Removal of temporal correlation in fMRI time-series by modelling residual movement effects and physiological noise

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Introduction: When assigning significance to fMRI activations a common problem is that the residuals are correlated and non-normal. The possible sources are numerous including: low-frequency drift in scanner hardware [1], aliased cardiac and respiratory oscillations [2,3] and residual movement artefacts including spin-history effects [4]. Recent versions of most fMRI analysis software try to estimate the covariance due to these effects (e.g. using an autoregressive model), and use the estimated process to whiten the errors. If the estimated covariance structure is correct this is procedure optimal. However, the modelling is time consuming and often global and/or low-order models need to be used in order to get a robust estimate. The purpose of this is to investigate if estimation of the covariance can be substituted by a comprehensive set of nuisance regressors modelling the above mentioned contributors to the non-white non-normal noise. The regression models has previously described in the literature [3,4], but only used separately.

Methods: Sixteen datasets each consisting of 381 volumes of forty slices (matrix size 64x64) was acquired on a 3T scanner (Siemens Trio) using a GRE EPI sequence: voxelsize:3mm isotropic, TE=30ms, TR=2.37s. During the scanning the subject was stimulated visually (reversing checkerboard (expanding ring and rotating wedge)). Each rotation/expansion lasted 30 seconds. Following rigid body-realignment using SPM2, each dataset was subsequently analysed with nine different general linear models: **"Simple"** A model including baseline plus sine and cosine of the first three harmonics of the (1/30s) oscillation" **"60sec-HP"** a model similar to "Simple", but now including a high-pass filter modelled as a discrete cosine set with a minimum period of 60s. **"SPM2-AR(1)"** A model similar to "60sec-HP" but with whitened residuals using a global AR(1) model estimated in a mask defined by the voxels where a significant effect of the paradigm was observed. (This is the recommended SPM2 procedure). **"FSL-FILM"** A model similar to simple, but with FILM pre-whitening of the residuals and FSL high-pass filter (cut-off=100s (default value)) **"FM-ECG"** A model similar to "60sec-HP" but including several extra nuisance regressors for modelling the autocorrelation. A Volterra expansion of the movement parameters giving was used to model residual movement effects including spin-history effects Friston et al. 1996 (24 regressors). Respiration and cardiac noise was modelled using 16 RETROICOR [3] regressors (5 cardiac harmonics and 3 respiratory harmonics). The RETROICOR regressors is a Fourier basis spanned by the oscillations of the aliased frequencies. The cardiac frequency and phase was determined using the scanner ECG system. The respiratory phase and frequency was measured using the scanner respiratory belt. **"FM-randperm"** A model similar to "FM-ECG" but with permuted nuisance regressors. **"FM-ox"** A model similar to "FM-ECG" but using the scanner pulsoximeter to measure the cardiac phase and frequency. **"Phys only"** A model similar to "FM-ECG" but without the movement regressors. **"Motion only"** A model similar to "FM-ECG" but without the movement regressors. After the analysis, Statistical Parametric Mapping diagnosis (SPMd) [5] was used to test the whiteness ("Dep" for arbitrary stationary dependence and "Corr" for AR(1)-type autocorrelation) and normality "Norm" of the residuals, from the different models.

Results: The results of the SPMd of the nine different analysis of the 16 different sessions are summarized in Figure 1, and for session 11 (dash-dotted line) the SPMd images from the first 6 analysis are shown.

Discussion: From the figures it is seen that the "FM-ECG" model seems to have the best over all performance in the SPMd tests. The "SPM2-AR(1)" and "FSL-FILM" models are best at removing AR(1) type correlations (SPM2 seems more stable but FSL is often better). The "FM-ox" gives almost similar results to the "FM-ECG" model and thus it is concluded that the phase of the cardiac cycle is no better determined in the ECG than in the pulseoximeter time course. Phys only and Motion only both performs worse than the full model indicating that all effects needs to be modelled if the technique has to be successful. The poor performance of the "FM-randperm" demonstrate that the performance obtained by the "FM-ECG" model is not an effect of just including a large number of regressors in the designmatrix..

