Bridging multitask representational geometry and intrinsic connectivity in the human brain

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Abstract:

Representational geometry and connectivity-based studies offer complementary insights into neural information processing, but it is unclear how representations and networks interact to generate neural information. Using a multi-task fMRI dataset, we investigate the role of intrinsic connectivity in shaping diverse representational geometries across the human cortex. Activity flow modeling, which generates neural activity based on connectivity-weighted propagation from other regions, successfully recreated similarity structure and a compression-then-expansion pattern of task representation dimensionality. We introduce a novel measure, convergence, quantifying the degree to which connectivity converges onto target regions. As hypothesized, convergence corresponded with compression of representations and helped explain the observed compression-then-expansion pattern of task representation dimensionality along the cortical hierarchy. These results underscore the generative role of intrinsic connectivity in sculpting representational geometries and suggest that structured connectivity properties, such as convergence, contribute to representational transformations. By bridging representational geometry and connectivity-based frameworks, this work offers a more unified understanding of neural information processing and the computational relevance of brain architecture.

Keywords: representational geometry, functional connectivity, activity flow modeling, fMRI, connectivity convergence

Introduction

Representational geometry offers a framework to understand the contribution of neural representations to computational (cognitive) goals. For example, untangling of manifold structure along the regions of the primate ventral visual stream provides insight into the transformations necessary for object recognition from early inputs (DiCarlo & Cox, 2007). Although informative, studies under this framework are limited in that they are unable to provide a mechanistic- or connectivity-based account of how those representational transformations occur. On the other hand, studies based on connectivity between brain regions have underscored the computational relevance of connectivity architecture in a variety of behavioral and computational phenomena (Ito et al., 2020, Kohn et al., 2020). Here we investigate the role of intrinsic connectivity architecture and its contribution to the diverse representational geometries observed across the human cortex.

We focus here on using activity flow modeling to generate neural activity patterns, allowing inferences regarding the generation of brain regions' representational geometries across stimuli and tasks. We hypothesized that high values of convergence (an increase in the vertex-wise degree between the sources and the target) correspond with high levels of relative compression of representations from sources to target regions.

Methods

Dataset

We used the multi-domain task battery fMRI dataset (King et al., 2019) given the diverse set of tasks employed. Dataset and preprocessing details were previously described in detail in King et al. (2019) and Ito et al. (2023), respectively. In brief, 18 subjects performed 24 tasks (96 active task conditions) over two identical sessions, each spanning eight fMRI runs.

Activity and connectivity estimation

We derived activity estimates (betas) for the 96 active task conditions (alongside nuisance regressors) by fitting the timeseries during each run using a general linear model with ridge regularization. Functional connectivity (FC) between vertices was estimated from rest dataset using a two-step procedure: connectivity between 360 Glasser parcels was first estimated using regularized partial correlation with graphical lasso. Principal components regression was then performed on the parcel-level FC scaffold to obtain vertex-wise FC estimates.

Representational geometry measures

Cosine similarity between observed activity patterns corresponding to 96 task conditions was computed among all pairs of tasks resulting in 96x96 sized RSMs in each brain region. Dimensionality was estimated from the cross-validated RSMs by computing the participation ratio of the eigen spectrum of each RSM (Figure 1B).

Activity flow modeling

Activity flow modeling (ActFlow) was used to predict activity (Ito et al. 2020). Briefly, predicted betas in a target region's vertices were obtained by the dot product of source regions' vertices (pooled together) and vertex-wise FC between source regions' vertices and target region's vertices (Figure 1A).

Convergence

Convergence C between sources and a target region is defined as mean degree of a target region's vertices subtracted from the mean degree of vertices of all of the source regions:

$$C(T, S(T)) = \frac{1}{t}\sum_{i=1}^{s} W_{ij} - \frac{1}{s}\sum_{j=1}^{t} W_{ij}$$

where W_{ij} is the absolute value of FC weight matrix between a target region T (with t vertices) and its sources $S(T)$ (with s vertices, pooled among sources).

