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Adaptive Embedding for Long-Range High-Order Dependencies via Time-Varying Transformer on fMRI

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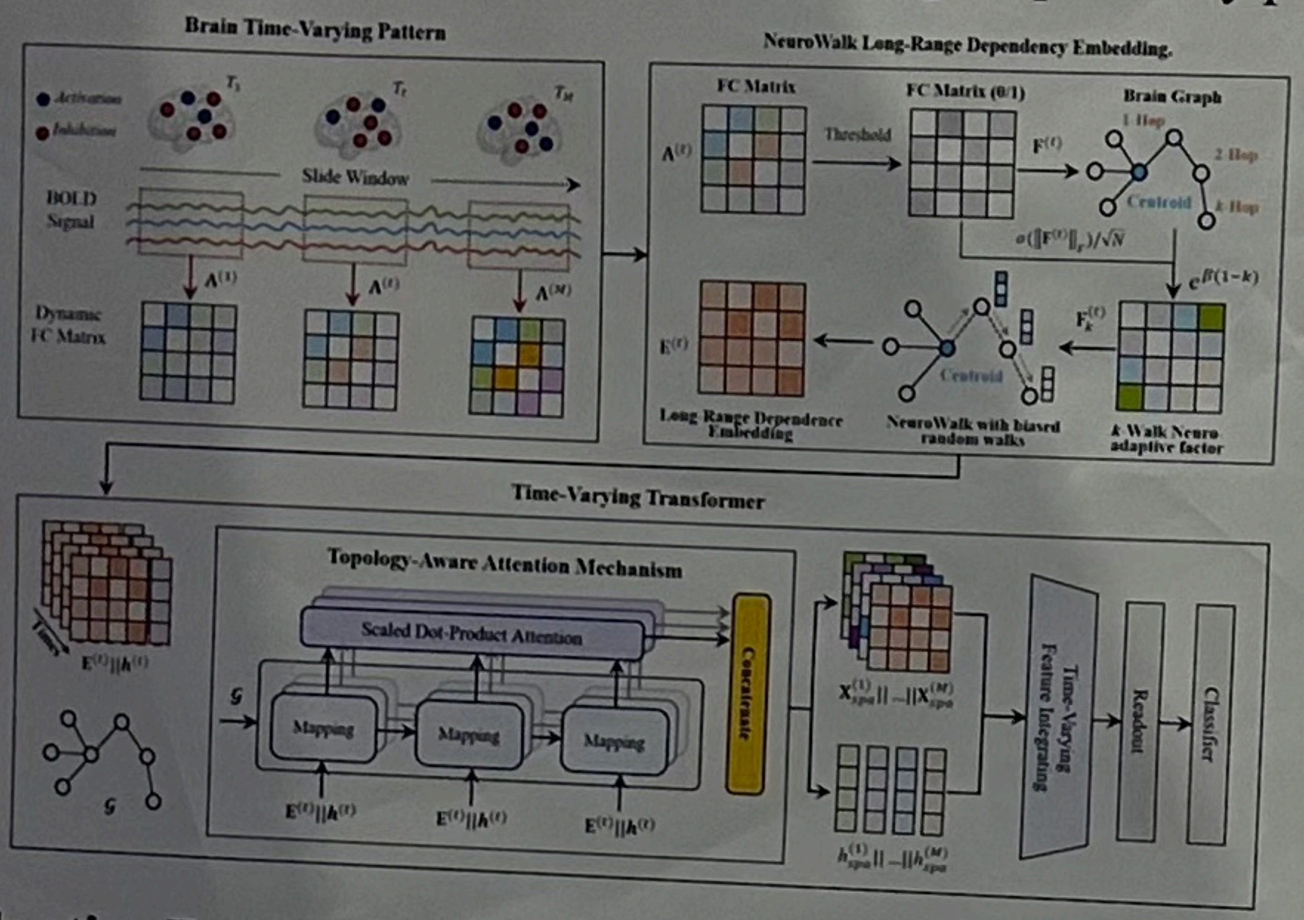
Introduction

- Existing methods for modeling dynamic brain networks typically analyze pairwise relationships through sliding window or time-frequency coherence, failing to capture long-range high-order information flow beyond immediate neighbors.
- Recent studies introduce random-walk kernels to model long range dependencies, the designed static kernels exhibit two critical shortcomings: 1) inability to adapt to the time-varying nature of functional connectivity and 2) failure to encode neurophysiological multi-scale long-range dependency patterns corresponding to different steps.



