

Novel Tools and Methods

Hierarchical Individual Naturalistic Functional Brain Networks with Group Consistency Uncovered by a Two-Stage NAS-Volumetric Sparse DBN Framework

Shuhan Xu,* Yudan Ren,* Zeyang Tao, Limei Song, and Xiaowei He

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School of Information Science and Technology, Northwest University, Xi'an, China, 710129

Abstract

The functional magnetic resonance imaging under naturalistic paradigm (NfMRI) showed great advantages in identifying complex and interactive functional brain networks (FBNs) because of its dynamics and multimodal information. In recent years, various deep learning models, such as deep convolutional autoencoder (DCAE), deep belief network (DBN), and volumetric sparse DBN (vsDBN), can obtain hierarchical FBNs and temporal features from fMRI data. Among them, the vsDBN model revealed a good capability in identifying hierarchical FBNs by modeling fMRI volume images. However, because of the high dimensionality of fMRI volumes and the diverse training parameters of deep learning methods, especially the network architecture that is the most critical parameter for uncovering the hierarchical organization of human brain function, researchers still face challenges in designing an appropriate deep learning framework with automatic network architecture optimization to model volumetric NfMRI. In addition, most of the existing deep learning models ignore the group-wise consistency and intersubject variation properties embedded in NfMRI volumes. To solve these problems, we proposed a two-stage neural architecture search (NAS) and vsDBN model (two-stage NAS-vsDBN model) to identify the hierarchical human brain spatiotemporal features possessing both group consistency and individual uniqueness under naturalistic condition. Moreover, our model defined reliable network structure for modeling volumetric NfMRI data via NAS framework, and the group-level and individual-level FBNs and associated temporal features exhibited great consistency. In general, our method well identified the hierarchical temporal and spatial features of the brain function and revealed the crucial properties of neural processes under natural viewing condition.

Key words: naturalistic fMRI; neural architecture search; deep belief network; hierarchical functional brain networks

Significance Statement

In this paper, we proposed and applied a novel analytical strategy, a two-stage neural architecture search (NAS)-volumetric sparse deep belief network (vsDBN) model to identify both group-level and individual-level spatiotemporal features at multiscales from volumetric functional magnetic resonance imaging under naturalistic paradigm (NfMRI) data. The proposed particle swarm optimization (PSO)-based NAS framework can find optimal neural structure for both group-wise and individual-level vsDBN models. Furthermore, with well-established correspondence between two stages of vsDBN models, our model can effectively detect group-level functional brain networks (FBNs) that reveal the consistency in neural processes across subjects and individual-level FBNs that maintain the subject-specific variability, verifying the inherent property of brain function under naturalistic condition.

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Introduction

Recently, functional magnetic resonance imaging (fMRI) has been considered as an effective tool to explore functional brain networks (FBNs) and temporal responses (Damascelli et al., 2021). Previously, various studies rely on task-based fMRI (tb-fMRI; Cui et al., 2019) and resting-state fMRI (rs-fMRI; Catalino et al., 2020). However, the simplified stimuli adopted in task paradigms rarely occur in isolation in real life, thus it is unclear whether it can reveal the complex neural responses evoked in daily life (Hasson et al., 2010). Moreover, subjects struggle to maintain vigilance during resting-state scanning, thus microsleeps and head movements occur commonly (Vanderwal et al., 2015). To avoid the limitations of these paradigms, researches propose naturalistic paradigm, which employs rich multimodal and dynamic stimuli that resemble the perceptual and cognitive experiences in real life (Sonkusare et al., 2019), and offers a way to identify hierarchical spatiotemporal patterns.

Therefore, researches have employed NfMRI to examine FBNs using diverse computational methods, including general linear model (GLM; Beckmann et al., 2003), independent component analysis (ICA; Salman et al., 2019), and sparse dictionary learning (SDL; Ren et al., 2017a). Although these methods can detect meaningful FBNs, they ignore the hierarchical structure of FBNs because of their shadow nature (Ferrarini et al., 2009). To address the limitations of shallow models, increasing deep learning approaches have been proposed to construct hierarchical spatiotemporal features from fMRI data, including deep convolutional autoencoder (DCAE; H Huang et al., 2018), deep belief network (DBN; ZA Huang et al., 2021), and recurrent neural network (RNN; Cui et al., 2019). These models reveal great capacity in extracting hierarchical FBNs and temporal features from fMRI time series. However, fMRI time series can cause more intersubject variability across subjects compared with spatial volumes, which can affect the reliability of derived FBNs (W. Zhang et al., 2019; Y. Zhang et al., 2019). Therefore, whether/how to uncover the complicated hierarchical temporal and spatial organization of brain function from NfMRI volumes remain unclear.

Moreover, existing researches still have some limitations. Deep learning models are usually composed of multiple layers structures with neurons in each layer, which

serve as the most vital hyperparameters in deep learning model and are particularly critical for the hierarchical FBNs. Hence, because of a variety of training parameters and the high dimensionality of fMRI volumes, it is difficult to manually design a suitable network architecture to model volumetric fMRI data, awaiting a computational framework to automatically construct the optimal neural architecture (NA). Furthermore, deep learning models that uncover the hierarchical FBNs and temporal patterns from high-dimensional NfMRI volumes usually lack ground truth and have to be trained in an unsupervised fashion, which are different from most existing NA search (NAS) methods designed for image classification problems (Pham et al., 2018; Real et al., 2019). To solve this problem, some studies have combined NAS framework with deep learning method and applied it to fMRI data to identify hierarchical FBNs (W. Zhang et al., 2019; Ren et al., 2021a,b). For instance, Ren and colleagues have proposed group-wise NAS-DBN to characterize the hierarchical spatiotemporal patterns from NfMRI volumes (Ren et al., 2021b). Specifically, these successful applications of DBN model on hierarchical FBN identification also reveal that a DBN model typically stacked by multiple restricted Boltzmann machine (RBM; Fischer and Igel, 2012) can naturally act as a hierarchical feature extractor to extract hierarchical brain spatiotemporal features.

