k-t FASTER: Acceleration of fMRI Data Acquisition using Low Rank Constraints

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Purpose Neuroscientific applications of functional MRI (FMRI) can benefit enormously from improvements to spatial and temporal resolution, provided that coverage, image contrast and data quality can be broadly preserved. Recent advances in high spatio-temporal resolution FMRI using simultaneous multi-slice [1] and 3D [2] acquisitions have seen rapid adoption within neuroscience due to the statistical benefits of fast sampling. Nevertheless, the acceleration with these techniques is fundamentally limited because they act only on spatial information, independent of time. FMRI data, however, contain significant spatio-temporal structure, in that spatially distributed sets of voxels can be expected to contain similar temporal information. We propose a novel mechanism for accelerating the acquisition of FMRI data by using low-rank constraints to exploit this inherent spatio-temporal redundancy. Our paper submitted for the Young Investigator Award introduced this technique, k-t FASTER (FMRI Accelerated in Space-time via Truncation of Effective Rank), demonstrating 4x acceleration without using coil information. We will also briefly highlight subsequent improvements using more sophisticated k-space trajectories and coil information to achieve up to 8.25x acceleration.

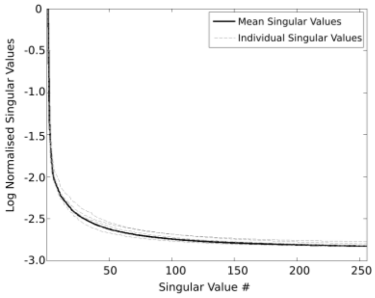

Figure 1 Low rank distribution of singular values in 6 FMRI datasets (dashed), and their mean (bold).

Theory & Methods FMRI data is commonly modelled as a linear combination of a limited number of spatial and temporal signal components. While implicit in task-based analyses, a low-rank space-time representation of the data is explicitly constructed in ICA-based resting-state analyses (see Figure 1). In the last decade, literature on low rank matrix completion has shown that under certain conditions, matrices known to be low rank can be robustly recovered in the presence of large amounts of undersampling [3]. While this concept has been applied to recovery of undersampled k-t data in other dynamic imaging applications [4], here we explicitly link the dimensionality-reduced resting-state FMRI data models with low-rank matrix recovery techniques, to efficiently sample and reconstruct FMRI data. We used an iterative hard thresholding with matrix shrinkage algorithm [5] to solve the rank-constrained optimisation problem:

$$\min_X \|y - \Phi X\|_2^2 \ s.t. \ rank(X) = r$$

where y is a vector of measured data, X is the estimated k-t matrix, Φ selects measured k-t samples, and r is the target matrix rank. Two sets of data with 6 subjects each were used to evaluate the method: i) retrospectively under-sampled simultaneous multi-slice EPI data [1], at 2 mm isotropic spatial and 836 ms temporal resolutions, and ii) prospectively under-sampled data at 7 T using a segmented 3D EPI readout, with pseudo-random k_z encoding, with 2 mm isotropic voxels and 975 ms effective temporal resolution in 5 minutes of data acquisition. The k-t FASTER reconstructions used a rank constraint of 128 and resulted in an acceleration of 4.27x (15/64 sampled k_z-indices). Resting state network reconstruction fidelity was evaluated using dual regression [6] compared to ground truth (retrospective) or canonical resting state networks (prospective).

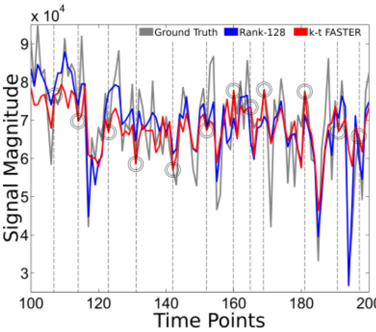

Figure 2 Reconstructed portion of the magnitude time-series of a representative k-space point (red), compared to the ground truth (grey) and a rank 128 reduced ground truth (blue). Circles (and dashed lines) represent the sampled time points.

