Signal-to-noise ratios in MRI

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Why you might care?

- To check image quality (e.g. to detect signal dropout in relevant regions)
- To compare different sequences in order to select the best one, or to compare acquisitions performed on different scanners
- To estimate the statistical power of an experimental design (fMRI)

What is a **Signal-to-Noise Ratio**?

In all generality:

SNR = Signal amplitude / STDDEV(noise)

Where STDDEV $\{x_i\}$ = sqrt(variance $\{x_i\}$) = sqrt(sum$(x_i - \bar{x})^2$ / n)

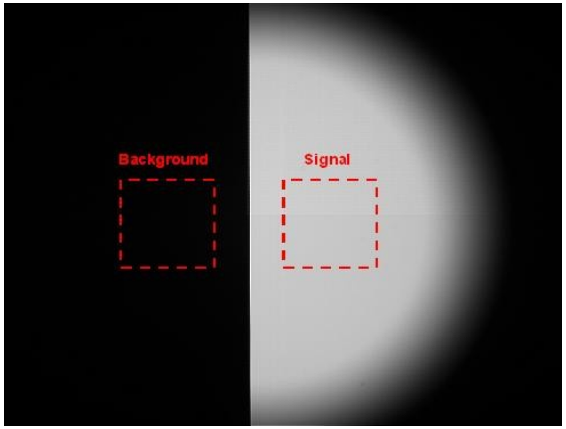
(remark: in physics, 'stddev' is also known as the 'root mean square' or RMS)

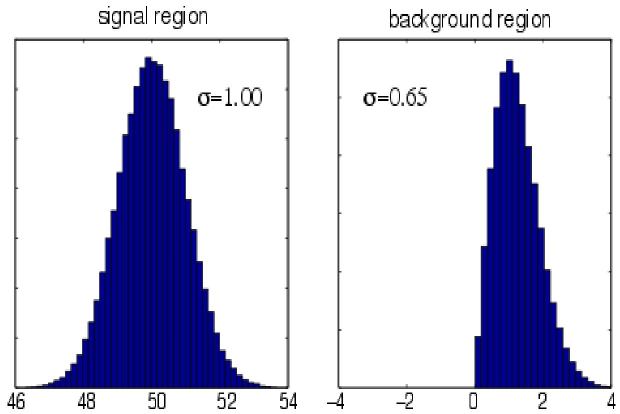
- The higher the SNR, the smaller the relative fluctuations → more stable signal over repeated measurements

  It provides an estimate of the reliability (~ reproducibility) of the measure (not be confounded with validity=agreement with truth; there may be bias).

- The 1.000.000$ question**: What is "noise"?**
  It depends on your aim!

MRI Image's SNR





SNR is typically computed by taking a ROI of interest to estimate signal stregnth) and a background region to estimate noise..

What is the SNR here? Answer: SNR=50/0.65 or 50/1.00?

Remark that the noise estimated in the background region is smaller than in signal region because all values are > 0 (solution: scale by 1/.65). We assume the noise is the same across the image.

To know:

In MRI, the image SNR increases in proportion to voxel volume (1/resolution)

In anatomical scans, one really cares about **contrast between tissues**

- Aim: to segment grey/white/CSF.
- Relevant measure= contrast-to-noise ratio (CNR), that is, ~ the difference in SNR between two relevant tissue types (A and B):

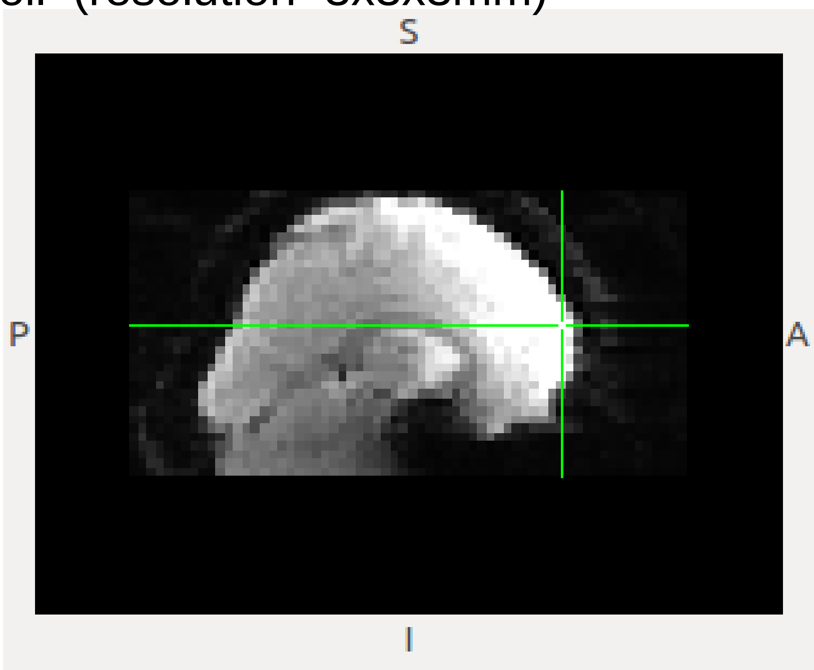
$$CNR = SNR_A - SNR_B$$

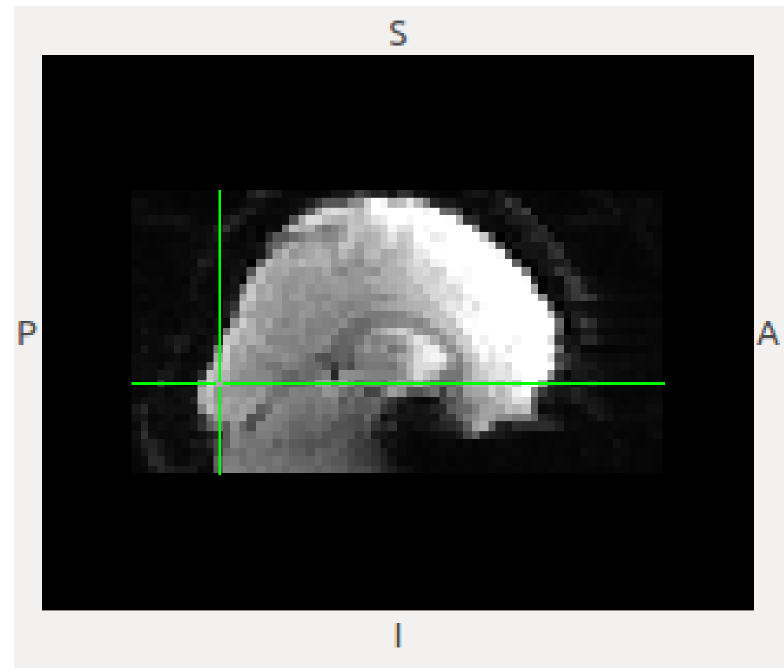
- CNR is manipulated by modifying TR, TE and flip angle.
- CNR values for GW/WM that I saw reported ranged from 5 to 20 (1.5T and 3T) (for SNR around 40-100)

- One important issue: variation in spatial sensitivity: see spatial bias correction (http://brainvisa.info/doc/axon/en/processes/VipBiasCorrection.html)

In EPI, variation of spatial sensitivity can be an issue

Example of an EP image acquired on Siemens TimTrio 3T with 32 channel coil (resolution=3x3x3mm)