Although the existing NAS-based frameworks can detect hierarchical spatiotemporal features (Dai et al., 2020; Li et al., 2021, 2022), there are still challenges. Previous studies reveal that though naturalistic paradigms trigger highly consistent brain responses across individuals, the neural temporal activities evoked by this condition also show great intersubject variability, especially in heteromodal association cortices, which reflects high degree of individuality and uniqueness in internal neural process (Golland et al., 2007; Ren et al., 2017b). However, previous models can only reveal the group-wise consistency among subjects, but cannot model the individual uniqueness (Qiang et al., 2020; Li et al., 2021). Moreover, it is not clear whether this property can be detected from volumetric NfMRI data (Y. Zhang et al., 2019). To address the challenges, we proposed a two-stage NAS-vsDBN model to automatically optimize NA and identify both group-consistent and individual-unique hierarchical spatiotemporal features from volumetric NfMRI data. Furthermore, we comprehensively validated the consistency and similarity between group-level and individual-level spatiotemporal features. Generally, based on the crucial property of NfMRI data, our model can effectively identify the hierarchical organization of brain function from NfMRI volumes.

Materials and Methods

Participants and video stimuli

Fifteen healthy subjects (eight females) participated in our study. Participants were interviewed to determine their eligibility through a telephone survey. We provided a complete and detailed description of our study and obtained written informed consent from all participants. The study was approved by the Yale Human Investigation

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*S.X. and Y.R. contributed equally to this work and should be considered co-first authors.

Correspondence should be addressed to Yudan Ren at yudan.ren@nwu.edu.cn.

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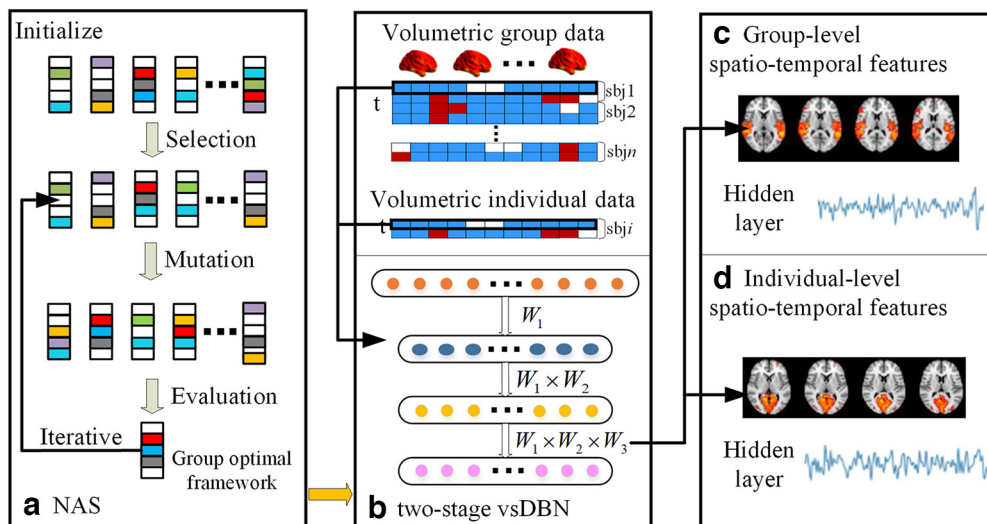


Figure 1. The computational framework of two-stage NAS-vsDBN model for whole-brain volumetric fMRI signals, including (a) NAS framework, (b) Two-stage vsDBN model, (c) Group-level spatio-temporal features, and (d) Individual-level spatio-temporal features (NAS, neural architecture search; vsDBN, volumetric sparse deep belief network).

Committee. In this experiment, we selected and presented a sad scenarios video as the input natural stimulation. In the video, an actress described the sad experience to the participants. More details of dataset and stimuli can be referred to previous studies (Kober et al., 2016).

Imaging data acquisition and preprocessing

Participants were scanned in a 3 T Siemens Trio MRI scanner. The preprocessing process is implemented by the Data Preprocessing Assistant for Resting-state fMRI (DARSF) toolbox. The preprocessing pipeline includes head motion correction, slice time correction, spatial smoothing, band-filtering (0.008–0.3 Hz), and registration to MNI standard space. By calculating the spatial intersection of all individual brains, we generated a group-wise common mask to extract the whole-brain signals of each subject, by which we can ensure the spatial correspondence of each voxel across all the subjects. The extracted whole-brain fMRI signals of each subject were then stacked into a 2D matrix, where each column represents the fMRI signals of each voxel containing 206 time points, and each row refers to the brain volume possessing 70,831 voxels. In addition, fMRI time series of each voxel were normalized to have zero mean and unit variance. All individual subjects' fMRI time series were concatenated, and then we transposed the connected matrix to a group-wise volumetric fMRI matrix for first stage DBN training.

The overview framework of two-stage NAS-vsDBN model

The two-stage NAS-vsDBN model we proposed is shown in Figure 1. We first performed 10 times NAS procedures on group-level fMRI data. Specifically, we iteratively evaluated, mutated, and updated the randomly initialized subnets (Fig. 1a,b), resulting in the

optimal NA for the group-wise vsDBN. Then the vsDBN model with the optimal NA was applied to train the group-level fMRI data, after which the group-level spatio-temporal features were identified (Fig. 1c). Finally, we initialized the individual vsDBN model of second-stage training with the weights obtained from the first stage training to generate individual-level FBNs and temporal features with group consistency (Fig. 1d).

NAS framework based on particle swarm optimization (PSO) algorithm

In order to search for the optimal network architecture (NA) of the two-stage vsDBN model, we adopted and designed a NAS framework based on the PSO algorithm. PSO is a representative and efficient swarm intelligent optimizer, which takes less time, has fewer parameters and is easy to implement (Kennedy and Eberhart, 1995). Specifically, we first randomly generated 30 subnets with different NAs, where each subnet was composed of the most vital hyperparameters for hierarchical organization characterization: the number of nodes and hidden layers. Subnets will be regarded as particles in PSO algorithm, which were then selected after initialization to perform mutations based on the idea of aging evolution to generate the new generations of subnets to increase the diversity of subnets (Real et al., 2019). The subnet after mutations will be mapped to the position of each particle. All the particles were evaluated by a fitness function, which was defined by the testing loss of vsDBN model (Kennedy and Eberhart, 1995). This NAS procedure was conducted iteratively. In the process of each iteration, the local best solution of each particle and the global best solution of whole swarm were recorded, and the original NA was replaced with the current global best NA with the minimum reconstruction error. Finally, after all the iterations, a single particle owning the most accurate reconstruction was selected

as global optimal NA. Overall, all particles' velocities and positions were updated by the following equations:

$$v_i^{h+1} = w * v_i^h + c_1 * Rand_1(pb_{best_i^h} - nas_i^h) + c_2 * Rand_2(g_{best_i^h} - nas_i^h) \tag{1}$$

