Sensitivity benefits from ultra-fast fMRI: Monte Carlo analysis based on temporal noise in PRESTO-SENSE acquisitions

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Introduction

Functional MRI is notorious for its fast scan speed. Image acquisitions of a whole brain volume in 2 or 3 seconds are commonplace, which is enough to capture most temporal characteristics of the relatively slow hemodynamic response signal. The sensitivity of fMRI to detect cortical activation, however, depends on the noise characteristics of the signal, which does includes fast components. Ultra fast scan techniques benefit from over-sampling of the high-frequency physiological noise components. On the other hand, fast scanning suffers from temporal correlations between samples that reduce the sensitivity and reliability of the analysis. The resulting effect (how sensitivity scales with dynamic scan-time) depends on the precise characteristics of the physiological noise in combination with the experimental design. In this study we use temporal noise measurements (obtained with ultra fast fMRI acquisitions of subjects in rest) and common experimental design properties in a Monte Carlo experiment. From this data we measure general (not specifically task-related) sensitivity properties. The results are applicable to real fMRI (with subjects performing a task) under the assumption that temporal noise properties, especially noise correlations and scan-speed dependencies, do not significantly change with activation.

Data acquisition

We acquired 16 series of PRESTO-SENSE image data in five healthy subjects during rest. PRESTO-SENSE [1] is a 3D, short TR, gradient echo imaging technique, suitable for ultra fast BOLD fMRI [1]. We acquired each series with different sequence parameters, to probe various imaging speeds and speedup methods. (scanner = Philips 1.5T Intera with 6 channel SENSE-head coil; SENSE factor = 1 to 2.5; EPI factor = 17 to 19; number of slices = 5 to 26; voxel volume = 44 to 91 μl; TR/TE = 24/37 ms in all cases, except for the fastest scan, which has TR/TE = 20/30 ms; flip angle = 9 to 9.5). The acquisition speed ranges between 0.12 and 2.4 seconds per dynamic volume. The number of volumes per series varies between 100 and 1008 and the total scan duration between 96 and 750 seconds. Image volumes were taken through the middle of the brain with axial slice orientation. Rigid motion realignment was applied prior to the analysis.

Monte Carlo sensitivity analysis

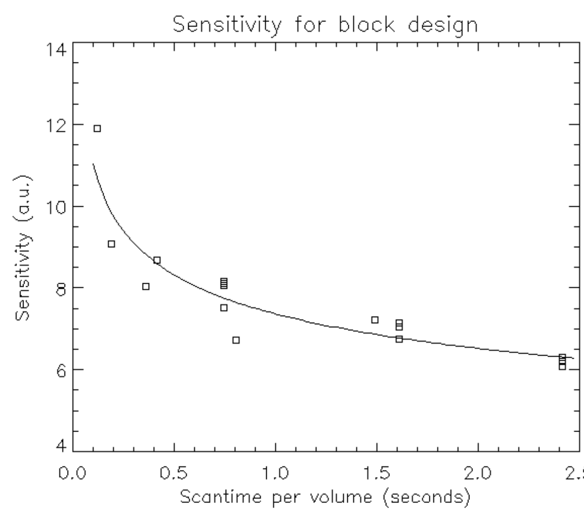
Temporal linear regression analysis is the most common method in fMRI to calculate task-induced activation levels. The sensitivity of this method depends linearly on the quality of the acquired time-series, which is measured by the temporal signal-to-noise ratio (*SNR*). Sensitivity also scales with the square-root of the number of acquired volumes (*N*), provided that there is no temporal correlation in the data. In practice, temporal correlations can be dealt with using pre-whitening, pre-coloring, or iterative regression methods [2], but in this study we use Monte Carlo simulation as a general tool to evaluate the influence of correlations on sensitivity. Our regression model includes terms for a linear trend and low frequency DCT components (up to 1 cycle per 2 minutes). We calculate the *SNR* for each voxel from the standard deviation of the residual errors after regression analysis (without task-related component). In the Monte Carlo simulation we repeat the regression analysis multiple times, each time with a single random task vector included. Random task vectors are constructed from filtered random Gaussian noise, using a box-car moving average filter with a width of 30 seconds to simulate block design tasks, and a width of 6 seconds for event-related designs. For each random task a *t*-statistic for detecting task-induced activation is calculated. The time-series contain no real task-related components, and the *t*-scores should (in theory) have zero mean and unity variance. However, due to correlations in the time-series, the measured *t*-scores will have a variance, $Var\{t\}$, different from unity. We use this variance to correct the sensitivity measure for the influence of temporal correlations. The sensitivity is then calculated (for each voxel separately) to be proportional to:

$$Sensitivity \propto SNR\sqrt{\frac{N/T}{Var\{t\}V_{voxel}}}, \qquad (1)$$

where T is the total scan duration of the time-series, such that N/T is the number of scans per unit time, and V_{voxel} is the voxel volume: the sensitivity is corrected for this parameter using an inverse square-root dependency, which was obtained empirically, and is theoretically equivalent to spatially smoothing different acquisitions to the same resolution. Other sequence parameters appear to have no explicit influence on sensitivity.

Results

We computed the sensitivity for 4000 random voxels in each scan, using 1000 random task repetitions in the Monte Carlo analysis. The variability of sensitivity across voxels is large in all sequences: the relative standard deviation of sensitivity over voxels is 33% for simulated block design tasks, and 23% for event related tasks. To obtain an average scaling behavior we averaged the sensitivity over all voxels for each scan and plotted this average against dynamic scan-time (see figure). We see (on average) an increase of sensitivity for faster scans. This scaling behavior is fitted with a power-low function: $(N/T)^{\gamma}$. The power coefficient (γ) is 0.175 ± 0.019 (SD) for block design tasks and 0.150 ± 0.019 (SD) for event related tasks, meaning that every speedup by a factor 2 provides a sensitivity gain of 13% or 11% respectively.



Discussion

We have found a sensitivity scaling behavior for PRESTO-SENSE acquisition that favors fast scanning sequences. However, the sensitivity gain from speed is small. It is, therefore, advisable to scan as fast as is reasonably possible, but without sacrifices (e.g. without reducing resolution or the number of slices). Currently the fastest available method is half k-space PRESTO-SENSE [3], acquiring one whole brain volume every 500 ms. The acquisition speed can potentially increase further by using SENSE-coils with more channels and SENSE in two directions.

References

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