Advanced methods for cleaning up fMRI time-series

How to minimize noise at the acquisition stage

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The challenge

- "Impacting the effect of fMRI **noise** through hardware and acquisition choices – Implications for controlling false positive rates"
  Ward & Polimeni, NeuroImage (in press)
- First sentence of their introduction
  - Applied to the intensity fluctuations of a pixel in an fMRI time- series, the term "noise" is so non-specific and carries such negative connotations that it should probably be eliminated from the fMRI vocabulary.
- Noise is
  - Measurement noise: thermal noise & imperfect image reconstruction
  - Temporal-signal-to-noise and Contrast-to-noise
  - Undesired signal fluctuations: Breathing, pulsation, head movement, chest movement, task non-compliance, unmodeled neural effects, unmodeled aspects of the hemodynamic actual responses

Overview

- Preventative scanner health
- Peripherals & Participants
- Parameters & Pulse Sequences

Preventative scanner health

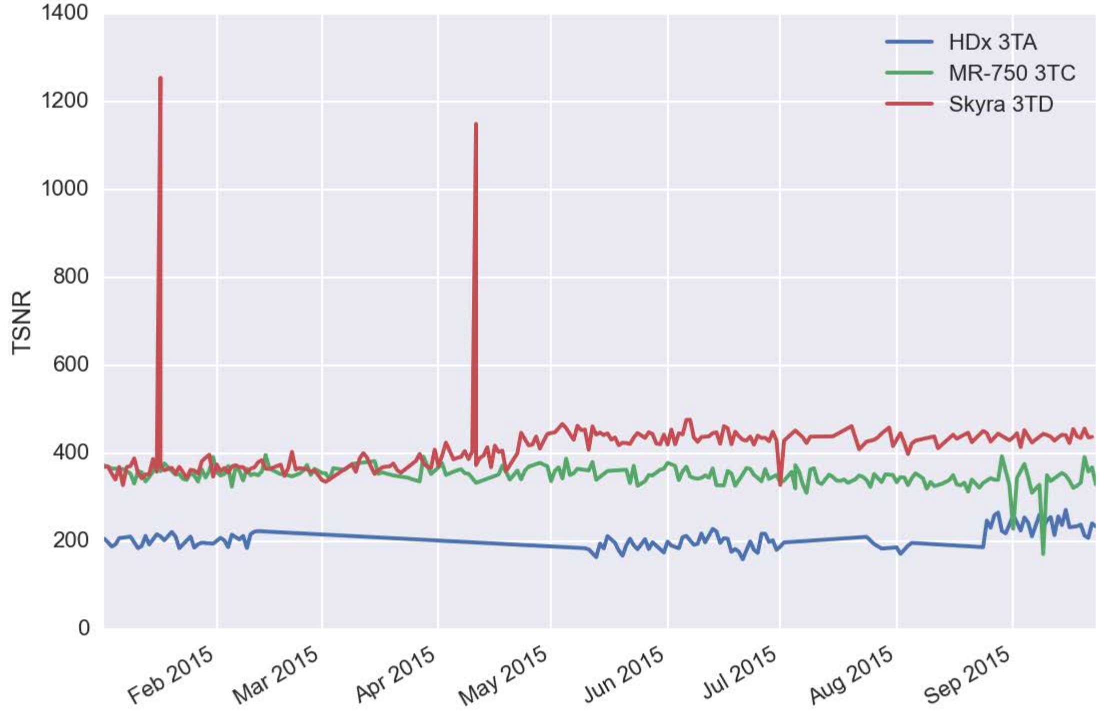
- Regular Quality Assessment (QA) scans
- Regular Overall Evaluation of Results
- Real Time Data Observation

Quality Assessment Scans
NIH Intramural example

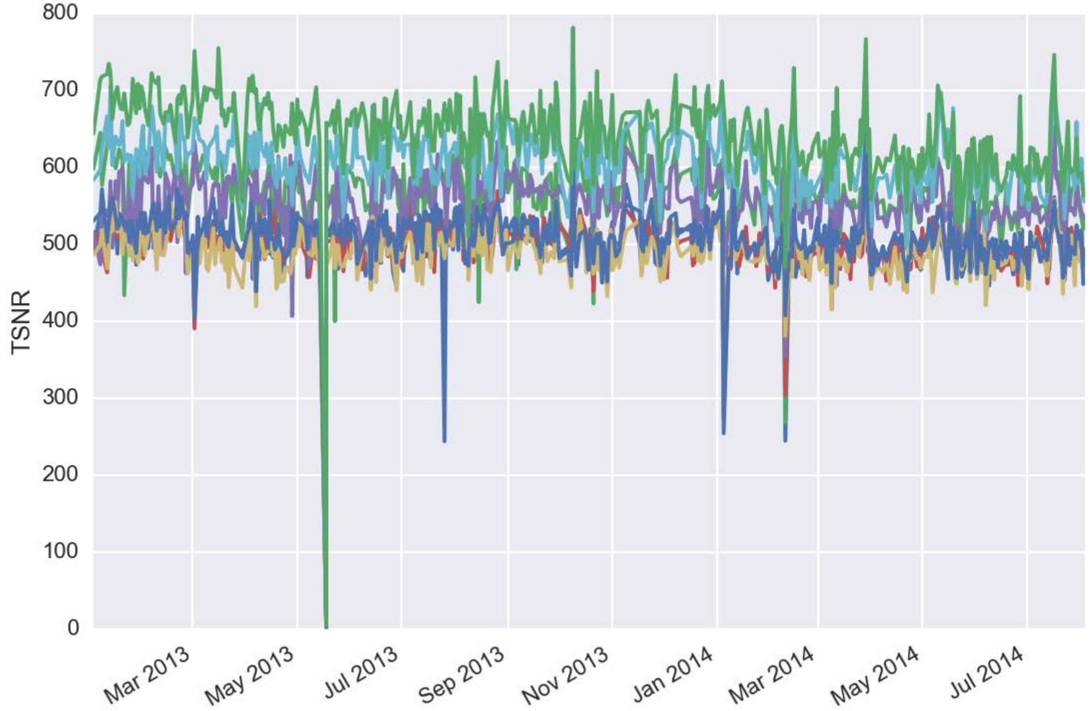
- Approximately daily scans of an oil phantom for every commonly used head coil on every scanner
- Parameters that can provide long-term consistency
  - Single Echo EPI, no acceleration; 72x72 grid; 37 slices; 3mm^3 voxels; 5-10 min of data per receiver coil
- Save reconstructed & (sometimes) raw data
- Try to automate processing & recording pipeline

Sample QA Plots of Temporal Signal To Noise Ratio

From different scanners



From each receiver coil on one scanner



Images from Vinai Roopchansingh

Regular Results Evaluations

MRIQC: group anatomical report

Summary

- Date and time: 2017-02-05, 12:27.
- MRIQC version: 0.9.0-rc2.

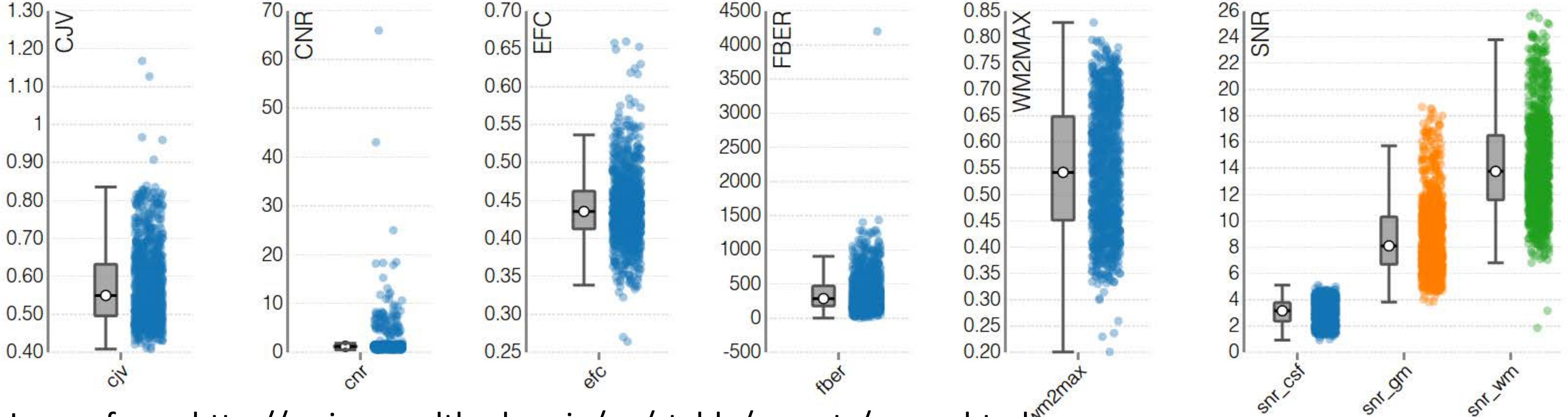
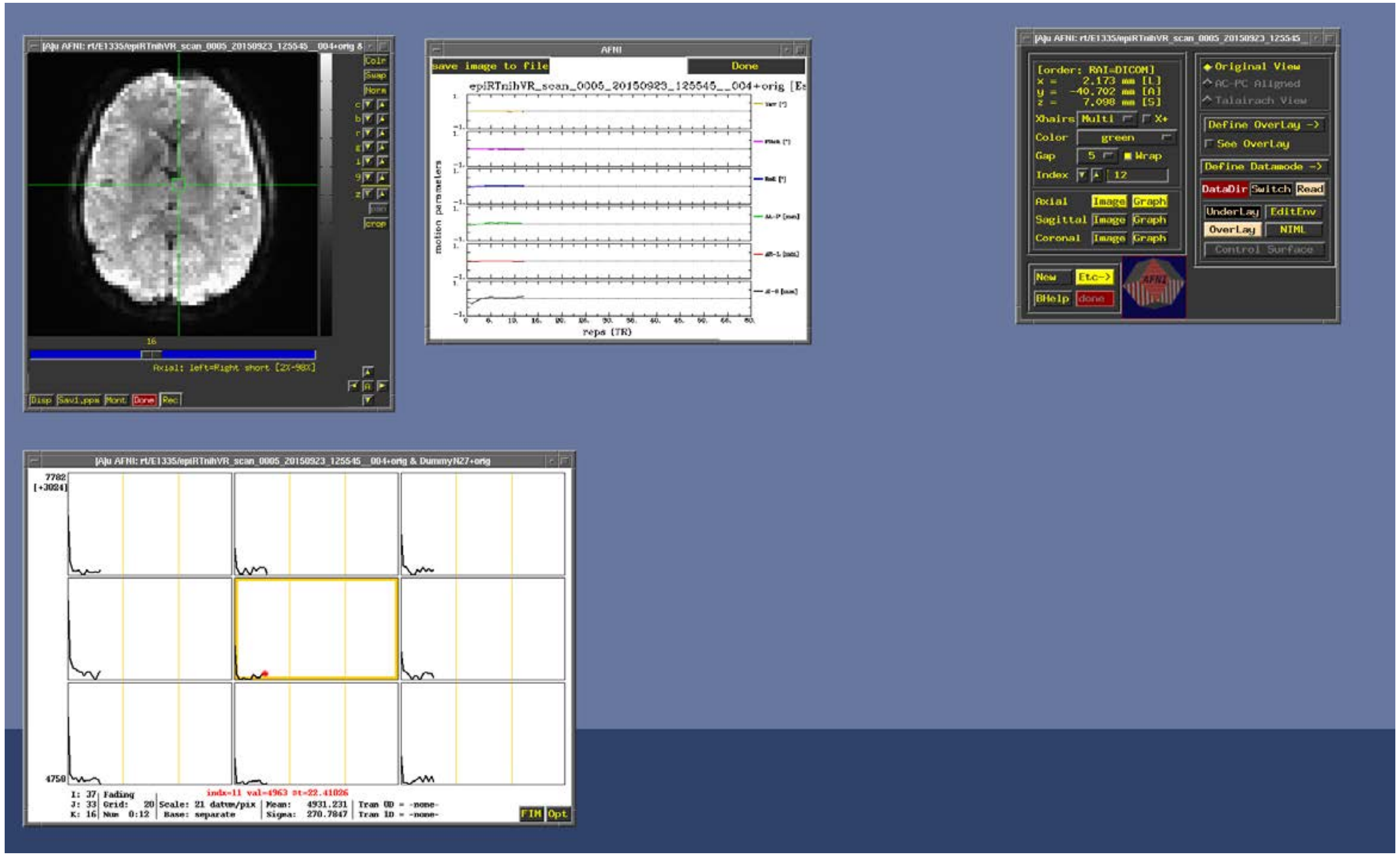


