Supporting Information for:

Delayed Brain Network Energy Development in Preterm Youth Impairs Cognitive Function: Evidence from the Longitudinal ABCD Study

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Appendices

rsfMRI Preprocessing

Resting-state fMRI (rsfMRI) data were preprocessed using FSL 5.0.11 and SPM12. The preprocessing pipeline included distortion correction, realignment to correct for head motion, normalization to MNI space, resampling to 3mm isotropic voxels, and spatial smoothing with a 6mm full width at half maximum (FWHM) Gaussian kernel, as shown in Fig.1. After preprocessing, spatially constrained independent component analysis (scICA) was applied to extract subject-specific time series and estimate functional connectivity matrices.

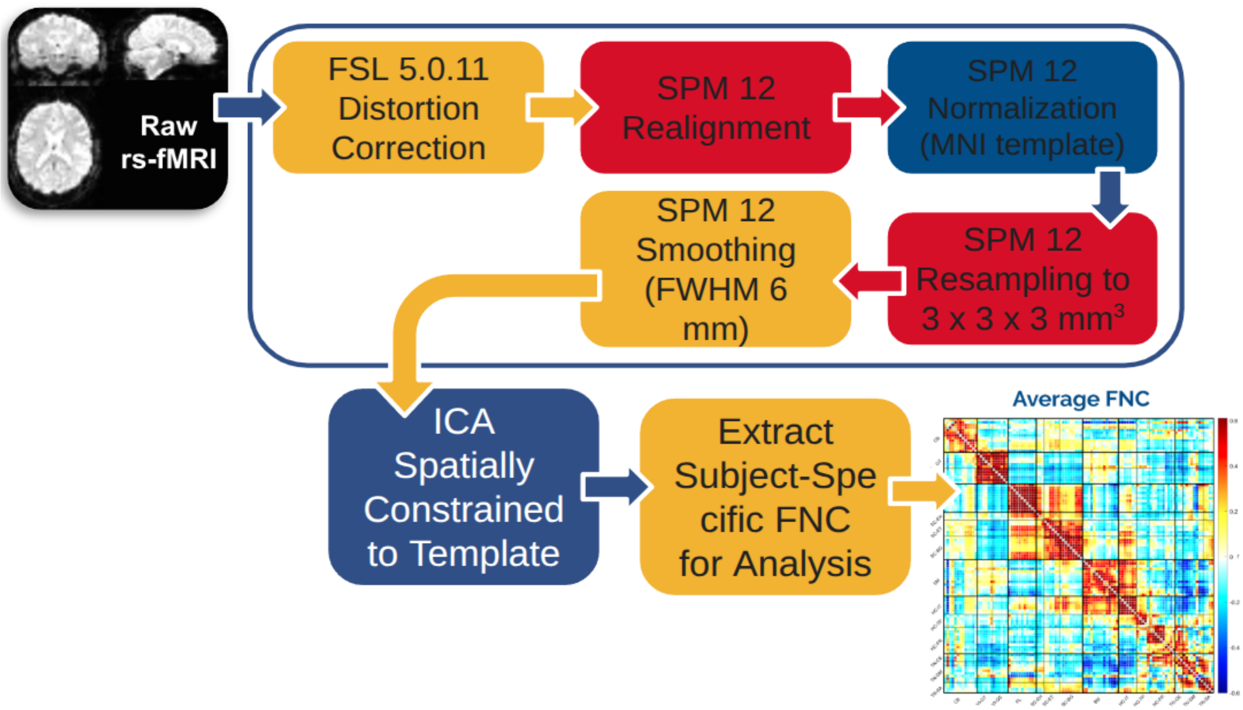


Figure 1: The rsfMRI preprocessing began with distortion correction of the raw data, followed by realignment, normalization, resampling, and spatial smoothing using SPM12. After preprocessing, a scICA was applied to estimate subject-specific functional connectivity matrices.

Multivariate Objective Optimization ICA

Multivariate Objective Optimization ICA with Reference (MOO-ICAR) is a scICA technique designed to extract subject-specific independent components (ICs) using predefined network templates as spatial priors [1], [2]. This method enhances the consistency of network identification across individuals by enforcing alignment with known functional network structures. A notable advantage of the MOO-ICAR framework is its capacity to maintain inter-subject correspondence in component estimation. In addition, the scICA framework offers customizable template selection, enabling researchers to adapt the analysis for either condition-specific studies or broader investigations of widely recognized brain networks across diverse populations [3], [4].

