BISCoT: Behavior-Informed Subgroup-Consistent Connectome Template for Interpretable Brain Network Analysis

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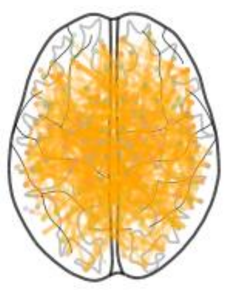
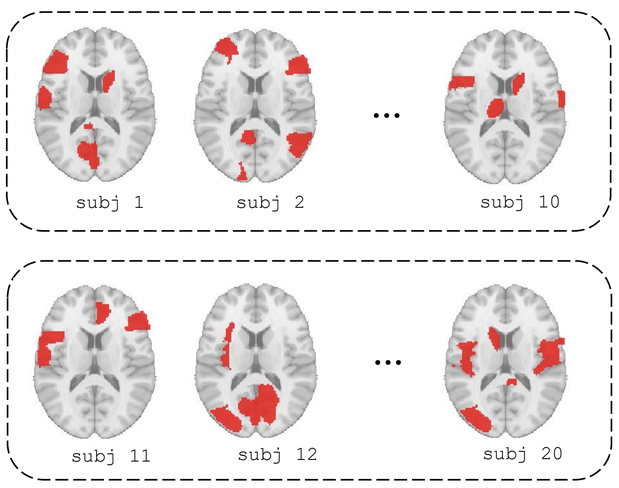
Motivation

Resting-state Brain Network



GNN

Identified Network Patterns (by group)



- Most GNN models do not control for a consistent feature map, nor do they account for heterogeneous phenotypes in patient cohorts
- These undermine the validity of inter-pretations of the identified patterns.
- These models also center at one-target prediction, limiting the generalizability of the patterns found.

Highlights

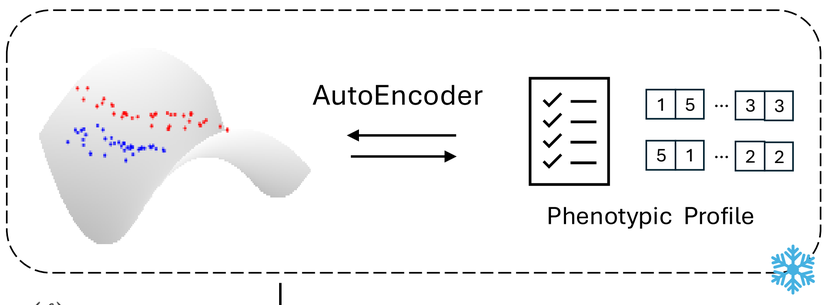
- BISCoT is a self-supervised model for graph sparsification.
- Phenotypic data guides the pooling. Similar profiles lead to similar patterns
- Consistent pattern across subjects with similar phenotypes
- Better generalizability to various downstream tasks

Our Solution: BISCoT

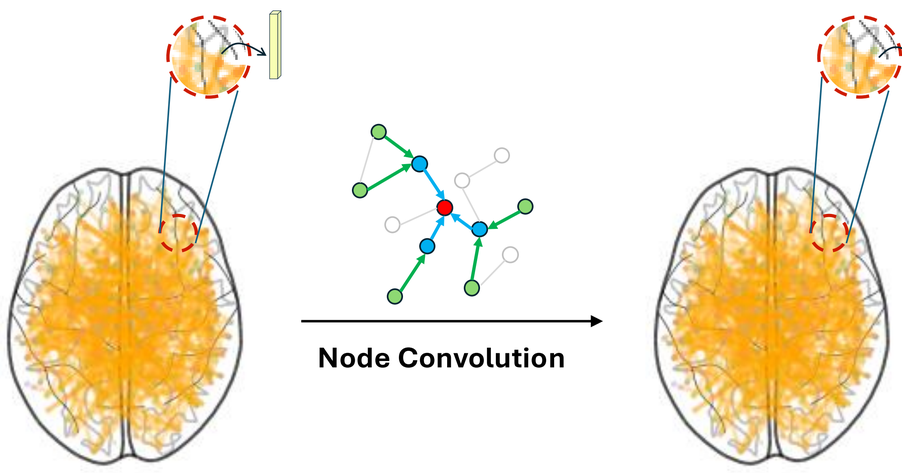
First trained, and then frozen

$$\mathcal{L}_{\text{dec}} = \frac{1}{M}\sum_{m=1}^{M} \|\mathbf{p}_m - \mathbf{p}'_m\|^2$$

$$\mathcal{L}_{\text{sc}} = \frac{1}{M}\sum_{m=1}^{M} \frac{-1}{|\mathcal{P}_i|} \sum_{p\in\mathcal{P}_m} \log\left(\frac{\exp\left(\mathbf{z}_m \cdot \mathbf{z}_p/\tau\right)}{\sum_{a\neq m}\exp\left(\mathbf{z}_m \cdot \mathbf{z}_a/\tau\right)}\right)$$