Image from: http://mriqc.readthedocs.io/en/stable/reports/group.html

MRIQC code: https://github.com/poldracklab/mriqc
MRIQC new web API: https://mriqc.nimh.nih.gov/

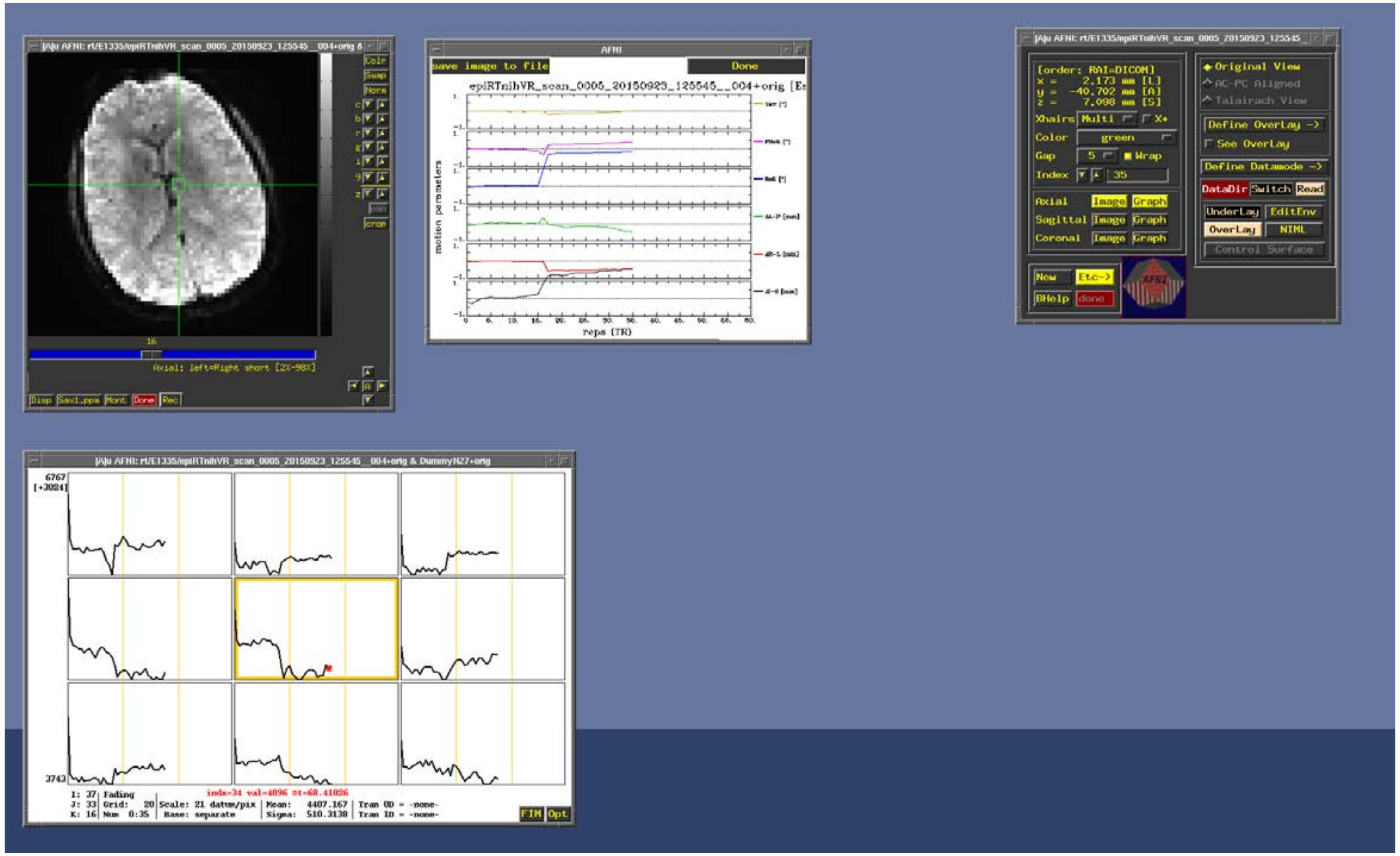
Real time observation of motion



AFNI real time interface

Images from Vinai Roopchansingh

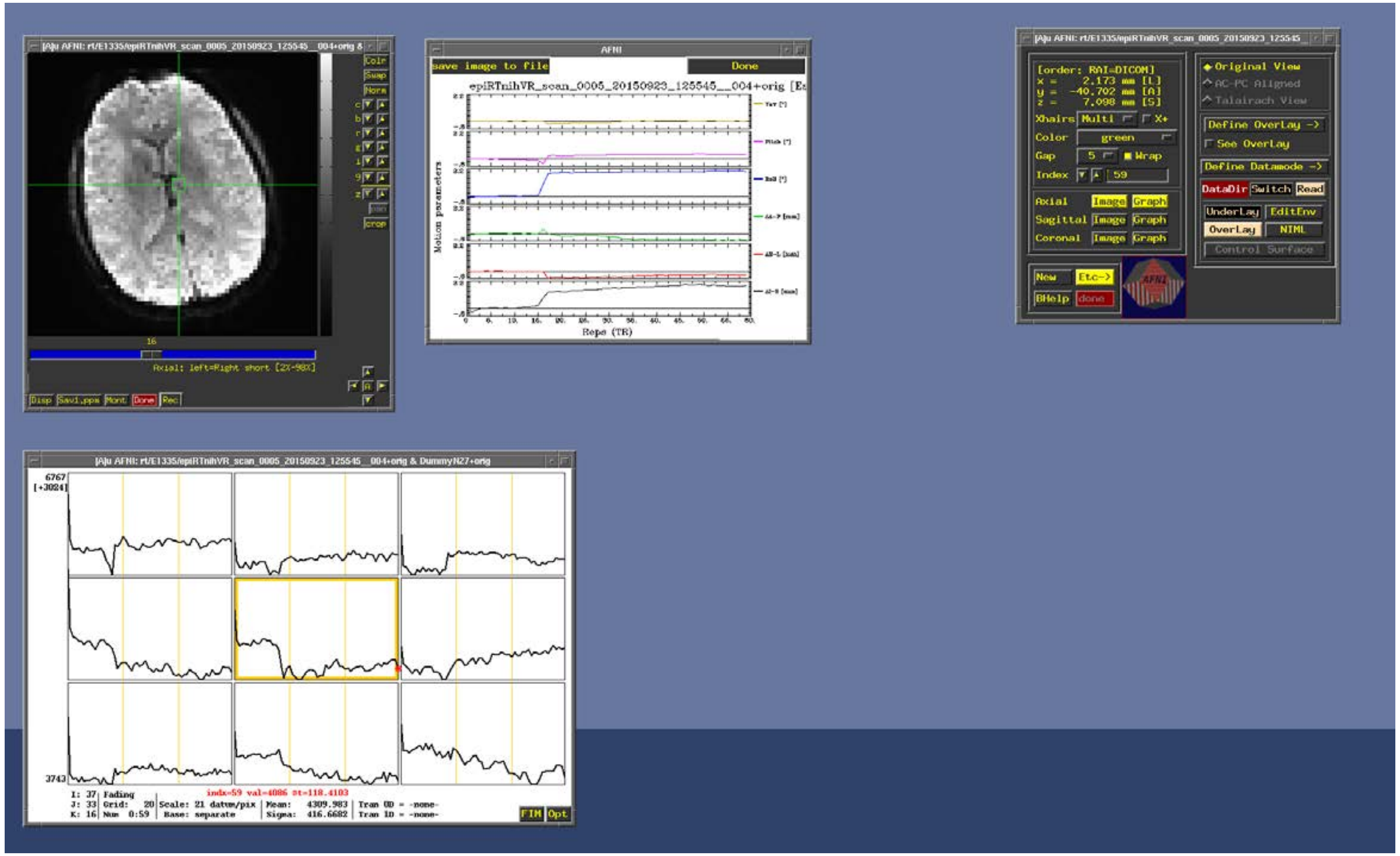
Real time observation of motion



AFNI real time interface

Images from Vinai Roopchansingh

Real time observation of motion

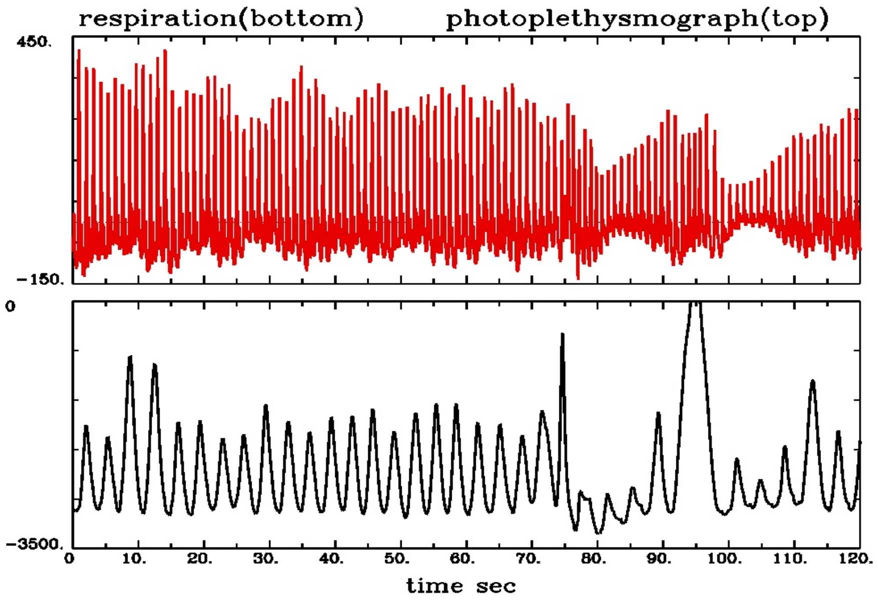


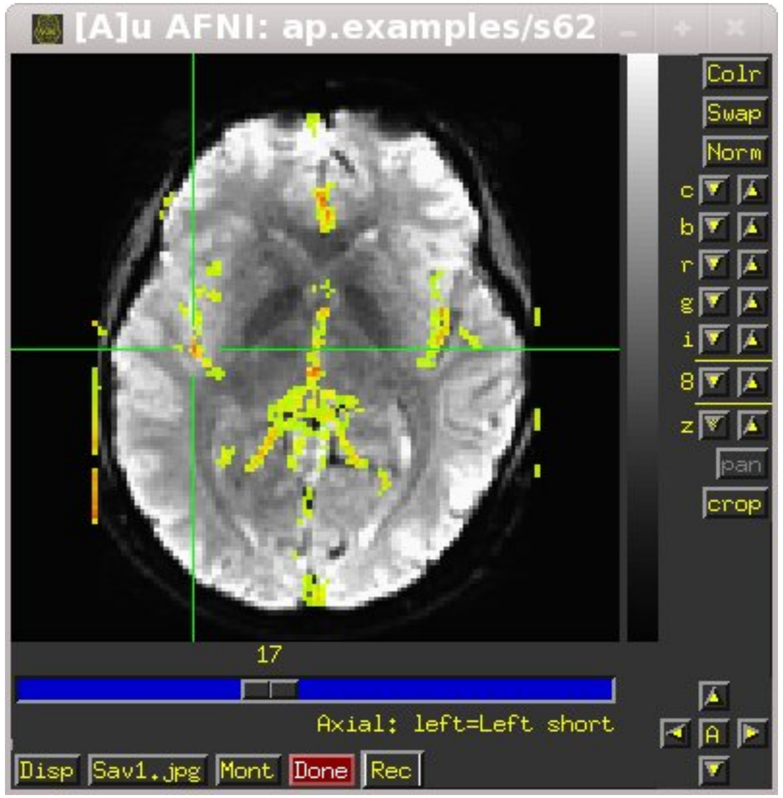
AFNI real time interface

Images from Vinai Roopchansingh

