Sources of signal fluctuations in single-shot 2D EPI and segmented 3D EVI acquisitions for fMRI at 7T

J. P. Jorge[1,2], P. Figueiredo[1,2], W. van der Zwaag[3,4], M. Narsude[3], and J. P. Marques[3,4]

[1]Instituto Superior Técnico, Lisbon, Portugal, [2]Institute for Systems and Robotics, Lisbon, Portugal, [3]Laboratory for Functional and Metabolic Imaging, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, [4]Department of Radiology, Université de Lausanne, Lausanne, Switzerland

Introduction: High-field MRI systems provide significant improvements in image SNR, potentially leading to higher sensitivity and spatial resolution in fMRI experiments[1]. However, recent studies have shown that these advantages are compromised by increased signal fluctuations arising from temporally-correlated, signal-dependent noise sources, namely physiological processes[2]. It is therefore essential to adequately characterize and mitigate these noise contributions, as well as to study their dependence on fundamental aspects of fMRI studies such as the imaging sequence used for data acquisition. This work comprises the analysis of BOLD fMRI data acquired at 7 T, utilizing a standard 2D EPI and a segmented 3D echo volumar imaging (EVI) sequence[3,4]. Segmented EVI provides higher image SNR due to the whole-volume excitations employed, but is thought to be more sensitive to physiological noise than 2D EPI. A physiological regressor (PR)-based approach[5] was adopted for noise characterization and correction.

Methods: 8 healthy subjects were scanned on a human 7-T/680-mm Siemens system. The study was approved by the local ethics committee and all subjects provided written informed consent. Each subject underwent 4 fMRI runs, counterbalanced across subjects; each run was conducted at rest, with eyes closed (*Rest*), or featuring a visual localizer paradigm[6] (*Loc*), with 2D or 3D data acquisition. Physiological data (respiratory amplitude and pulse oximetry) were acquired simultaneously with the fMRI images. 2D EPI images consisted of 40 slices of 104×104 voxels, while segmented EVI[4] (3D) images had a 104×104×40 matrix size – both with a spatial resolution of 2×2×2mm^3; in both cases, full volumes were acquired in 3.2s (TR^{2D}=3200ms, TR_{seg}^{3D}=80ms). Pre-processing steps in FSL included motion correction, temporal high-pass filtering, slice timing correction (2D only), and spatial smoothing (Gaussian, 3mm FWHM); voxel time courses were then submitted to GLM analyses with design matrices composed of slow-drift regressors (3rd degree polynomials), paradigm regressors in *Loc* runs (boxcar convolved with a single-gamma HRF), and nested physiological regressors[5] – these were extracted from physiological recordings and were intended to account for noise related to cardiac rate (CR), respiration volume per time (RVT), and cardiac/respiratory cycle phases (RETROICOR)[5].

In order to characterize noise contributions, in *Rest* data, the percentage of signal variance explained by each component was determined as the difference in the coefficient of determination adjusted for the number of degrees of freedom, R_{adj}^2, obtained in GLM analyses performed with and without the inclusion of that specific component in the GLM[5]. Improvements in activation sensitivity with PR-based corrections were evaluated by submitting *Loc* data to GLM analyses performed with and without PR sets; variations in contrast estimation variance and number of active cluster voxels were investigated for a global "visual stimuli *vs* fixation" (*FHOS*) contrast. For each subject, results were averaged across ROI_{Act}, defined as the intersection between a V1 mask from the MNI brain atlas, and an *FHOS* cluster mask (Z threshold=2.3, cluster *p*-threshold=0.05) obtained from GLM analyses performed with drift and *Loc* paradigm regressors only. Finally, spatial (sSNR) and temporal SNR (tSNR) of uncorrected and PR-corrected data were evaluated based on a white matter ROI (ROI_{WM}) and a background ROI (ROI_{BG}); sSNR was calculated as the average voxel intensity in ROI_{WM} over the standard deviation in ROI_{BG}, averaged across time; tSNR was determined as the mean time course intensity over signal standard deviation, averaged across ROI_{WM}.

