CONCURRENT MAGNETIC FIELD MONITORING OF EPI TIME SERIES: CHARACTERIZING ENCODING FIELD AND IMAGE FLUCTUATIONS USING PRINCIPAL COMPONENT ANALYSIS

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Introduction:

In fMRI, stimulus-correlated changes in voxel time series are analyzed to infer on activation patterns. Changes in image intensity are induced by signal fluctuations, e.g. related to the brain metabolism (BOLD). They can also be caused by gradient system instabilities and drifts, thus leading to confounds in time series analyses.

We use concurrent magnetic field monitoring to investigate EPI trajectory and B_0-field fluctuations on large timescales and the effects of these fluctuations on image reconstruction. First, we perform a Principal Component Analysis (PCA) to disentangle *systematic* B_0-field and trajectory fluctuations, which could be used for calibration, from *random* fluctuations and quantify their proportion. Second, we apply PCA on the reconstructed images to detect typical image fluctuations induced by trajectory variability.

Materials and Methods:

We acquired 9 sets of EPI data on 3 different days following the course of a typical fMRI protocol (Fig. 2). Each session contained 400 dynamics (2.5 mm isotropic resolution, TR 3 s, readout duration 41.1 ms, 10 axial slices) and lasted 20 minutes. Phantom data was acquired from a $CuSO_4$-doped water sphere (15 cm diameter) on a Philips Achieva 3 T system with an 8-channel head coil and a concurrent magnetic field monitoring setup (12-channel T/R ^{19}F NMR probes) [1]. The probe phases measured with this setup were fitted to a spatial model of 2nd order spherical harmonics. The 0th order phase coefficient k_0 corresponds to the B_0-field modulation. The 1st order phase coefficients k_x and k_y are the k-space trajectory. We used these measured phase coefficients in an iterative, gridding-based image reconstruction [2,3]. Table 1 shows the different image reconstruction schemes that were used to determine the influences of k_0- and k_{xy} -fluctuations on the reconstructed images.

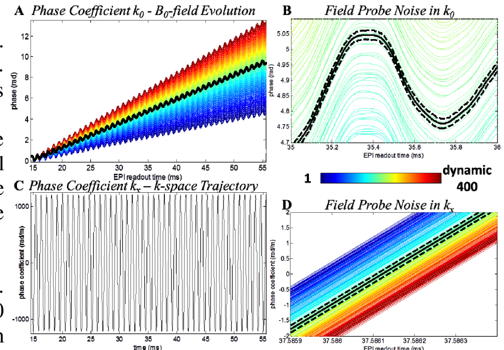

Figure 1: Evolution of the measured phase coefficients during 400 EPI readouts (20 min). (A) B_0-field evolution. (B) Mean k_0 (black) ± the standard deviation of the noise of the monitoring setup (dotted black), which is in the range of the fluctuations between 2 consecutive dynamics. (C) k-space trajectory in measurement direction. (D) Mean k_x (black) ± the standard deviation of the noise of the monitoring setup (dotted black), which is in the range of the fluctuations between 20 consecutive dynamics.

Key contributions to the observed trajectory and image fluctuations were characterized using Principal Component Analysis (PCA): PCA computes a new set of basis vectors (Principal Components, PCs) along dimensions of high variance in the data [4]. The PCs are ordered according to the amount of variance they explain. We computed the PCs of the phase coefficients k_0 and k_{xy} on all data sets, where each PC represents a characteristic modulation of the readout time course. The PCA of the reconstructed images was performed individually for each day, and yielded PCs in image domain, separated for influences of k_0 and k_{xy}. To detect correspondences between trajectory and image PCs we computed the projection of each PC over all 3600 dynamics. This projection visualizes the change of a certain PC contribution over dynamics, and thus provides a measure of the fluctuation patterns over time.

Table 1.

Reconstruction Schemes	Coil data	k_0-data (demodulation)	k_{xy}-data (trajectory, gridding)
k_0 fluctuations	set 1…set 9	mean k_0 of set 1	set 1…set 9
trajectory fluctuations	set 1…set 9	set 1…set 9	mean k_{xy} of set 1

Figure 2: Measurement Protocol.

Results:

The sensitivity of the field monitoring setup is sufficient to detect fluctuations in k_0 and k_x, the k-space trajectory in measurement direction (Fig. 1). Fluctuations in k_y were small and in the order of the setup sensitivity. Using this concurrent monitoring data for image reconstruction, a mean standard deviation (STD) of 0.3% over all images was observed, attributable not to encoding field fluctuations, but most likely caused by signal fluctuations, e.g. flip angle or receiver gain instabilities. Reconstructing the same coil data with incomplete monitoring information (s. Table 1) yielded a considerable increase in image fluctuations: Neglecting the B_0-field fluctuations resulted in a 4 times as high mean STD, whereas ignoring the k_x/k_y-fluctuations led to a 1.33 times as high mean STD.