Method

We propose **LHDFormer**, a physiologically grounded framework that combines **neuroadaptive long-range dependency embedding** with **temporal dynamic integration**. Specifically, we develop a biased random walk sampling strategy with a time-varying NeuroWalk kernel that enables dynamically regulating the process of multi-step information propagation to generate long-range high-order dependency embeddings. Subsequently, local spatial dependencies within the brain and global dynamic connectivity patterns are integrated via a time-varying transformer based on the long-range embed dings.

Adaptive Embedding for Long-Range High-Order Dependencies

- ***k*-Walk Neuroadaptive Factors:** $\mathbf{F}_k^{(t)} = e^{\beta(1-k)} \cdot \sigma(\| \mathbf{F}^{(t)} \|_F / \sqrt{N})$,
- **Time-varying NeuroWalk Kernel:** $\mathbf{R}^{(t,k)} = (\mathbf{F}_k^{(t)} \odot \mathbf{A}^{(t)})(\mathbf{D}^{(t)})^{-1}$
- **NeuroWalk Long-Range Dependency Embedding:** $e_i^{(t)} = \left[\mathbf{I}, \mathbf{R}^{(t,1)}, \prod_{k=1}^{2} \mathbf{R}^{(t,k)}, \ldots, \prod_{k=1}^{K-1} \mathbf{R}^{(t,k)}\right]_{i,i}$.

Time-Varying Transformer

- **Local Spatial-Domain Feature Encoding:** $(\mathbf{X}^{(t)}, \boldsymbol{h}^{(t)}) \rightarrow (\mathbf{X}_{spa}^{(t)}, \boldsymbol{h}_{spa}^{(t)})$.

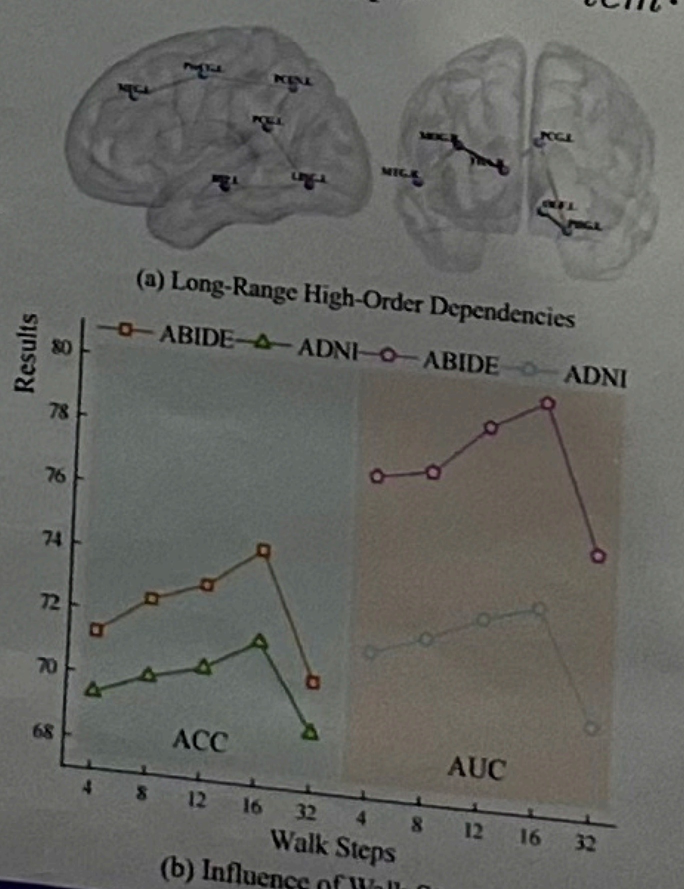
$Q_i^{(t)}, K_i^{(t)}, V_i^{(t)} = \mathrm{ReLU}((\mathbf{D}^{(t)})^{-1/2}\mathbf{A}^{(t)}(\mathbf{D}^{(t)})^{-1/2}\mathbf{X}^{(t)})(W_Q, W_K, W_V)$, $\mathbf{X}_{spa}^{(t)} = W_o(\|_{i=1}^{D} \mathbf{X}_i^{(t)})$, $\mathbf{X}_i^{(t)} = \mathrm{softmax}\left(\frac{Q_i^{(t)}(K_i^{(t)})^\top}{\sqrt{d}}\right)V_i^{(t)}$.