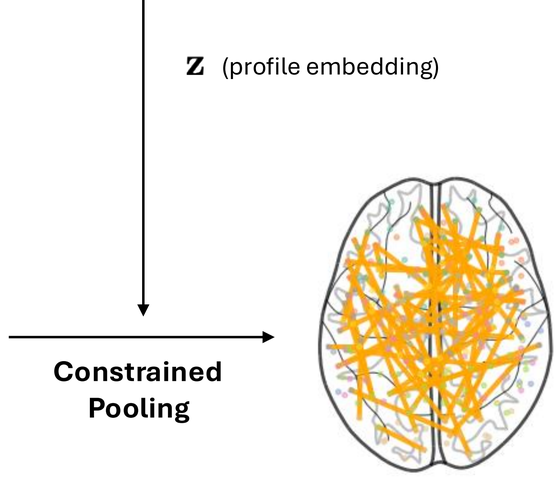
Each node has a feature vector $\mathbf{X}_{i\cdot}^{(\ell-1)}$ — feature vector is updated $\mathbf{X}_{i\cdot}^{(\ell)}$



$$\mathbf{X}_{i\cdot}^{(\ell)} = \text{MLP}^{(\ell)}\left(\left(1+\epsilon^{(\ell)}\right)\cdot \mathbf{X}_{i\cdot}^{(\ell-1)} + \sum_{j\in\mathcal{N}(i)} \mathbf{X}_{j\cdot}^{(\ell-1)}\right)$$

Current node — Aggregated info from adjacent nodes

$\mathbf{z}$ (profile embedding)



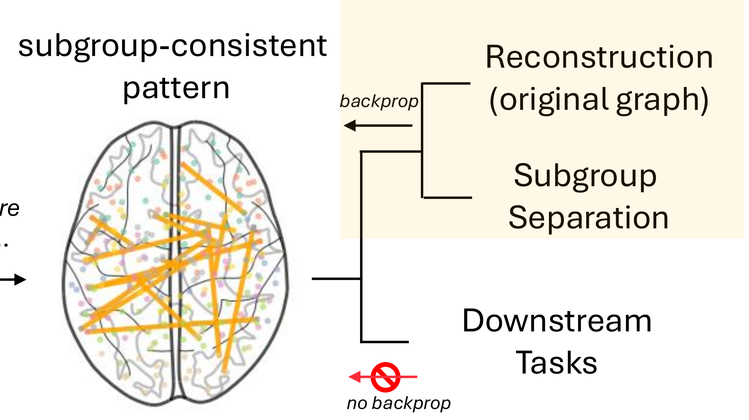
Step 1: Compute scores: $\mathbf{f}_i\left(\mathbf{X}_{i\cdot}^{(L)} \mid \mathbf{z}\right) = \phi\left(\mathbf{w}(\mathbf{z})^\top \mathbf{X}_{i\cdot}^{(L)} + b\right)$

$$\mathbf{w}(\mathbf{z}) = \Theta_2 \cdot \underbrace{\text{Softmax}\left(\Theta_1\mathbf{z} + \mathbf{b}_1\right)}_{\text{Mixing Probability of belonging to each subgroup}} + \mathbf{b}_2$$

Step 2: Retain nodes with TOP p% scores.