The MOO-ICAR algorithm simultaneously optimizes two objective functions to extract subject-specific ICs: one objective maximizes the statistical independence of the estimated networks, while the other ensures spatial similarity with a predefined network template [1]. The following equation illustrates how the l^{th} network component for the k^{th} subject is estimated using the corresponding template S_l as a spatial reference:

$$\max \begin{cases} J\left(S_l^k\right) = \left\{E\left[G\left(S_l^k\right)\right] - E[G(v)]\right\}^2 \\ F\left(S_l^k\right) = E\left[S_l S_l^k\right] \end{cases} \quad \text{s.t. } \left\|w_l^k\right\| = 1 \tag{1}$$

Here, $S_l^k = \left(w_l^k\right)^T X^k$ denotes the estimated l^{th} network for the k^{th} subject, where X^k is the whitened fMRI data matrix and w_l^k is the associated unmixing column vector to be optimized. The term $J(S_l^k)$ quantifies independence through a measure of negentropy, where $G(\cdot)$ is a non-quadratic function, v is a standard Gaussian variable (mean zero, unit variance), and $E[\cdot]$ represents expectation. The term $F(S_l^k)$ quantifies the similarity between the subject-specific component and the network template. These two objectives are combined into a single cost function using a linear weighted sum, with equal weights of 0.5. Applying MOO-ICAR within the scICA framework yields individualized ICNs for each of the $N = 105$ predefined templates along with their associated time courses, ensuring consistent network alignment across subjects.

BrainMap: Five Behavioral Domains and 51 Subdomains

We present detailed information on the five behavioral domains defined by BrainMap (`https://www.brainmap.org/`) [5]–[8], which include Action, Cognition, Emotion, Interoception, and Perception (as shown in Table.1). Each of these broad domains is further divided into a total of 51 sub-domains, providing a comprehensive framework for categorizing a wide range of brain-related behaviors and functions.

Relationship Between Functional Network Energy and Behavioral Measures Across Preterm and Full-Term Cohorts

The relationship between network energy in the sensorimotor (SM) and high-cognitive temporoparietal (HC-TP) networks and behavioral measures across preterm and full-term cohorts was illustrated in Fig.2. The analysis showed no significant associations between network energy in either the SM or HC-TP networks and behavioral measures in both groups.

Meta-Analytic Functional Decoding of Sensorimotor Networks

Meta-analytic functional decoding was performed on the SM networks, revealing that the most significantly associated behavioral domain was Action, particularly related to motor execution and motor imagery, as illustrated in Fig.3.

Functional Network Energy and Its Association With Cognitive and Behavioral Measures in Preterm and Full-Term Groups

In Table.2, we present the statistical analysis examining the associations between functional network energy in the SM and HC-TP networks and both behavioral and cognitive performance scores, comparing preterm and full-term birth groups. The analysis includes group-wise comparisons as well as correlation assessments to evaluate how alterations in network energy may relate to behavioral and clinical outcomes across birth status.

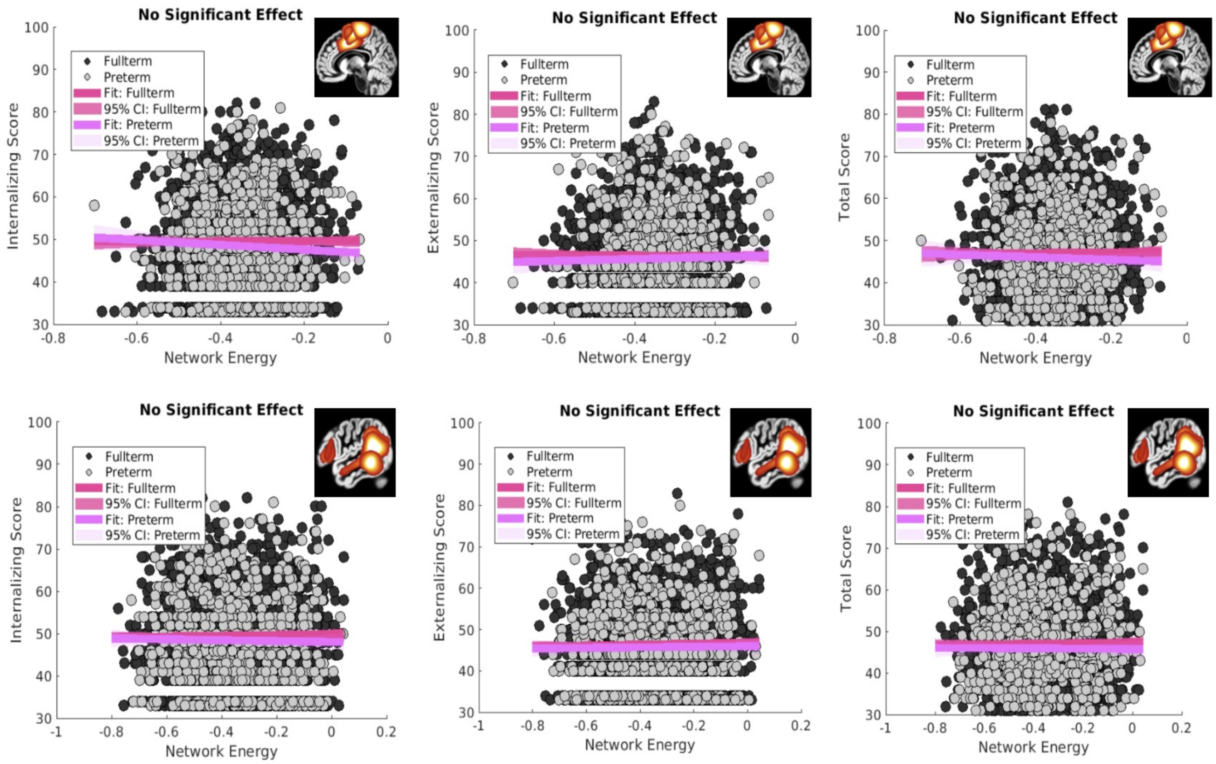
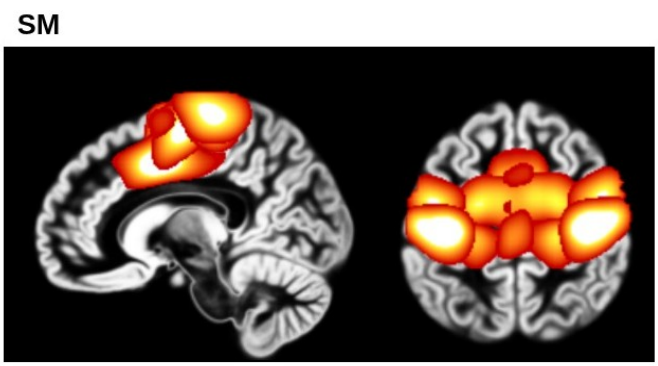