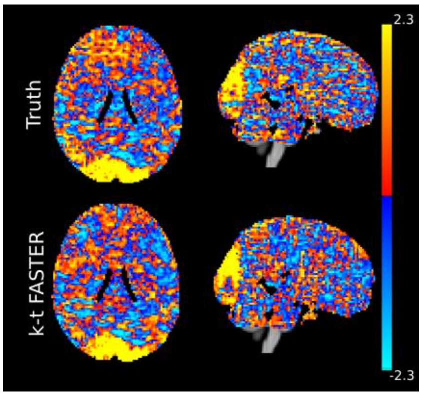

Figure 3 Visual area resting state network z-statistic map derived from dual regression, with ground truth (top) and accelerated k-t FASTER reconstruction (bottom) showing good correspondence.

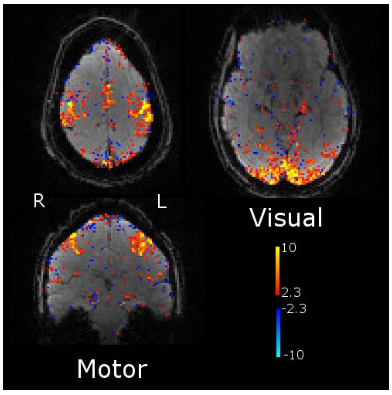

Figure 4 Current capability of k-t FASTER, demonstrated in a z-stat map of a 6.67x accelerated visuo-motor task experiment using a 3D hybrid radial-Cartesian readout and coil information.

Results Figure 2 shows a portion of a representative time-series reconstructed using k-t FASTER (from the retrospectively undersampled data), compared to the ground truth and a rank-reduced ground truth at the same rank as the k-t FASTER output. Dynamic features of the time-course are well recovered in between sampled points (dashed lines). Relative Frobenius norm errors for the estimated k-t matrices compared to ground truth were < 4.5% in all retrospectively sampled datasets. Figure 3 shows a comparison of a visual resting state network from a representative subject, highlighting the fidelity of network recovery. Point-wise spatial correlations between k-t FASTER and ground truth z-statistic maps across all subjects and evaluated networks was 0.73 ± 0.06. Prospectively under-sampled data also showed good recovery of resting state network features that fully sampled acquisitions with reduced temporal resolution were unable to recover (details in paper).

Discussion In this work, we demonstrated the feasibility of using rank-constrained optimisation for recovering undersampled FMRI data, with knowledge that FMRI data are approximately low rank. In both retrospective and prospectively 4.27x under-sampled experiments, the k-t FASTER approach to FMRI acceleration was able to robustly recover both spatial and temporal information contained in the datasets without the use of coil profiles. This relies on the intrinsic spatio-temporal structure present in FMRI data matrices, compared to parallel imaging methods which act solely on spatial information. In follow up work, we demonstrate higher acceleration factors (6.67x and 8.25x) and incorporate coil sensitivity information with hybrid radial-Cartesian sampling for further improvements in reconstruction fidelity (Figure 4) [7].

Conclusion The remarkable correspondence between low-rank models of FMRI data and the properties of under-sampled low rank matrices presents an opportunity to accelerate FMRI data using data-specific structure. In essence, k-t FASTER increases the efficiency of FMRI data acquisition by directly estimating the spatial and temporal sub-spaces (principal components) that describe the signals of interest, which can be a powerful shortcut for FMRI experiments that use principal component dimensionality reduction as a pre-processing step (e.g., ICA-based resting state analyses) or for direct identification of high variance signal components (e.g. task-based FMRI).

References 1. Feinberg et al., PLoS One 2010; 2. Poser et al., NeuroImage 2010; 3. Candes et al., Proc IEEEE 2010; 4. Haldar et al., ISBI 2010; 5. Chiew et al., ISMRM 2013; 6. Beckmann et al., OHBM 2009; 7. Chiew et al., ISMRM 2015