma_T + C_T$$

$$\Rightarrow \quad \Im\left(\left\langle \hat{\sigma}_T \hat{\sigma}_S^* \right\rangle\right) = \Im\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right) + \Im\left(\left\langle C_T C_S^* \right\rangle\right)$$

When $\left\langle C_T C_S^* \right\rangle$ is real-valued, taking imaginary part removes the error term due to the interference.

What condition makes $\left\langle C_T C_S^* \right\rangle$ to be real-valued?

$\boldsymbol{b}_I$: sensor interference time course

$\boldsymbol{b}_I(t)$ is stationary $\rightarrow$ $\left\langle C_T C_S^* \right\rangle$ is real-valued

When $\boldsymbol{b}_I(t)$ has non-stationary components, $\left\langle C_T C_S^* \right\rangle$ has a non-zero imaginary part.

Summary

•Seed blur, manifestation of spurious coherence in source-space coherence analysis, can be removed by using imaginary coherence.

•Values of imaginary coherence are biased by the leakage of imaging algorithms.

•Residual coherence gives small intensity bias, unless the real part of true coherence is very large.

•Interference terms in the seed and target spectra do not cause the imaginary component only when the interferences are stationary.


Thank you very much for your attention.
Please visit our poster: Mo-184,185 in Monday afternoon

Effects of interference terms

Seed voxel spectrum:

$$\hat{\sigma}_S = \sigma_S + C_S$$

Target voxel spectrum:

$$\hat{\sigma}_T = \sigma_T + C_T$$

$$\Rightarrow \quad \Im\left(\left\langle \hat{\sigma}_T \hat{\sigma}_S^* \right\rangle\right) = \Im\left(\left\langle \sigma_T \sigma_S^* \right\rangle\right) + \Im\left(\left\langle C_T C_S^* \right\rangle\right)$$

When $\left\langle C_T C_S^* \right\rangle$ is real-valued, taking imaginary part removes the intereference term.

Sensor interference time course: $\boldsymbol{b}_I \xrightarrow[FT]{}$ Sensor interference spectrum: $\boldsymbol{\beta}_I$

$$C_T = \boldsymbol{w}^T(\boldsymbol{r}_T)\boldsymbol{\beta}_I \text{ and } C_S = \boldsymbol{w}^T(\boldsymbol{r}_S)\boldsymbol{\beta}_I \;\Rightarrow\; \left\langle C_T C_S^* \right\rangle = \boldsymbol{w}^T(\boldsymbol{r}_T)\left\langle \boldsymbol{\beta}_I \boldsymbol{\beta}_I^H \right\rangle \boldsymbol{w}(\boldsymbol{r}_S)$$

$$\left\langle \boldsymbol{\beta}_I \boldsymbol{\beta}_I^H \right\rangle \xleftrightarrow[FT]{} \boldsymbol{R}_I(\tau), \text{ and } \boldsymbol{R}_I(\tau) = \int \boldsymbol{b}_I(t)\boldsymbol{b}_I^T(t+\tau)\,dt$$

$\boldsymbol{b}_I(t)$ is stationary $\rightarrow$ $\boldsymbol{R}_I(\tau)$ is even function $\rightarrow$ $\left\langle \boldsymbol{\beta}_I \boldsymbol{\beta}_I^H \right\rangle$ is real-valued

When $\boldsymbol{b}_I(t)$ is non-stationary, $\boldsymbol{R}_I(\tau)$ has an odd-function component, and $\left\langle \boldsymbol{\beta}_I \boldsymbol{\beta}_I^H \right\rangle$ has a non-zero imaginary part.