Cognitive control networks contain a mixture of diverse connectivity patterns characteristic of predicted flexible hub mechanisms

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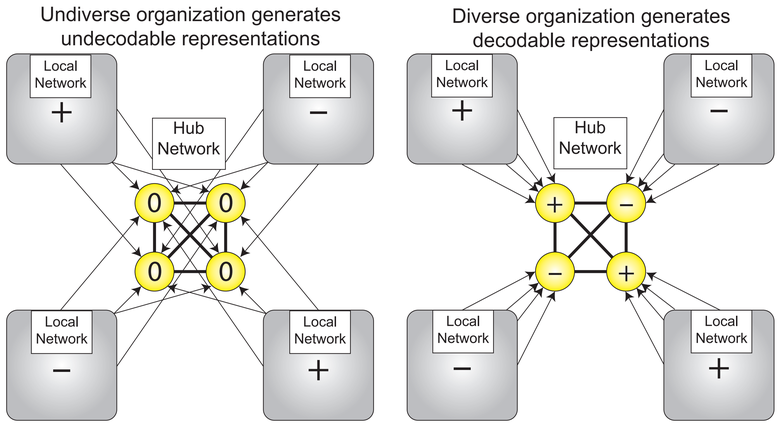
A network mechanism of flexible task representation through intrinsic network properties

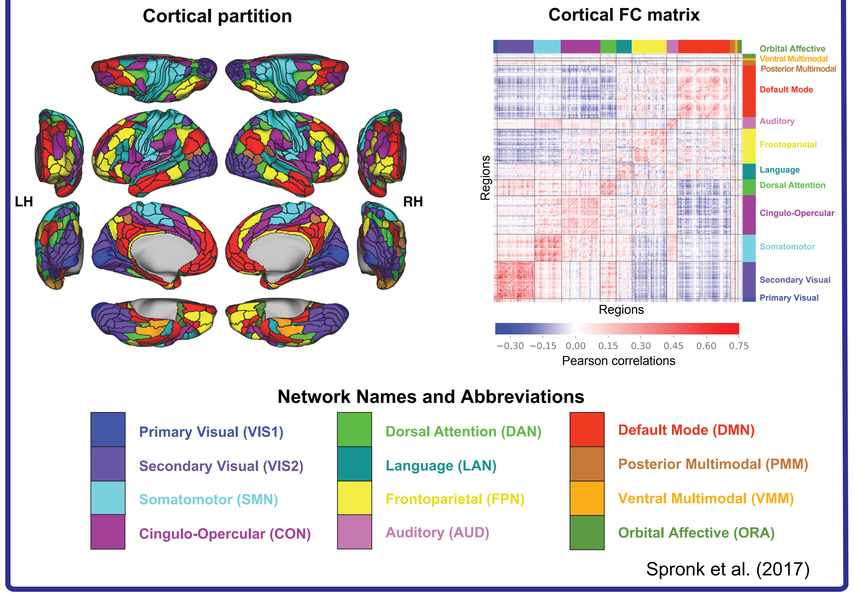
The flexible hub theory posits that a set of regions or networks flexibly adapt to task demands. Recent evidence has suggested the frontoparietal network (FPN) as a likely candidate, as demonstrated by its adaptive task-evoked FC (Cole et al., 2013) and its flexible task activations (Yeo et al., 2015). Here we investigate the relationship between a network's intrinsic network architecture and its flexible task activations. Recent evidence suggests that resting-state functional connectivity describes the routes of task-evoked activity flow between brain regions (Cole et al., 2016; Ito et al., 2017). We extend these findings to investigate the role of intrinsic graph-theoretic properties in producing flexible task representations. We hypothesized that functional networks with diverse intrinsic connectivity patterns, as estimated with integrated pattern diversity (IPD) and FC dimensionality, would produce highly separable and distinct representations across a variety of tasks. Evidence for this hypothesis would provide a network mechanism in support of the flexible hub theory, linking intrinsic network properties with activity-based task representations.

Predicting network-level representations through intrinsic connectivity



Hypothesis: The diversity of a network's intrinsic connectivity drives its activation-based representational flexibility across a variety of tasks.

Network partitioning



Spronk et al. (2017)

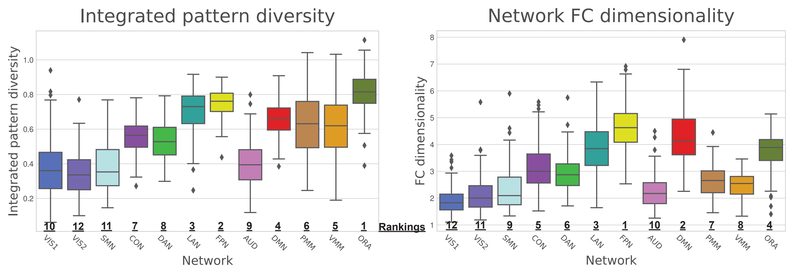
Estimating the diversity and dimensionality of network-level resting-state connectivity patterns

Integrated pattern diversity (IPD)

Measures the average diversity (or dissimilarity) of global connectivity patterns for each pair of regions within a network

