Preprocessing pipeline considerations to compensate for paradigm-related subject movement

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Introduction

Blood-oxygenation level-dependent (BOLD) functional magnetic resonance imaging (fMRI) is sensitive to spatial and temporal perturbations in main magnetic field homogeneity within the brain due to movement outside the imaging field of view (FOV) [1]. In addition to unavoidable sources of movement due to respiration, cardiac pulsatility, and swallowing [2,3], more elaborate paradigms require subjects to perform tasks that include, but are not limited to, speaking, swallowing, jaw clenching, and tongue movement [3], as well as movement of the forearm to reach or grasp an object [4]. Such paradigms may also require movement of equipment or another person within or adjacent to the bore during scans. These sources of paradigm-related movement outside the FOV further perturb magnetic field homogeneity and create significant geometric distortions in echo-planar fMRI [1,3]. The goals of this abstract are to emulate and characterize field inhomogeneities in the brain due to a subject's reaching or grasping motion, and to investigate preprocessing pipelines [5] that combine complementary techniques of navigator correction and a complex phase regressor to further reduce geometric distortions due to paradigm-related subject movement (PRSM) in BOLD fMRI data.

Methods

Experiments were performed on a Varian *Unity* INOVA whole-body 4 Tesla MRI scanner (Palo Alto, CA) with a Siemens Sonata gradient coil (Erlangen, Germany). AFNI [6] was used to perform in-plane spatial smoothing and BrainVoyager QX 1.9 (Brain Innovation, Maastricht, The Netherlands) was used to perform the functional analysis. A phantom arm (Fig. 1a) was constructed to emulate the movement of a real arm so that subjects could remain stationary, thus minimizing head movement. The phantom arm (PA) models the humerus and ulna bones as two identical pieces of wood (each 30 cm in length and 2 cm in diameter) and connected with a tie at the "elbow" joint. Soft tissues are modeled by securing 1.00 L of distilled water to each piece of wood (using two half-filled 1 L intravenous bags to create a relatively uniform distribution of water). One end of the PA is securely fastened in a right arm restraint with foam padding and Velcro straps, and the other end is rested on the subject's chest (and also attached to a 1.5 m wooden pole so that it may be moved).

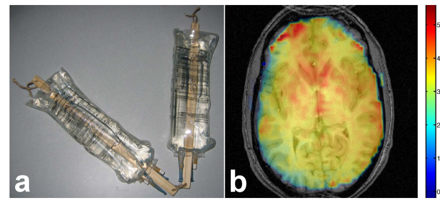

Fig. 1: (**a**) Phantom arm and (**b**) axial field inhomogeneities between resting and grasping positions of the phantom arm.

Nine subjects were recruited to partake in a visual activation experiment using an 8 Hz radial flashing checkerboard. Data from one subject was discarded due to excessive movement. Functional planes were planned parallel to the calcarine sulcus, and a 2-shot echo-planar imaging sequence (matrix = 64 x 64, TE = 15 ms, TR = 1000 ms, FOV = 19.2 cm, θ = 40°, 17 3 mm slices) was used to acquire 105 volumes during a 3.5-minute run. The block design paradigm consisted of seven alternating segments of activation (flashing checkerboard) and baseline (central fixation). A general linear model with a predictor formed by convolving a boxcar waveform coincident with the paradigm with a double-Gamma hemodynamic response function was used to generate activation maps. Each subject performed a total of 10 runs, alternating between "normal" runs (NRs) (PA remained in resting position) and "movement" runs (MRs) (PA moved continually but aperiodically between resting and grasping positions (40 cm translations) by the experimenter to maximize distortions). An additional subject was recruited and performed 12 "grasping" runs (GRs) (PA moved from resting to grasping and back to resting every 30 sec to simulate individual grasps) using the same visual paradigm. All subjects provided written informed consent with a protocol approved by the university Human Subjects Research Ethics Board.

