国立研究開発法人 情報通信研究機構
National Institute of Information and Communications Technology

脳情報通信融合研究センター
Center for Information and Neural Networks

Using Multi-Slice Modularity Partitions to Characterize fMRI Data

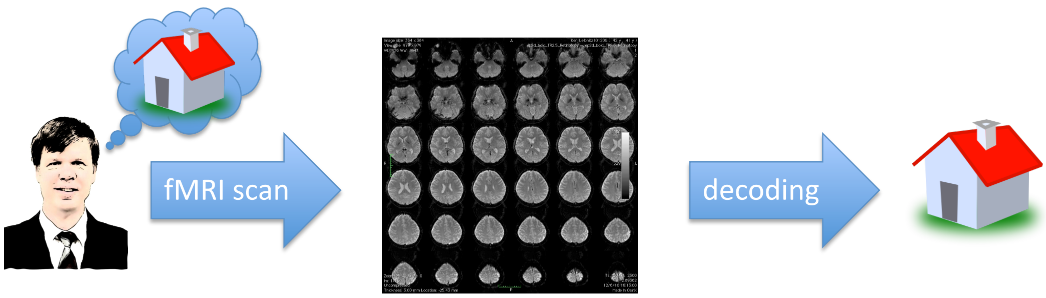
マルチスライスモジュール分割によるfMRIデータの特徴付け

Kenji Leibnitz, Norberto Eiji Nawa,
Tetsuya Shimokawa

{leibnitz, eiji.nawa, shimokawa}@nict.go.jp

Motivation

- Goal of neuroscience is to help understand the organization of the brain ➔ possibility of classification based on brain measurement data ("brain decoding")



- Recent studies have been utilizing network science for high-level abstraction and evaluation of brain network graphs
- Modularity structure (communities) particularly important: modules contain nodes with similar functionalities

Modularity in Networks

- Modularity characterizes possible divisions of networks with high connectivity within modules and less between modules compared to null model (random network)
- *Modularity quality function* by Newman (*PNAS*, 2006)

adjacency

degree

$$Q = \frac{1}{2m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right) \delta(g_i, g_j)$$

number of links

δ function equals 1 if node i in same module as node j, otherwise 0

- *Community structure:* partitioning of nodes that maximizes Q
- Calculation is performed by heuristic algorithm, e.g., Louvain method by Blondel *et al.* (*J. Stat. Mech.*, 2008)

Multiple Realizations of Communities

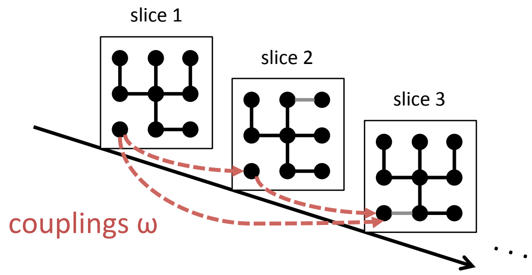
- There are multiple realizations of communities due to:
  - Repetitions from multiple runs (heuristic algorithm)
  - Variations of conditions leading to different partitionings (brain networks from different subjects or different tasks)
- We are interested in the *common modularity structure* for all subjects/repetitions and in *comparing communities* across tasks
- *Multi-slice modularity* method introduced by Mucha *et al.* (*Science*, 2010) to find time-dependent, scale-dependent, or multiplex structures in communities across slices of networks
  - Generalized version of modularity with adapted Q-function for multiple slices

resolution

couplings

$$Q = \frac{1}{2\mu} \sum_{ijsr} \left[\left(A_{ijs} - \gamma_s \frac{k_{is} k_{js}}{2m_s} \right) \delta_{s,r} + \delta_{ij} C_{jsr} \right] \delta(g_{is}, g_{jr})$$

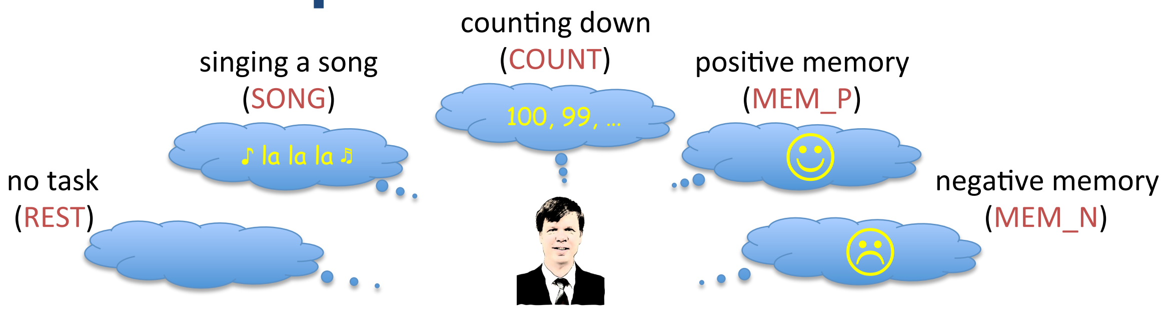
Multi-Slice Modularity



Each slice may contain the adjacency matrix of a network
- at different points in time
- at different resolutions
- from different subjects
- from a subject performing different tasks

