Resting-state fMRI activity in the basal ganglia predicts unsupervised learning performance in a virtual reality environment

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Introduction

Learning in real-world environments is often self-supervised without feedback, a type of learning referred to as unsupervised learning. Prior work suggests that the ability to learn and perform in complex cognitive environments can be predicted from the volume and vascularization of the structures in the basal ganglia [1,2]. In this study, we examined the ability of resting-state fMRI measures in the basal ganglia to predict the performance of subjects engaged in a virtual-reality (VR) unsupervised learning experiment.

Methods

Unsupervised Learning Protocol: Subjects visited a VR lab on two consecutive days. They wore a wide-field-of view head-mounted display and freely walked about a large-scale, richly textured room (~4x5m) containing numerous objects resting on shelves, tables, and the floor. Their motions were tracked with a 24-camera 3D motion tracking system. On the first visit, subjects entered the VR room containing a set of 39 objects and performed free exploration for 10 minutes. In 5 subsequent "interest' blocks, the objects were covered with an opaque bubble that disappeared when the subject touched it, revealing the object underneath. Subjects then judged how interesting they felt the object was. For the second visit, subjects participated in 6 to 8 "memory" blocks in which 1/3 of the objects were shuffled to a new location at the start of each block. Upon uncovering an object (by touching the opaque bubble), subjects were asked to judge whether or not the object had been in that location on the previous day. Unsupervised learning performance was defined as the percentage of correct judgments across the blocks.

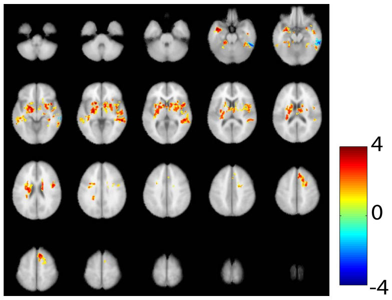

Figure 1: Whole brain thresholded (corrected $p<0.05$) z-score maps of correlation between BOLD amplitude and performance scores across subjects.

fMRI Protocol: Resting state fMRI data were acquired on ten of the subjects who participated in the learning protocols using a GE MR750 3T system with a 32 channel receive coil (Nova Medical), with scans occurring 6 to 12 months after the learning experiment. Resting state scans (two 8 minute scans; eyes open with fixation cross) were performed using multiecho simultaneous multislice (3 echoes) echoplanar imaging (EPI) acquisition, where the acquisition used a 2.5-fold phase encode acceleration factor and a blipped-CAIPI EPI k-space trajectory [3] with 3 sagittal slices per RF excitation to achieve 2mm isotropic resolution with whole brain coverage (FOV 20cm, 100x100 matrix, 72 slices). Other acquisition parameters were: TR=2s (240 volumes), TEs=15.5ms, 36.7ms, 57.9ms, FA=30°. To reconstruct the images, we used SENSE reconstruction with a fast Conjugate Gradient Toeplitz-based iterative algorithm, regularized with a spatial roughness penalty to achieve an effective FWHM of 1.25 voxels [4]. For each session, high resolution anatomical data were acquired using a magnetization prepared 3D fast spoiled gradient (FSPGR) sequence. Each anatomical volume was registered with the functional data and then segmented into cortical regions using Freesurfer parcellation [5]. For preprocessing of the fMRI data, nuisance regressors (0^{th}-2^{nd} order Legendre, 6 motion time courses and their first derivatives, BOLD signal from the cerebral spinal fluid and white matter and their first derivatives) were removed from the raw data through linear regression. For each voxel, a percent change BOLD time series was obtained from the preprocessed 2^{nd} echo of the MR time series by subtracting the mean value and then dividing the resulting difference by the mean value and the BOLD amplitude was defined as the standard deviation of the percent change time series. The relation between the BOLD amplitude and the performance scores across subjects was assessed with linear regression both on a per-voxel basis and within the pre-defined ROIs.

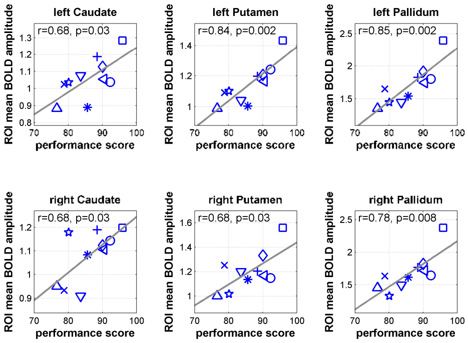

Figure 2: Correlations between BOLD amplitude and performance score for basal ganglia ROIs (left and right putamen, pallidum, and caudate)

Results & Discussion

Figure 1 shows the voxel-based z-score map (corrected $p<0.05$) indicating a significant correlation between resting-state BOLD amplitudes and performance scores in the basal ganglia. Figure 2 uses the pre-defined ROIs to show the significant positive correlation ($p<0.03$) between resting-state BOLD amplitudes and performance scores in the caudate, putamen, and pallidum. As part of an exploratory analysis, we also found that the functional connectivity between basal ganglia regions (e.g. left caudate) and the posterior cingulate cortex was significantly correlated with performance. In conclusion, measures of resting-state fMRI activity in the basal ganglia are able to predict individual differences in the ability to learn without feedback in a complex virtual reality environment.

References: [1]Vo et al, PLOS ONE, e16093, 2011; [2]Erickson et al, Cereb. Cort. 2522, 2010. [3]Setsompop et al, MRM 2011. [4]Fessler et al, IEEE TSP, 53:3393, 2005. [5]Desikan et al, Neuroimage, 2006.

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