$$nas_i^{h+1} = nas_i^h + v_i^{h+1}. \tag{2}$$

Equations 1 and 2 are for mutative velocity and position updating, respectively, where nas_i^h and nas_i^{h+1} represent current and next search of NA, and v_i^h and v_i^{h+1} are the current and next velocities, respectively. The subscript h and i denote current iteration and subnet, respectively, w is the inertia weight that reflects the inertia of particle motion; c_1 and c_2 are constant real values; $Rand_1$ and $Rand_2$ are random real numbers selected from the interval $[-1, 1]$; $pb_{best_i^h}$ represents historical optima for each subnet during iterations, and $g_{best_i^h}$ is global optimal NA. The parameter settings of NAS are as follow: the constant values of w , c_1 , and c_2 are, respectively, set as 0.1, 2, 2 according to previous study (Qiang et al., 2020; Ren et al., 2021b). Alternatively, as the value of w can be also updated by linearly decreasing weight method (Shi and Eberhart, 1998), we also repeated the NAS framework using this strategy. In the meanwhile, the search range of layers is set at $[2, 10]$ and the search range of nodes is set to $[100, 800]$.

Two-stage vsDBN model of volumetric fMRI data

A DBN model consists of multiple stacked RBMs (Hinton et al., 2006). Inputs are modeled by RBMs via latent factors expressed through the interaction between hidden and visible variables (Hu et al., 2018). The stacked architecture of DBN model acts as a hierarchical feature extractor as a whole, generating an ideal model for extracting the hierarchical temporal and spatial features from high-dimensional volumetric NfMRI data. Specifically, a DBN model consists of visible layer variable v and hidden layer variable h , of which energy function is as follows:

$$E(v, h | \theta) = - \sum_{i=1}^n a_i v_i - \sum_{j=1}^m b_j h_j - \sum_{i=1}^n \sum_{j=1}^m v_i W_{ij} h_j. \tag{3}$$

In the above formula, $\theta = \{W_{ij}, a_i, b_j\}$ represents the model parameters, where W_{ij} is the connection weight between the visible layer unit i and the hidden layer unit j , a_i represents the bias of the visible layer unit i , and b_j represents the offset of the hidden layer unit j . After 10 times of NAS processes, we obtained the optimal network structure of DBN model, which was applied to define the architecture of group-wise vsDBN model. In this work, our optimal architecture of DBN has three RBM blocks. In the first stage, the individual NfMRI matrices of all the participants were first concatenated along time and then transposed, resulting in the group-wise volumetric NfMRI data matrix $F \in R^{(v \times n) \times m}$ (v represents the number of fMRI time

points, n is the number of individuals, and m represents the number of voxels in each fMRI volume, i.e., neurons in visible layer) for first-stage training. The optimized DBN was then applied to the group-level volumetric NfMRI data. After training, the weight matrices $W_1 \in R^{m \times q_1}$, $W_2 \in R^{(q_1 \times q_2)}$, $W_3 \in R^{(q_2 \times q_3)}$ (q_1, q_2, q_3 are the number of neurons in each hidden layer, respectively, and the value of q_1, q_2, q_3 are determined according to NAS process) between each hidden layer were learnt. In addition, we obtained the output of each hidden layer $T_1 \in R^{(v \times n) \times q_1}$, $T_2 \in R^{(v \times n) \times q_2}$, $T_3 \in R^{(v \times n) \times q_3}$. In the second stage, we performed subject-specific vsDBN (ss-vsDBN) models using individual volumetric fMRI data to improve individual fMRI data representation, while retaining the spatiotemporal correspondence across subjects and groups. For this purpose, we used the optimal network structure and the weight matrices learned in the first stage (W_1, W_2, W_3) to initialize ss-vsDBN. Specifically, W_1 was used to initialize the weights of the visible layer and the first hidden layer, and W_2, W_3 were used to initialize the weights of the first and second hidden layer as well as the second and third hidden layer, respectively. Then, the initialized ss-vsDBN models were trained using each individual NfMRI data to obtain the individual-level weight matrices and temporal features ($t_1 \in R^{v \times q_1}$, $t_2 \in R^{v \times q_2}$, $t_3 \in R^{v \times q_3}$), respectively.

In previous FBNs identification studies, extracting spatiotemporal features from fMRI data using DBN/RBM model was regarded as a blind source separation problem (Hu et al., 2018; W. Zhang et al., 2019), which shared similar structures with matrix factorization problem in terms of the relationship among the observed fMRI data, latent temporal features, and spatial maps. Thus, volumetric NfMRI data can be decomposed as the temporal features and spatial maps through our vsDBN model. Specifically, for group-level and subject-level vsDBN model, the output of hidden layer represented temporal features, and the weight matrix of each layer represented the latent spatial features reflecting the extent of each voxel contributing to a latent variable, of which row can be directly mapped back into original 3D brain space to derive FBNs in a hierarchical manner. Specifically, the linear combination approach was used to extract the latent FBNs, where $W_1 \times W_2 \times W_3$ was visualized for the third hidden layer as FBNs and $W_1 \times W_2$ and W_1 for the second hidden layer and the first hidden layer, respectively (Fig. 1b).

Intersubject correlation (ISC) analysis for temporal features

Besides obtaining the hierarchical spatial features, we would like to further investigate the hierarchical organization of temporal responses derived from the two-stage NAS-vsDBN framework. Specifically, we calculated the ISC by using individuals' temporal responses extracted from the output of each hidden layer, where ISC measured the intersubject consistency for temporal responses of each atom from each hidden layer across individuals (Hasson et al., 2004; Nastase et al., 2019). The ISC value was calculated for each atom of each hidden layer for all the subjects, separately. We then derived the ISC metric

for each layer and each subject by averaging the ISC values across all the atoms belonging to the same layer, respectively. Moreover, the group-level ISC metric was derived by averaging all the individual's ISCs for each layer, respectively.

The spatial consistency between individual-level and group-level FBNs

The two-stage NAS-vsDBN model can identify the FBNs with both group consistency and individual uniqueness. Inspired by previous research, to further explore the spatial similarity between group-level and individual-level FBNs, we adopted the spatial correlation coefficient (SCC) as an indicator, which was defined in Equation 4 as r_{gd}

$$r_{gd} = \frac{\sum_{p=1}^p (z_{gp} - \bar{z}_g)(z_{dp} - \bar{z}_d)}{\sqrt{\sum_{p=1}^p (z_{gp} - \bar{z}_g)^2 \sum_{p=1}^p (z_{dp} - \bar{z}_d)^2}}, \quad (4)$$

where z_g represents the group-level FBNs identified from first stage vsDBN, and z_d is the individual-level FBNs identified from second-stage vsDBN. z_{gp} and z_{dp} is z score value of p -th voxel of z_g and z_d , \bar{z}_g and \bar{z}_d is the mean value of z_g and z_d , respectively. p represents the total number of voxels in the whole brain, which refers to 70,831 in our experiment.