Cross Entropy between predicted subgroup and ground truth label

$$\mathcal{L} = \overline{\text{CE}(\hat{y}, y)} + \frac{1}{M}\sum_{m=1}^{M}\underbrace{\left\|\text{logm}\left(\widehat{\mathbf{X}}^{-\frac{1}{2}}\mathbf{X}^{(0)}\widehat{\mathbf{X}}^{-\frac{1}{2}}\right)\right\|_F^2}_{\text{geodesic distance between reconstructed } (\widehat{\mathbf{X}}) \text{ and original } (\mathbf{X})}$$



Experiments and Results

Downstream Tasks
- Behavioral Profile Reconstruction
- ADOS Score Prediction *(measures overall severity of autism)*
- SRS Score Prediction *(measures social impairment severity)*

Original Network Reconstruction Performance

Method	Geodesic ↓	Frobenius ↓	Separation ↑	EigDev ↓
BISCoT	**112.48 ± 9.28**	**65.55 ± 4.04**	**0.77±0.12**	**0.35±0.07**
GIN+TopK	181.09 ± 2.97*	65.64 ± 4.62	0.59 ± 0.07*	0.37 ± 0.09
GIN+SAGPool	180.55 ± 0.98*	67.94 ± 5.79*	0.60 ± 0.11*	0.42 ± 0.13*
GIN+EdgePool	179.51 ± 2.22*	79.16 ± 3.13*	0.56 ± 0.10*	0.61 ± 0.07*
GraphSAGE+TopK	179.12 ± 1.64*	66.89 ± 4.66	0.52 ± 0.14*	0.41 ± 0.10*

Downstream Tasks Performance

	Method	Profile (0-60)		ADOS (0-30)		SRS (0-100)	
		MAE	RMSE	MAE	RMSE	MAE	RMSE
	BISCoT	**4.53±0.48**	**5.80±0.59**	**3.58±0.83**	**4.77±0.69**	**13.43±1.29**	**16.19±0.92**
	GIN+TopK	7.15±0.82*	9.20±1.26*	4.10±1.08	5.38±1.43	16.81±1.87*	20.93±2.50*
	GIN+SAGPool	6.79±0.75*	9.00±0.82*	4.27±0.51*	5.36±0.81*	23.93±2.87*	27.78±3.01*
	GIN+EdgePool	6.90±0.83*	9.10±0.91*	4.62±1.44*	5.69±1.77*	23.47±4.94*	27.59±0.93*
	GraphSAGE+TopK	6.74±0.55*	8.63±0.76*	4.72±0.47*	5.92±0.59*	25.03±2.84*	28.91±2.89*
SOTA	BrainGNN	6.25±0.78*	7.97±0.99*	3.77±0.82	4.80±0.97	16.34±1.92*	20.97±1.98*
SOTA	MGCN	5.14±0.64*	6.54±0.79*	4.20±0.69	5.09±0.85	14.01±1.54	18.24±1.81
SOTA	BPI-GNN	19.19±1.31*	20.71±9.21*	7.21±0.71*	8.44±3.65*	18.45±4.46*	26.54±9.89*

Dataset: in-house autism data

Modalities:
- rs-fMRI
- Sensory Profile: Questionnaire with responses on scale 1-5

Sample Size (ASD): 105

Age: 14.21±2.06

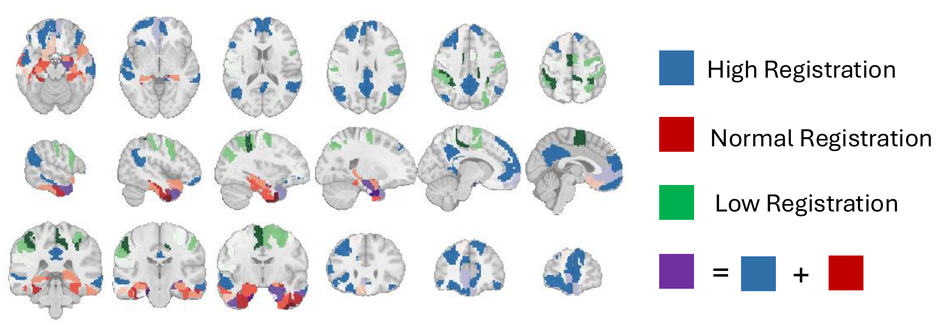
Gender: F:M = 58:47

defines sensory subgroups

Item		B. Movement Processing
	9	I'm afraid of heights.
	10	I enjoy how it feels to move about (for example, dancing, running).
	11	I avoid elevators and/or escalators because I dislike the movement.
	12	I trip or bump into things.

60 questions in total

Patterns identified by BISCoT:



Appear in at least 85% of the patients in each subgroup!

GitHub repo — Paper — LinkedIn

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