Real time correlations as a monitoring tool

Respiration artifacts





Using InstaCorr in AFNI

Image by Ziad Saad: https://afni.nimh.nih.gov/pub/dist/edu/latest/afni_handouts/BiasSources_RS-FMRI.pdf

Correlations for artifact monitoring

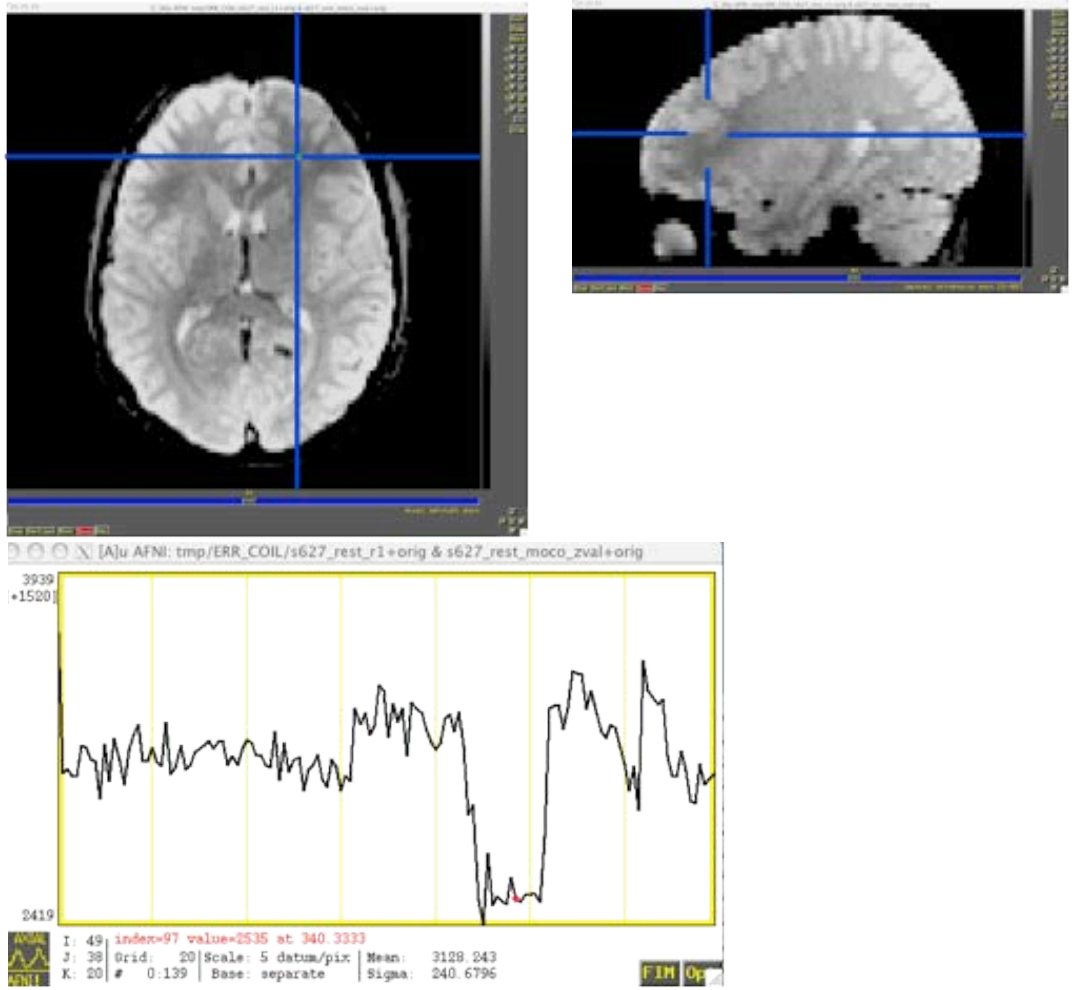
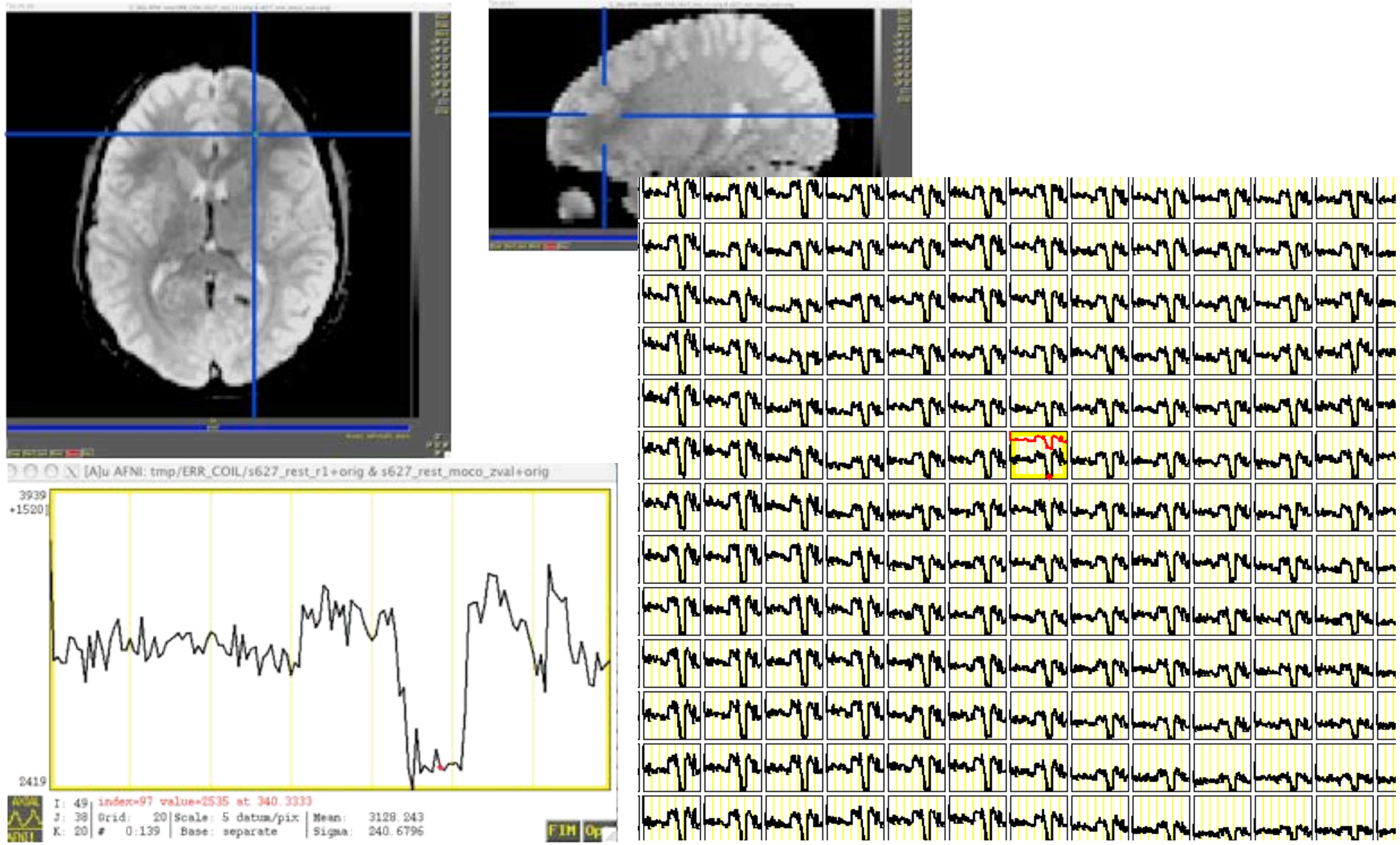
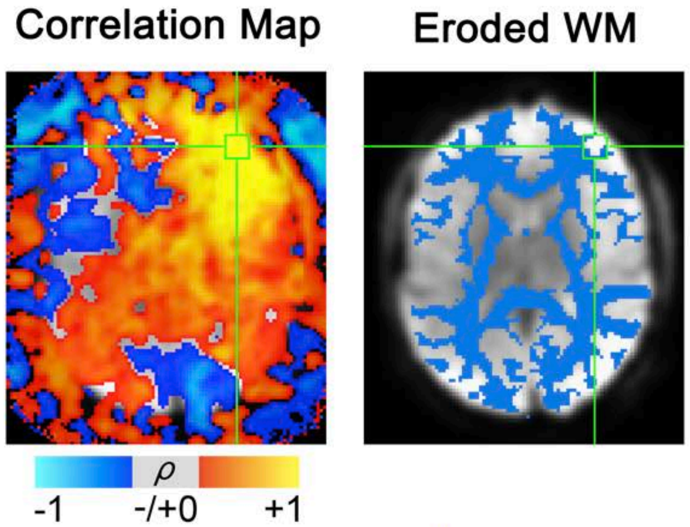


Image by Ziad Saad: https://afni.nimh.nih.gov/pub/dist/edu/latest/afni_handouts/BiasSources_RS-FMRI.pdf

Correlations for artifact monitoring





Using AFNI InstaCorr

Images by Ziad Saad: https://afni.nimh.nih.gov/pub/dist/edu/latest/afni_handouts/BiasSources_RS-FMRI.pdf