In addition to SCC, we also employed the overlap rate as a metric to explore the similarities/differences in spatial distribution between individual-level networks and corresponding group-level networks, where the spatial pattern overlap rate R was defined as:

$$R(S, T) = \frac{|S \cap T|}{|T|}, \quad (5)$$

where S is the individual-level networks and T is corresponding group-level networks, respectively.

The temporal consistency between individual-level and group-level dynamic functional connectivity (DFC)

Besides evaluating the spatial consistency of two-stage FBNs, we here further investigated the consistency of DFC derived from two-stage temporal responses. By the training of the two-stage NAS-vsDBN model, we have obtained both group-level (T_3^i) and corresponding individual-level (t_3^i) temporal features for each subject from the third layer of group-level and subject-level vsDBN model, respectively, where the group-level temporal features $T_3 \in R^{(v \times n) \times q_3}$ can be also temporally divided into segments corresponding to each subject $T_3^i \in R^{v \times q_3}$ (i is the index of the subjects), representing the individual-specific temporal features derived from group-level model. To explore whether the temporal features learned from two stages have consistent/different dynamic expressions, we derived all the subjects' group-level and individual-level DFC, respectively. In detail, DFC was estimated with a commonly-used sliding window approach (Allen et al., 2014; Calhoun et al., 2014). Specifically, we

first manually selected 43 meaningful networks from the third layer of group-level FBNs, and classified them into medial visual (V1), occipital pole visual (V2), lateral visual (V3), default mode (DM), sensorimotor (SM), auditory (Aud), executive control (EC), salience (SA) networks. Then, we selected both group-level and individual-level temporal features corresponding to these representative FBNs for sliding window analysis. Afterwards, for both group-level and individual-level temporal features, sliding time window approach was applied to obtain a series of windowed temporal features at different time points, and the windowed temporal features were then employed to measure the functional connectivity between each pair of representative FBNs within each corresponding time window $w_i (i = 1 \dots W)$ using the Pearson correlation coefficient. Here, we used tapered window, created by the convolution of a rectangle (width=22 TRs=33 s) and Gaussian ($\sigma = 3$ TRs), with a step size of 2, resulting in $W = 82$ windows for each subject's group-level and individual-level DFC. Based on the above steps, we can define both group-level and individual-level DFC matrix for each subject. Following this, a k -means clustering was both performed on the group-level and individual-level DFC patterns separately, to identify their representative connectivity "states," where the k was set to four according to experience (Allen et al., 2014). Finally, to measure the similarity between group-level DFC states and individual-level DFC states, the similarity of DFC (SDFC) was defined by the following equation:

$$SDFC = \sum_{i=1}^W \frac{1}{W} \times \text{corr2}(S_{ig}, S_{id}), \quad (6)$$

where W represents the total number of windows, i is the index of the window, S_{ig} and S_{id} represent group-level and individual-level state matrices corresponding to the i -th window, respectively, and corr2 calculates the Spearman rank correlation coefficient between two matrices used to measure the similarity between S_{ig} and S_{id} .

Code accessibility

The code of two-stage NAS-vsDBN framework described in the paper can be accessed in [Extended Data 1](#).

Result

In this study, we proposed and applied a novel two-stage NAS-vsDBN model to model the volumetric fMRI data, and examined the underlying hierarchical spatio-temporal organization of brain function. Overall, inspired by the inherent properties of neural process under natural viewing condition, our model aims to detect both group-consistent and individual-unique spatiotemporal features contained in fMRI volume images. First, as designating suitable network architecture lays the foundation for extracting hierarchical organization of brain function, we performed 10 NAS processes independently to obtain the optimal NA of a reliable vsDBN model. Second, based on the optimized first-stage vsDBN model, we

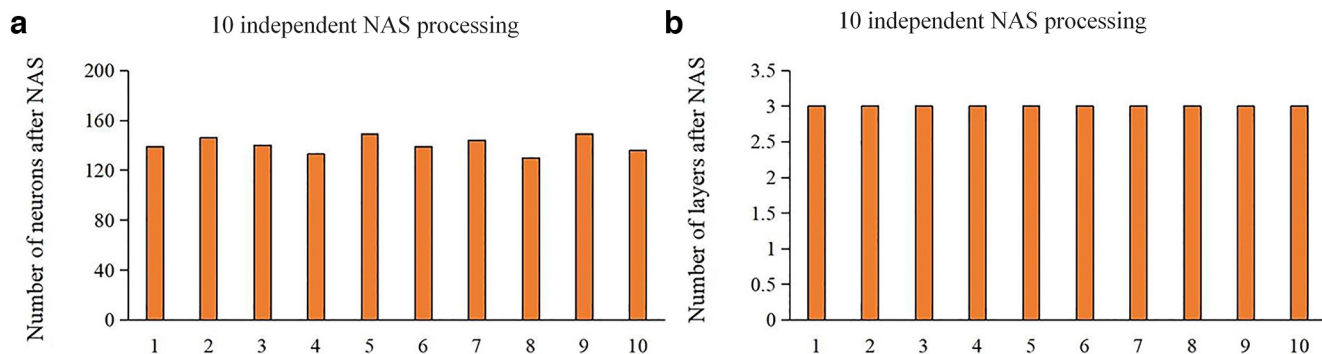


Figure 2. Results of 10 independent NAS processes. **a**, Number of neurons after NAS. **b**, Number of layers after NAS (NAS, neural architecture search). See also Extended Data Figures 2-1 and 2-2.

detected meaningful hierarchical group-level FBNs for the all subjects at multiple scales. In addition, by the second-stage vsDBN model training, the individual-level FBNs with both group consistency and individual uniqueness were obtained. Third, besides identifying both group-level and individual-level hierarchical spatial features, we further investigated the hierarchical organization of temporal responses using ISC analysis. Fourth, we calculated and compared the SCC between corresponding individual-level and group-level FBNs, so as to assess their consistency/difference in spatial features. Finally, we further investigated the consistency/difference of DFC derived from two-stage temporal responses.

