Deconvolved fMRI correlates with source-localised MEG as a function of neural frequency oscillation

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Introduction: The relationship between neuronal events and haemodynamic changes measured with blood-oxygenation-level-dependent (BOLD) functional MRI (fMRI) is still unknown, although many recent studies have provided a qualitative correspondence. The local neuromagnetic fields generated by the dendrites of cortical pyramidal cells can be measured non-invasively at the scalp with magnetoencephalography (MEG); these fields have been shown to have a spatial overlap with BOLD [1] and to be the cause of the majority of metabolic demand which is thought to drive the BOLD response [2]. Recent studies have also examined the relationship between BOLD and the power of neural activity across frequency bands. Using invasive recordings and comparing to fMRI, Mukamel *et al.* [3] showed a negative correlation of low-frequency local field potentials (LFPs) with BOLD and a positive correlation with higher frequencies. BOLD responses are often modelled as a convolution of neural events with a haemodynamic impulse response function (HRF), however neural events are usually approximated by the stimulus timing and not actually measured. Deconvolving the fMRI response with the HRF is important to understand the dynamics of the underlying neural activity [4]. Previous studies have used EEG sensor data [5] or MEG dipole-fit broadband power [6], instead of stimulus timing, to convolve with the HRF to improve detection of BOLD changes. Here, we extend previous work by using a time-frequency beamformer on MEG data to extract a time-frequency plot at every 'virtual sensor' location and compare with BOLD fMRI data acquired at 7T using a subject-specific HRF. Two spatial-temporal-spectral comparisons were made: fMRI deconvolved with the HRF to predict MEG and MEG convolved with the HRF to predict BOLD.

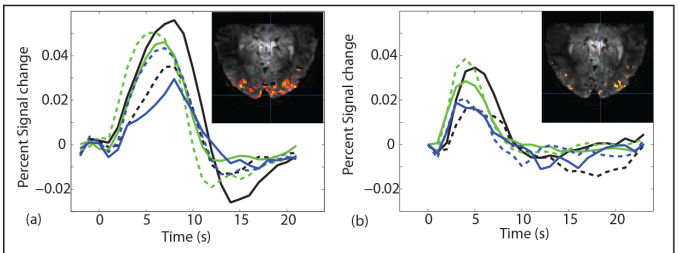

Figure 1: (a) BOLD response for all 6 subjects to 4s stimulus (inset: Significant voxels in one subject). (b) HRF response for all 6 subjects to brief stimulus (inset: Signficant voxels in same subject as (a)).

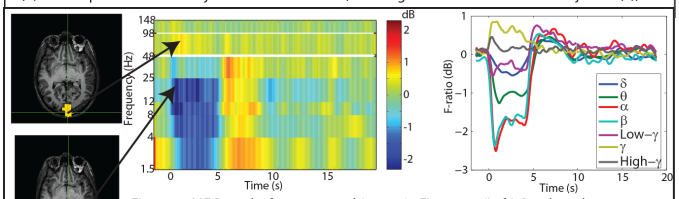

Figure 2: MEG results from same subject as in Figure 1. (Left) Overlays show power of gamma sychronisation (top) and beta desynchronisation (bottom) about 1s after stimulus onset. (Centre) Time-frequency plot shows F-ratio (dB) of power resulting from 4s stimulus at location in visual cortex indicated by crosshairs in both MRI overlays. (Right) Power changes averaged over all subjects.

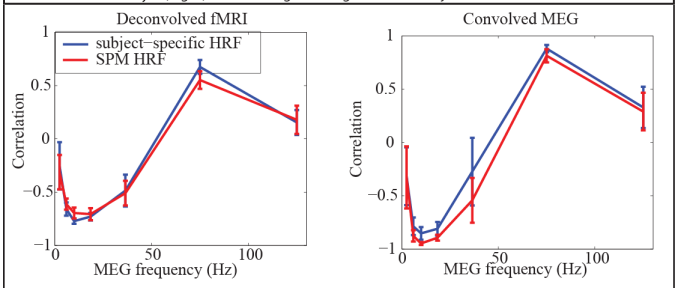

Figure 3: (Left:) Correlation of deconvolved fMRI with MEG power changes as a function of frequency. (Right:) Correlation of fMRI with HRF-convolved-MEG power changes.