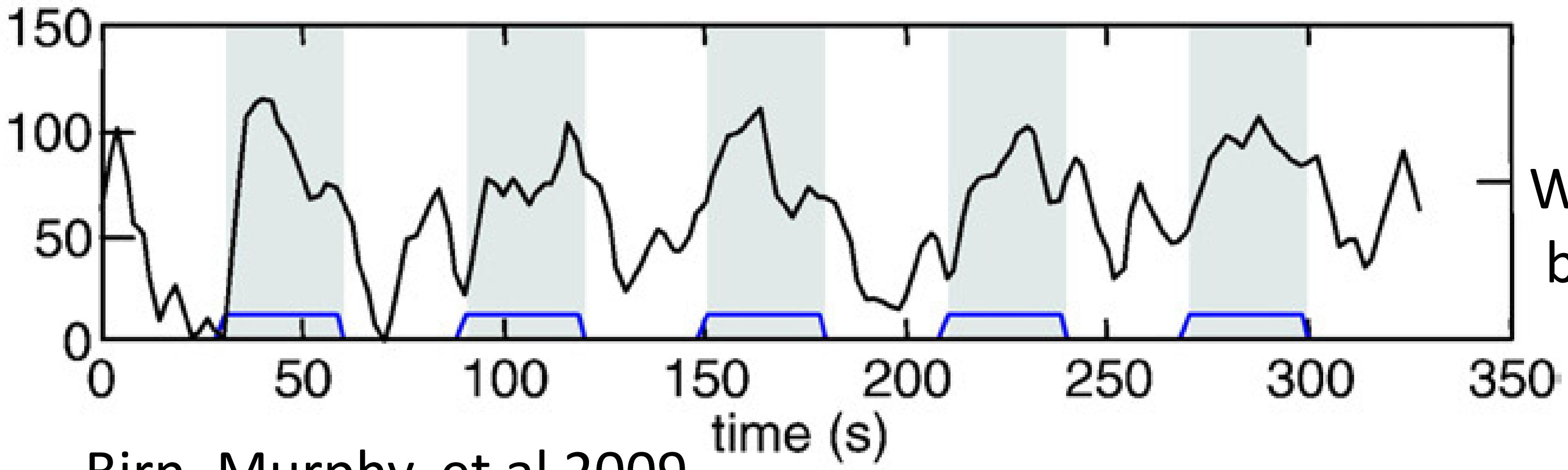
Peripherals and Participants

- Peripherals
  - Respiration, Pulse, Peripheral NIRS
  - Eye movement
  - Head movement
  - Multimodal neural measures: EEG, optical, Galvanic skin response
- Participants
  - Head restraints
  - Good instructions, training, & feedback
  - Good task design & response monitoring

Collect respiration & pulse data

- Removal of physiological noise during post processing is nice
  - RETROICOR (Glover, Li, Ress 2000)
  - Respiration Volume / Time (RVT) (Birn, Diamond et al 2006)
  - Heart rate (Chang, Metzger, et al 2013)

- **Knowing what your volunteer is doing is essential**

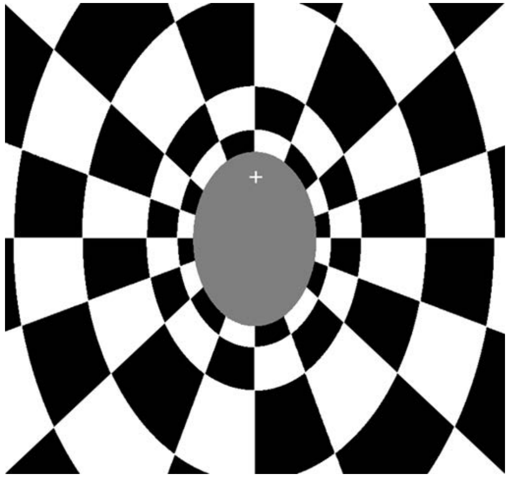


RVT (black).
Word/nonword task block design (blue)

Birn, Murphy, et al 2009

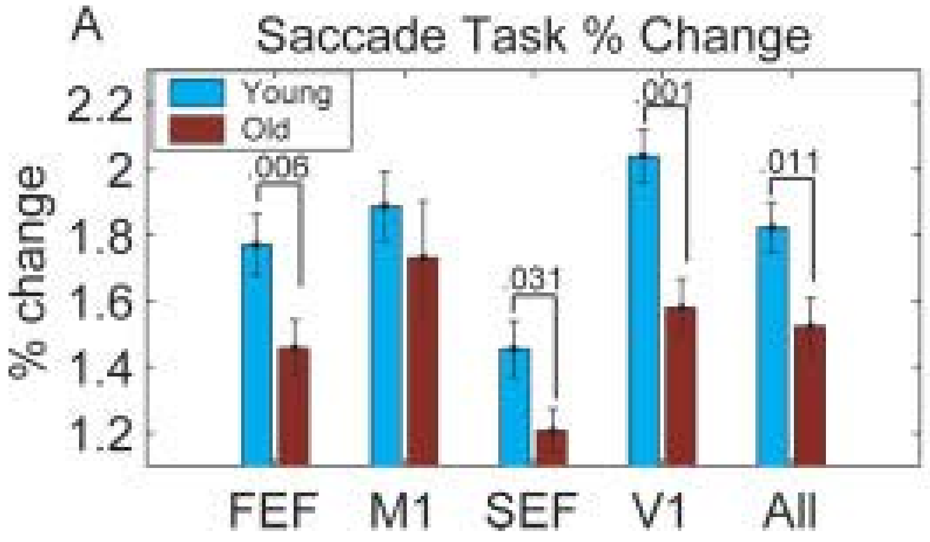
Collect respiration & pulse data

A minor confession



Present a 200ms flickering checkerboard every 18-24s

Volunteers press a button and move their eyes



Handwerker, Gazzaley, et al 2007

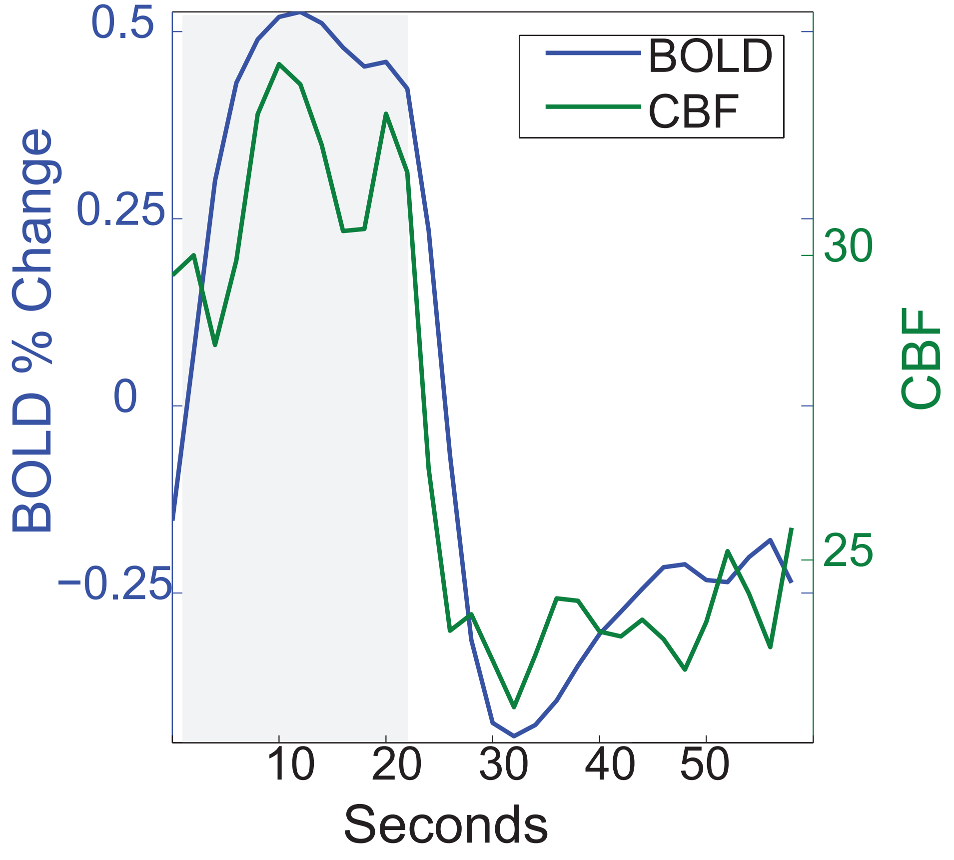
The unpublished part

- Stimuli presented for 3s, 6s & 12s durations to examine response scaling across populations
- A non-trivial # of volunteers held their breath for whatever the hold duration was
- If I hadn't collected respiration data, I would have published a visually appealing results that were severely confounded by task-locked breath holds
- How many fundamental task duration studies recorded respiration traces???