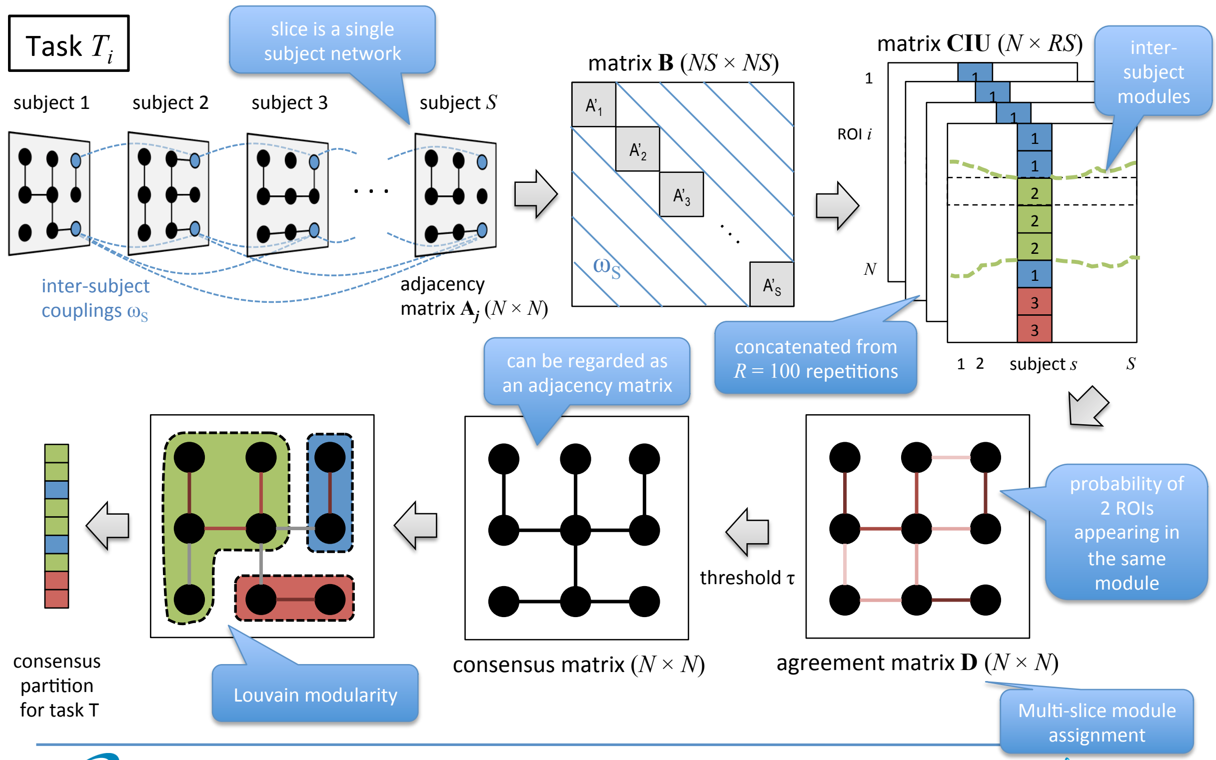
- Couplings must be set depending on type of slices:
  - *ordered* has only couplings of same node between nearest slices (e.g. time, resolution)
  - *categorical* has couplings of same node to all other slices (e.g. subjects, tasks)
- Application to brain networks by Bassett *et al.* (*PLOS Comput. Biol.* 2013) and Cole *et al.* (*Neuron*, 2014)

Experimental fMRI Data



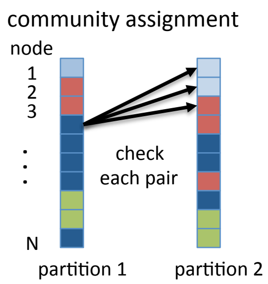
- Time series ($T = 300$ scans) from fMRI data for $N = 24$ subjects (14 females, ages 21-37)
- Each subject performs 5 tasks: REST, SONG, COUNT, MEM_P, MEM_N
- Network nodes are *regions of interest* (ROIs) following Power *et al.* (*Neuron*, 2011) with $M = 264$ ROIs
- Two nodes i and j are connected by a link $A_{ij} = 1$, if the correlation coefficient of their time series exceeds the threshold θ, which is set individually for each subject/task that all 264 nodes remain connected