FC dimensionality

Measures the dimensionality of the out-of-network connectivity space for each functional network (akin to a PCA on the out-of-network connections)



$$\mathbf{div_C} = \frac{\sum_{i,j \in C, i \neq j}\left(1 - scorr(\mathrm{Conn}_i, \mathrm{Conn}_j)\right)}{N_C^2 - N_C}$$

$$\mathbf{dim_C} = \frac{(\sum_{i=1}^{M} \lambda_i)^2}{\sum_{i=1}^{M} \lambda_i^2}$$

$\boldsymbol{div_C}$: integrated pattern diversity for a network C
scorr: rank correlation
$\boldsymbol{Conn_i}$: out-of-network connectivity vector for region i
$\boldsymbol{N_C}$: number of regions in network C

$\boldsymbol{dim_C}$: FC dimensionality for network C
$\boldsymbol{\lambda_i}$: i^{th} eigenvalue of the eigendecomposition of network C's out-of-network FC space
M: total number of eigenvalues
(Litwin-Kumar et al., 2017)

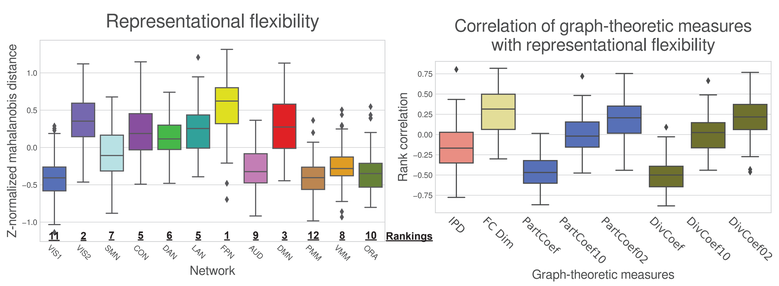
FPN consistently has highly separable and diverse connectivity patterns, as evidenced by high IPD and high FC dimensionality

Estimating the flexibility of activity-based representations across a variety of tasks

Using the HCP task data set

Representational flexibility: The multivariate pattern distinctness (using task-evoked activation patterns) of each condition within a task (similar to decodability), averaged across all 7 HCP tasks

How flexibly can a network represent task conditions across a variety of tasks?



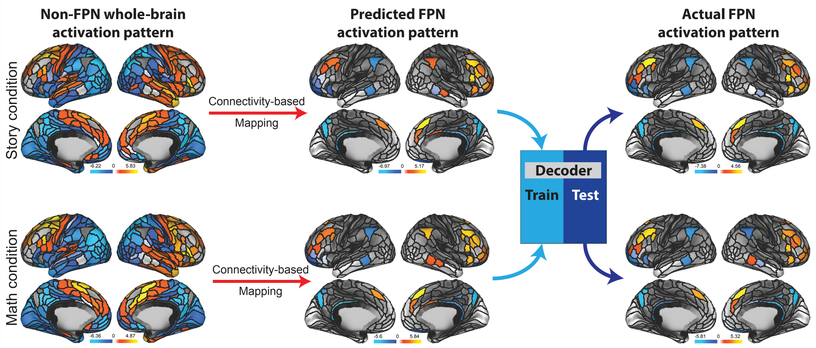
- FPN has the highest representational flexibility across all functional networks
- We correlated graph-theoretic measures with representational flexibility across networks, and performed a t-test across subjects

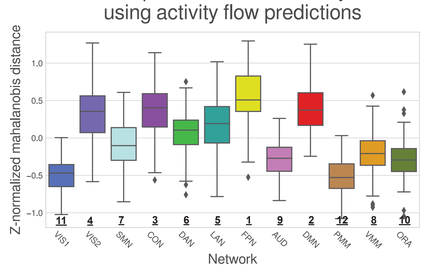
Network-level FC dimensionality correlates with representational flexibility significantly greater than other similar graph-theoretic measures

Relating intrinsic connectivity properties to the flexibility of activity-based task representations

Predicting network-level task representations by estimating activity flow over intrinsic network connections

Example: Predicting Language task activations (story versus math condition) for the FPN

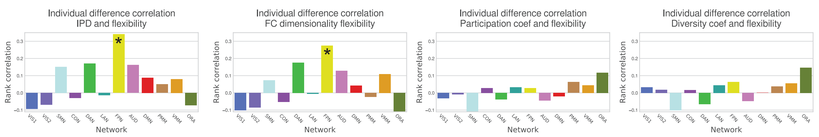




Activity flow over a network's intrinsic organization accurately recapitulates its activation-based representational flexibility

Correlation between actual representational flexibility and activity flow-based representational flexibility:
Spearman rho = 0.65, p < 0.0001

Integrated pattern diversity and FC dimensionality of FPN predict individual differences of FPN representational flexibility



FPN's integrated pattern diversity and FC dimensionality correlate with its representational flexibility, while other graph-theoretic measures do not

Summary & Conclusions

- Converging measures suggest FPN has high intrinsic connectivity diversity, as evidenced by IPD and FC dimensionality
- Connectivity diversity measures are correlated with activation-based representational flexibility across networks
- Activity flow over a network's out-of-network resting-state connectivity can predict its task-evoked activation pattern across a variety of tasks
- FPN's diverse intrinsic connectivity predicts individual differences in its representational flexibility during tasks

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