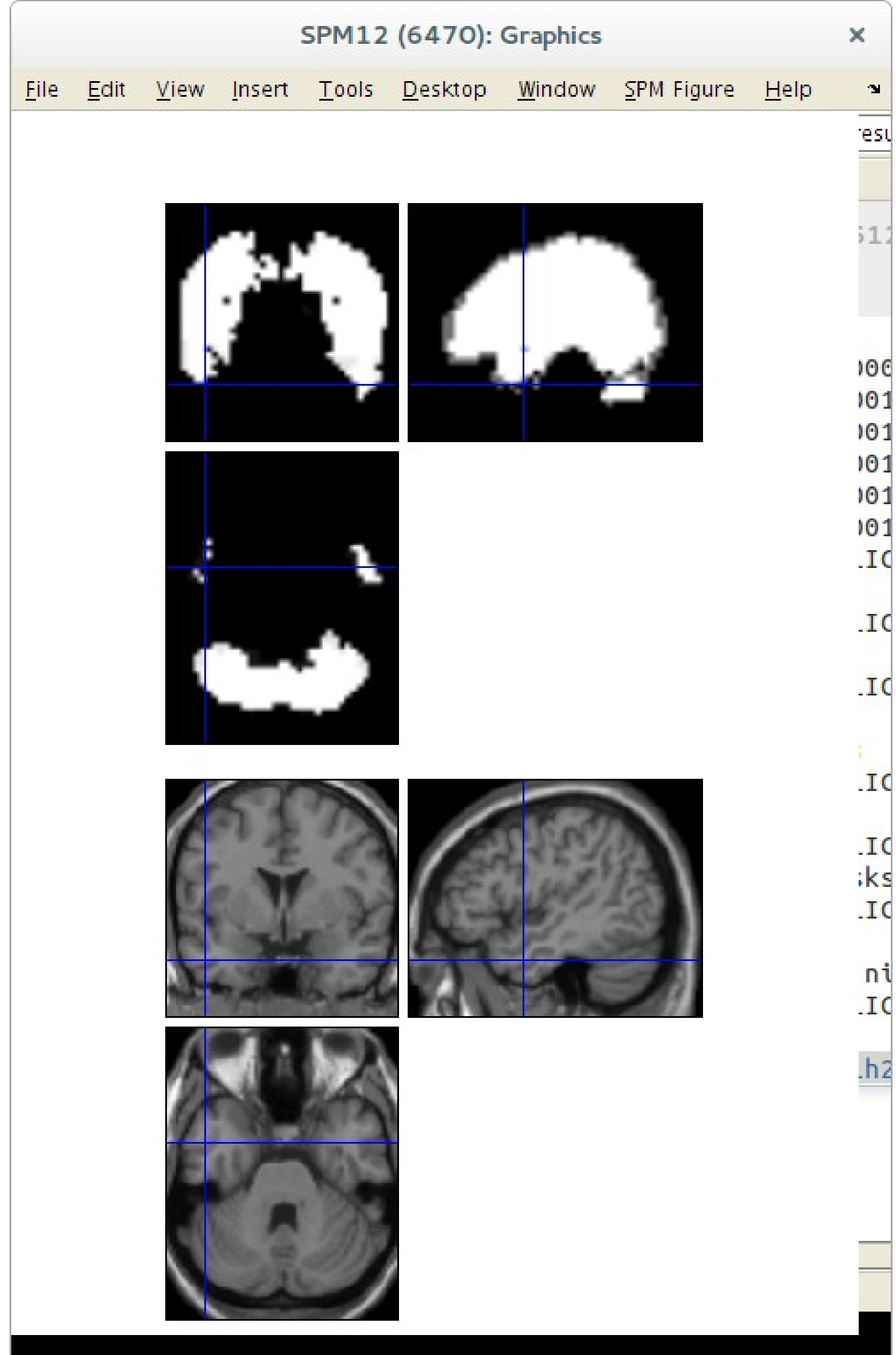


Intensity = 1267

Intensity = 571

Be aware of the masking issue in SPM: before estimaging a GLM, SPM scales the 4D EPI files so that the average of brain voxels is 100, and eliminates voxels with values <80 (“Implicit mask option”. Check mask.img !)

Example of a problematic mask.img (from a multiecho acquisition)



Temporal SNR (tSNR)

- In EPI, a time-series is obtained at every voxel.
  For univariate analyses, the temporal variabillity of noise is more relevant that the spatial variability noise.

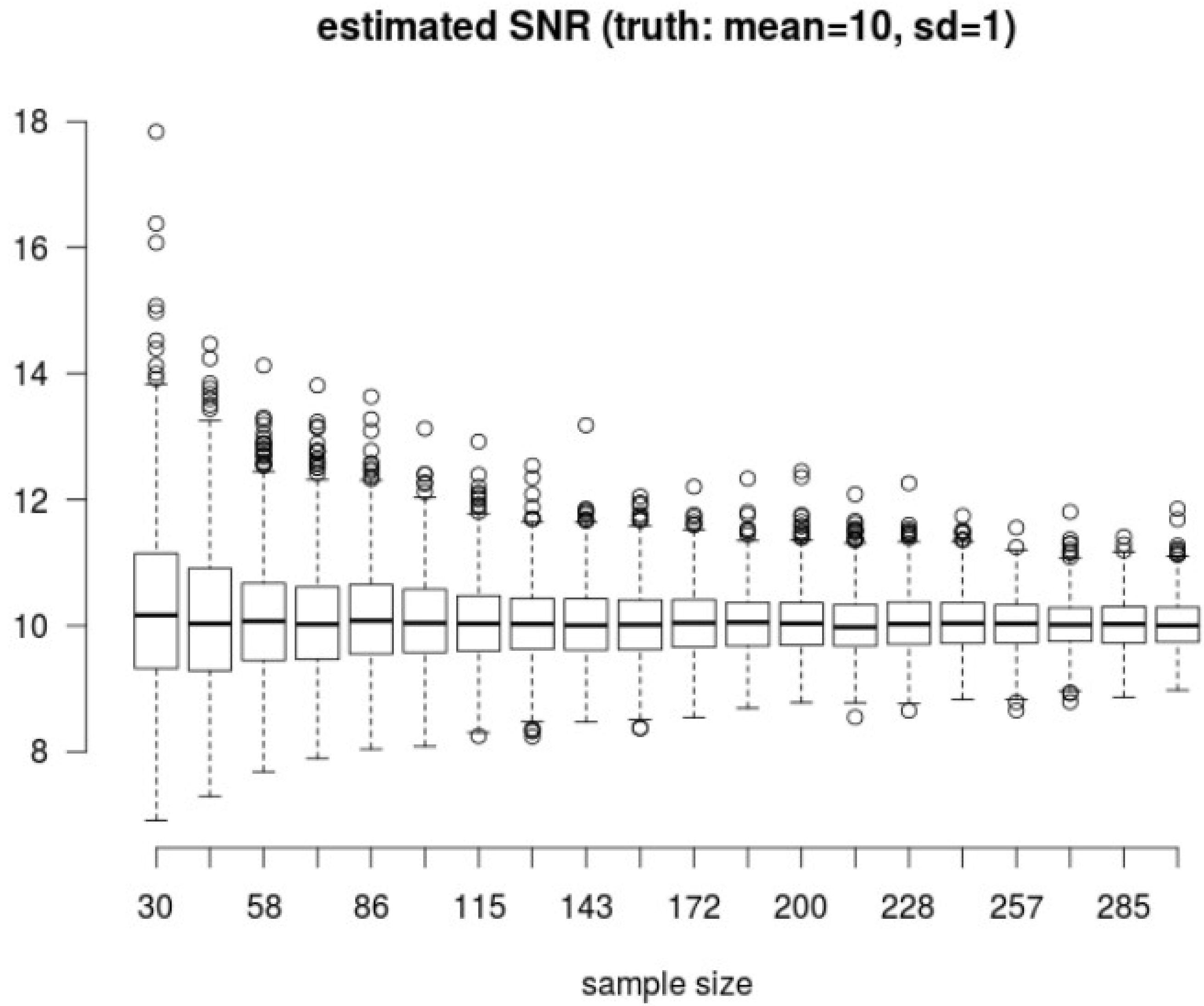
tSNR = mean/stdev of times series (high is good)

Remark: some software report the Coefficient of Variation which is just the inverse of tSNR:

CV=stdev/mean (low is good)

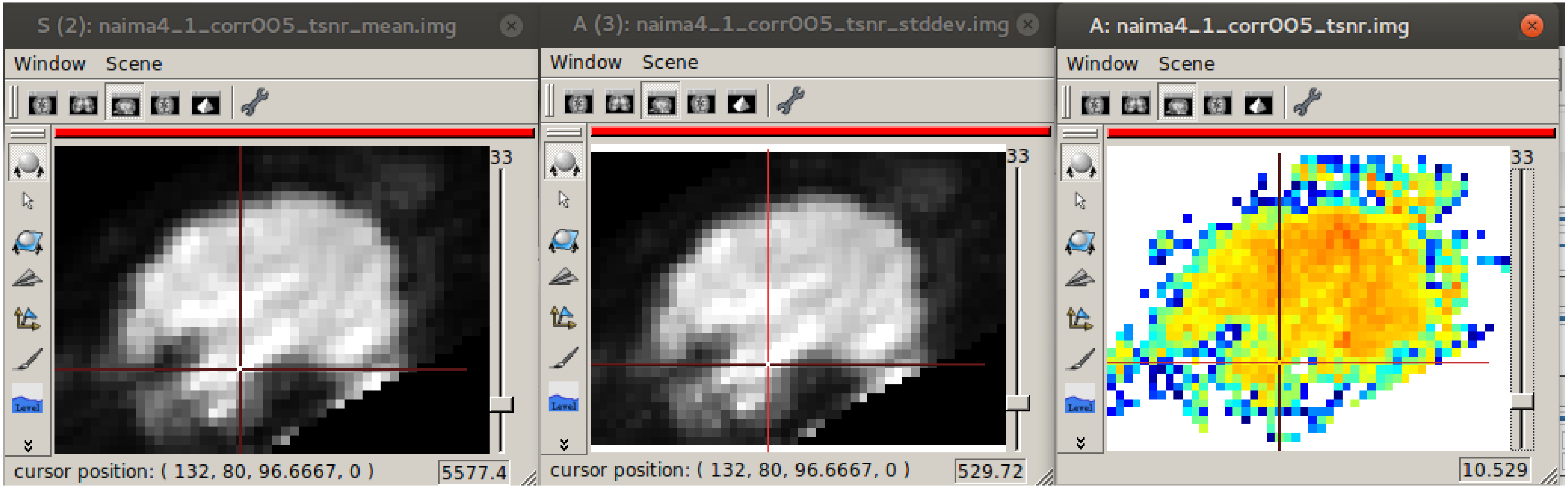
- **Why is tSNR relevant?**
  In fMRI, we often characterize the effects as **% of signal change** – thus even if if the average signal in a voxel is low, if there is still enough signal variance, it may still contain interesting (e.g. task-based) signal.
- **Remark:** Beware SPM: *betas* are globally but not locally scaled. It is difficult to relate them to '% signal change'.