Consensus Partitioning (Single Task)

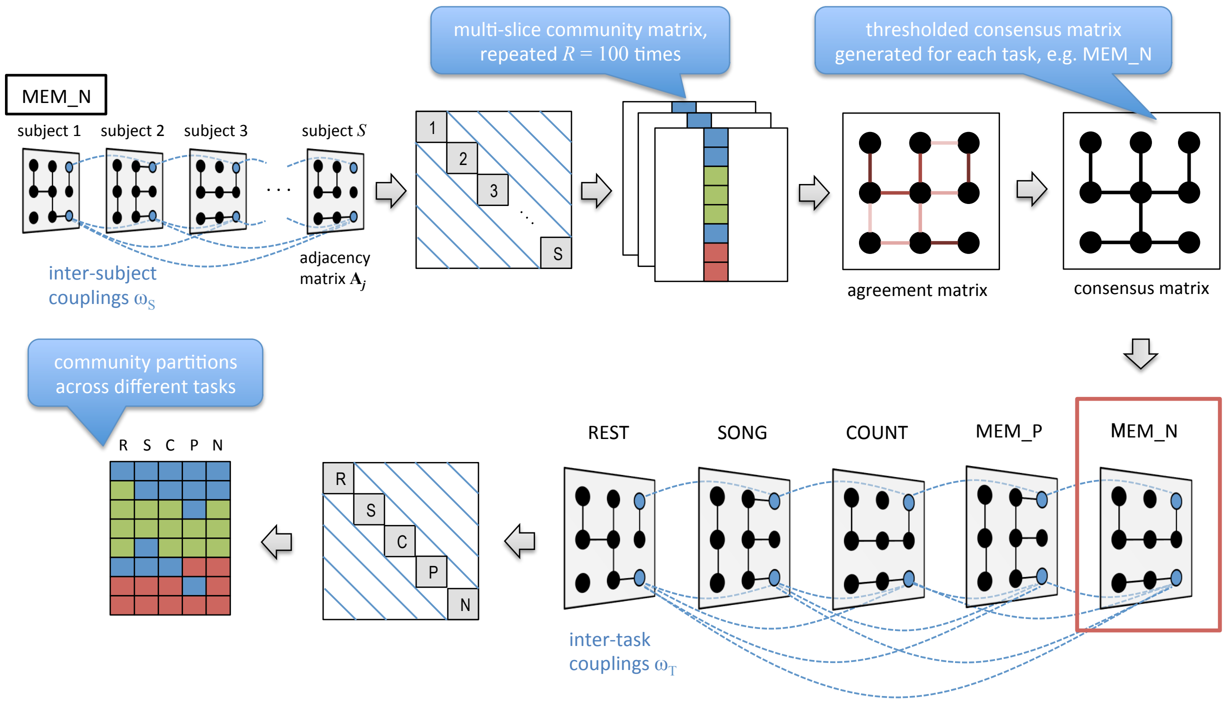


Comparing Partitions

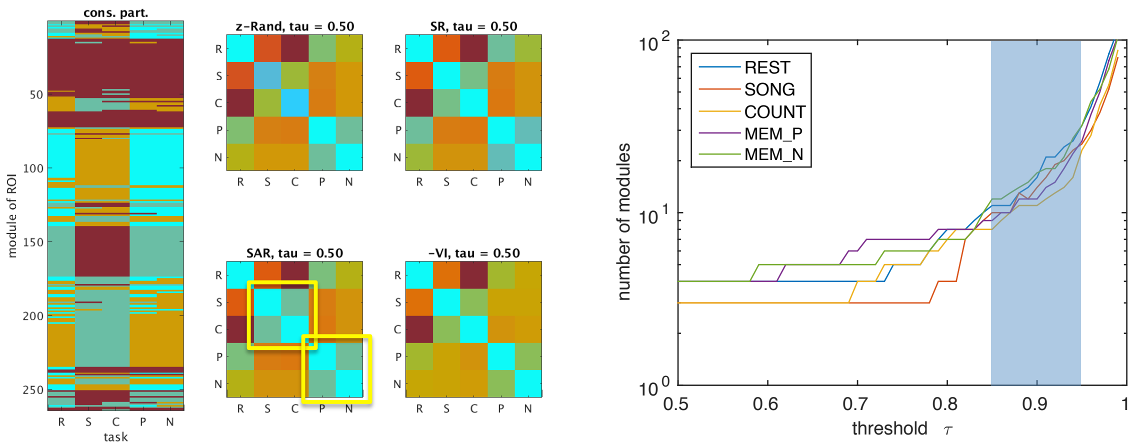
- Strategies for comparing community partitions between tasks:
  - pair counting: Rand coefficient (SR), adjusted Rand (SAR), z-Rand (Traud et al., *SIAM Rev.*, 2011)
  - information-theoretic measure: variation of information (VI) (Melia, *J. Multivar. Anal.*, 2007)
- Comparison of all possible node pairs that fall into same or different partitions, divided by the total number of pairs (similar to consensus mechanism)
- Metrics can be arranged in 5 × 5 matrix of partition similarities/differences among tasks
- Community structure for each task determined independently ➔ multi-slice computation can determine cross-task modules



