High-resolution functional MRI of retinotopic and laminar activation using a 3T scanner

D. Ress[1], G. H. Glover[1], B. A. Wandell[2]
[1]Radiology, Stanford University, Stanford, CA, United States, [2]Psychology, Stanford University, Stanford, CA, United States

Introduction

High-resolution functional MRI has the potential to reveal new information about the processing of visual information in the human brain. Although several previous investigations have demonstrated the feasibility of high-resolution fMRI in human subjects, these experiments used methods and scanners that limit their general utility in visual and cognitive neuroscience. Here, we demonstrate the successful application of high-resolution fMRI at 3T to study both retinotopic and laminar activation patterns in early visual areas.

Methods

MR imaging: Functional images were obtained on a 3T scanner using BOLD contrast, a spiral readout[1] and a 0.375-μL voxel (10-cm FOV, 0.5 × 0.5 mm effective pixel size, eight 1.5-mm slices, TE = 30 ms, TR = 750 ms, 4 interleaves). A custom 6-cm-diam surface coil was used to improve SNR. Oblique slices were chosen perpendicular to the calcarine sulcus with the caudal-most slice nearly tangent to the occipital pole of the left hemisphere; this prescription covered the central 3º of visual eccentricity for visual areas V1, V2, and V3. High-resolution (0.4×0.6×1.5 mm voxels) T1-weighted anatomical images were obtained on the same slice prescription to facilitate subsequent registration. Protocol: Subjects (N=3) passively viewed alternating 4-Hz flickering "checkerboard" patterns presented on a flat-panel display with visual dimensions of 4º × 3º. The display alternated between an annulus (inner/outer radius 0.75º/2.5º), and its complement (18-s period). Data analysis: After trend removal, the time series of data at each voxel in the volume was fit with a sinusoid to generate maps of amplitude, phase, and coherence. The functional activity was registered with anatomical images obtained for each subject in a separate session. This reference volume was segmented to identify the location of the gray-white boundary, and gray matter was "grown" onto this boundary as a series of layers, thus allowing the measurement of laminar structure.

Results

General character: The individual high-resolution functional images (Fig. 1) show good anatomical detail with SNR ≈ 15. The color overlay shows the activation amplitude, which has a much larger amplitude and more punctate character than is typical with lower resolution fMRI (e.g., 64-μL voxels). Sinusoidal amplitudes of 6% (12% peak-to-peak) are not uncommon; 3% amplitudes are typical, in agreement with studies at 7T.[2] Noise amplitudes are also near 3%, yielding coherence values in the range of 0.2—0.5. The noise is spectrally white, suggesting that thermal noise is dominant. Retinotopic organization: A map of the response phase is overlaid on an image of flattened occipital cortex (Fig. 2). The response phase defines the activity driven by the annulus (yellow) and its complement (blue). The position of these activations conforms to the expected pattern of retinotopic organization. The annulus-driven activity is surrounded on both sides by activity driven by the annulus complement. The activity extends beyond calcarine cortex, spanning areas V1, V2, and V3. Laminar organization: Activation shows significant variation with cortical depth (Fig. 3). Deeper layers respond more weakly than superficial layers, qualitatively similar to fMRI measurements in rat somatosensory cortex.[3]

Conclusions

High-resolution fMRI, with sub-μL voxel volumes, is feasible for neuroscience studies in visual cortex at 3T. The smaller voxels greatly increased BOLD contrast, mitigating the volumetric signal loss. The full complement of image registration and analysis was possible, despite the use of a small surface coil and small FOV. Our results confirm the expected retinotopic organization of early visual cortex at high resolution, and they suggest a laminar character to the BOLD activations in visual neocortex, with greater activation evident in more superficial layers. This pattern could be caused by differential neural activity or by variable perfusion.

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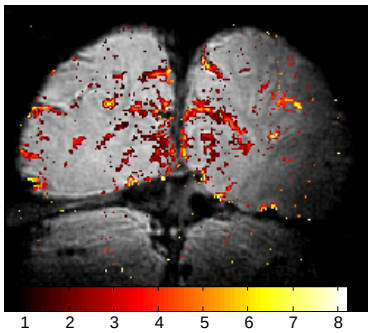

Figure 1: Typical functional image with amplitude map (Δ%).

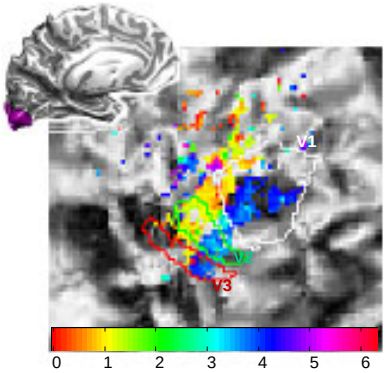

Figure 2: Curvature image of flattened cortex with phase map (radians). Purple region on inset shows flattened region in 3D.

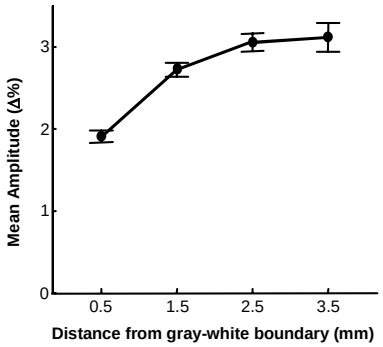

Figure 3: Mean functional amplitude vs. cortical depth.