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Increasing SNR in high resolution fMRI by spatially adaptive smoothing

Structural adaptive fMRI analysis

FMRI. In order to reduce the noise, improve signal detection and to solve the multiple test problem fMRI data is spatially smoothed. However, the common application of a Gaussian filter does this at the cost of loss of information on spatial extent and shape of the activation areas. The use of structural adaptive smoothing procedures significantly improves the information on the geometry of the activation regions with similar power of signal detection.

Data Preparation	Linear Model	Smoothing / Thresholding
• Registration • Motion correction • Normalization	• $Y = X\beta + \epsilon$ • prewhitening AR(1) model • $\tilde{Y} = \tilde{X}\beta + \tilde{\epsilon}$ • estimate β	• structure adaptive smoothing (AWS) • define t-statistic for a contrast • threshold using RFT

Initialization:

$$\hat{\gamma}_i^{(0)} := \tilde{\gamma}_i, \quad w_{ij}^{(0)} = \delta_{ij}, \quad h^{(k)} = h^{(0)} \cdot h_{incr}^k$$

Iteration: adaptive weights

$$w_{ij}^{(k)} = K_s(s_{ij}^{(k)}) K_l(l_{ij}^{(k)})$$

where K_l, K_s are kernel functions and

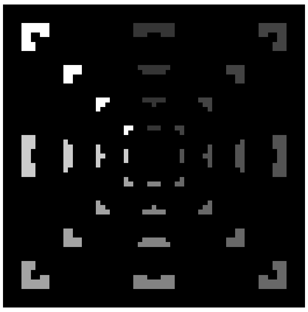
$$l_{ij}^{(k)} = |X_i - X_j| / h^{(k)}$$

$$s_{ij}^{(k)} = \frac{N_i^{(k-1)}}{\lambda(h^{(k-1)}, g)} \left(\hat{\gamma}_i^{(k-1)} - \hat{\gamma}_j^{(k-1)}\right)^2 / \tilde{\sigma}_i^2$$

is the location and the statistical penalty, respectively. $N_i^{(k-1)} = \sum_l w_{il}^{(k-1)}$. New estimate

$$\hat{\gamma}_i^{(k)} := \sum_j w_{ij}^{(k)} \tilde{\gamma}_j / \sum_j w_{ij}^{(k)}.$$

SNR and spatial resolution



For 2D MR images aquired in fMRI:

$$\sigma^2[i_n(x,y)] = K \frac{N_x N_y \langle V^2 \rangle}{N_{ave} FOV_x^2 FOV_y^2 \Delta t}$$

where FOV_x, and FOV_y are the field of view, N_x, N_y the acquisition matrix size, N_{ave}, ν, K, Δt acquisition parameters. Since SNR is proportional to $1/\sigma$, we get

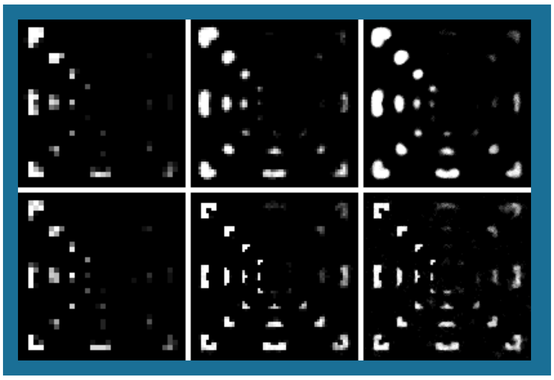
$$SNR \propto \frac{FOV_x}{\sqrt{N_x}} \frac{FOV_y}{\sqrt{N_y}}$$

which leads to

$$SNR \propto \frac{FOV_x}{N_x} \sqrt{N_x} \frac{FOV_y}{N_y} \sqrt{N_y}$$

or

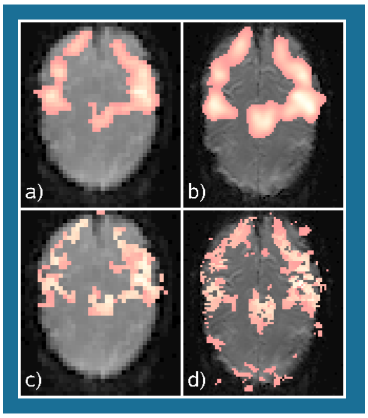
$$SNR \propto \Delta x \Delta y \sqrt{N_x} \sqrt{N_y}$$



Location of activated regions and size of the simulated signal. Eight different signal-to-noise ratios, increasing clockwise, coded by gray values.

Upper left figure Definition of the simulation data.
Upper right figure Simulation of the phantom fMRI data at different resolutions (matrix size) and different noise levels according to SNR formula. Left - Matrix size: 32x32. Center - Matrix size: 64x64. Right - Matrix size: 128x128. Non adaptive smoothing as shown in the upper row achieves the same effective resolution at comparable signal detection. Structural adaptive smoothing can reveal fine structure even at higher noise levels as illustrated in the lower row of the figure!

Experimental data



With physiological noise (dominate at high field strength)

$$\sigma = \sqrt{\sigma_T^2 + \sigma_S^2 + \sigma_P^2}$$

$$SNR = \frac{SNR_0}{\sqrt{1 + \lambda^2 (SNR_0)^2}}$$

Since σ_P^2 is proportional to the signal, the influence is higher at lower resolutions.

Left figure (a,b) Signal detection for the bimanual motor task in one particular slice at the two measured resolutions. Non-adaptive smoothing with Gaussian filter and FWHM=11.25mm has been applied to enhance signal detection. The typical activation connected with the task can be clearly seen at comparable effective resolution. (c,d) Same but with adaptive smoothing as introduced in [1]. Here, the finer structure at the higher spatial resolution (right) is not oversmoothed.

Conclusions: Adpative smoothing as suggested in [1] is capable to reveal finer activation structure in functional MRI at higher resolutions even when the lower SNR needs spatial smoothing to detect signals. Using this method one should be able to fully use the advantages of functional imaging at higher resolutions.

Software

R-package (Windows, Unix) see cran.r-project.org

fmri version 1.2-0 (05/24/07)

Software for single subject structural adaptive fMRI analysis
This package reads BRIK, ANALYZE, NIFTI, or DICOM datasets. Analysis is done with simple R-scripts. For a typical dataset it takes about 5 minutes on common hardware. No registration, motion correction, or normalization is provided. The package can write out the results as BRIK and ANALYZE file(s).

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Publications

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2. H.U. Voss, K. Tabelow, J. Polzehl, O. Tchernichovski, K. Maul, D. Salgado-Commissariat, D. Ballon, and S.A. Helekar, Functional MRI of the zebra finch brain during song stimulation suggests a lateralized response topography, *Proceedings of the National Academy of Sciences (PNAS)* (2007), to appear.
3. J. Polzehl, K. Tabelow. fmri: A package for analyzing fmri data, *RNews* (2007), to appear.
4. K. Tabelow, J. Polzehl, A. M. Ulug, J.P. Dyke, R. Watts, L.A. Heier, H. U. Voss (2006). Accurate Localization of Brain Activity in Presurgical fMRI by Structure Adaptive Smoothing. WIAS-Preprint No. 1119. http://www.wias-berlin.de/publications

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