Visualization of Distinct Functional Cortical Units Using Kernel Principal Component Analysis of fMRI Data

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Introduction

A sensory map of large rabbit whiskers can be provided by the cortical barrel field. The barrels are aggregated cells in the layer IV of the somatosensory cortex, and can be visualized in vitro or in vivo using voltage-sensitive dyes. With increased spatial resolution using high field MRI equipments, it is possible to visualize brain function based upon the structure and distribution of barrels in response to stimulations of single or double whiskers. However, the activation detected using correlation analysis or hypothesis test usually covers all cortical layers in the whisker barrel cortex. We developed a machine learning based approach to resolve functional units within the active cortex using high field fMRI.

Data Acquisition

Female rabbits (Dutch-belted) were used in this study. fMRI experiments were performed on a Bruker Biospec 9.4T imaging spectrometer. A single-turn, 40mm-dia., circular RF surface coil was used for both transmission and reception. For fMRI data acquisitions, a single-shot, gradient-echo multi-slice EPI sequence was used. MR signal was detected from four consecutive, 1mm-thick slices of brain in the axial plane, with FOV of 28mm×28mm, TR of 2s and TE of 13ms. The raw matrix was 80×80. The data matrix was zero-filled to 128X128 during image reconstruction, which gives displayed pixel size of 220 μm. One session of an fMRI experiment consisted of ten trials with 65 images acquired in each trial. The whisker stimulation was induced by a 15mm-dia., six-turn, circular coil that was placed in the magnet bore, and was driven by an alternating current [1]. Single (A1) or two whiskers (A1 and A2) on the left side of rabbit face were selected for stimulation. The vibration amplitude was controlled to be ±0.75mm; while the vibration frequency was 75Hz. The stimulus paradigm consisted of a baseline period (25 images), a stimulation period (20 images), and a rest period (20 images). The first five images were removed from each trial to ensure stable image intensities.

Data Analysis

Motion compensation was first performed to remove subject movement. Correlation analysis was then applied using experimental paradigm to detect the activated brain region in the rabbit somatosensory cortex. Kernel principal component analysis (KPCA) was used to decompose the activated region into multiple components, each of which corresponds to an activated sub-region. KPCA is a nonlinear principal component analysis technique [2]. It uses a kernel function to project the input data into a high dimensional feature space, and then a linear PCA performed in the feature space is equivalent to a nonlinear PCA in the input space. As a discriminant analysis tool, KPCA is more appropriate than linear PCA and independent component analysis (ICA) for this study. Voxels in the activated region are related to each other with second and high order dependencies. PCA can only capture second order statistics, and ICA assumes statistical independence in spatial or temporal domain that is not true here. KPCA can access the high order statistics, and provide a better characterization of the data structure in the activated region. In this work we used the 11th order polynomial kernel function defined as: $k(\boldsymbol{x},\boldsymbol{y})=(\boldsymbol{x}\cdot\boldsymbol{y})^{11}$, where $(\boldsymbol{x}\cdot\boldsymbol{y})$ is the inner product of the feature vectors $\boldsymbol{x}$ and $\boldsymbol{y}$. After the decomposition, the first ten kernel principal components were extracted, and the projections to these components were computed. Correlation map was calculated between each projection and voxels' time courses, resulting in ten correlation maps. The activated sub-regions corresponding to barrels were identified based on their spatial location, and the temporal profiles were extracted for further analysis.

Results

Fig. 1(a) shows the correlation map with correlation coefficients (cc) above 0.5 overlaid on the EPI image covering somatosensory cortex, and (b) is the average time course of the activated region in somatosensory cortex. After KPCA decomposition, the correlation map between the projection to the first component and voxels' time courses is shown in Fig. 1(c), with the average time course of the activated region in (d). Fig. 2 is the functional activation map generated from the projection to the 2nd KPCA component and time courses. Distinct functional units are observed at the cortical depth corresponding to layer IV. Another functional unit is observed at the cortical depth corresponding to upper layer IV as shown in Fig. 3, which was obtained from the projection to the 3rd KPCA component.

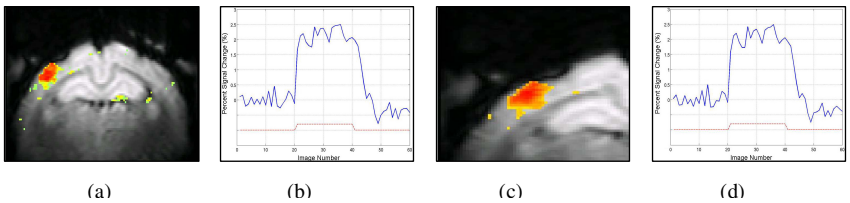

Fig. 1 Functional activation map of left A1 and A2 whisker stimulation generated by (a) correlation with the stimulus and (c) from the projection to the 1st KPCA component. (b) and (d) are the corresponding time courses.

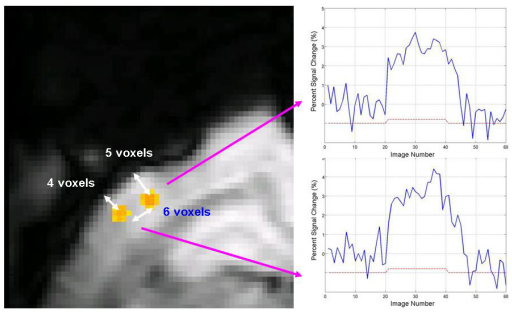

Fig. 2 Functional activation map of left A1 and A2 whisker stimulation generated from the projection to the 2nd KPCA component and time courses.

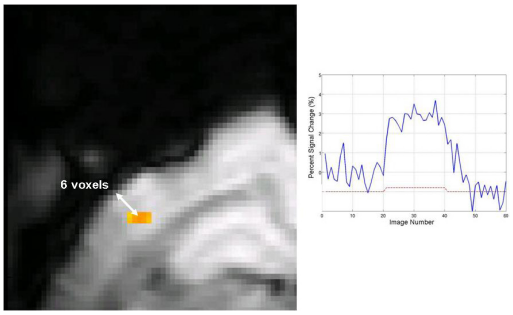

Fig. 3 Functional activation map of left A1 and A2 whisker stimulation generated from the projection to the 3rd KPCA component and time course.

Conclusion

This study shows that a combination of high spatial resolution fMRI and KPCA enables us to delineate functional cortical units in the rabbit somatosensory cortex during single or multiple whisker stimulation. High field fMRI provides detailed image structures that make it possible to separate distinct cortical modules. KPCA can characterize the high order dependencies between the modules and provide a reasonable separation between them. The experimental results indicate the effectiveness of the proposed approach.

Reference

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