- **Global Time-Varying Feature Integrating:** $(\|_{t=1}^{M} \mathbf{X}_{spa}^{(t)}, \|_{t=1}^{M} \boldsymbol{h}_{spa}^{(t)}) \rightarrow \mathbf{X}_{tem}$.

Result

Table 1. Experimental Results of the Comparison Methods.

Dataset	Method	ACC(%)	SEN(%)	SPE(%)	AUC
ABIDE	STGCN [15]	$65.52_{\pm 2.46}$	$62.96_{\pm 7.51}$	$67.74_{\pm 5.00}$	$0.6628_{\pm 0.0243}$
	BrainIB [16]	$69.21_{\pm 8.64}$	$65.32_{\pm 5.70}$	$72.94_{\pm 5.32}$	$0.6902_{\pm 0.0327}$
	RGTNET [17]	$69.75_{\pm 1.41}$	$70.30_{\pm 4.71}$	$68.87_{\pm 3.84}$	$0.7051_{\pm 0.0117}$
	MSSTAN [7]	$71.40_{\pm 1.49}$	$70.35_{\pm 1.80}$	$72.55_{\pm 1.83}$	$0.7678_{\pm 0.0076}$
	ALTER [9]	$71.23_{\pm 2.86}$	$71.27_{\pm 3.84}$	$71.22_{\pm 2.02}$	$0.7547_{\pm 0.0207}$
	LHDFormer	$\mathbf{74.29}_{\pm 1.17}$	$\mathbf{73.48}_{\pm 1.10}$	$\mathbf{75.09}_{\pm 2.04}$	$\mathbf{0.7978}_{\pm 0.0103}$
ADNI	STGCN [15]	$62.82_{\pm 4.46}$	$65.23_{\pm 5.49}$	$60.36_{\pm 4.65}$	$0.6254_{\pm 0.0582}$
	BrainIB [16]	$64.68_{\pm 2.94}$	$66.36_{\pm 9.01}$	$63.62_{\pm 8.14}$	$0.6583_{\pm 0.0390}$
	RGTNET [17]	$65.75_{\pm 3.23}$	$66.32_{\pm 4.28}$	$64.54_{\pm 3.15}$	$0.6826_{\pm 0.0449}$
	MSSTAN [7]	$67.88_{\pm 2.84}$	$69.38_{\pm 3.83}$	$66.40_{\pm 2.73}$	$0.7130_{\pm 0.0457}$
	ALTER [9]	$68.50_{\pm 1.17}$	$69.32_{\pm 2.28}$	$67.33_{\pm 2.58}$	$0.7200_{\pm 0.0181}$
	LHDFormer	$\mathbf{71.42}_{\pm 1.70}$	$\mathbf{72.52}_{\pm 2.02}$	$\mathbf{70.27}_{\pm 1.10}$	$\mathbf{0.7347}_{\pm 0.0209}$



(a) Long-Range High-Order Dependencies

(b) Influence of Walk Steps

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THU-iMoonLab

DeepHypergraph

Code: iMoonLab/LHDFormer