Results and Discussion

Significant correspondence was detected between observed and ActFlow-predicted activity patterns and activity profiles in all brain regions, replicating previous results. Predicted and observed shared task representations (RSMs, Figure 2A) and the dimensionality of task representations (Figure 2B) also correspond with one another in all brain regions.

A previously reported (Ito et al., 2023) compression-then-expansion pattern was seen in both observed (Figure 2C) and predicted (Figure 2D) dimensionality. This was also observed with double cross-validated RSMs (Figure 2E). This reflects that activity flow modeling can recreate multitask representational geometrical properties, suggesting intrinsic connectivity contributes to the geometrical properties of task representations in a generative manner.

Further, as hypothesized, we observed that the pattern of convergence conferred by the intrinsic connectivity between brain regions likely plays a role in generating representational compression (rho=0.16, p<0.00001). The average convergence across subjects follows an inverted-U shaped pattern along the sensorimotor FC gradient, complementing the dimensionality pattern (p<0.00001).

Figures

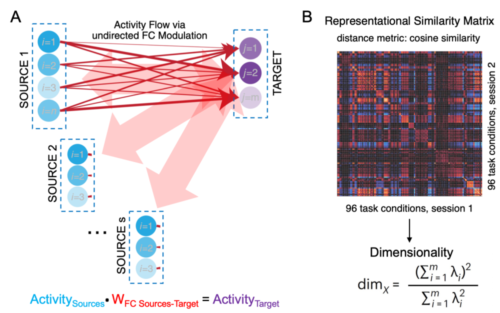

Figure 1: (A) Activity flow mapping procedure. (B) Activity patterns (observed and ActFlow-predicted) were used to create RSMs cross-validated between sessions in each brain region. λ_i is the i[th] eigen value of RSM. *m* is total number of eigen values (96).

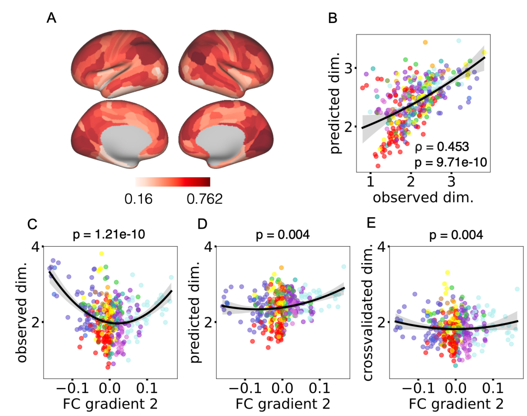

Figure 2: (A) Spearman r between observed and predicted RSMs displayed across cortical regions (cross-subject average), (B) Observed vs. predicted dimensionality (cross-subject average), (C) Quadratic pattern of dimensionality from observed, predicted and cross-validated RSMs along sensorimotor FC gradient.

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References

Cole, M. W., Ito, T., Bassett, D. S., & Schultz, D. H. (2016). Activity flow over resting-state networks shapes cognitive task activations. *Nature neuroscience*, *19*(12), 1718-1726.

DiCarlo, J. J., & Cox, D. D. (2007). Untangling invariant object recognition. *Trends in cognitive sciences*, *11*(8), 333-341.

Ito, T., Hearne, L., Mill, R., Cocuzza, C., & Cole, M. W. (2020). Discovering the computational relevance of brain network organization. *Trends in cognitive sciences*, *24*(1), 25-38.

Ito, T., & Murray, J. D. (2023). Multitask representations in the human cortex transform along a sensory-to-motor hierarchy. *Nature Neuroscience*, *26*(2), 306-315.

King, M., Hernandez-Castillo, C. R., Poldrack, R. A., Ivry, R. B., & Diedrichsen, J. (2019). Functional boundaries in the human cerebellum revealed by a multi-domain task battery. *Nature neuroscience*, *22*(8), 1371-1378.

Kohn, A., Jasper, A. I., Semedo, J. D., Gokcen, E., Machens, C. K., & Byron, M. Y. (2020). Principles of corticocortical communication: proposed schemes and design considerations. *Trends in Neurosciences*, *43*(9), 725-737.