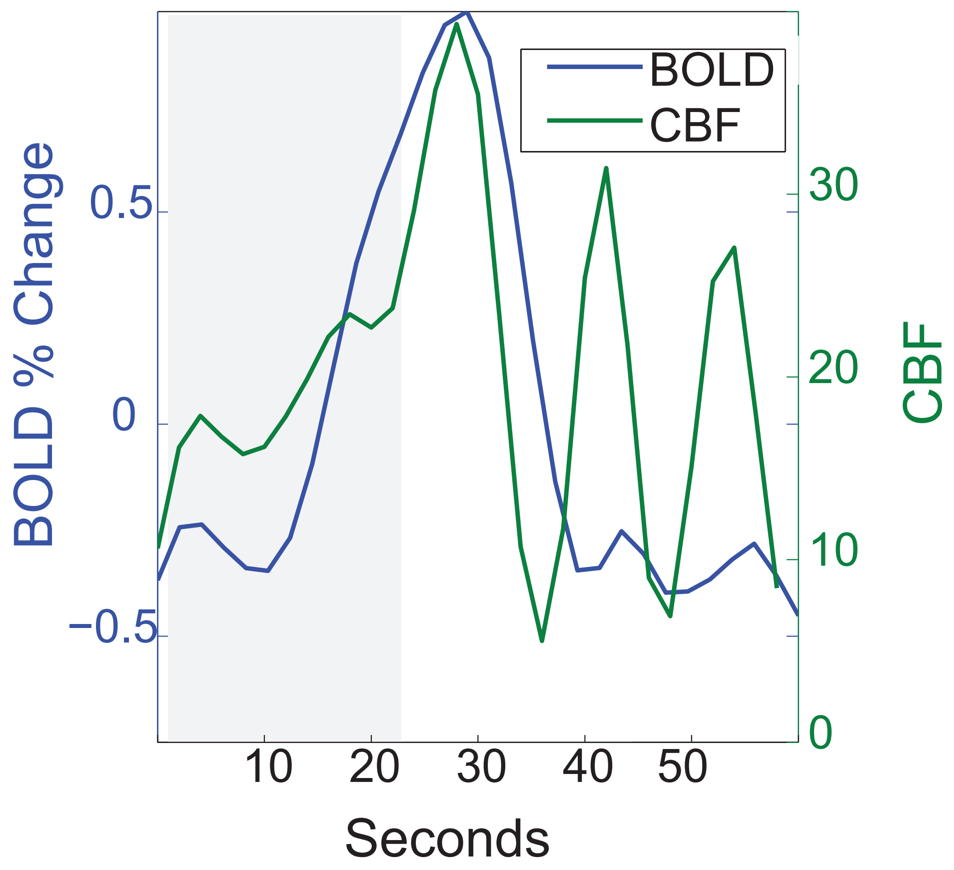
Collect respiration & pulse data

Respiration can really mess up your data

Flickering Checkerboard



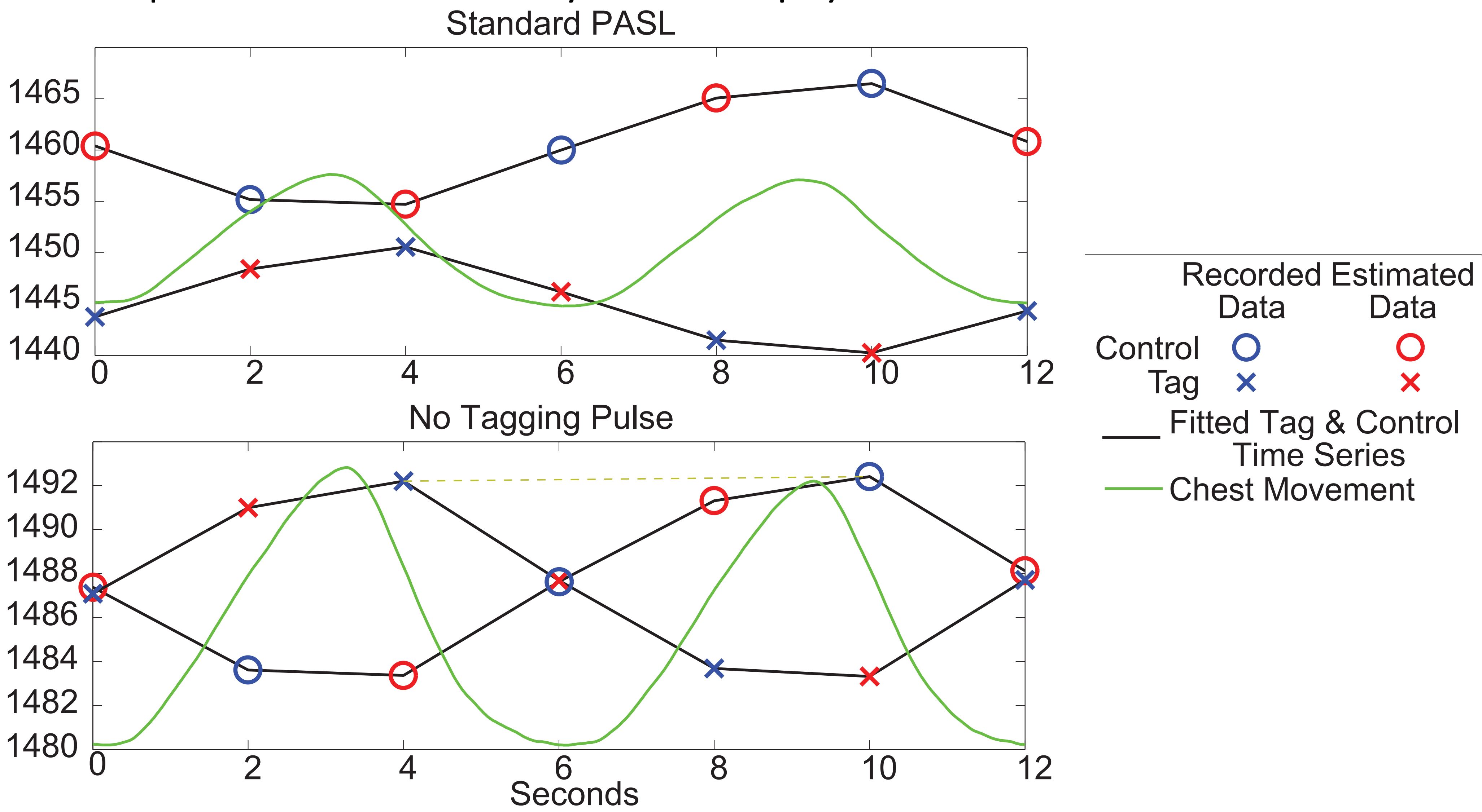
20sec Breath Hold



Handwerker, Luh, et al OHBM meeting 2012

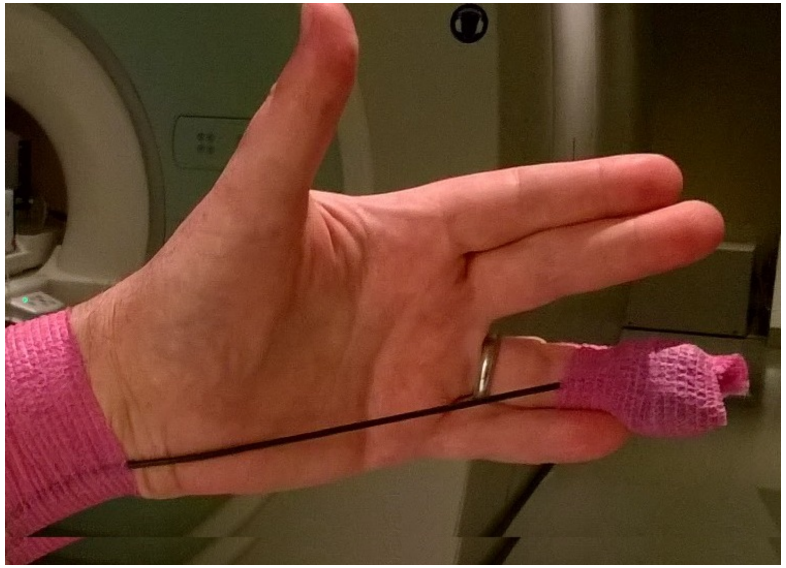
Collect respiration & pulse data

Respiration can really mess up your data

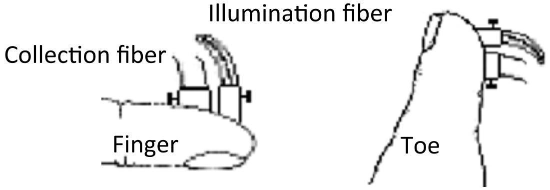


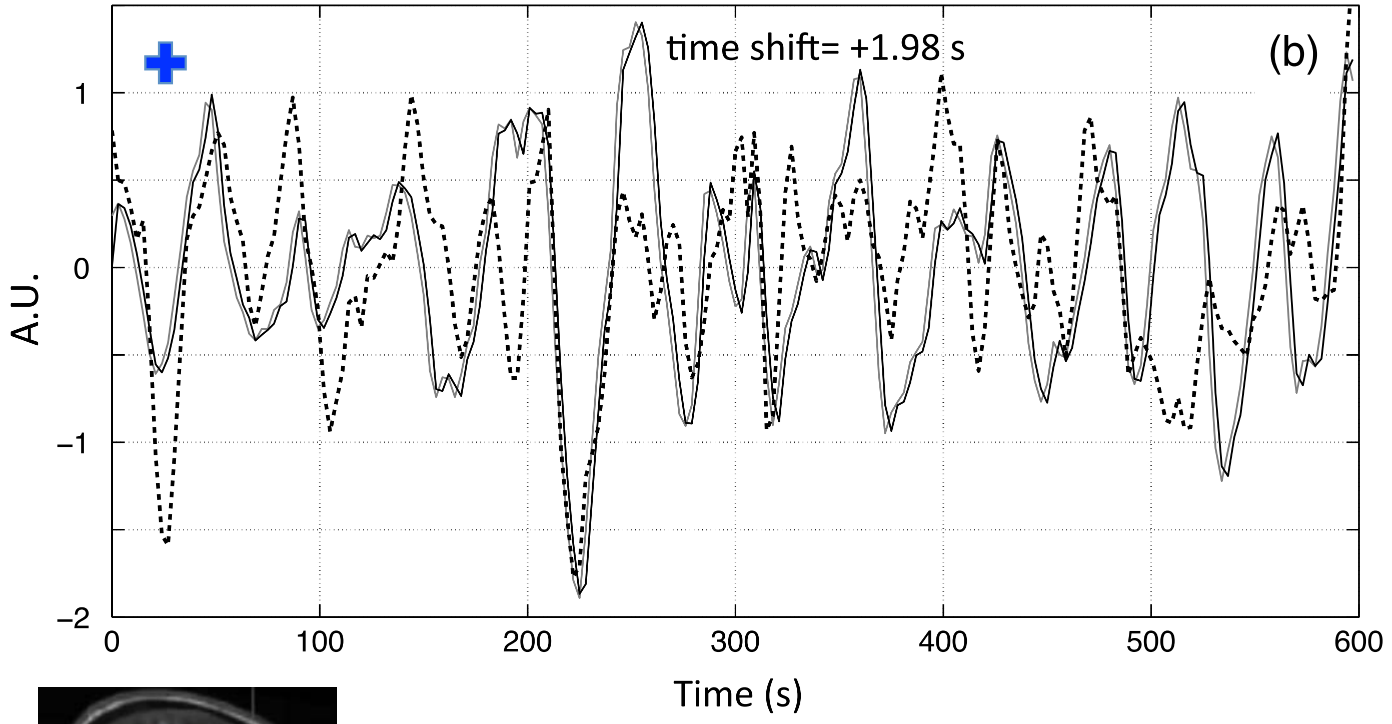
Advice for collecting respiration & pulse data

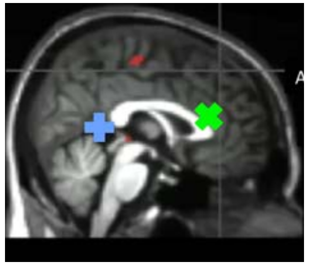
- If you want to use post-processing removal methods, make sure respiration and cardiac traces are connected to MRI acquisition times
- For respiration: To conduct an RVT correction, make sure the response magnitude doesn't auto-scale and you now the relationship between chest movement & signal
- For cardiac: Pulse oximeters are sensitive to finger movement. Take the time to make sure the oximeter is secure and tell the volunteer to minimize finger movement during a scan
- Monitor traces before & during scanning