In the PCA, we found very typical fluctuations in the B0-field, the trajectory and the corresponding images over several days. About 81 % (k_0) and 65 % (k_{xy}) of the image fluctuations could be attributed to image PCs whose systematic evolution corresponded to phase coefficient PCs: For k_0, the correlation between the projections of PC 1 of the phase coefficient and PC 1 of the images was very strong and significant (0.97, p<1e-16) (Fig. 3). The 1st PC of k_0 models a linear drift, and correspondingly, the 1st 3 image PCs model a downward shift of the object of about 1 pixel per session. For phase coefficient k_x we found a correspondence between an asymmetric widening (PC 3) in the trajectory and the typical EPI-N/2-ghost (PC 1) with a strong and significant (0.89, p<1e-16) correlation between their projections (Fig. 4).

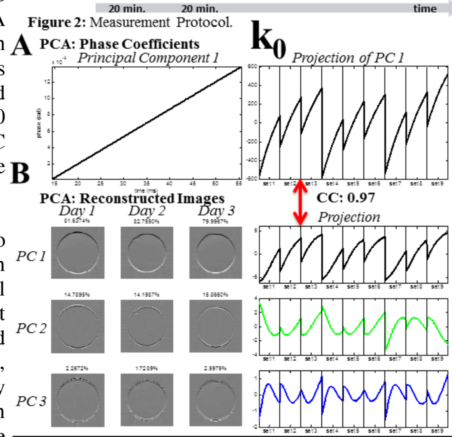

Figure 3: PCA of B_0-field and corresponding image fluctuations. (A) PC 1 models a linear increase within one readout and explains 99.98% of the total variance. The projection shows a non-linear increase within one session; no steady-state is reached. Between sessions, no return to the initial condition, but between days. (B) The first three PCs show the same characteristics on all three days. Summed up, they explain more than 98 % of the total variance. The effect of these components is a downwards shift of about one pixel in one session. The mean STD of the reconstructed images is 1.2 % (max. STD: 34.2 %). The projection of PC 1 shows correspondence to the projection of the PC 1 of the phase coefficient k_0 (red arrow). The correlation coefficient of the projections is 0.97 and significant ($p < 1e-16$).

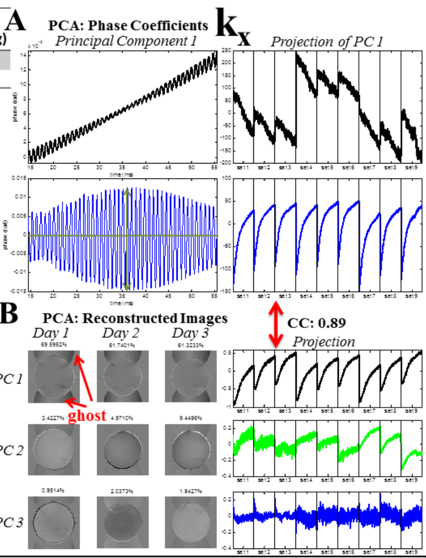

Figure 4: PCA of trajectory and corresponding image fluctuations. (A) PC 1 shows a linear increase and a modulation which is strongest at the beginning and the end of an readout and explains 66.38 % of the total variance. The projection shows a decrease within one sessions and an irregular behavior. PC 3 shows an asymmetric widening of left and right traverse (green arrows) and explains 9.30 % of the total variance. The projection shows an initial increase; no steady-state is reached. (B) PC 1 shows the same characteristics on all three days and models a typical N/2-EPI-ghost. PCs 2 and 3 have separate characteristics at each day and show effects at the edges and the ghost, but with rather noisy projections. The 3 PCs explain only about 70 % of the total variance, which means there is a large range of effects that influence the image. The mean STD of the images is 0.4 % (max. STD: 2.2 %). The projection of PC 1 shows correspondence to the projection of PC 3 of the k_x-trajectory. The correlation coefficient of the projections is 0.89 and significant ($p < 1e-16$).

References: [1] Barmet et al, 2010;Proc.ISMRM.10, p.216; [2] Barmet et al, 2008;MRM.60; [3] Pruessmann et al, 2001;MRM.46; [4] Pearson, K, 1901 Phil. Mag. S. 6, p.559-572

Discussion:

We detected characteristic EPI trajectory fluctuations and B_0-modulations over several days and could identify corresponding image artifacts using comparative PCAs. We saw a not necessarily linear relationship between trajectory and image fluctuations, i.e. small variance in the former can lead to major fluctuations in the latter. The B_0-field modulation shows very characteristic properties which mainly reflect thermal drifts. The quantitative evolution of these fluctuations depends on the history of the system and is hard to calibrate for. We found a characteristic k_{xy} fluctuation, which could be calibrated for. As the resulting noise in the images is in the range of the BOLD effect, correcting for these fluctuations for fMRI applications seems highly beneficial.