Suspicious of fluctuations?
A signal processing view on dynamic functional connectivity

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Estimating dynamic FC

- Look at network dynamics
  - Parcellation can be atlas based or functional
  - Sliding-window pairwise correlations

- which fluctuations might be introduced due to the estimation method?
- what is the effect of sampling and noise?
- how to deal with high number of connections?

[Chang and Glover, NeuroImage, 2010]
\[ x_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \]

region 1

region 2

\[ y_i = \sqrt{2} \cos(2\pi f_i \text{TR} + \theta) \]

\[ x_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \]

\[ y_i = \sqrt{2} \cos(2\pi f_i \text{TR} + \theta) \]

"average" FC (0.87)

frequency \( f = 0.035 \text{ Hz} \)

window length \( w = 40 \text{ sec} \)
\[ x_i = \sqrt{2} \cos(2\pi fi \ \text{TR}) \]

\[ y_i = \sqrt{2} \cos(2\pi fi \ \text{TR} + \theta) \]
\[ x_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \]

\[ y_i = \sqrt{2} \cos(2\pi f_i \text{TR} + \theta) \]

frequency \( f = 0.035 \) Hz

window length \( w = 10 \) sec
Spurious fluctuations of dynFC

- Sliding-window covariance revisited:

\[
c_{xy}[n] = \cos(\theta) + \frac{1}{w^2 \pi f^2} \cos(2\pi fnTR + \theta) \sin(\pi fwTR) - \frac{2}{w^2 \pi^2 f^2} \cos(2\pi fnTR) \cos(2\pi fnTR + \theta) \sin^2(\pi fwTR)
\]

- Average FC
- Zero-crossing at multiples of wavelength 1/f
- Different n
Spurious fluctuations of dynFC

- Max-min for all different window shifts $n$

Original timecourses should be high-pass filtered with cut-off $1/w$ to avoid spurious fluctuations of dFC
\[ x_i = \sqrt{2} \cos(2\pi f_i \text{ TR}) \]

\[ y_i = \sqrt{2} \cos(2\pi f_i \text{ TR} + \theta) \cos(2\pi f_0 i \text{ TR}) \]

frequency \( f = 0.035 \) Hz
window length \( w = 30 \) sec
modulation at 0.005 Hz
Real fluctuations of dynFC

- Two deterministic signals:
  \[
  x_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \\
  y_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \cos(2\pi f_0 i \text{TR})
  \]

  - modulatory component with frequency \( f_0 \ll f \)

- Sliding-window covariance revisited:
  \[
  c_{xy}[n] = \frac{\text{TR}}{w} \frac{\sin(\pi f_0 w)}{\sin(\pi f_0)} \cos(2\pi f_0 n \text{TR}) + \text{harmonics}
  \]

  - weighting depends on low-pass filtering properties of window: \( f_0 \) below \( 1/w \)
  - dynFC recovers modulatory component!

  (or equivalent cut-off in case of tapering)
Real fluctuations of dynFC

- Two deterministic signals:
  \[ x_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \]
  \[ y_i = \sqrt{2} \cos(2\pi f_i \text{TR}) \cos(2\pi f_0 i \text{TR}) \]

- modulatory component with frequency \( f_0 << f \)

- Sliding-window covariance revisited:
  \[ c_{xy}[n] = \frac{\text{TR} \sin(\pi f_0 w)}{w \sin(\pi f_0)} \cos(2\pi f_0 n \text{TR}) + \text{harmonics} \]
Effect of sampling (TR) and noise

5% (parametric) confidence interval for $H_0 : \rho = 0$

- Other null hypothesis; e.g., $H_0 : \rho = \bar{\rho}$
- Non-parametric test (phase randomization)
- Correction for m’comparisons; e.g., per time unit

TR=1s
TR=2s
TR=3s
DynFC is not about data reduction

- Sliding window correlation in 3 healthy subjects
  - Window length is 30 TRs, step of 2 TRs, TR=1.1 sec

- Number of connections grows quadratically with #regions
- Rank of each FC frame is limited by window length (in TRs)
Building blocks of dynFC

- Various types of matrix factorizations are possible
  - k-means
  - PCA
  - sparsity constraints
  - ...

- FC patterns are in common for all subjects

Co-variance (PCA, k-means, HOSVD)
global fluctuations in FC

cingulate gyri, medial frontal gyri, precuneus (default-mode network)
primary sensory in red

inferior and middle frontal gyri, inferior parietal
(fronto-parietal)

presentation O-W2
1750: “Dynamic functional connectivity: Better characterized by separated states or a mixture of patterns?” (Nora Leonardi)

posterior DMN
temporal and inferior frontal

[Leonardi et al, NeuroImage, 2013]
Thank you for the dynamical attention