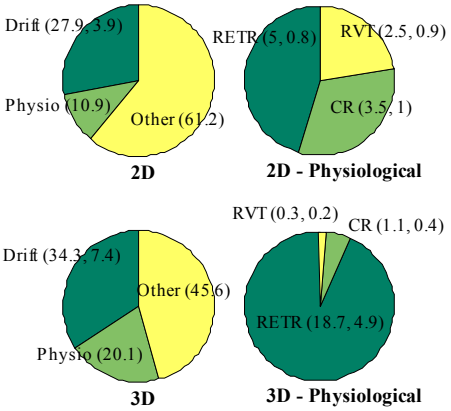

Fig.1 Average physiological noise contributions (average, SE) to explained variance in 2D and 3D.

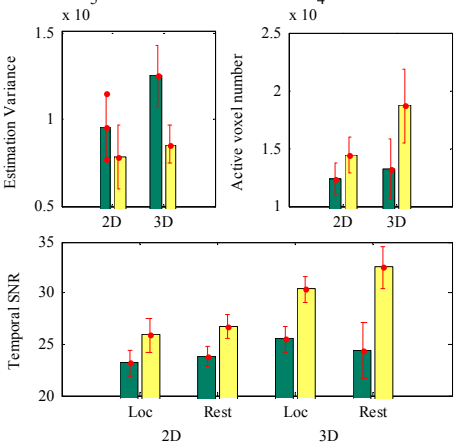

Fig.2 Sensitivity and SNR group results (mean, SE).

Results: As seen in Fig.1, in 2D data, physiological noise as a whole yielded a significant fraction of total signal variance, even if smaller than those from slow drift or "other" sources (including thermal noise and spontaneous neural activity). Within physiological noise, RETROICOR sets showed the largest contributions, followed by CR and finally RVT. From 2D to 3D, significant increases were observed in relative contributions from total physiological noise (p=0.002), accompanied by decreases in relative contributions from "other" sources, with drift contributions remaining fairly similar (p=0.993). Within physiological noise, RETROICOR contributions were found to increase strongly and significantly from 2D to 3D (p<0.001), while those of CR and RVT both decreased (p=0.045 and p=0.024), becoming an even smaller fraction of total physiological noise. In general, improvements in BOLD sensitivity with PR-based corrections, in terms of estimation variance and number of active voxels, tended to be larger in 3D than in 2D data (see Fig.2 and Fig.3). As for SNR (Fig.2), in both *Loc* and *Rest* data, uncorrected 3D acquisitions displayed higher sSNR (p<0.001) but comparable tSNR (p=0.416) to 2D acquisitions; with PR-corrected models, however, tSNR values became significantly higher in 3D than in 2D (p=0.002).

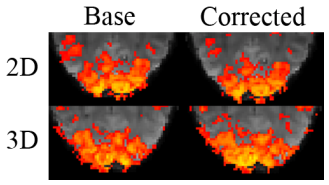

Fig.3 Examples of activation maps (Z>2.3, p<0.05).

Discussion: Physiological noise contributions form a larger fraction of signal variance in 2D than in 3D, while drift contributions remain fairly similar and "other" noise sources decrease; these results are consistent with those of a previous study[3], and suggest that while thermal noise is reduced in 3D, physiological noise contributions do increase. Within physiological noise, however, it is seen that RETROICOR components are in fact the only ones whose relative contributions increase, with those from CR and RVT actually becoming smaller There may be two explanations for this: the 3D technique may be specifically more sensitive to rapidly fluctuating noise, rather than to lower-frequency fluctuations related to cardiac and/or respiratory rates, or the RETROICOR method may be more effective in 3D data because of the need to perform slice timing correction in 2D. The 2D results obtained here were found to be close to those of a previous study[5], particularly regarding the contributions from drift, physiological noise as a whole, and "other" sources. The PR-based noise correction method produced improvements in the estimation variance, number of active voxels, and tSNR, which were greater for the 3D relative to the 2D technique.

Conclusion: Despite its gains in image SNR, segmented 3D EVI data are more susceptible to physiological noise than data acquired using standard 2D EPI, at 7 T. However, the use of a physiological signal-based noise correction method proved adequate to improve the tSNR and BOLD sensitivity to levels comparable or superior to those of standard EPI fMRI data, in this way partially recovering the expected SNR advantage of 3D acquisitions.

References: [1]Edelstein, 1986, MRM, [2]Krüger, 2001, MRM, [3]van der Zwaag, 2009, ISMRM proc, [4]Poser, 2010, NI, [5]Bianciardi, 2009, MRI, [6]Ishai, 2000, JCN.

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