Methods: Six healthy subjects participated in the study. The paradigm comprised a sinusoidal drifting grating, presented in a circular window with a visual angle of 5°. The circle was shifted through an angle of 3° into the lower left hand quadrant of the visual field. For both MEG and fMRI a single trial comprised 4s of stimulation and 20s rest. On stimulus cessation, subjects executed a button press to maintain concentration. 90 trials were used in MEG and 30 trials in fMRI. MEG data were acquired at a sample rate of 1200Hz, on a 275-channel CTF system, in third order gradiometer configuration. Co-registration to an anatomical MRI was performed using head digitisation (Polhemus Isotrack). fMRI data were acquired using a 7T Philips Achieva system running GE-EPI (TR=1s, 11 slices, TE=25ms, 1.5x1.5x1.5mm^3 voxels, 144x144mm FOV, SENSE factor 2). An additional event-related fMRI run to measure the subject-specific HRF was also acquired with 1s stimulus duration and 23s rest.

Data Analysis: MEG data were analysed using a time-frequency beamformer [7]. Spatial localisation of oscillatory power changes in all frequency bands (δ 1.5-4Hz, θ 4-8hz, α 8-12Hz, β 12-25Hz, low γ 25-48Hz, γ 52-98hz, and high γ 102-148Hz) was achieved by computing an F-ratio of active contrast windows (durations 1500, 1000, 650, 550, 450, 450, and 450ms respectively) to a passive contrast window of equal length. Active windows were created every 50ms and overlapped. The time-frequency power changes from three locations were extracted from each subject. Location 1 showed largest β decrease, 2 showed largest γ increase, and 3 was spaced in between. Areas of significant ($p<0.05$ corrected) BOLD contrast were identified using SPM5. Time courses from voxels significant in both the 4s and event-related fMRI runs from right medial visual cortex were extracted. First, the fMRI response to 4s stimulus was deconvolved with both the subject-specific HRF and the SPM canonical HRF to compute an estimate of neural activity and the temporal correlation of this neural estimate with the MEG power time course was computed for all frequency bands. Secondly, the MEG power time course in each band was convolved with both the measured HRF and SPM HRF to compute a prediction of the BOLD response, and the correlation of this BOLD estimate with the measured BOLD response was computed.

Results and Discussion: Figure 1 shows the location of significant BOLD contrast from one subject, and the time courses of all subjects for both the 4s stimulus and HRF. V1 is active in both, as well as lateral areas, consistent with previous results [8]. Figure 2 shows the MEG results: the spatial localisation of neuronal activity from the same subject as Fig. 1 in both the γ and the β bands, and the time-frequency plot of power changes (dB) from the peak voxel. The right hand plot shows MEG power changes averaged over all subjects, highlighting a large desynchronisation in the β, α and θ bands, as well as a rebound several seconds after stimulus cessation. A weaker γ synchronisation is also seen during stimulus presentation. Figure 3 shows the temporal correlations of the deconvolved fMRI with MEG power (left) and the convolved-MEG with the fMRI (right), as a function of frequency band in MEG. Significant ($p<0.05$) negative correlations are seen for θ, α and β bands, and significant ($p<0.05$) positive correlations for the γ band. Interestingly, no significant difference in correlation was seen between the subject-specific HRF and the SPM HRF, possibly due to noise in the measured HRF or close similarity of subject specific HRF to the canonical SPM HRF.

Conclusion: Both MEG and fMRI activity is seen in primary visual cortex as well as surrounding areas, indicating a general correspondence of underlying activity between the methods. These results highlight that the deconvolution of fMRI data with the HRF can give a good estimate of neural activity as measured by MEG time-frequency beamforming. However, there is no one simple measure of neural activity that directly corresponds to BOLD fMRI, but rather is a function of frequency of neural oscillation and this function can be quite variable [9]. The correlations shown here indicate the same frequency response profile as in [3] although the shift from negative to positive correlations occurs at a different frequency. It remains to be tested how this function of frequency holds for other brain areas and stimulus durations or types, how it might relate to a spectral-based energy-consumption profile [10], or how a direct voxel-to-voxel comparison might differ. Furthermore, as beamformer localisation can be used to successfully suppress noise in EEG collected concurrently with 7T fMRI [11], this comparison can be extended to simultaneous EEG/fMRI data to compare data from individual trials.

References: [1] Brookes et al. NeuroImage 26 (2005) p302-308; [2] Atwell and Loughlin, J. Cerebral Blood Flow and Metabolism 21 (2001) 1133-1145; [3] Mukamel et al. Science 309 (2005) p951-954; [4] Glover NeuroImage 9 (1999) p416-29; [5] Martinez-Montes et al. 22 (2004) p1023-34. [6] Nangini et al. Human Brain Mapping 29 (2008) p97-106. [7]; Dalal et al. 40 (2008) p1686-1700; [8] Stevenson et al. Proc. ISMRM 2008. [9] Winterer et al. Human Brain Mapping 28 (2007) p805-816; [10] Kilner et al. NeuroImage 18 (2005) p280-286; [11] Brookes et al. NeuroImage 40 (2008) p1090-1104.