Quantitative evaluation of fMRI acquisition strategies at 7T using NPAIRS

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Introduction

Ultra high field functional magnetic resonance imaging (fMRI) at 7 Tesla facilitates new discoveries in human brain function due to the increase in blood oxygenation level dependent (BOLD) sensitivity to microvascular structures with increasing field strength [1]. However, a fundamental question must still be addressed to realize the full potential of 7T: *What is the optimal way of acquiring fMRI data at 7T to produce the highest quality activation maps?* Although the use of 2D single-shot echo-planar imaging (EPI) is common in BOLD fMRI, a recent 3T study suggests that the 3D pulse sequence PRESTO(-SENSE) [2] may offer superior BOLD contrast-to-noise ratio (CNR) through improved temporal efficiency [3]. Furthermore, whereas some studies have suggested that voxels should be large to match the extent of underlying activation features [4], others have advocated that voxel volumes should be small to minimize partial volume effects and contamination by physiological noise at higher fields [5,6]. Thus, the goal of this work is to simultaneously address these two issues by performing a four-way analysis between 2D and 3D pulse sequences at two matching in-plane resolutions to compare different fMRI acquisition strategies. The fast field echo (FFE) sequence was used for large k-space matrices (176 x 176) whereas shorter echo train lengths for smaller k-space matrices (96 x 96) permitted the use of PRESTO to shift the echo (TR < TE) and increase temporal efficiency.

Methods

Experiments were performed on a Philips 7T scanner. Twelve volunteers were recruited to take part in fMRI studies under a protocol approved by the institutional review board. The visual paradigm was a block design with four segments of 24 sec baseline (central fixation) and 24 sec activation (stationary flashing checkerboard 22.5º wedge in the left visual field). Slices (2 mm thick) were planned parallel to the calcarine sulcus. The four acquisition strategies in Table 1 were performed twice with different permutations across subjects (to minimize the influence of attention and fatigue) for a total of eight functional runs. Preprocessing was performed using AFNI [7]. Data were spatially smoothed (`3dmerge`) with 7 full-width-at-half-maximum (FWHM) kernel sizes (7, 9, 11, …, 19 mm) and transformed (`3dWarp`, `@auto_tlrc`, `adwarp`) to MNI space (ICBM-152) with 2 x 2 x 2 mm^3 voxels. The quality of fMRI data was evaluated via independent and unbiased metrics of *prediction* and *reproducibility* using NPAIRS† (Non-parametric Prediction, Activation, Influence and Reproducibility re-Sampling) [8,9]. Reproducibility (**r** ∈ [0,1]) measures the similarity (Pearson correlation coefficient) of activation maps generated from two independent data sets, and prediction (**p** ∈ [0,1]) evaluates the degree to which a trained model can assign correct class labels to an independent test set. NPAIRS uses principal component analysis to reduce the dimensionality of the data followed by split-half resampling and canonical variate analysis. Reported values for prediction and reproducibility are the median values of split-half samples for a range of principal components selected to maximize both prediction and reproducibility for each acquisition sequence.

Table 1: fMRI acquisition parameters for four sequences.

	SINGLE-SHOT		MULTI-SHOT	
pulse sequence	2D EPI		3D FFE	3D PRESTO
k-space matrix	176 x 176	96 x 96	176 x 176	96 x 96
voxel size (mm^3)	1.19 x 1.19 x 2	2.19 x 2.19 x 2	1.19 x 1.19 x 2	2.19 x 2.19 x 2
# of slices	12			
TE (ms)	28			
TR (ms)	2000		44.45	22.22
vol. acq. time (ms)	2000			1000
# of dynamics	96			192
flip angle (deg)	87		17	12
SENSE factor	3.2			
EPI factor	57	33	19	11
Freq/PE BW (Hz)	1474.6 / 20.0	1766.4 / 42.5	997.1 / 42.6	2930.4 / 142.5

Results

Figure 1 plots prediction vs. reproducibility for each acquisition strategy and spatial smoothing (SS) kernel, where "perfect" fMRI data would be mapped to the point (1,1). EPI demonstrated higher prediction and reproducibility than either competing sequence. The overall highest (**p**,**r**) is (.858, .827) for ~1x1 mm^2 EPI with SS = 11 mm FWHM. The highest value for ~2x2 mm^2 EPI is (.826, .806) with SS = 11 and 13 mm FWHM. The highest values for PRESTO and FFE are (.772, .701) with SS = 13 mm FWHM and (.761, .672) with SS = 11 mm FWHM, respectively.

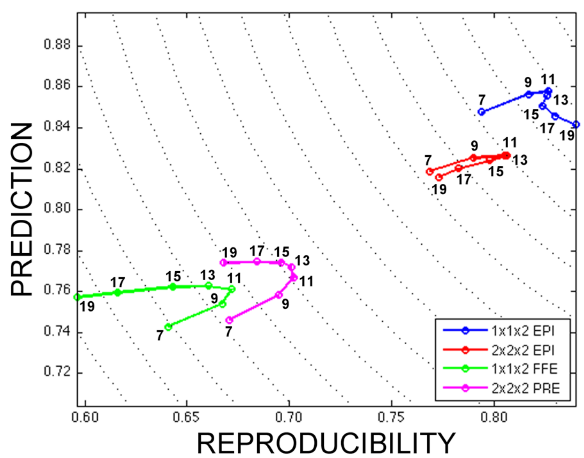

Fig. 1: Plot of prediction vs. reproducibility for ~1x1x2 mm^3 EPI, ~2x2x2 mm^3 EPI, ~1x1x2 mm^3 FFE, and ~2x2x2 mm^3 PRESTO. The number beside each point is the applied spatial smoothing kernel (FWHM). Each concentric dotted curve is equidistant to perfect reproducibility and prediction at (1,1).

Discussion

NPAIRS provides a quantitative evaluation of each acquisition strategy to show that 2D EPI offers substantially higher prediction and reproducibility than 3D FFE or PRESTO for this study. Results for EPI confirm previous work [6,10] stating that amplified physiological noise at ultra high fields can be mitigated by acquiring data in a regime where voxels are dominated by thermal noise (< 3 mm^3 at 7T), and then spatially smoothing to the desired resolution to increase CNR.

The performance of PRESTO in this study, although notably less than ~2x2 mm^2 EPI, does not necessarily contradict findings of higher BOLD CNR for PRESTO than conventional EPI from earlier reports [3]: our study implemented PRESTO with SENSE acceleration in one phase encode direction whereas the cited study implemented k-space undersampling in both phase encode directions (achieving whole-brain coverage in one-quarter of the time compared to EPI).

This study suggests that EPI is preferable to FFE and PRESTO for fMRI studies with a focused region of interest (such as the visual cortex), and that larger k-space matrices should be used whenever possible to mitigate the influence of physiological noise. Future work will compare 2D EPI with 3D PRESTO-SENSE for a 7T fMRI study requiring whole-brain coverage, and extend the analyses to include within-subject optimization and Gaussian naïve Bayes classification.

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† The NPAIRS platform is freely available at http://code.google.com/p/plsnpairs

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