Consensus Partitioning (Multiple Tasks)

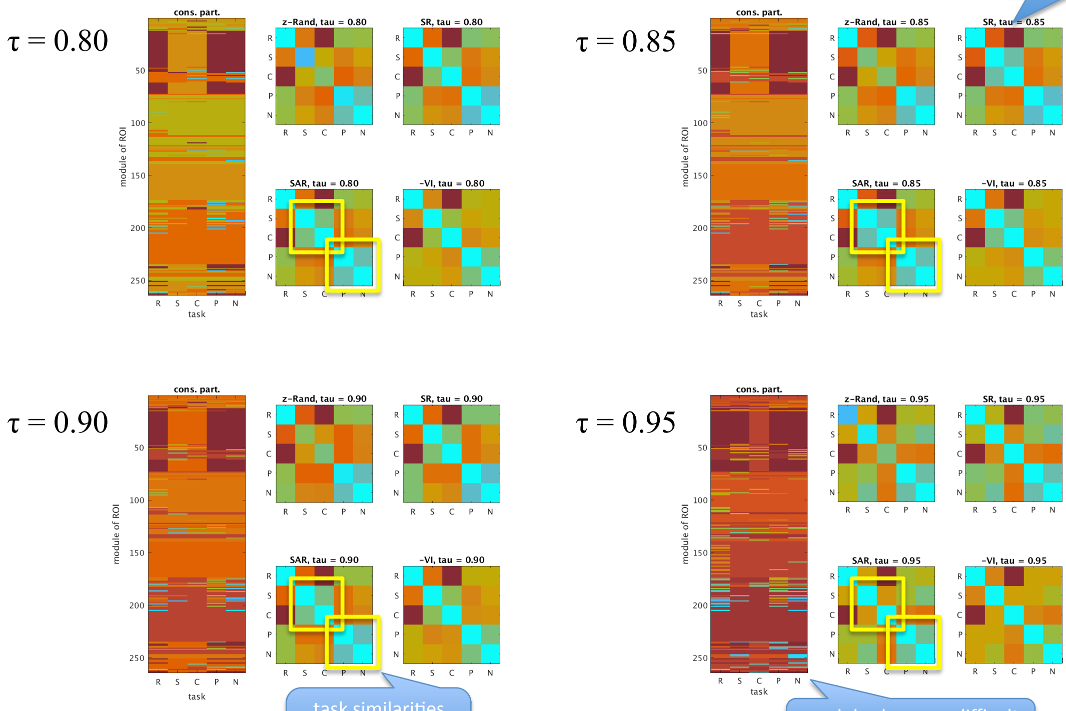


Example Result for $\tau = 0.5$



- All links are binary and all couplings between slices $\omega_S = \omega_T = 1$
- "Best" range of threshold is $0.85 < \tau < 0.95$ leading to around 10 modules per task (too few and too many modules hard to compare)
- All metrics qualitatively show the same partition similarity: MEM_P and MEM_N (+ REST) similar, SONG and COUNT similar

Variation of Threshold τ



Conclusion

- Classification of mental tasks based on complex network measures of brain functional networks from fMRI data
- Multi-slice modularity effective for computing modules across different networks (subjects, tasks, or both)
- Cluster comparison based on pair counting method for showing similarity of partitions
- Considered 5 tasks showed similarities between *unconstrained tasks* (MEM_P, MEM_N, and REST) and *rhythmically constrained tasks* (SONG and COUNT) ➔ Further experiments with additional similar tasks are needed
- Future work includes considering weighted networks and couplings, studying the sensitivity of parameters, and a more thorough neuroscientific investigation of commonalities/differences in communities