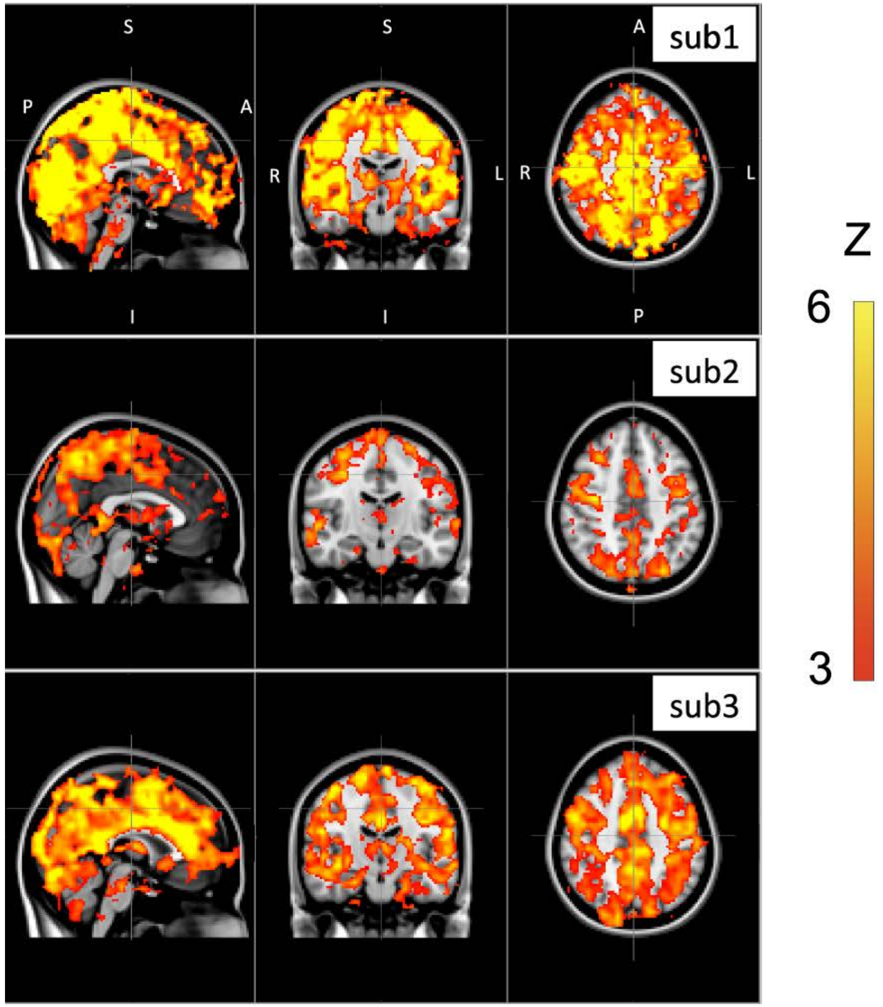
Peripheral near-infrared spectroscopy





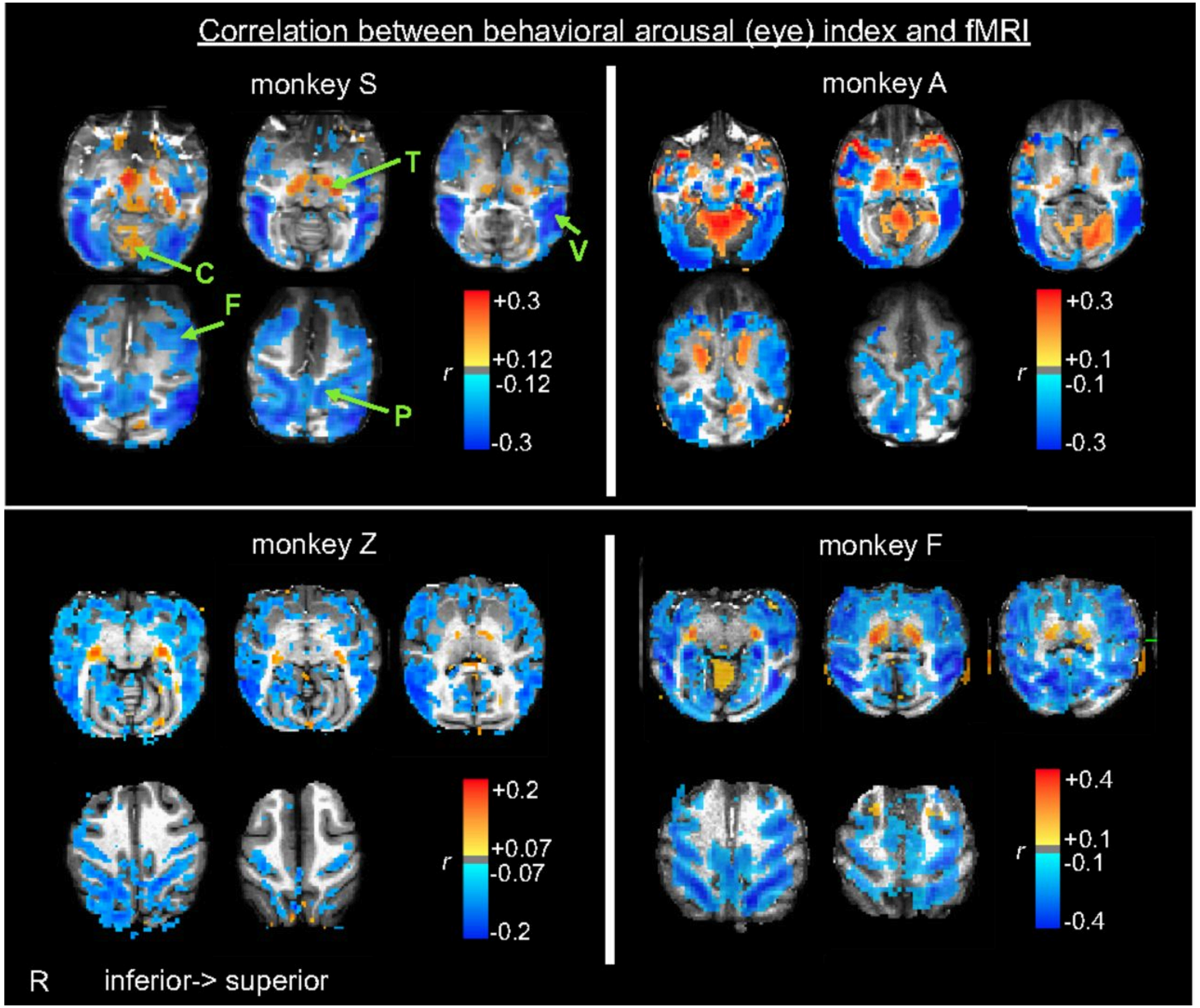


- - - BOLD from brain
— Δ[tHb] from finger
— Δ[tHb] from finger with time shift



Tong, Hocke, et al 2012

Eye tracking



- Correlations to eyelids open vs closed
- Other studies have shown gaze to also be an arousal/attention measure
- This variation my have a neural origin, but it can still be noise when unmodeled

Chang, Leopold, et at 2016

Head Movement

- Less head motion -> Less need to remove motion in data processing
- Head movement may systematically vary across populations
- Don’t assume the way you saw someone else restrict head movement is the best way
  - “The best” varies by head coil, head size, & population
  - There are more and more options

http://www.magmedix.com/pearltec-multipad-slim.html

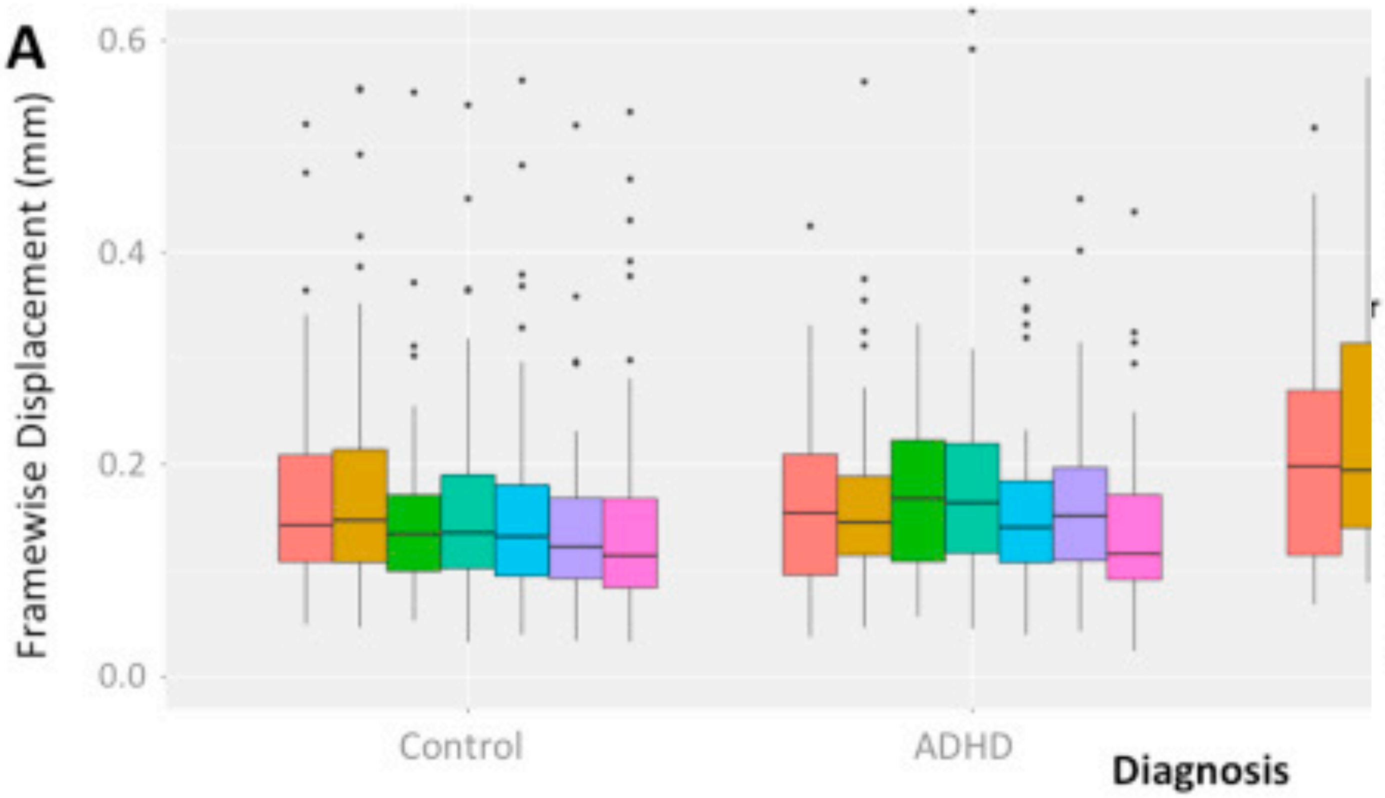
caseforge.co

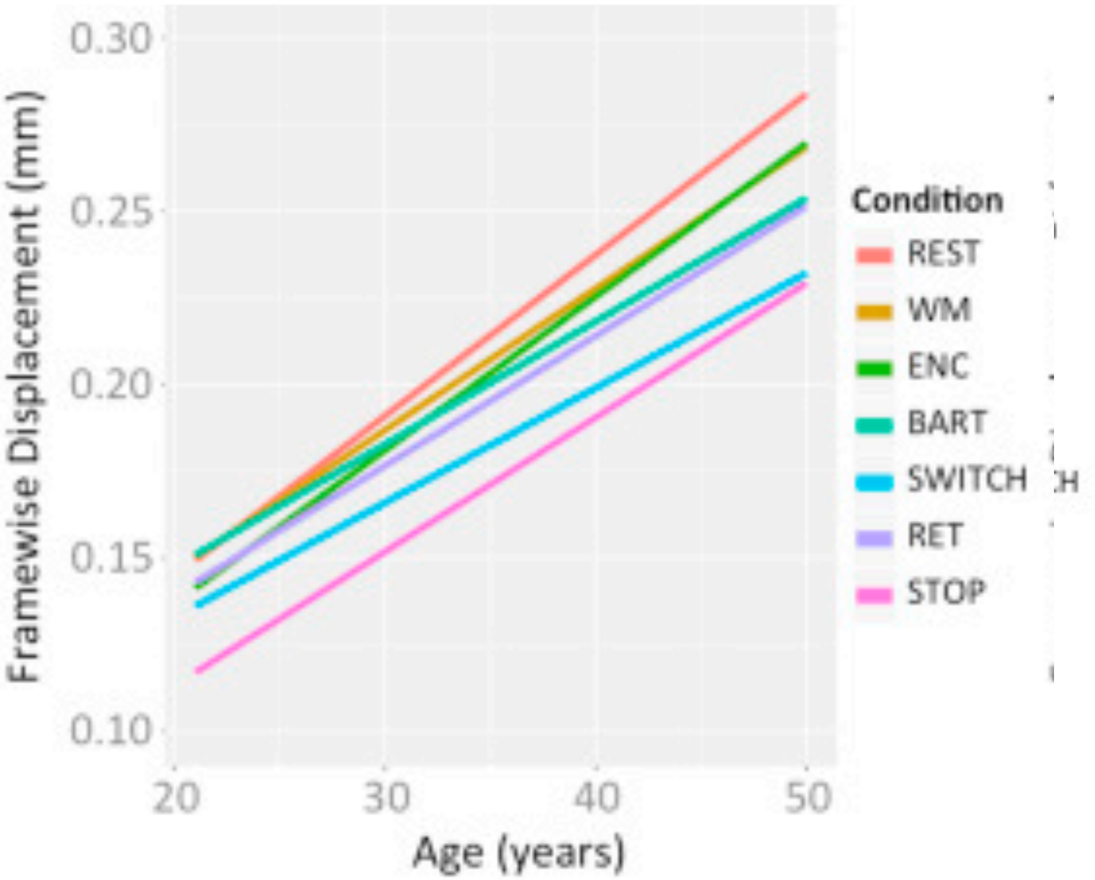
Prepare participants

- Take the time to make sure a participant knows what to do in the MRI and is comfortable
- The more feedback you get in a task, the better you know what a participant is doing
  - For classic ”resting state” scans, peripheral measurements are particularly useful
- Noise IS NOT independent from task design