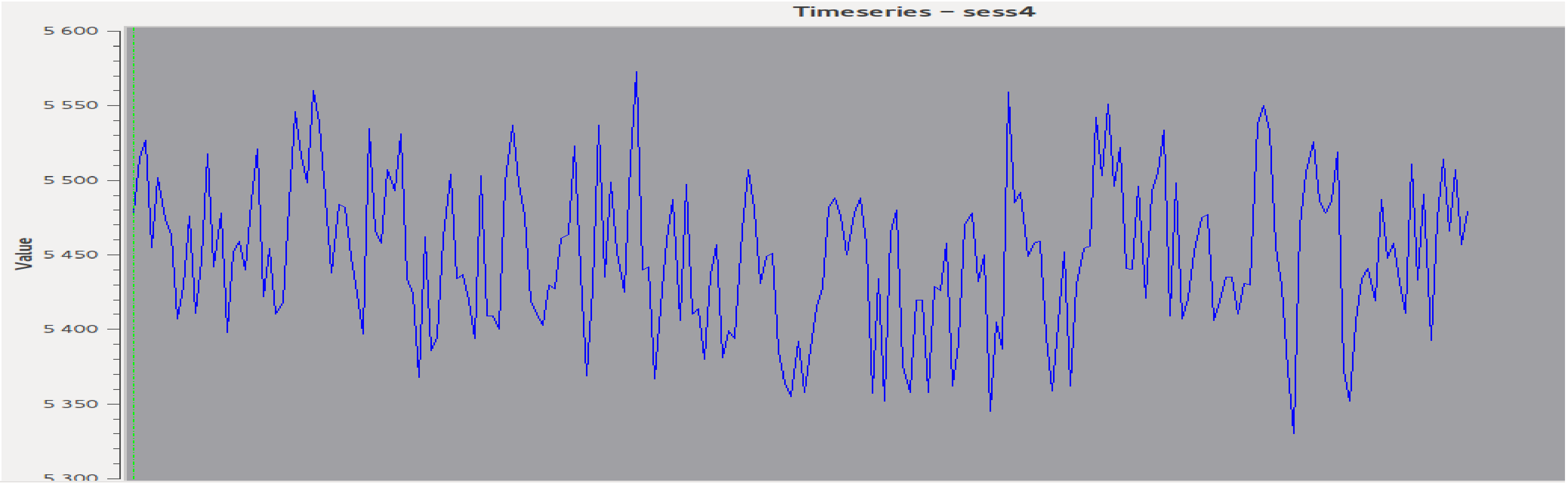
Precision of estimation of a SNR as a function of number of scans



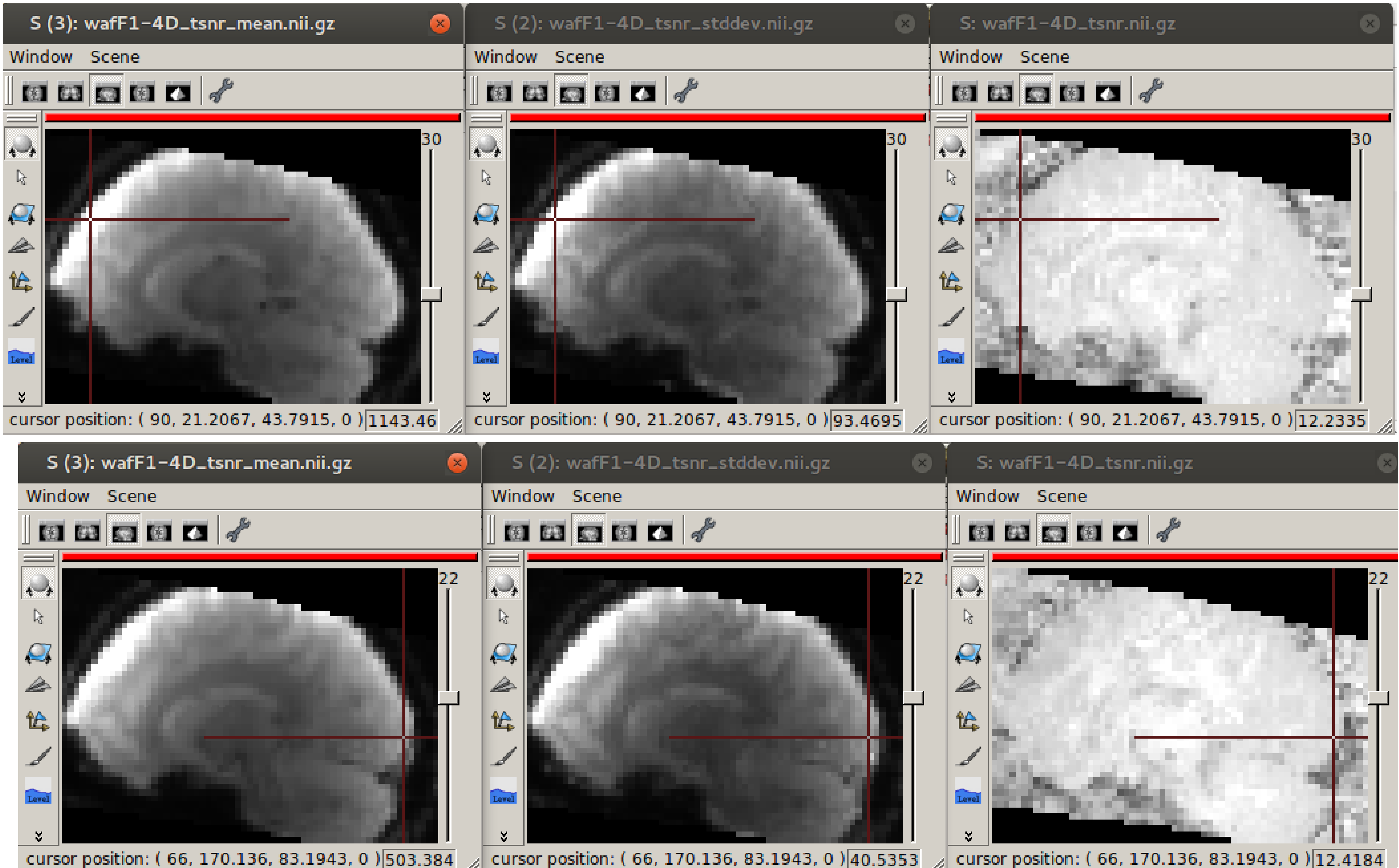
Results of a simulation where 1000 samples from a *random normal distrib*. (mean=10, sd=1), of various size were generated and their SNR computed

Example 1: 216 EPI (normalized) images from Bruker 3T (SHFJ, 2001)

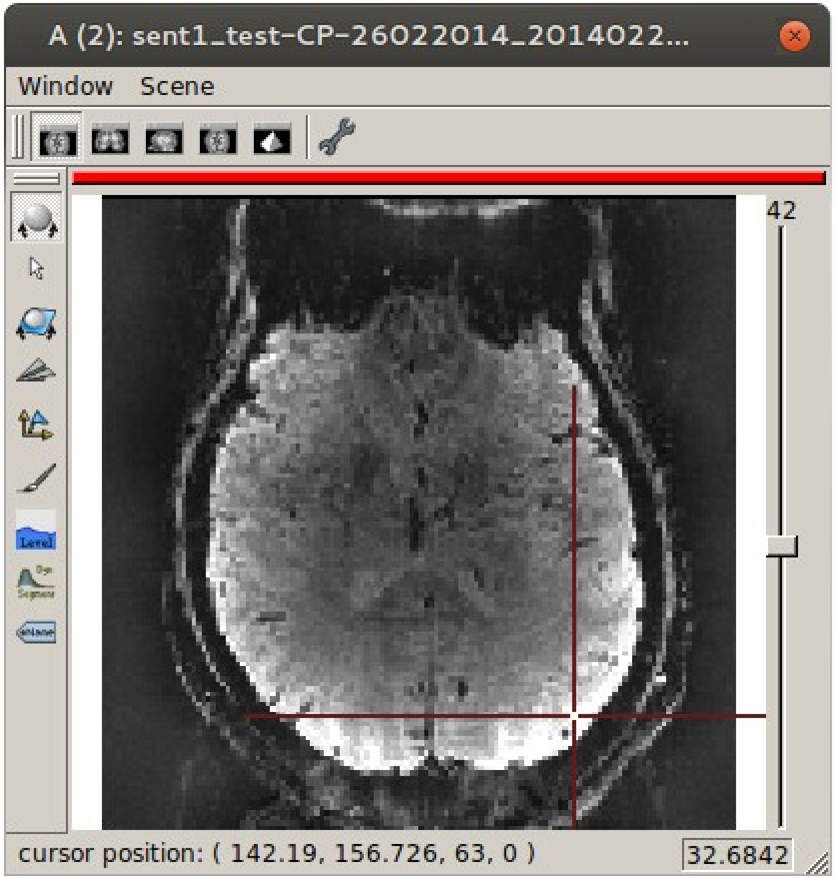


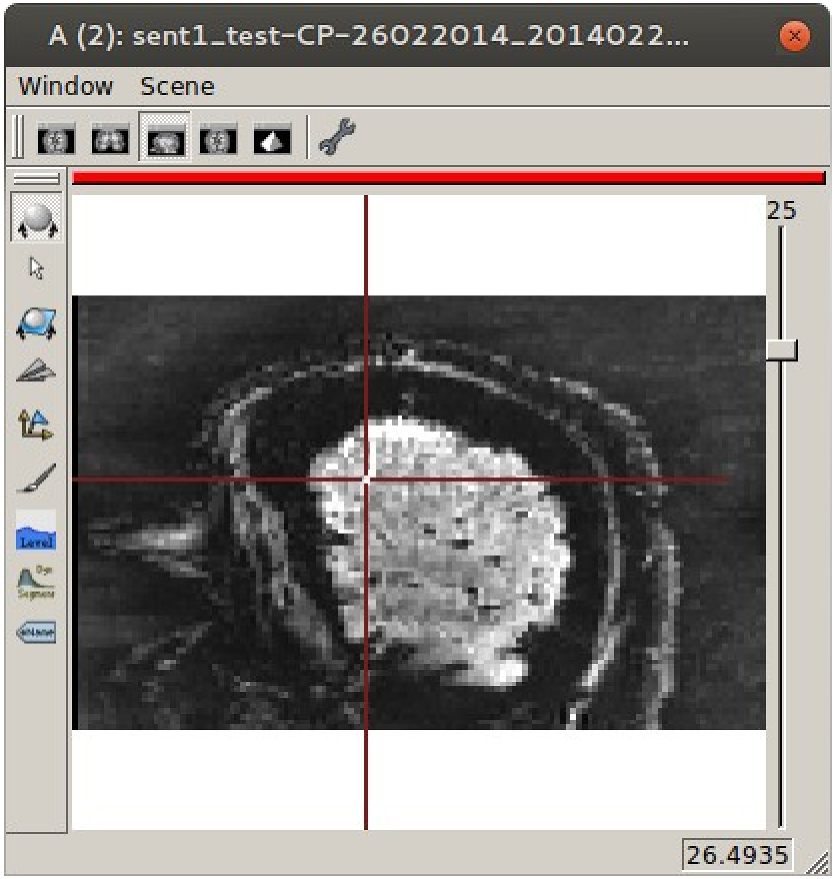


tSNR of an fMRI series with strong spatial bias
(3T siemens trio, 3x3x3mm after realigning & normalization; order=2)