Two-stage NAS-vsDBN implementation

In order to quantitatively evaluate the effectiveness and stability of the NAS framework and obtain the optimal architecture for vsDBN model, we conducted 10 times NAS processes independently. We used group-wise fMRI volume data as the training data set for NAS process.

The NAS results showed that the number of neurons has been maintained between 120 and 150, and the number of layers were always three, which suggest our NAS process can generate highly consistent and robust NA (Fig. 2). In addition, we also repeated the NAS process using linear weight decreasing method, which yielded similar optimal NA and convergence rate (Extended Data Figs. 2-1, 2-2). After the optimization of NAS process, the reconstruction error of the third layer was $<10^{-5}$. Thus, the optimal NA with the minimum reconstruction error among the 10 NAS results was selected, resulting in the optimal architecture of vsDBN model had three layers and 146 neurons. The optimized vsDBN model was further used to verify and obtain group-level and individual-level hierarchical spatiotemporal features of volumetric fMRI.

As vsDBN model takes a volume image from the fMRI as a training sample and the volumetric fMRI image has 70 831 voxels, the number of visible units of the vsDBN in the first stage is 70 831. In addition, the number of neurons and layers of first-stage vsDBN is determined according to NAS process. Thus, the vsDBN model is composed of three layers of RBM, and the numbers of neurons in each layer (q_1, q_2, q_3) are set to 146-146-146,

respectively. The code was developed using the Deepnet framework (<https://github.com/nitishsrivastava/deepnet>) and ran on a deep learning server with GeForce GTX 1080 TI. The NAS process was accomplished on one GPU card within acceptable time (15 h).

Hierarchical group-level and individual-level FBNs

After identifying the optimal NA of vsDBN model by NAS framework, we first applied first-stage NAS-vsDBN model to obtain hierarchical group-level FBNs. Figure 3 shows the representative meaningful FBNs composed of several activated regions derived from each layer as example. In the first layer, there are medial-visual network, sensorimotor network, default mode network, auditory network (Fig. 3a). In the layer2, we detect auditory network, executive control network, occipital pole-visual network and sensorimotor network (Fig. 3b). Most of these networks identified in the shallow layer are related to primary sensory process, or simple and classic networks that are established well previously. However, some complex FBNs with several interacted brain regions/networks can be detected in deeper layer. In the layer3, there are executive control-dorsal attention network, occipital pole visual-auditory network, executive control-visual network (Fig. 3c). By comparing the FBNs identified from three layers of first-stage vsDBN model, while simple or primary FBNs are derived from shallower layers, networks obtained from deeper layer appear to be combinations of different functional networks/regions, which suggests the hierarchical organization of FBNs under naturalistic stimuli.

Previous literatures demonstrated that naturalistic stimuli can trigger highly consistent neural responses in primary sensory areas, however, neural activities excited by naturalistic condition in the higher-order heteromodal cortices reveal great intersubject variability (Golland et al., 2007; Ren et al., 2017a, 2021b). Thus, we used the second-stage vsDBN model to train individual volumetric

fMRI data, and obtained individual-level FBNs. Specifically, to intuitively delineate the correspondence and difference between group-level and individual-level FBNs, we randomly selected a subject and compared its individual-level FBNs with group-level FBNs, including three visual networks, default mode network, sensorimotor network, auditory network, executive control network, salience network,

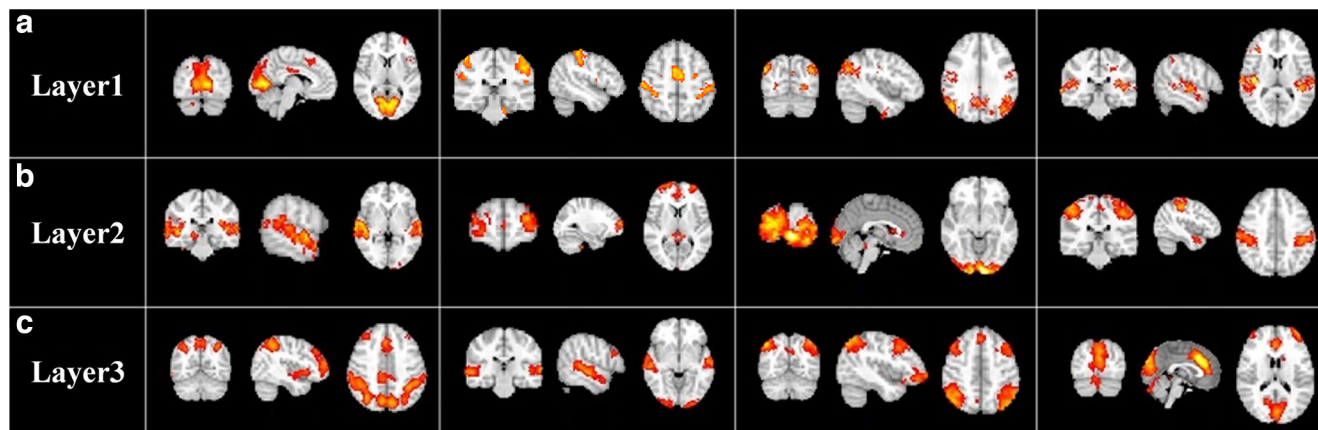


Figure 3. Representative group-level functional brain networks of (a) layer1, (b) layer2 and (c) layer3 identified by first-stage vsDBN model, respectively.

dorsal attention-executive control network and dorsal attention network (Fig. 4). In general, the group-level and individual-level FBNs corresponds well, where the overall spatial patterns of the group identified from the first stage are well preserved in the individual-level results. However, the functional activations and region sizes of individual-level FBNs are different from group-level FBNs. These results reveal that our model can establish great correspondences between individuals and group in hierarchical spatial features, and can also maintain individual-specific variability.

Hierarchical organization of temporal responses revealed by ISC analysis

In addition to exploring the hierarchical brain spatial features, we further investigated whether the proposed model can uncover the hierarchical structure of temporal

responses from NfMRI volume images. Overall, we measured and compared the ISC of individual temporal responses for both individual-level and the group-level (Fig. 5a). The results indicate that compared with lower layer, the higher layer has higher ISC values at both individual and group level, which indicates that the higher-level temporal responses show higher intersubject consistency. Thus, the temporal features identified by the two-stage NAS-vsDBN model defer to a hierarchical structure under naturalistic paradigm.