Head Movement

Experimental design affects head motion

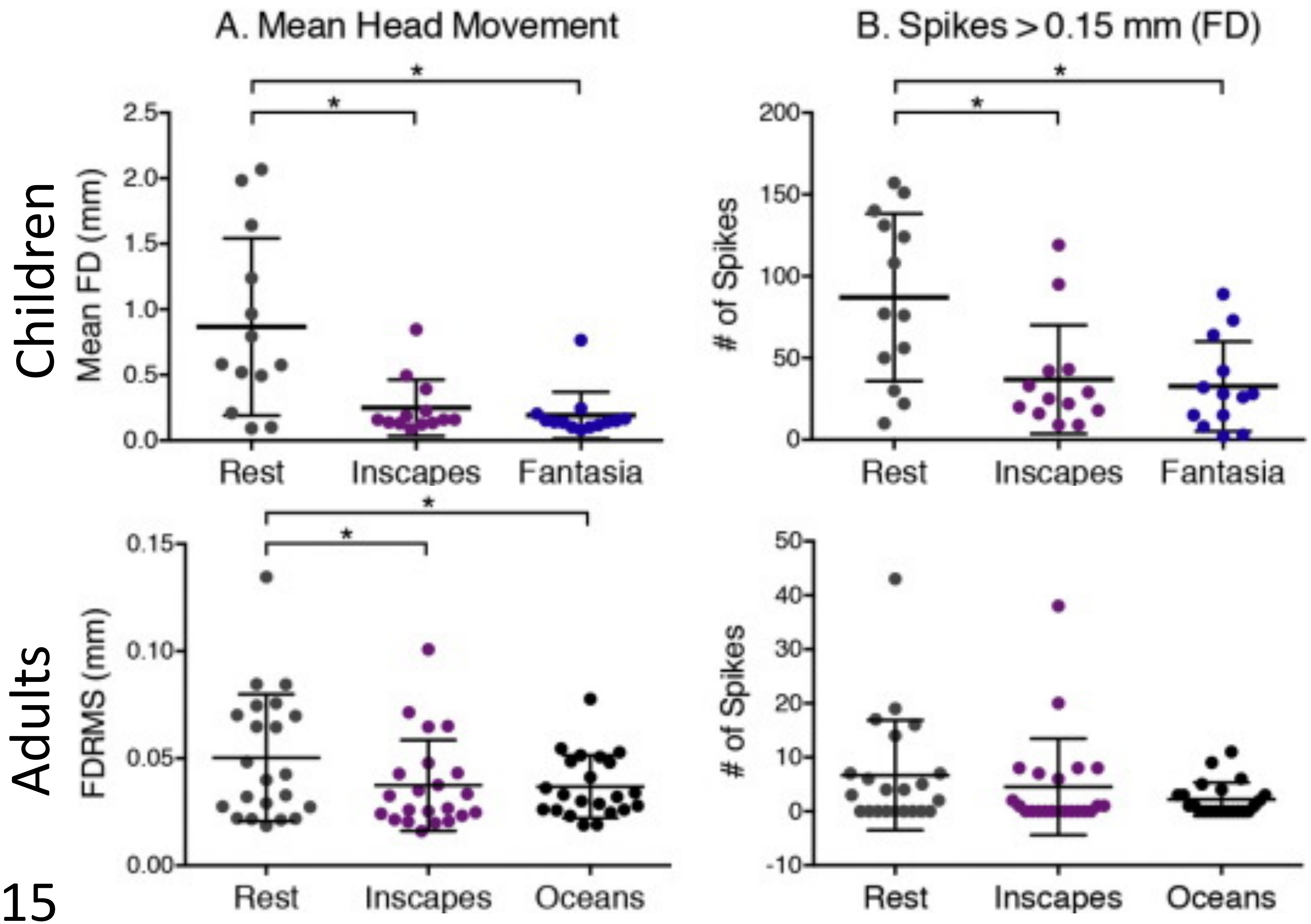




Huijbers, Van Dijk, et al 2017

Head Movement

Experimental design affects head motion



Vanderwal, Kelly, et al 2015

Parameters and Pulse Sequences

A semi-arbitrary and semi-ordered series of examples

- Examples of how parameter choices matter
- Preparatory scans matter
- SMS vs 3D-EPI
- Contrast options
- Motion correction
- Calibration scans

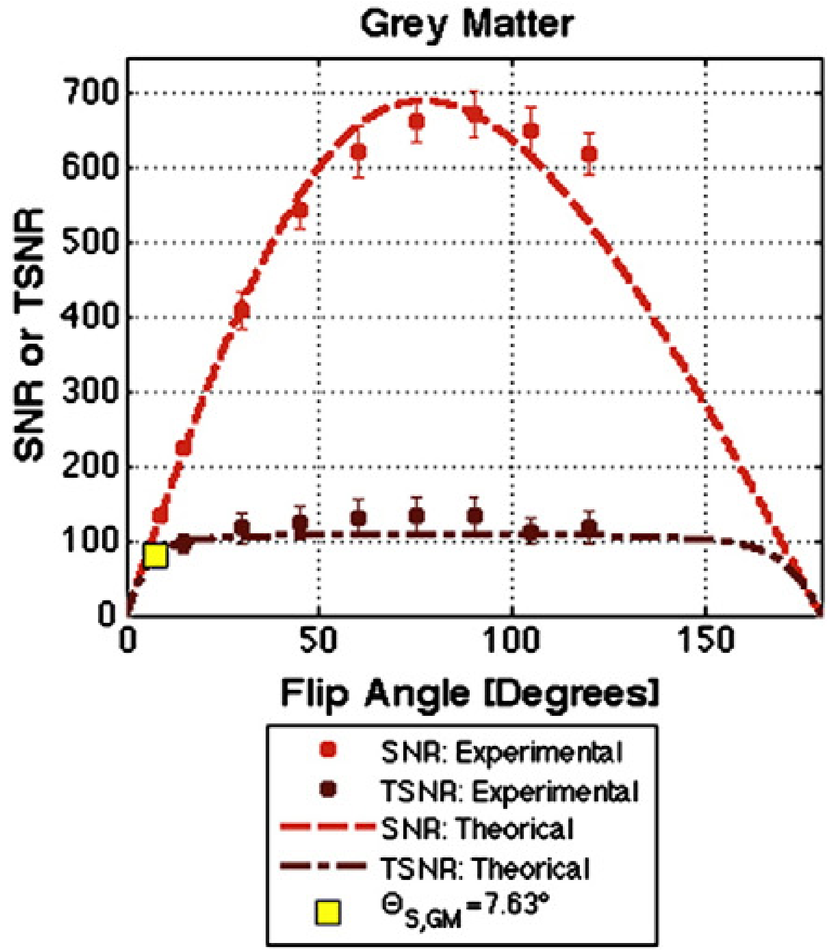
General acquisition goals

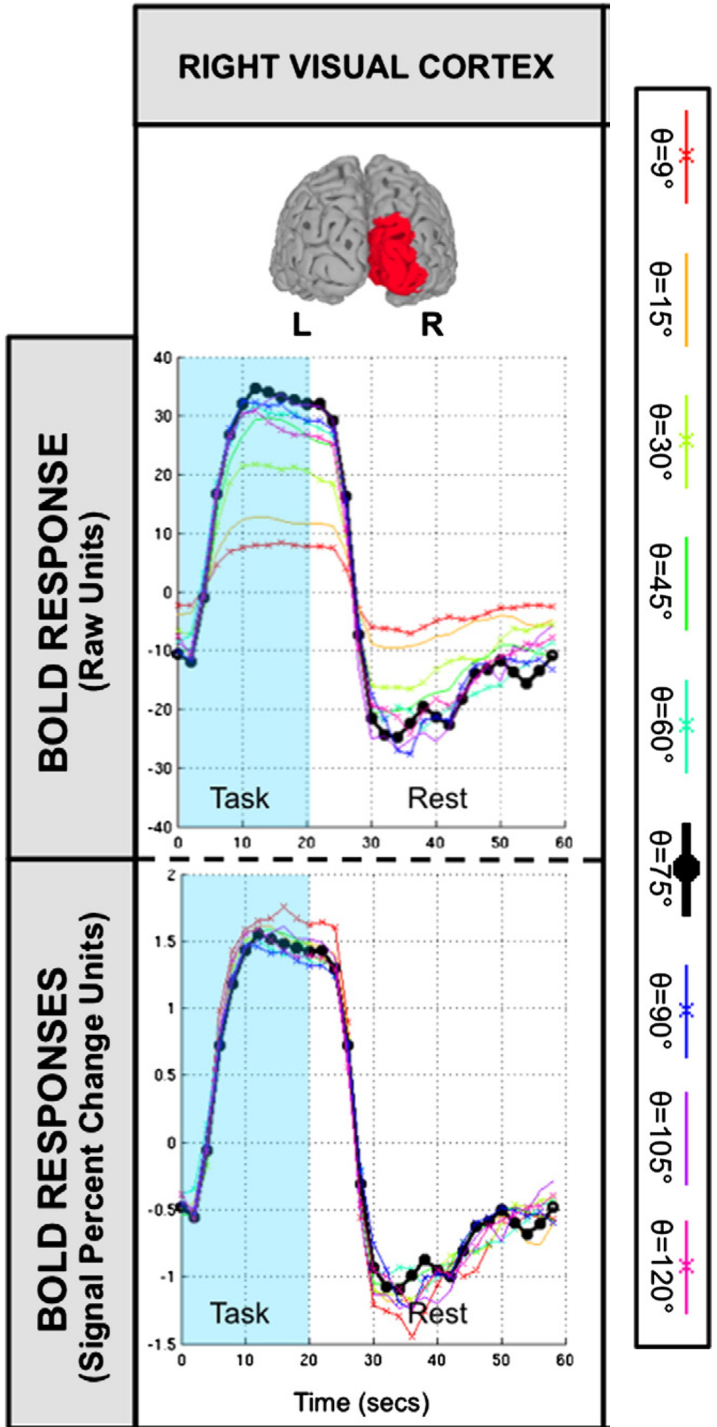
- Give thought to the specific priorities of a study
  - Response shape sensitivity vs specificity
  - Anatomical accuracy
  - Robustness against general artifacts
  - Robustness against artifacts that can bias a study

- The optimal acquisition options aren’t always obvious.

  - What is the best flip angle for an fMRI study?