tSNR of a MB4 1.5^4 EPI

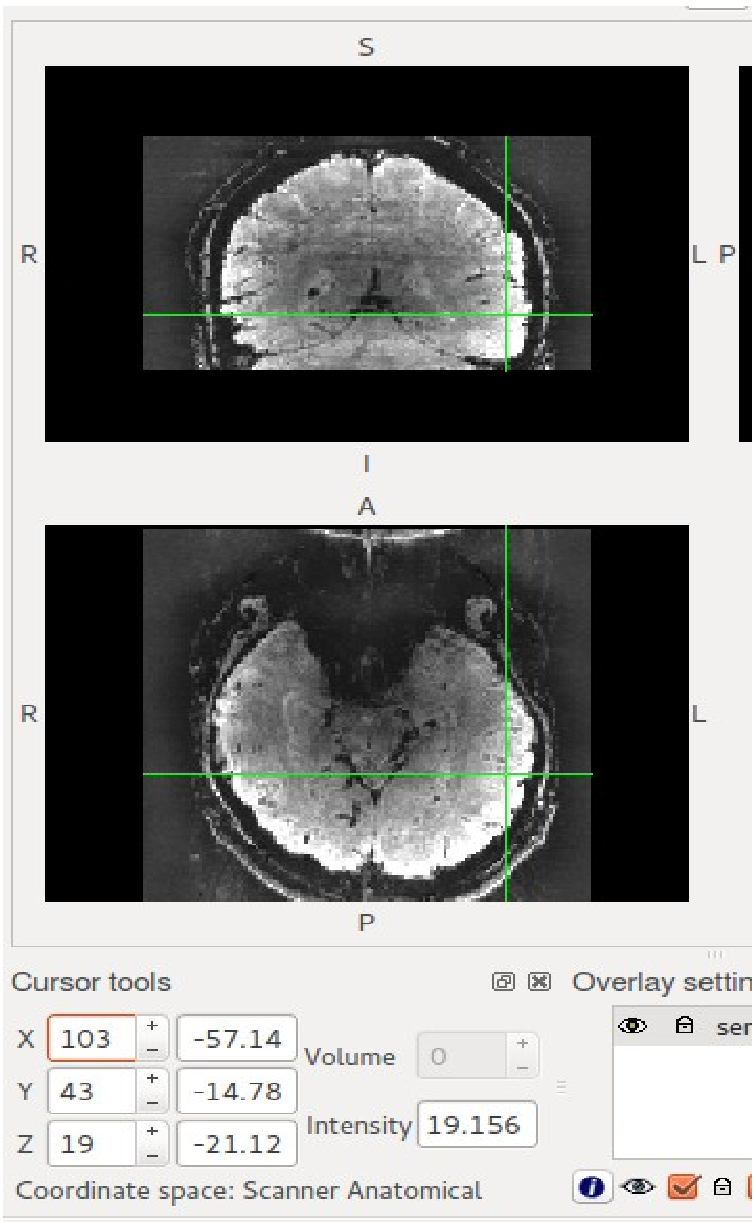




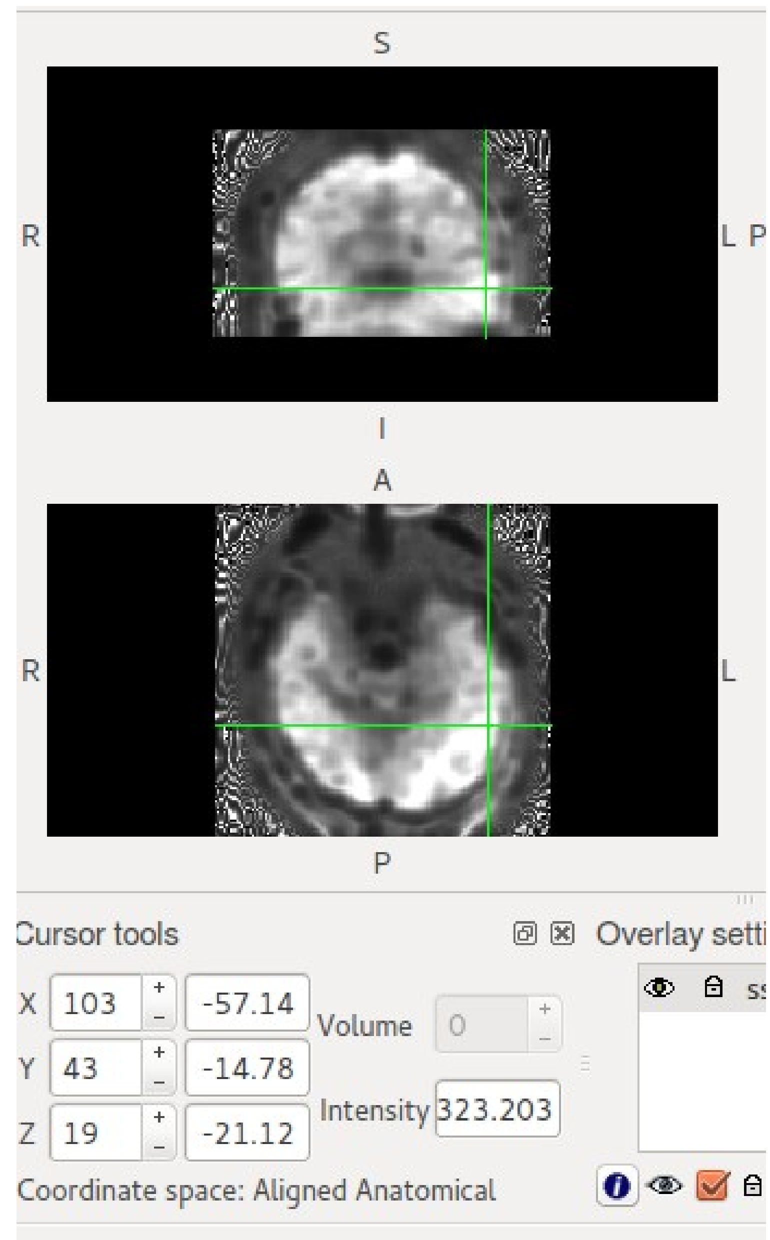
Beware: no detrend here it because of crash...