Moreover, we also compared the ISC values of each FBN and selected the top five FBNs with the highest group-level ISC in each layer (Fig. 5b). Generally, these top FBNs are mostly composed of visual, auditory and primary sensory regions/networks, suggesting that temporal features related to primary sensory processes have higher intersubject consistency driven by external naturalistic stimuli. However, FBNs associated with higher-order

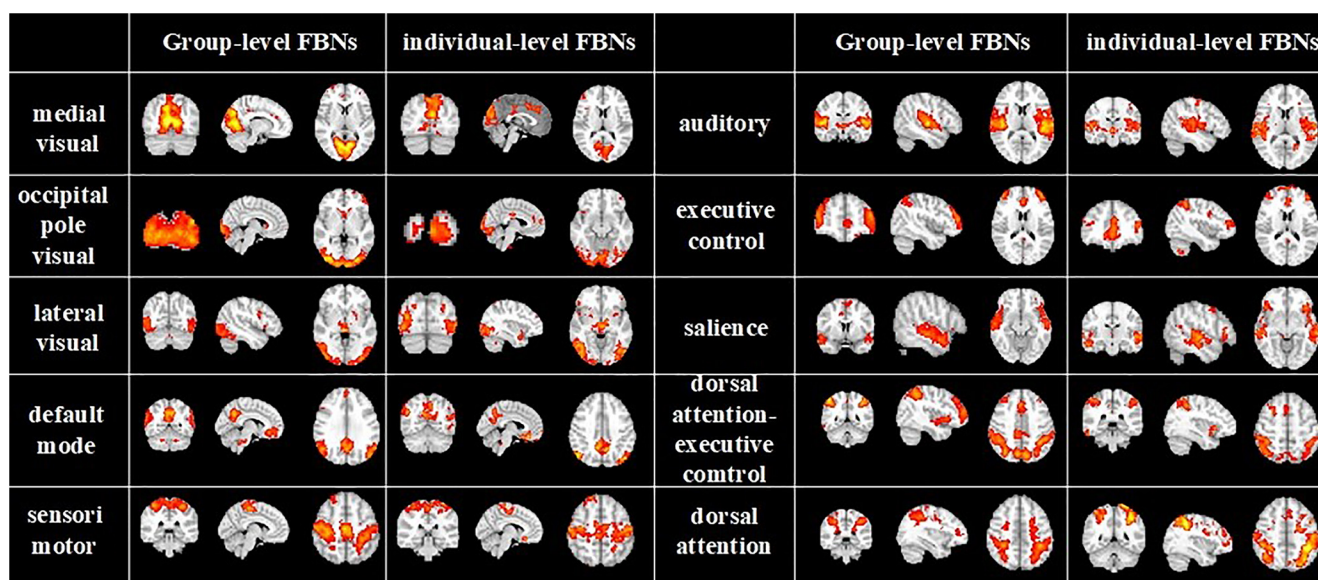


Figure 4. Representative group-level FBNs and corresponding individual-level FBNs in an exemplar subject (FBNs, functional brain networks).

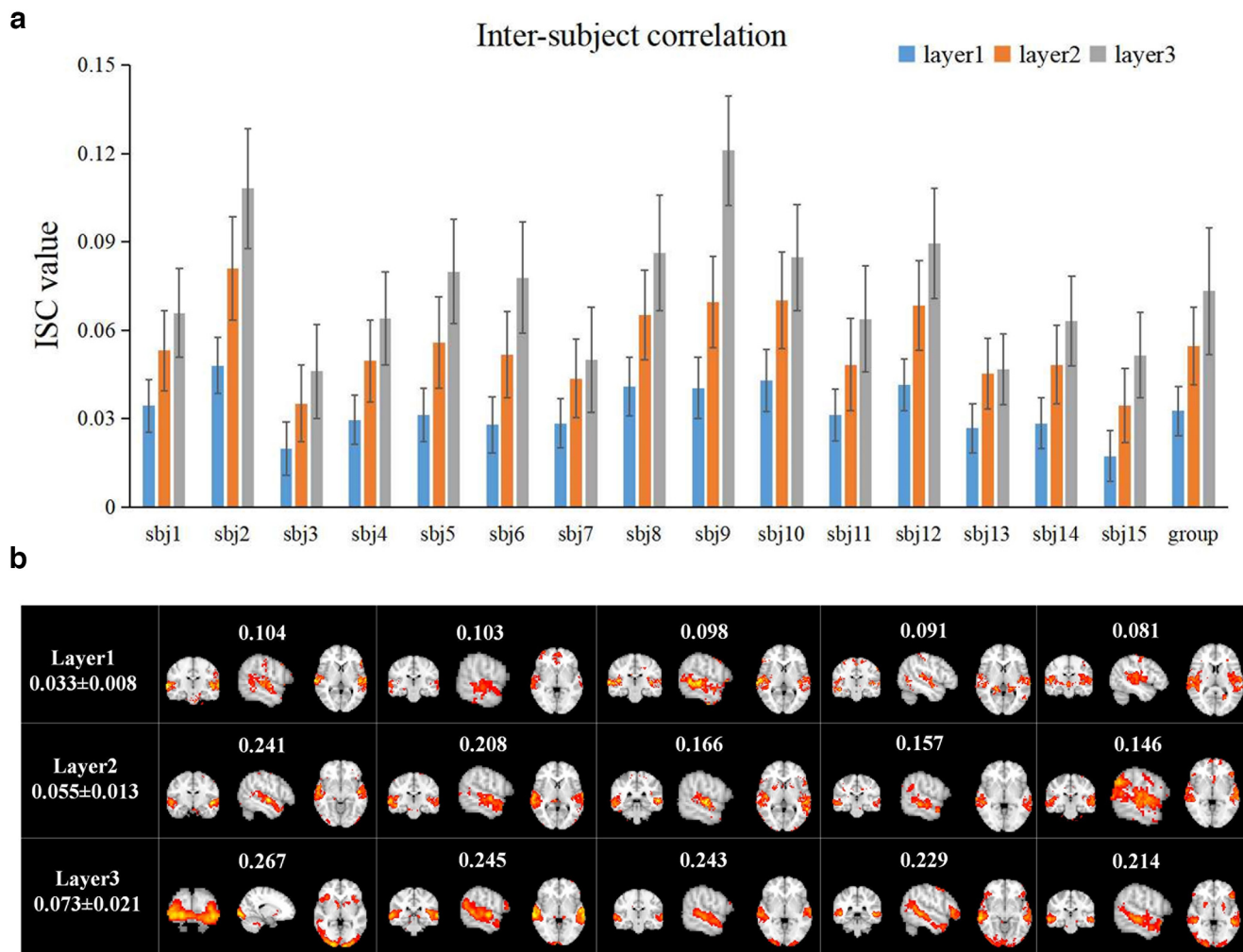


Figure 5. *a*, The ISC metrics in each layer at individual-level and group-level. Error bar indicates SD. *b*, Top 5 group-level spatial maps with highest ISC metrics at each layer. ISC value corresponding to each FBN, and the average and SD ISC value of each layer are labelled (ISC: inter-subject correlation). See also Extended Data Figure 5-1.

association regions at the third layer, such as prefrontal cortex and anterior cingulate cortex, also reveal high consistency across subjects. These association regions are not commonly associated with sensory processing, which further demonstrates the capability of proposed model in extracting hierarchical temporal features.