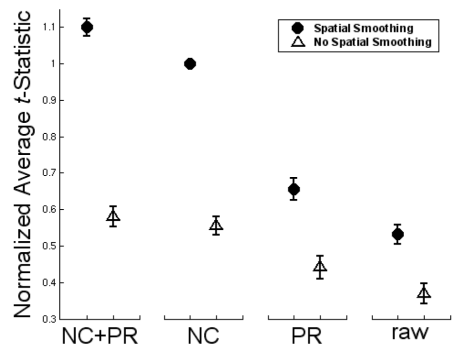

Fig. 2: Average t-statistics for 40 "movement" runs normalized with respect to NC+SS on a per-pixel basis for each run.

The three preprocessing options considered in this study are (1) hybrid 2D navigator correction (NC) to compensate for low-frequency field inhomogeneities [7]; (2) a complex phase regressor (PR) [8] applied to each pixel to remove correlated phase and magnitude fluctuations; and (3) in-plane 2D spatial smoothing (SS) using a 7.5 mm FWHM Gaussian kernel. Each of these steps are either performed or not performed on the data, resulting in eight (2^3) unique processing pipelines: NC+PR+SS, NC+SS, PR+SS, SS, NC+PR, NC, PR, and 'raw' (where none of these steps are performed). A volume of interest (VOI) was selected for each of the 80 runs containing contiguous pixels in the occipital cortex with t-statistics ≥ 4.0 in the NC+PR+SS pipeline.

Results

Figure 1b displays the spatially varying field inhomogeneities (6 Hz peak-to-peak) in a mid-axial slice caused by PA movement between the grasping and resting positions, calculated as the average of three measurements of phase differences in the 3D field maps (acquired using RASTAMAP [9]). The 95% confidence interval (CI) [10] is used to verify statistical significance. Average t-statistics (t_{avg}) for 'raw' are 2.50 (CI = 2.32 to 2.67) and 2.80 (CI = 2.67 to 2.93) for MRs and NRs, respectively. Similarly, t_{avg} for NC+PR+SS are 6.85 (CI = 6.60 to 7.10) for MRs and 7.93 (CI = 7.65 to 8.20) for NRs. Figure 2 presents t_{avg} for MRs normalized on a per-pixel basis with respect to NC+SS. Error bars represent the 95% CI. Although there is no significant difference between NC and NC+PR, there is a 10.1% increase in t_{avg} (CI = 7.87% to 12.3%) between NC+PR+SS and NC+SS. Figure 3 displays t_{avg} for GRs normalized with respect to NC+SS (FWHM = 2.5 pixels). These data show that a minimum smoothing kernel size of two pixels is necessary for statistical significance between NC+PR and NC+PR+SS, and that the chosen kernel size of 2.5 pixels (7.5 mm) is close to optimal for this subject [11].

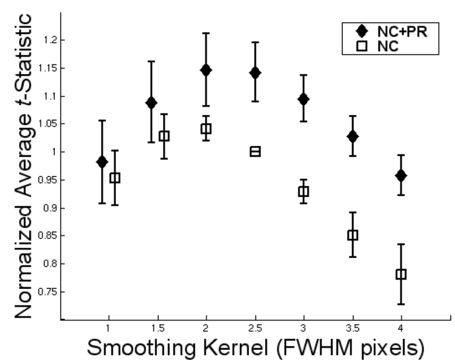

Fig. 3: Average t-statistics for 12 "grasping" runs from one subject normalized with respect to NC+SS (FWHM = 7.5 mm).

Discussion

Statistically significant differences between 'raw' data (MRs and NRs) indicate that PRSM distortions were successfully simulated through PA movement. The persistence of statistically significant differences between MRs and NRs after NC+PR+SS suggests that further refinements may be made in the preprocessing pipeline to reduce distortions due to PRSM. In activated pixels with correlated phase and magnitude changes, the phase regressor decreases both the BOLD signal change as well as extraneous noise fluctuations due to respiration and PRSM, resulting in t_{avg} that is statistically unchanged between NC+PR and NC. An advantage of NC is that it can apply different corrections to k-space segments, which is important for multi-shot sequences. An advantage of PR is that it operates on individual pixels in image space and can correct temporal fluctuations that have high spatial frequencies. Therefore, NC and PR are complementary techniques, and their sequential application in the preprocessing pipeline reduce geometric distortions and precondition data to make them more amenable to the well-recognized benefits [5] of spatial smoothing.

Acknowledgments

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