Effect of spatial smoothing

No smoothing 1.5x1.5x15



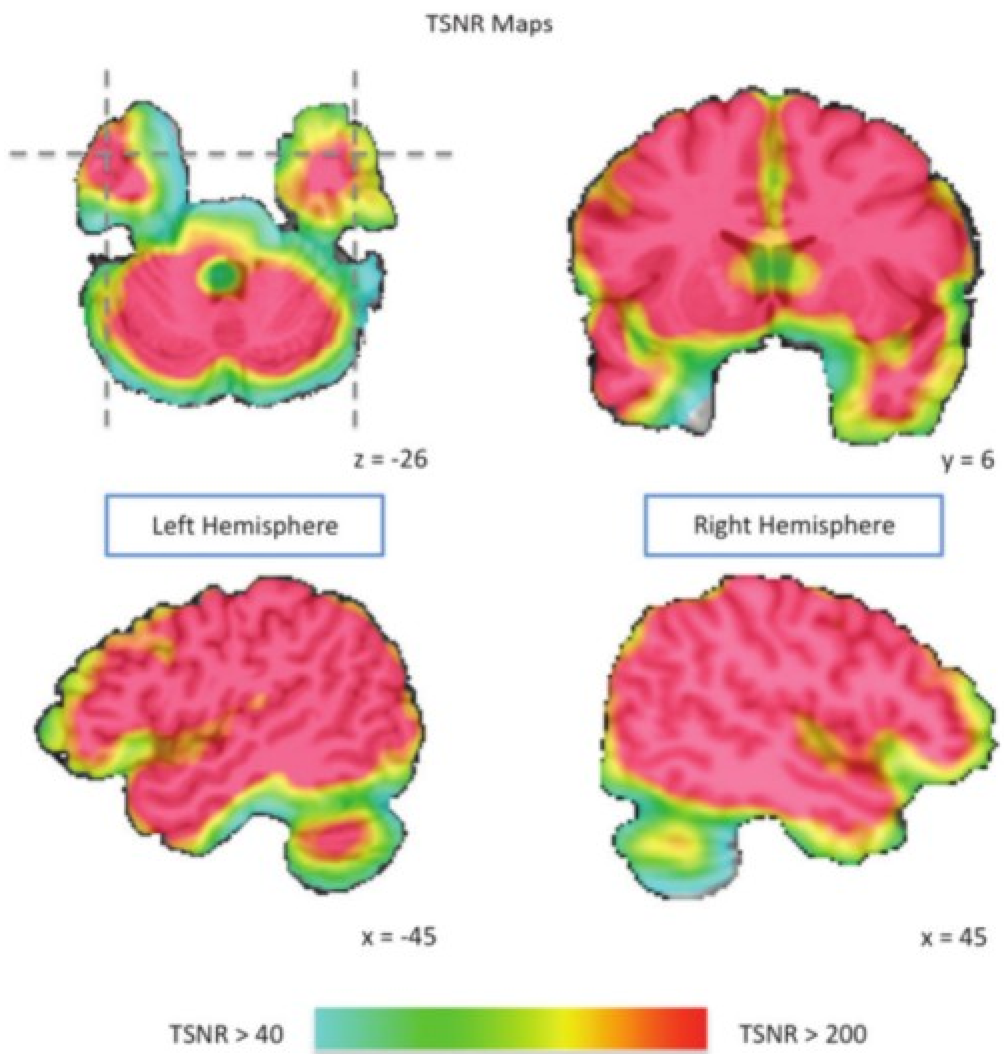
After smoothing by 8mm kernel



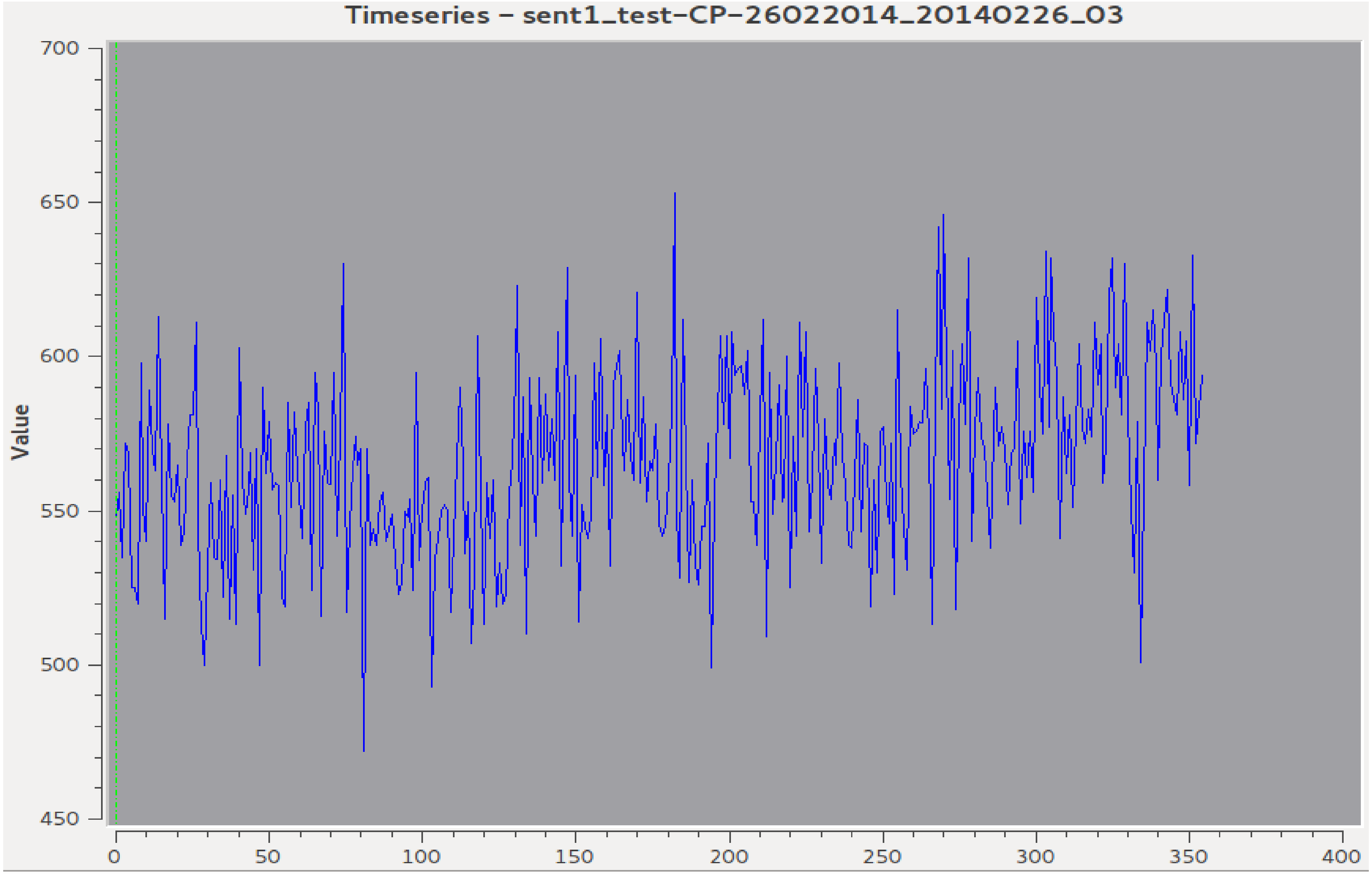
In the literature

Simmons, Reddish, Bellgowan, and Martin. (2010) “The Selectivity and Functional Connectivity of the Anterior Temporal Lobes.” Cerebral Cortex 20, no. 4 813–25.

From this map, the authors argue that the tSNR is large enough an ATL (>40) refering to Murphy et al. (2006)



Time-course in a voxel from MB4 TR=1.5s, 1.5mm isotropic

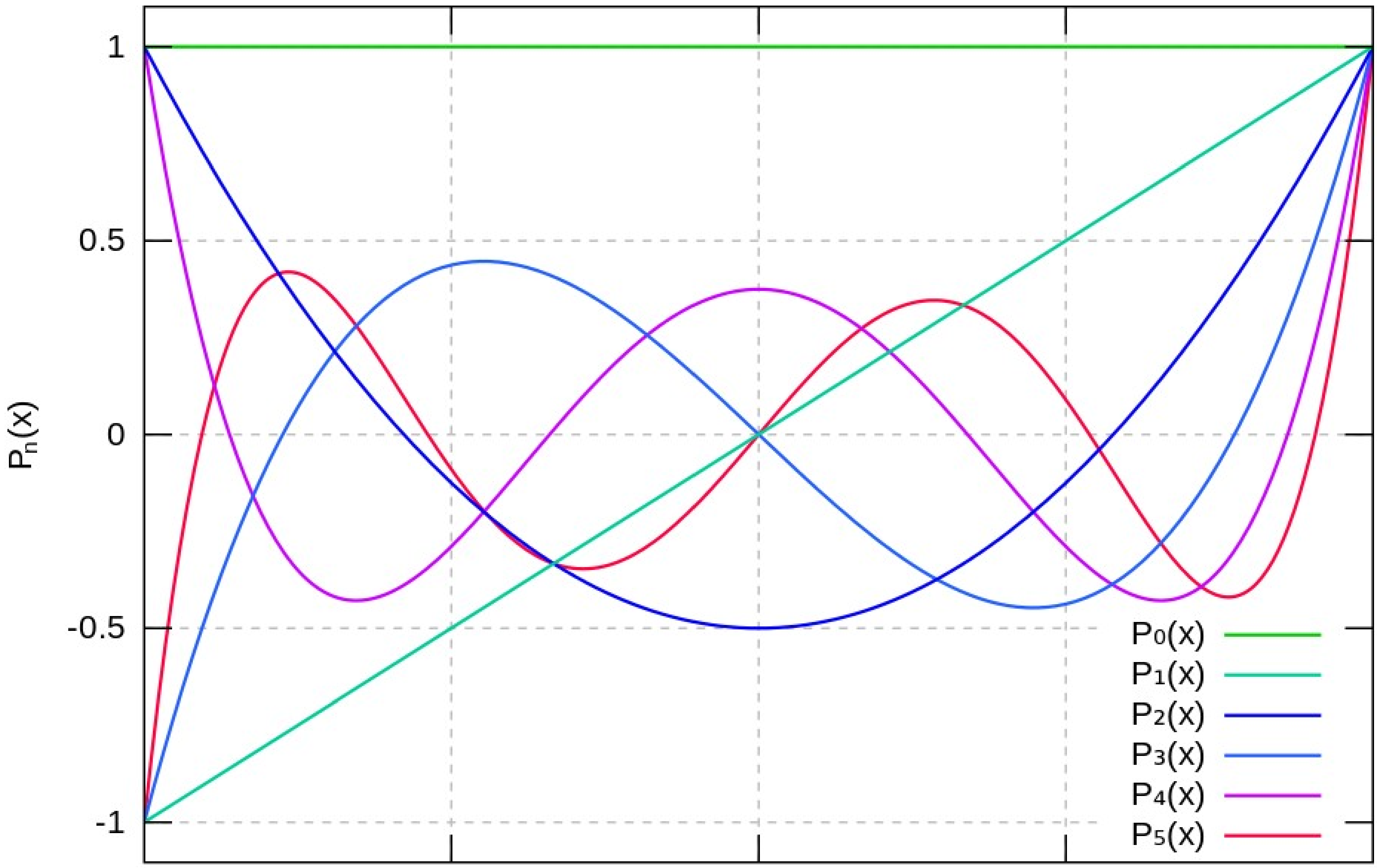


Detrending

Removing low-frequency drifts

- High-pass filter (e.g. by fitting low-freq cosines)
- Fitting low-order polynomials (to remove linear, quadratic, cubic, … trends)
- Fitting splines

Detrending with Legendre Polynomials (nipype)