The consistency in spatial features between individual-level FBNs and group-level FBNs

The experimental results in the previous sections show that our two-stage NAS-vsDBN framework can well identify hierarchical spatiotemporal features and establish the correspondence of spatial distribution between individuals and groups. Nonetheless, the individual-level FBNs also retain their uniqueness in functional activation. Therefore, we here further quantitatively explored and assessed the similarity/differences in spatial features between individual-level networks and the corresponding group networks. Specifically, we selected 8 most representative group-level FBNs identified in the

first-stage vsDBN for comparison, including auditory network, medial-visual network, occipital pole-visual network, sensorimotor network, dorsal attention network, executive control network, default mode network and salience network. We thus calculated the SCC values between individual-level and corresponding group-level FBNs as a measurement of similarity in spatial features (Fig. 6). It can be seen those FBNs that are associated with primary sensory processes, including auditory network, medial-visual network, sensorimotor network and occipital pole-visual network, exhibited higher overlap rates (0.68, 0.64, 0.63, 0.62, respectively). In comparison, for those networks associated with higher-order cognitive processes or emotional perception, such as salience network, default mode network and executive control network, there are significant decreases in their overlap rates (0.59, 0.55, 0.49, respectively).

To further quantitatively evaluate the differences in SCC among different networks, we performed two-sample *t* tests with false discovery rate (FDR)-corrected ($p < 0.01$) on the overlap rate values among eight FBNs, and the *p*-value were shown in Table 1. The statistical results show

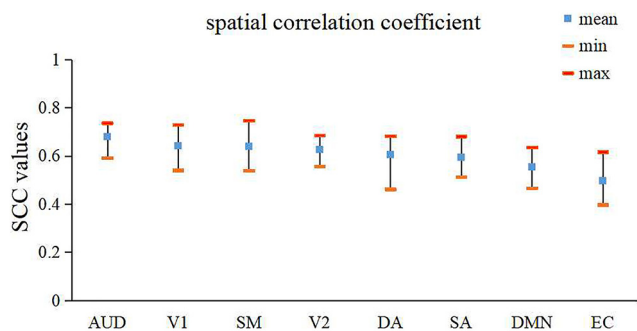


Figure 6. The spatial correlation coefficient (mean, minimum and maximum) between each individual-level FBN and corresponding group-level FBN (SCC, spatial correlation coefficient; AUD, auditory; V1, medial visual; SM, sensorimotor; V2, occipital pole visual; DA, dorsal attention; SA, salience; DMN, default mode network; EC, executive control). See also Extended Data Figures 6-1, 6-2, and 6-3.

that the SCC values of salience network, default mode network and executive control network are significantly lower than those of auditory networks ($p < 1 \times 10^{-4}$). In addition, the SCC of executive control network is significantly lower than those of visual network, sensorimotor network, dorsal attention network and salience network ($p < 1 \times 10^{-4}$). These results indicate that the networks related to primary sensory regions have higher consistencies between individual-level and group-level FBNs, while networks involved in cognitive or emotional perception processes show stronger intersubject variabilities in spatial distributions, further supporting the underlying hypothesis of our two-stage vsDBN model. In addition, we also calculated the overlap rates between individual-level and corresponding group-level FBNs, which produces similar results as SCC analyses and basically reflect the same conclusion. Therefore, we presented the results based on overlap rate in the Extended Data as a further validation (Extended Data Fig. 6-1; Extended Data Table 1-1).

The temporal consistency between individual-level and group-level DFC

Based on the existing experimental results, we find that the group-level FBNs and individual-level FBNs identified by proposed model maintain great consistency in spatial distributions, while individual-level FBNs retain their uniqueness in functional activations and spatial

distributions. Besides this, we want to further explore whether the temporal features extracted from two stages can maintain consistency. To measure the similarity of temporal features identified from the two stages, we calculated the DFC at the group-level and individual-level, and then obtained four representative functional connectivity states at both group-level and individual-level for each individual, respectively. Then we calculated and summarized the SDFC of each individual as shown in Figure 7. According to Figure 7a, the SDFC values of all the individuals exceed 0.6, and more than half of individuals' SDFC exceeded 0.8, which indicating that temporal features extracted from the two stages maintain great consistency. These results also further indicate the effectiveness of proposed model in identifying reliable temporal features from volumetric NfMRI data.

We further illustrated the correspondence between representative DFC states of the group-level and individual-level by randomly selecting a subject as an example (Fig. 7b). According to the order of occurrence of each DFC state, we marked the clustering states as states 1–4. The DFC states derived from group-level and individual-level show high consistency in functional connectivity network topology, where the correlations within visual networks and sensorimotor networks are mostly positive and strong among all the states, and the correlations within and between executive control and salience networks has also have strong and positive values. In addition, we calculate the correlation coefficients between the corresponding state matrices illustrated in Figure 7b, and the values are 0.79, 0.88, 0.73, and 0.82, respectively, which suggests high consistency between DFC states at group-level and individual-level.

Discussion

In this paper, we proposed and applied a novel two-stage NAS-vsDBN model to uncover the hierarchical organization of spatiotemporal features from volumetric NfMRI data. Our main work is summarized as follows. First, we proposed NAS framework based on PSO, which can automatically construct a feasible optimal network structure for the vsDBN model under limited computing resources and an acceptable time. Based on the established optimal NA, the proposed two-stage vsDBN model can effectively reveal the hierarchical organization of spatial patterns and temporal responses with both group-consistency and individual-uniqueness properties. Specifically, different from the simple NAS-DBN model, our two-stage NAS-vsDBN framework has been established and developed

Table 1: P-values of two-sample t tests on the SCC among eight representative FBNs

	AUD	V1	SM	V2	DA	SA	DM	EC
AUD								
V1	0.056							
SM	0.034	1						
V2	9×10^{-4}	0.464	0.504					
DA	1×10^{-3}	0.147	0.153	0.356				
SA	1×10^{-4}	0.038	0.038	0.088	0.708			
DM	6×10^{-8}	1×10^{-4}	1×10^{-4}	1×10^{-4}	0.034	0.056		
EC	8×10^{-10}	4×10^{-7}	3×10^{-7}	2×10^{-7}	1×10^{-4}	1×10^{-4}	0.009	

AUD, auditory; V1, medial visual; SM, sensorimotor; V2, occipital pole visual; DA, dorsal attention; SA, salience; DMN, default mode network; EC, executive control. See also Extended Data Table 1-1.

