Enhancing Local Linear Models Using Functional Connectivity for Brain State Decoding

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ABSTRACT

The authors propose a statistical learning model for classifying cognitive processes based on distributed patterns of neural activation in the brain, acquired via functional magnetic resonance imaging (fMRI). In the proposed learning machine, local meshes are formed around each voxel. The distance between voxels in the mesh is determined by using functional neighborhood concept. In order to define functional neighborhood, the similarities between the time series recorded for voxels are measured and functional connectivity matrices are constructed. Then, the local mesh for each voxel is formed by including the functionally closest neighboring voxels in the mesh. The relationship between the voxels within a mesh is estimated by using a linear regression model. These relationship vectors, called Functional Connectivity aware Mesh Arc Descriptors (FC-MAD) are then used to train a statistical learning machine. The proposed method was tested on a recognition memory experiment, including data pertaining to encoding and retrieval of words belonging to ten different semantic categories. Two popular classifiers, namely k-Nearest Neighbor and Support Vector Machine, are trained in order to predict the semantic category of the item being retrieved, based on activation patterns during encoding. The classification performance of the Functional Mesh Learning model, which range in 62-68% is superior to the classical multi-voxel pattern analysis (MVPA) methods, which range in 40-48%, for ten semantic categories.

Keywords: Brain Decoding, Feature Extraction, Functional Magnetic Resonance Imaging (fMRI), Machine Learning, Multi Voxel Pattern Analysis (MVPA), Pattern Classification

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Several methods have been developed to understand how brain processes information. One in particular, aims to predict or decode the brain state, and/or the type of information associated with cognitive processes, based on distributed patterns of activation in the brain, acquired with functional magnetic resonance imaging (fMRI) using machine learning methods (Battle, Chechik, & Koller, 2006; Bressler & Tognoli, 2006; Haynes & Rees, 2006; Norman, Polyn, Detre, & Haxby, 2006; Richiardi, Eryilmaz, Schwartz, Vuilleumier, & Van De Ville, 2011; Shirer, Ryali, Rykhlevskaia, Menon, & Greicius, 2012; Wang, Hutchinson, & Mitchell, 2003). One of the major motivations of this study is to propose a model for pattern analysis of fMRI data pertaining to different cognitive states using statistical learning theory. This representation involves understanding, manipulating and predicting the behavior of the very complex nature of human brain. Massively coupled dynamic interactions of the brain at many scales cannot be fully understood by only employing the measurements recorded from the individual voxels. Therefore, there has been growing interest in using brain connectivity to reveal interactions between spatially distant regions. Brain connectivity describes neural processes as the outcomes of dynamic coordination among smaller elements (Bullmore & Sporns, 2009). Three main types of brain connectivity are reported in the literature: i) structural connectivity, basically reveals anatomic connections (pathways) of brain, such as physical links between neural elements, ii) functional connectivity, defined as statistical dependence between remote neural elements or regions across time, e.g. correlation and iii) effective connectivity, which analyzes brain connectivity using causal effects between neural elements, resulting in causal activation paths (Bressler & Menon, 2010; Friston & Friston, 1994).

Connectivity for decoding is mostly used for model selection and/or defining the neighborhood of seed neural elements, or regions (Li, Guo, Nie, Li, & Liu, 2009). For instance, in a study by (McIntosh, Nyberg, Bookstein, & Tulving, 1997), partial least squares for activation analysis were performed to construct a cross block covariance matrix using PET data. Correlation based measures such as correlation/partial correlation, Granger causality, mutual-information or coherence are used for the selection of different functional interdependence functions. Ryali et al. (2012) measure sparse-partial correlation between multiple regions using elastic net penalty, which combines L1 and L2 norm regularization terms, in order to improve the sensitivity of the correlation measure. Patel, Bowman, and Rilling (2006) proposed a conditional dependence model which accounts for an imbalance between class conditional and posterior probabilities, to achieve at a measure of connectivity. Unlike correlation measures, Shirer et al. (2012) train a classifier to decode cognitive states after constructing functional connectivity matrices, analyzing increasing connectivity regions by subtracting connectivity matrices for each state. Richiardi et al. (2011) constructed functional connectivity matrices by using pairwise Pearson correlation coefficients and employ graph matching to decode brain states.

In this study, we introduce an algorithm for modeling cognitive processes, based on the functional and structural connectivity in the brain. Structural connectivity is utilized for anatomic parcellation of the brain regions by clustering the voxel intensity values measured by fMRI. Next, functional connectivity is utilized within the clusters by different correlation measures. Functional connectivity matrices are formed to define functional neighborhood of a voxel. A local mesh is formed for each voxel (called the seed voxel) by including the functionally closest neighbors (called the surrounding voxels) in the mesh. The relationships between the seed voxel and the surrounding voxels are modeled by estimating the arc weights of the mesh in a linear regression model. The arc weights, called Functional Connectivity-aware Mesh Arc Descriptors (FC-MAD) represent the relationship of each voxel to its functionally closest neighbors. Finally, the proposed FC-MAD features are used to train a classifier which recognizes type of information and/or cognitive state. In the current study, we particularly focused on classification of the type of information
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