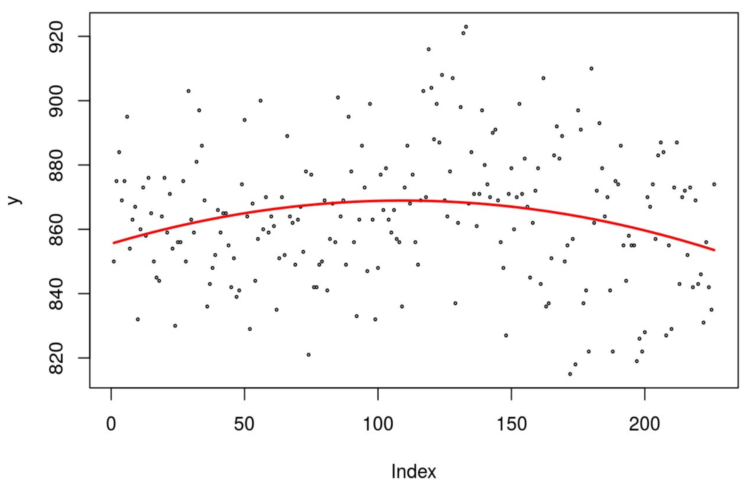


- To go further (probably not worth it), see Porges & Bohrer "The analysis of periodic processes in psychophysiological research" http://terpconnect.umd.edu/~sporges/bohrer.htm

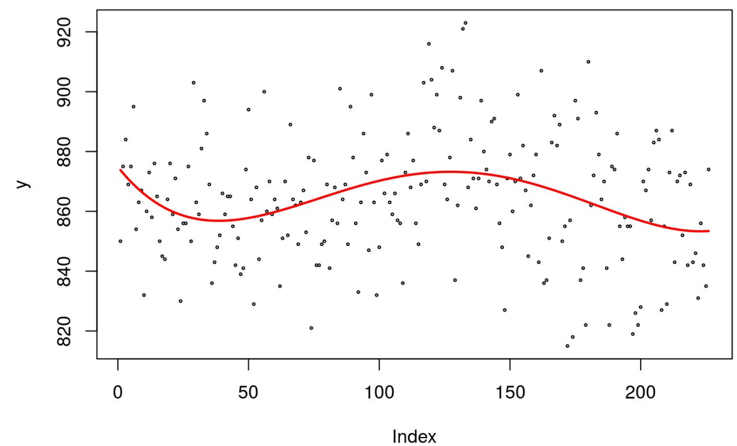
Estimating and removing drift

RAW tSNR= 40.9

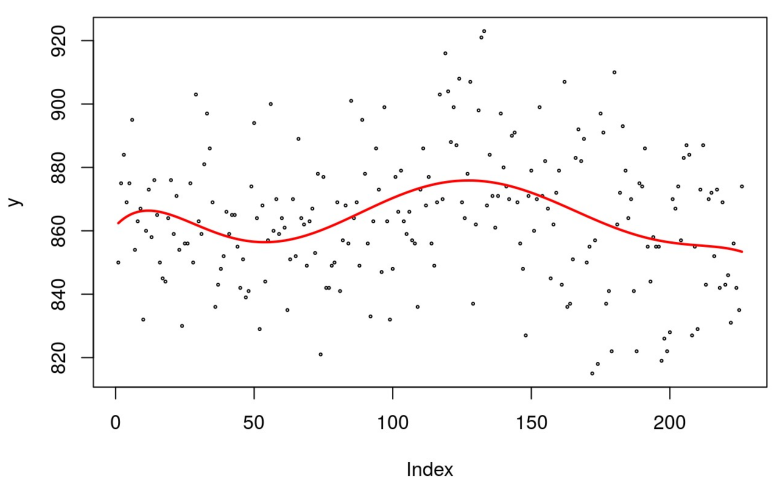
tSNR=42.4



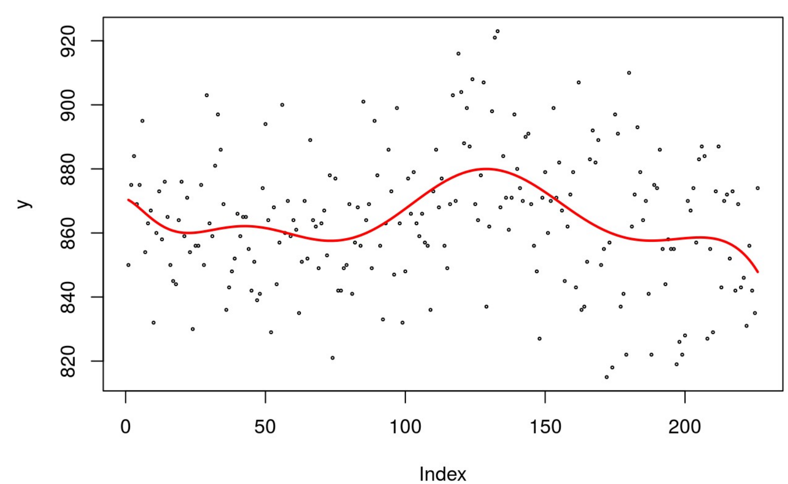
TSNR=42.9



TSNR=43.2



tSNR=43.8



See tsnr.html

How to compute a tSNR map?

Using nipype, this script, given a 4D nii file or a series of 3D nii files, will output the mean image, stddev image, and tSNR image.

```
#! /usr/bin/env python
import sys
from nipype.algorithms.misc import TSNR

tsnr = TSNR()
tsnr.inputs.in_file = sys.argv[1:]
tsnr.input.regress_poly=10 # detrending
tsnr.run()
```

But but but... with 'regress_poly', it crashes on many (but not all) datasets

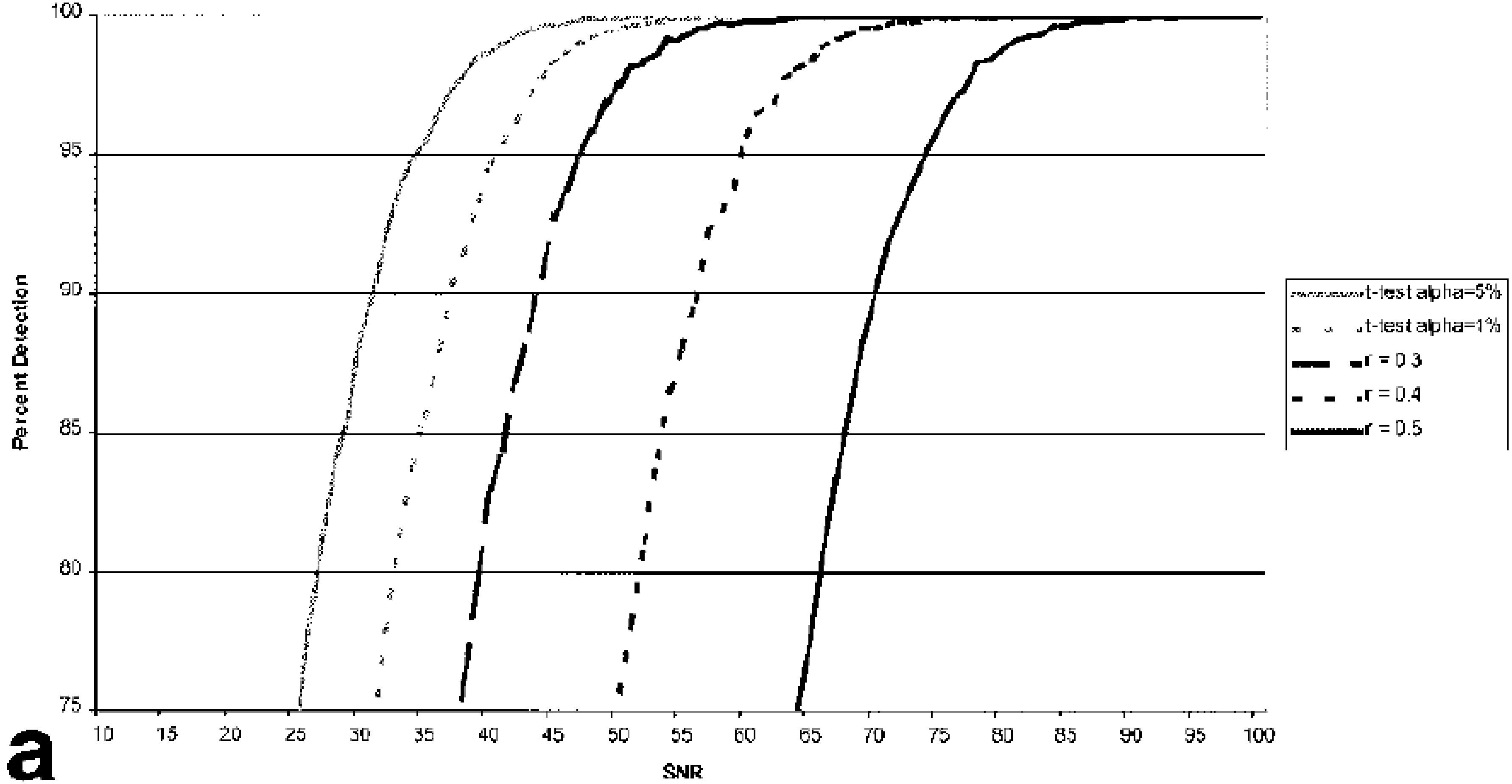
tSNR in task

- TSNR is typically computed in resting state blocks.
- If the subjects perform a task, some of the variance of the signal can be explained by the task. If you are obsessive, you could compute tSNR on the **residuals** of the linear model that include the theoretical HRF.