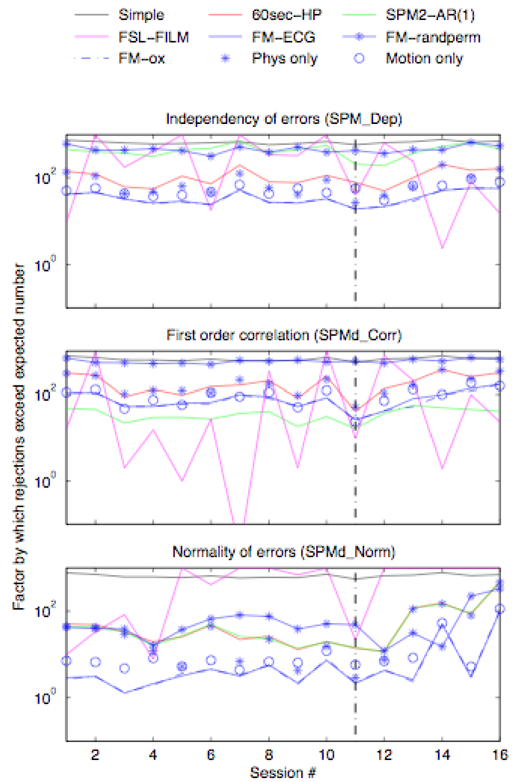

Figure 1: The figure shows for the three different tests, across the 16 datasets, the factor by which rejections exceed the expected number. The different curves correspond to several different analysis of the same dataset The dataset used in Figure 2 is from session 11 marked with the dash dotted line.

References:
[1] Smith et al. 1999 NeuroImage **9,** 526-33.
[2] Weisskoff et al. 1993 12'th SMRM,7.
[3] Glover et al. 2000, MRM, **44**, 162–7.
[4] Friston et al. 1996, MRM, **35**, 346-355.
[5] Luo et al. 2003, NeuroImage, **19**, 1014–32.

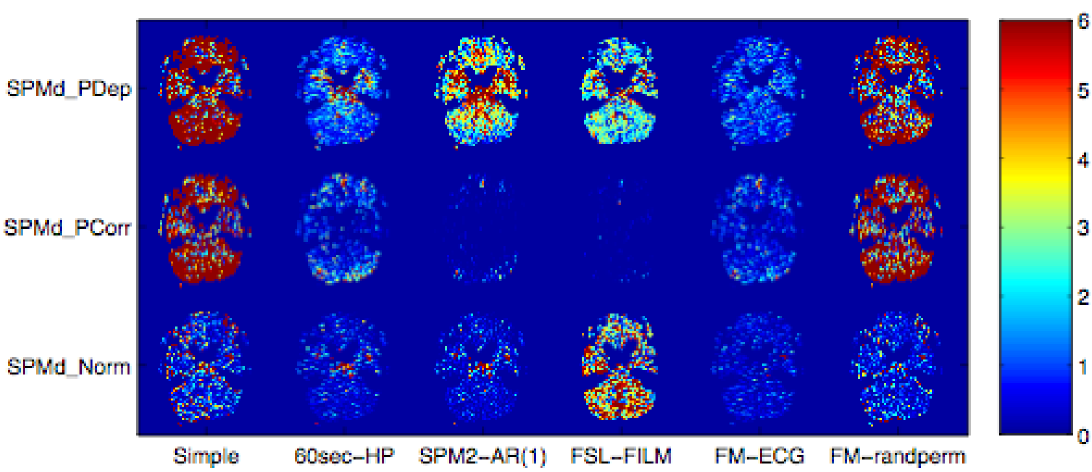

Figure 2: The figure shows the output of a SPM-diagnosis (log(p) values) from the several different analysis of the same dataset. Only the proposed model "FM-ECG" is capable of adequately modelling the non-white noise near Circle of Willis and Medial Cerebral Artery. SPM2 and FSL are superior at removing first order correlation, but are both unable to remove higher order correlations satisfactory.

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