Figure 2: The relationship between functional network energy in the SM and HC-TP networks and mental health scores, including internalizing, externalizing, and total scores, was assessed in both preterm and full-term participants. No significant associations were found between SM or HC-TP network energy and any mental health scores in either group.



Domain	Category	Z-score
Action	Execution	19.465
Action	Imagination	8.125
Cognition	Music	6.18
Perception	Vision.Motion	5.535
Cognition	Attention	5.102
Perception	Somesthesis.Pain	5.023
Cognition	Language.Speech	4.305
Action	Motor Learning	4.083
Cognition	Memory.Working	3.714
Perception	Somesthesis	3.696
Action	Inhibition	3.685
Action	Execution.Speech	3.672
Perception	Audition	3.274
Interoception	Gastrointestinal/Genitourinary	3.126

Figure 3: Meta-analytic functional decoding results for the SM networks (ICNs 55–68). Only terms with z-scores ≥ 3.0 were considered statistically significant, corresponding to $p \leq 0.05$ after false discovery rate (FDR) correction for multiple comparisons.

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Table Legends

Table 1: Behavioral categorization in BrainMap across major domains and sub-domains.

Action	**Cognition**	**Emotion**	**Interoception**	**Perception**
Execution: Other	Attention	Anger	Air-hunger	Audition
Execution:Speech	Language:Orthography	Anxiety	Bladder	Gustation
Imagination	Language:Other	Disgust	Hunger	Olfaction
Inhibition	Language:Phonology	Fear	Other	Somethesis
Motor:Learning	Language:Semantics	Happiness:Humor	Sexuality	Somethesis:Pain
Observation	Language:Speech	Happiness	Sleep	Vision:Color
Other	Language:Syntax	Other	Thermoregulation	Vision:Motion
Preparation	Memory:Explicit	Sadness	Thirst	Vision:Other
Rest	Memory:Other			Vision:Shape
	Memory:Working			
	Music			
	Other			
	Reasoning			
	Social			
	Soma			
	Space			
	Time			

Table 2: Statistical analysis of the association between functional network energy in the SM and HC-TP networks and behavioral and cognitive measures in preterm vs. full-term groups.

		SM	**HC-TP**
Behavioral	Internalizing	Network Energy: β=0.11, p_FDR=0.97 Network Energy-Group: β=-5.72, p_FDR=0.35	Network Energy: β=0.96, p_FDR=0.59 Network Energy-Group: β=-2.02, p_FDR=0.59
	Externalizing	Network Energy: β=-0.52, p_FDR=0.85 Network Energy-Group: β=2.85, p_FDR=0.80	Network Energy: β=1.14, p_FDR=0.48 Network Energy-Group: β=-0.46, p_FDR=0.86
	Total	Network Energy: β=0.69, p_FDR=0.79 Network Energy-Group: β=-3.68, p_FDR=0.55	Network Energy: β=0.80, p_FDR=0.68 Network Energy-Group: β=-1.16, p_FDR=0.68
Cognitive	Fluid	Network Energy: β=-4.21, p_FDR=0.65 Network Energy-Group: β=-6.88, p_FDR=0.65	Network Energy: β=-0.97, p_FDR=0.77 Network Energy-Group: β=10.44, p_FDR=0.20
	Crystallized	Network Energy: β=1.01, p_FDR=0.86 Network Energy-Group: β=-9.28, p_FDR=0.51	**Network Energy: β=-7.14, p_FDR=0.03** **Network Energy-Group: β=13.7023, p_FDR=0.03**
	Total	Network Energy: β=-4.54, p_FDR=0.64 Network Energy-Group: β=-5.43, p_FDR=0.64	Network Energy: β=-3.96, p_FDR=0.37 Network Energy-Group: β=13.3279, p_FDR=0.08