Suppose your model explains 20% of variance (r=.44):

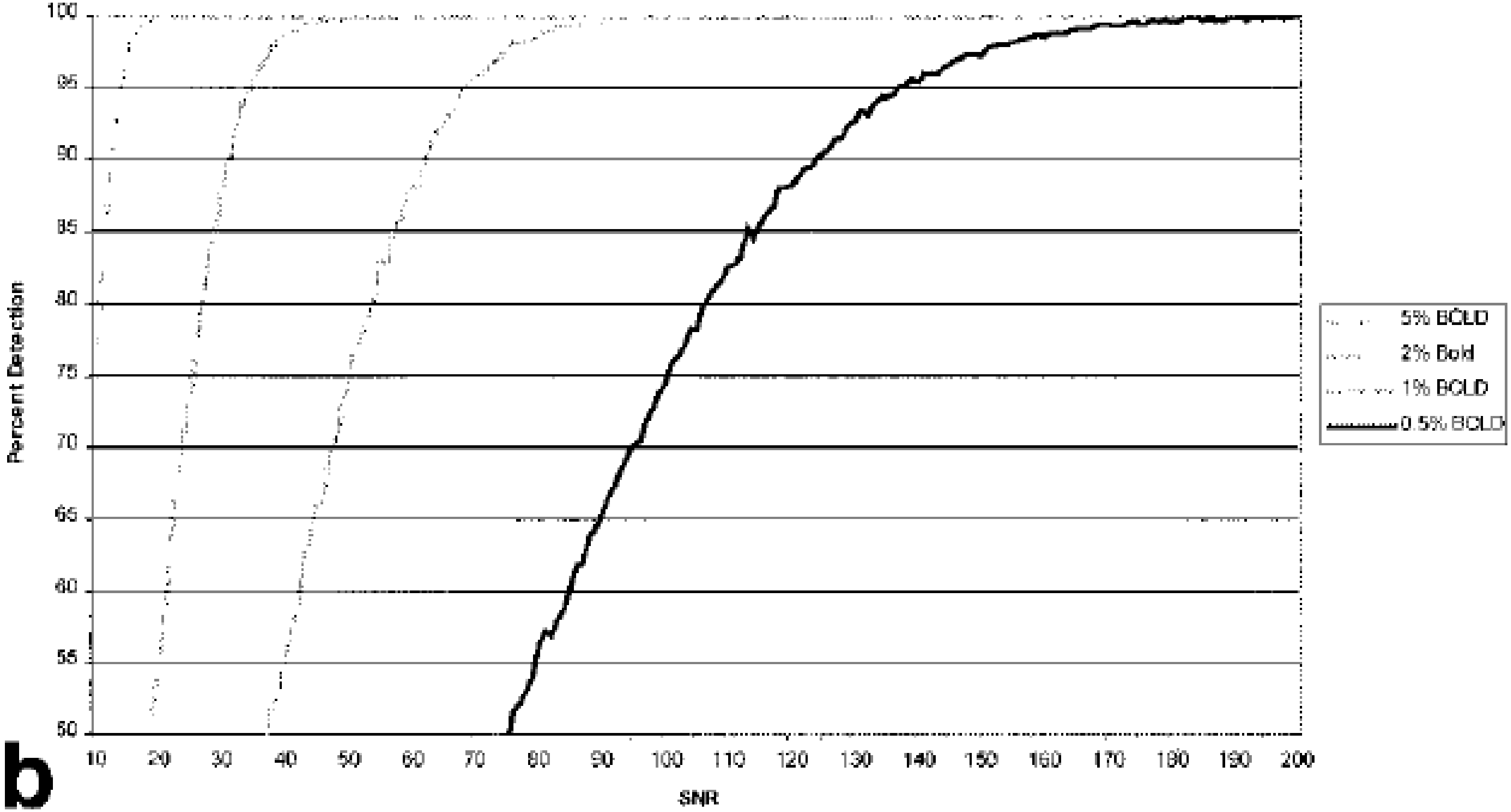
```
Signal: sqrt(1000) = 31.6

Noise: sqrt(4000) = 63.2

Both: sqrt(5000) = 70.7 (12% increase)
```

Power to detect a 2% effect as a function of SNR



Parrish et al. 2000 simulated time-series (N=112 scans) with various SNR and computed the power to detect a 2% signal increase with 5 criteria: (t-test pval=.05, pval=.1, or correlations r=0.3, 0.4, 0.5)

Power (for t-test at 5%) as a function of SNR and effect size



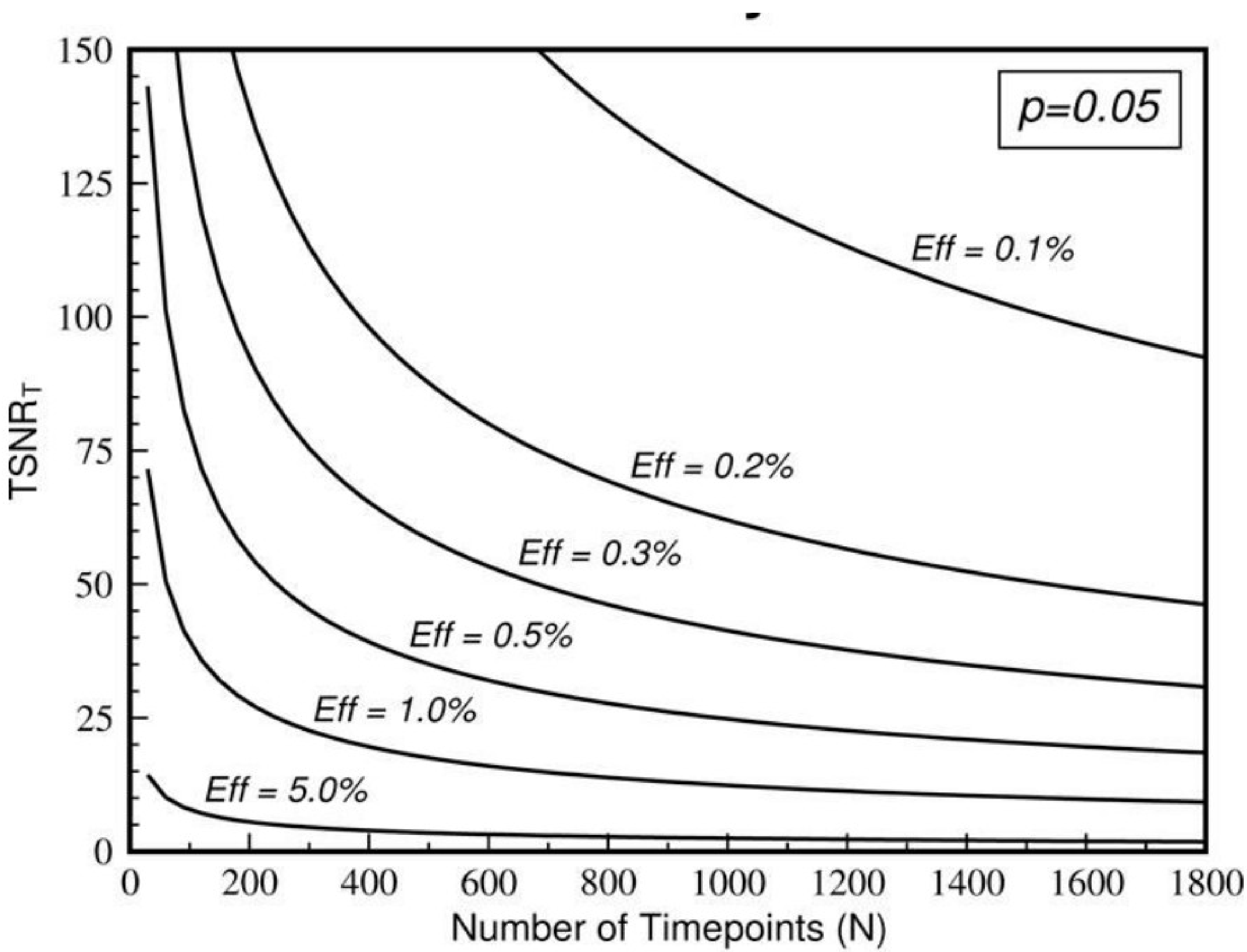
t-test with an alpha of 5% and N = 112. Note that the large signal changes (5%, small gray dashed line) are easier to detect because the required SNR is so low (SNR б 14). However, if smaller changes (<1%) are expected, the required SNR is much larger (SNR > 70)

Where do the signal fluctuations in a given voxel come from?

- **Thermal noise** (from electronics circuits of the scanner)
- **System noise** (instabilities in gradients, inhomogeneities, changes of B0...) => scanner drift
- **Physiological noise** (present only in vivo)
  - cerebral metabolism (CMRO 2), blood flow (CBF), and blood volume (CBV)
  - cardiac and respiratory functions
- **Subject's movements**

“How Long to Scan? The Relationship between fMRI Temporal Signal to Noise and Necessary Scan Duration.”
Murphy, Bodurka & Bandettini. 2007 NeuroImage 34 (2): 565–74.

tSNR needed to detect an effect (with power 80%?)