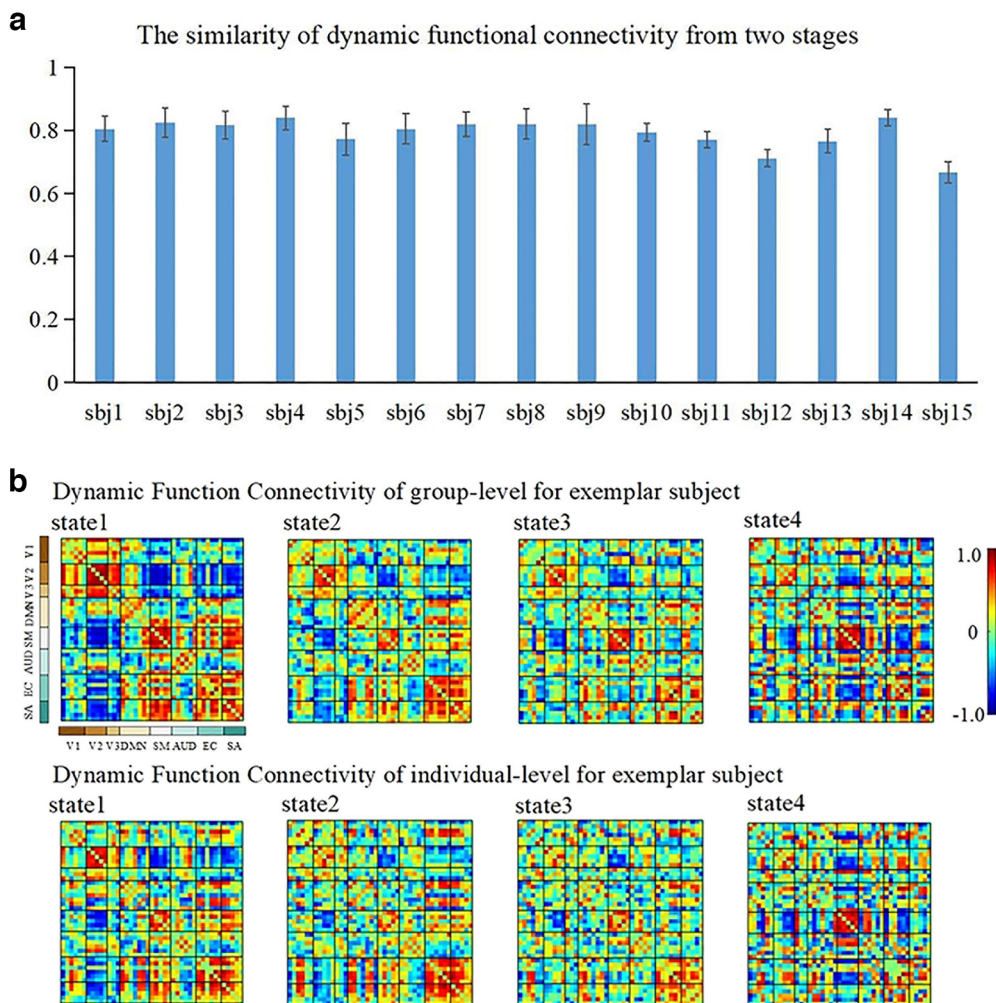


Figure 7. a, The dynamic functional connection similarity (SDFC) metrics between individual and group levels. Error bar indicates SD. **b**, Representative DFC states at group-level and individual-level for an exemplar subject (sbj, subject; V1, medial visual; V2, occipital pole visual; V3, lateral visual; DMN, default mode network; SM, sensorimotor; AUD, auditory; EC, executive control; SA, salience).

based on the critical properties of naturalistic paradigm, that is, while this paradigm trigger highly consistent brain responses in primary sensory areas across subjects, the neural activities evoked by this paradigm also show great intersubject variability, especially in heteromodal association cortices (Golland et al., 2007; Ren et al., 2017b). Consequently, while the simple NAS-DBN model can only identify group-level spatial patterns and the individual-level variations across subjects might be overlooked, our framework could establish correspondence between two stages of vsDBN models. Second, as previous literature revealed that volatile fMRI time series possess more intersubject variability compared with spatial volumes in different imaging sessions (Schmithorst and Holland, 2004), by systematic comparisons between our proposed two-stage vsDBN and a two-stage temporal DBN (two-stage tDBN) with same training parameters and network architecture, we further verified the potential superiority of volumetric fMRI in identifying brain functional spatio-temporal features. Specifically, the comparative results demonstrated that ISC values of identified temporal features, and SCC and spatial overlap values between

group-level FBNs and individual-level FBNs of vsDBN are superior than those metrics derived from two-stage tDBN (Extended Data Figs. 5-1, 6-1, 6-2), further supporting the adoption of volumetric fMRI data for modeling functional spatiotemporal features. Third, based on further comparison of the consistency/difference in spatial distribution between group-level and individual-level FBNs, our experimental results demonstrate that functional networks/regions related to cognitive or emotional perception processes exhibited greater intersubject variability than primary sensory associated regions such as visual and auditory networks, further verifying the hypothesis of proposed model. Finally, by calculating individual-level and group-level DFC from temporal features and measuring the SDFC between them, we found that the temporal features identified from the two-stage model show high similarity. Overall, our experimental results indicate the superiority and effectiveness of our model in uncovering hierarchical spatiotemporal features from NfMRI volumes that conform to the most critical property of neural process during natural viewing condition.

In the future work, we will focus on improving the efficiency of our NAS optimization framework and applying our model

to datasets with larger sample size and richer types of naturalistic stimuli, and further investigating the hierarchical spatiotemporal organization of brain function under natural viewing condition. Furthermore, we expect that in the near future our framework can be applied to clinical populations to characterize the abnormal brain function and develop neuroimaging markers under naturalistic condition.

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