Dependence on Field Strength

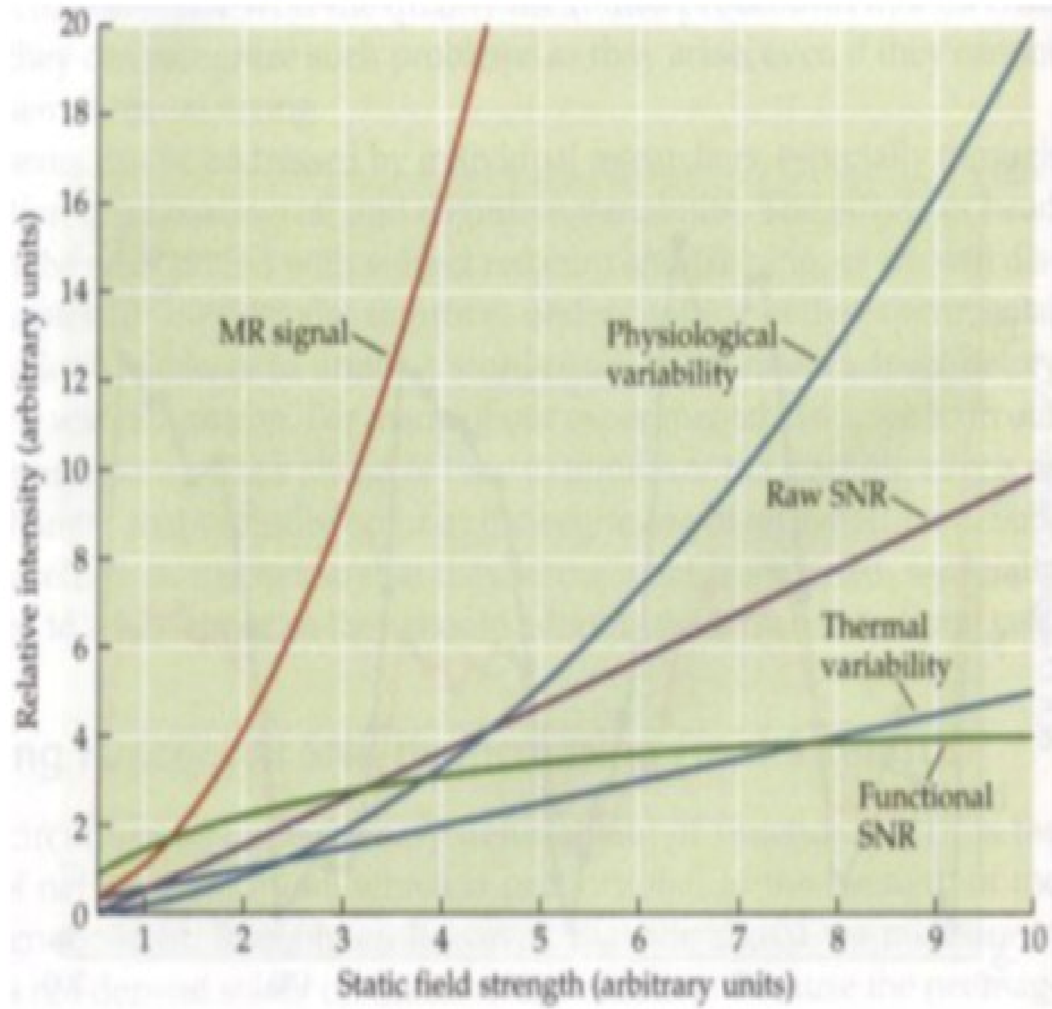


Figure 9.13 Changes in signal and noise with increasing static field strength. MR signal increases with the square of the field strength, while thermal noise increases linearly with field strength. The ratio of these quantities, raw SNR, thus increases linearly with field strength. However, because physiological noise increases with the square of field strength, functional SNR (which is dependent on both thermal and physiological noise) may reach an asymptote at high fields. Note that here the field strength is indicated in arbitrary units; the field strength beyond which such an asymptote would occur is not yet established.

- Physiological noise increases quadratically with B0 and dominates at high field. tSNR asymptotes

Relationship between tSNR and SNR and effect of voxel size

From Murphy, Bodurka & Bandettini. 2007. “How Long to Scan? The Relationship between fMRI Temporal Signal to Noise and Necessary Scan Duration.” NeuroImage 34 (2): 565–74.

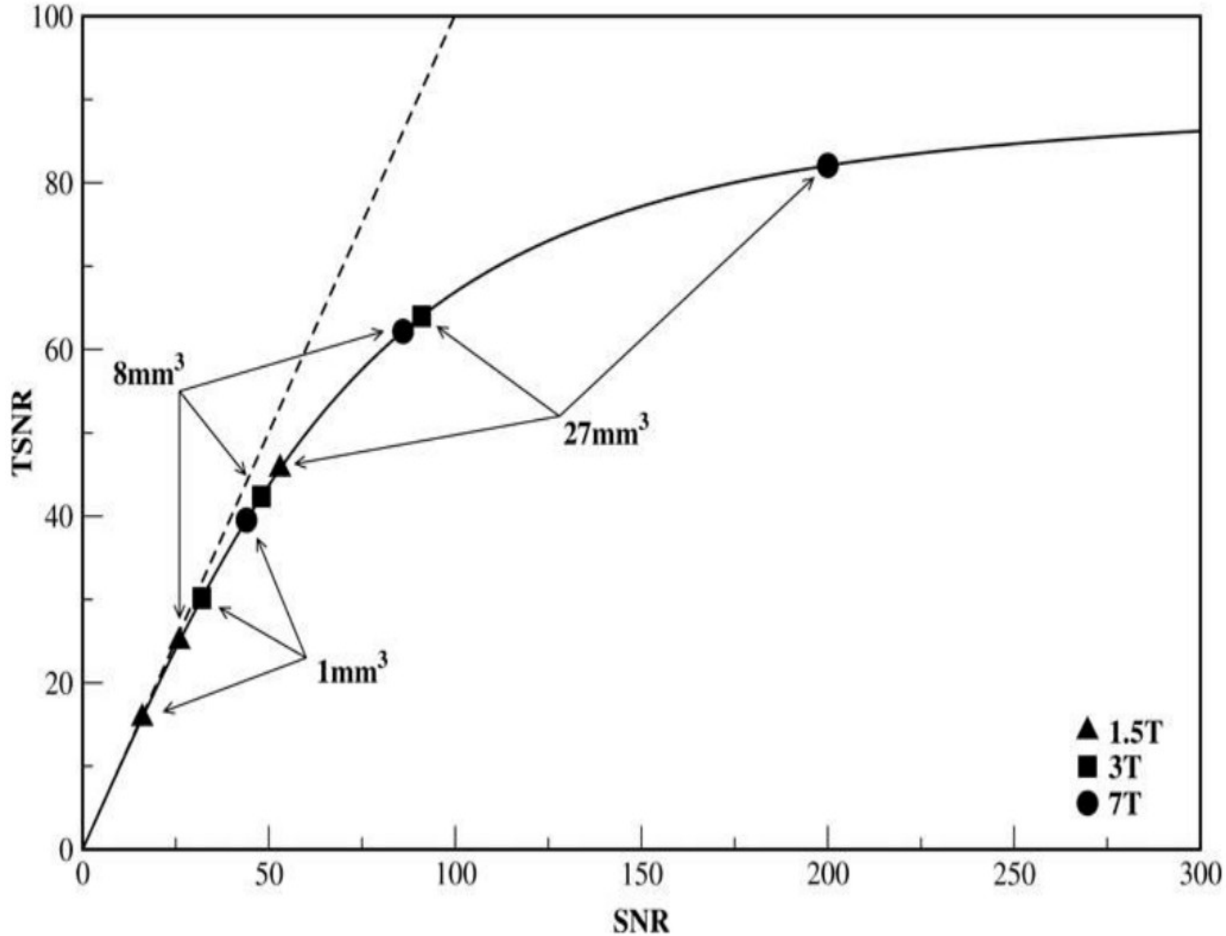


Figure 1.
A schematic of the relationship between TSNR and SNR in gray matter is shown. The dashed line represents this relationship in the absence of physiological noise. In vivo, gains in TSNR are limited by physiological noise as SNR is increased and this relationship is displayed with the solid line. For gray matter, the TSNR limit is approximately 87 (Bodurka et al., 2005). Using values derived from those reported by Triantafyllou and colleagues (Triantafyllou et al., 2005), estimates of SNR for 1.5T, 3T and 7T scanners equipped with standard head coils are shown for voxel sizes of $1\times1\times1 mm^3 = 1 mm^3$, $2\times2\times2 mm^3 = 8 mm^3$ and $3\times3\times3 mm^3 = 27 mm^3$.

Effect of smoothing

- Triantafyllou, Hoge, and Wald. 2006. “Effect of Spatial Smoothing on Physiological Noise in High-Resolution fMRI.” *NeuroImage* 32 (2): 551–57 wrote:

At 7T, 5 x 5 x 3 mm3 resolution images derived from smoothing 1.5 x 1.5 x 3 mm3 data improved time-course SNR by a factor of 1.89 compared to a time-series acquired at 5 x 5 x 3 mm3.

Presumably, this effect was derived from the reduced physiological-to-thermal noise ratio in the high spatial resolution data followed by a smoothing operation that improves SNR without adding physiological noise.

References to go further

- Murphy, Bodurka & Bandettini. 2007. “How Long to Scan? The Relationship between fMRI Temporal Signal to Noise and Necessary Scan Duration.” NeuroImage 34 (2): 565–74.
- Parrish, Gitelman, LaBar & Mesulam, and others. 2000. “Impact of Signal-to-Noise on Functional MRI.” Magnetic Resonance in Medicine 44 (6): 925–32.
- Krüger, Kastrup & Glover. 2001. “Neuroimaging at 1.5 T and 3.0 T: Comparison of Oxygenation-Sensitive Magnetic Resonance Imaging.” Magnetic Resonance in Medicine 45 (4): 595–604.
- Triantafyllou, Polimeni, and Wald. 2011. “Physiological Noise and Signal-to-Noise Ratio in fMRI with Multi-Channel Array Coils.” NeuroImage 55 (2): 597–606.

Happy Xmas & NewYear's eve!