Optimal flip angle?





$$TSNR = \frac{SNR}{\sqrt{1 + \lambda^2 \cdot SNR^2}}$$

λ is amount of physiological noise

Increases in SNR also increase the physiological noise signal and dampen the temporal SNR benefits from a signal increase

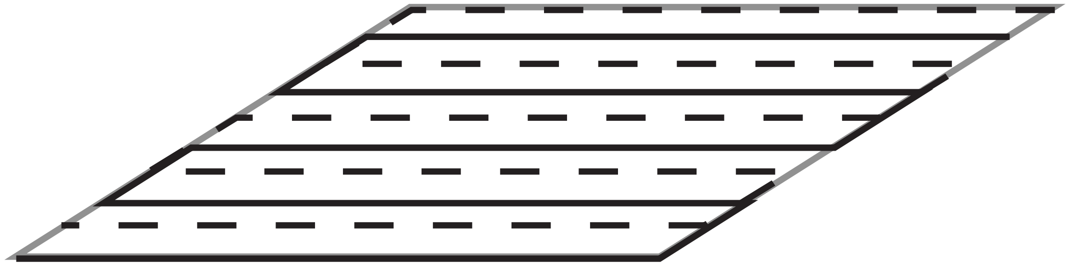
Gonzalez-Castillo, Roopchansingh, et al 2011

MRI acquisition general parameters

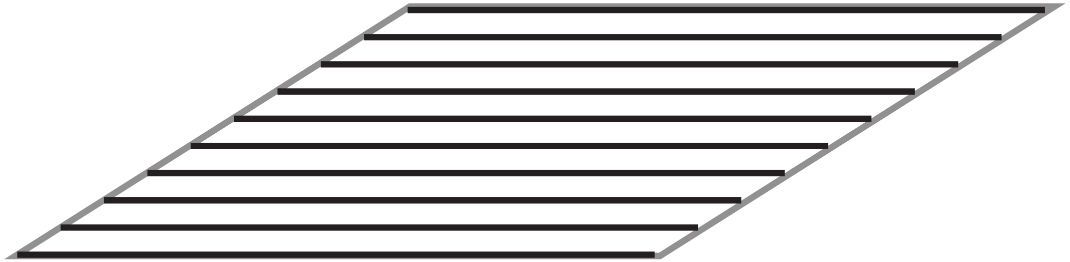
- Voxel size
  - Smaller -> Lower SNR
  - Smaller -> More anatomical specificity -> Higher TSNR of interest
- TR
  - Shorter -> lower SNR, but better temporal resolution and possibly higher TSNR
  - Shorter -> Better filtering of high frequency artifacts (if not removed using other methods)
  - Still limited by the speed of the hemodynamic response
- Acceleration (collecting incompletely sampled data sets and estimating what was missing during reconstruction)
  - Sometimes lower SNR
  - Makes shorter TRs, smaller voxels, and multi-echo practical
  - Potentially less susceptibility dropout & distortion
  - Imperfect reconstruction can create or amplify artifacts
    - Possibly more sensitivity to B0 fluctuations linked to respiratory chest movement

GRAPPA acceleration reconstruction affected by calibration scan

Conventional EPI calibration scan
can contain phase errors



FLASH calibration scan is more robust



FLASH GRAPPA for fMRI: Talagala et al., 20015 MRM
FLEET GRAPPA for fMRI: Polimeni et al., 2016 MRM
dual polarity GRAPPA for fMRI: Hoge et al., 2016 MRM

Images from Laurentius Huber

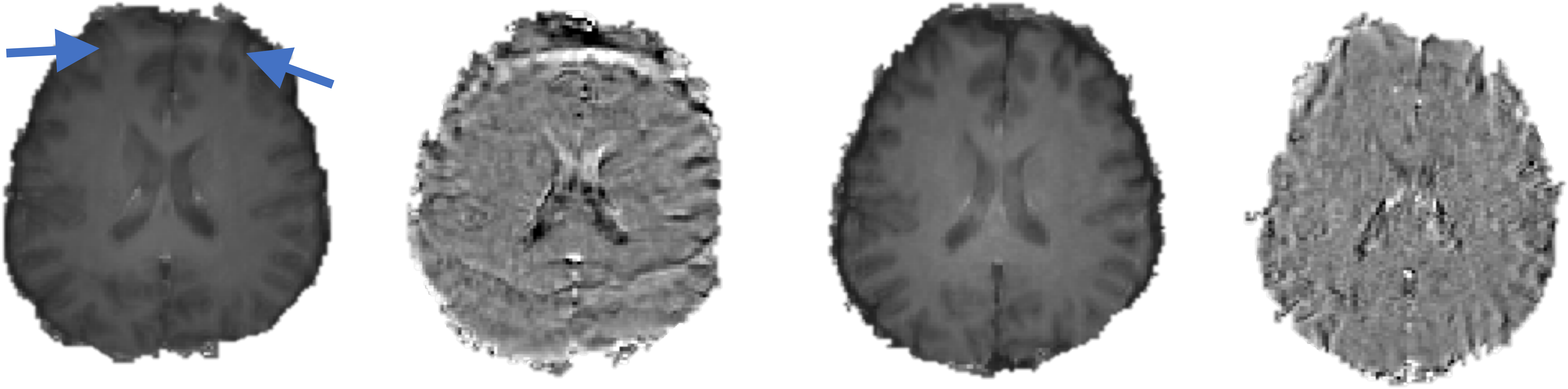
Fat ghosts: small signal but large instability

Mean signal with normal fat saturation

Standard devision with normal fat saturation

Mean signal with ultra strong fat saturation

Standard deviation with ultra strong fat saturation

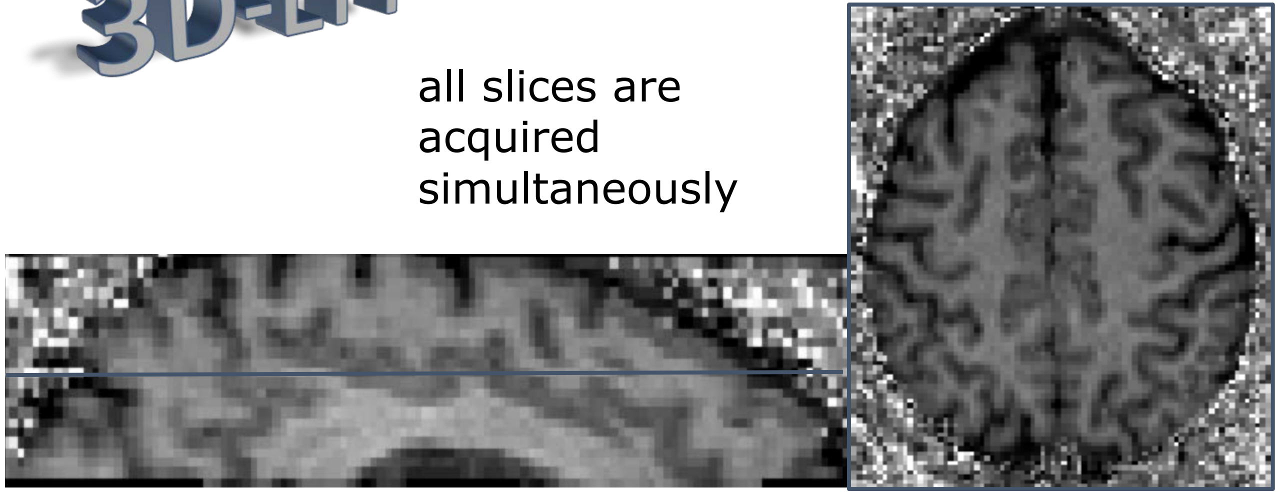


VASO data presented at OHBM 2016. Handwerker, Huber et al

SMS and (task-induced) motion

3D-EPI

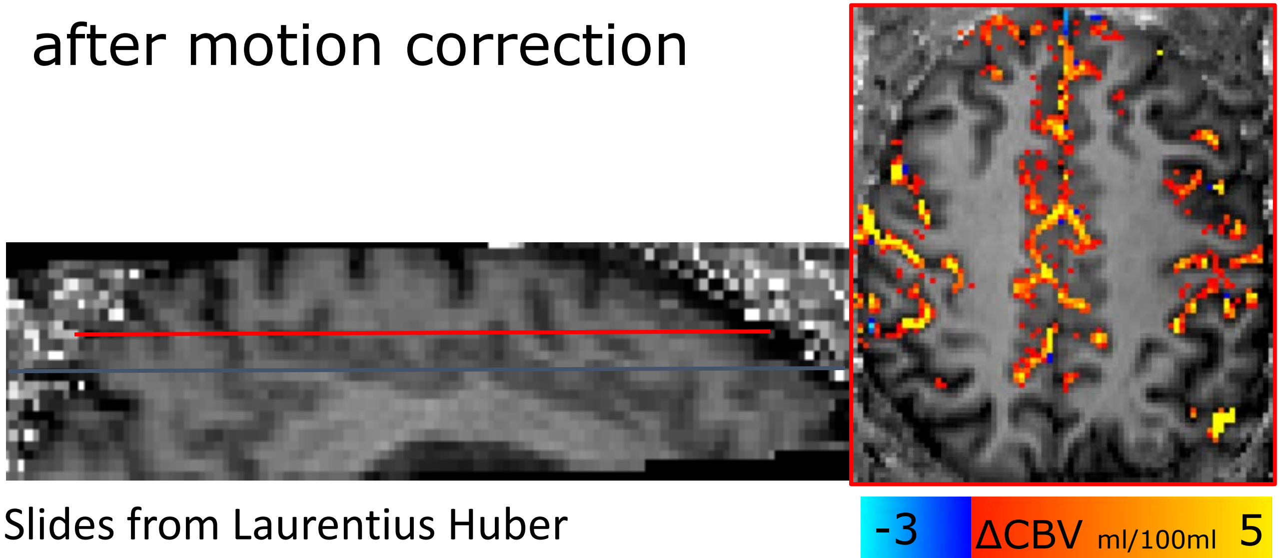
all slices are acquired simultaneously



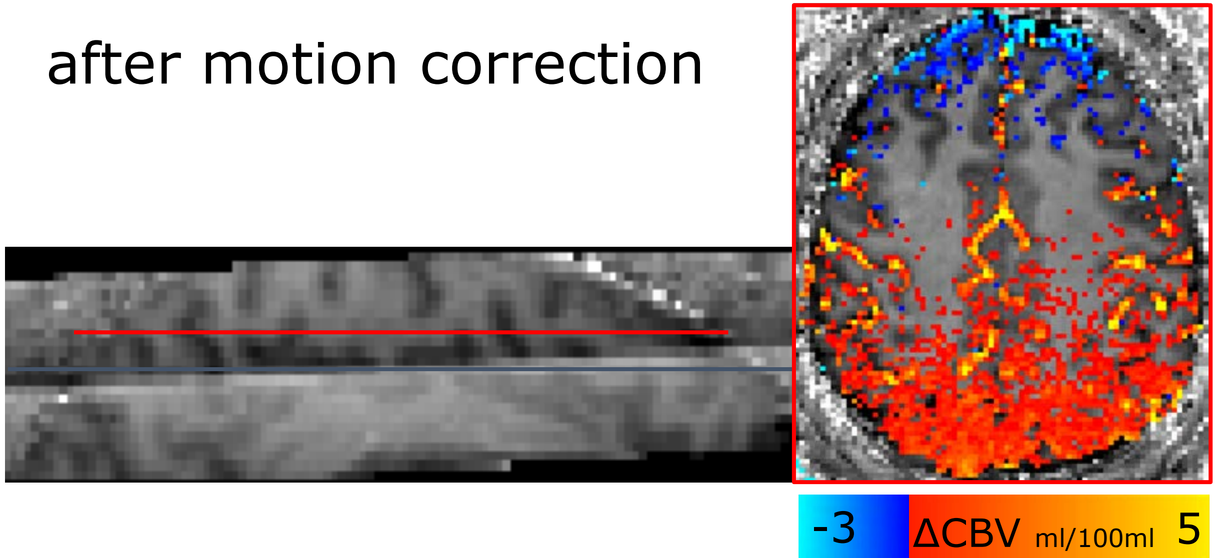
2D-SMS-EPI

spatially neighbor
slices are acquire
distant in time

after motion correction

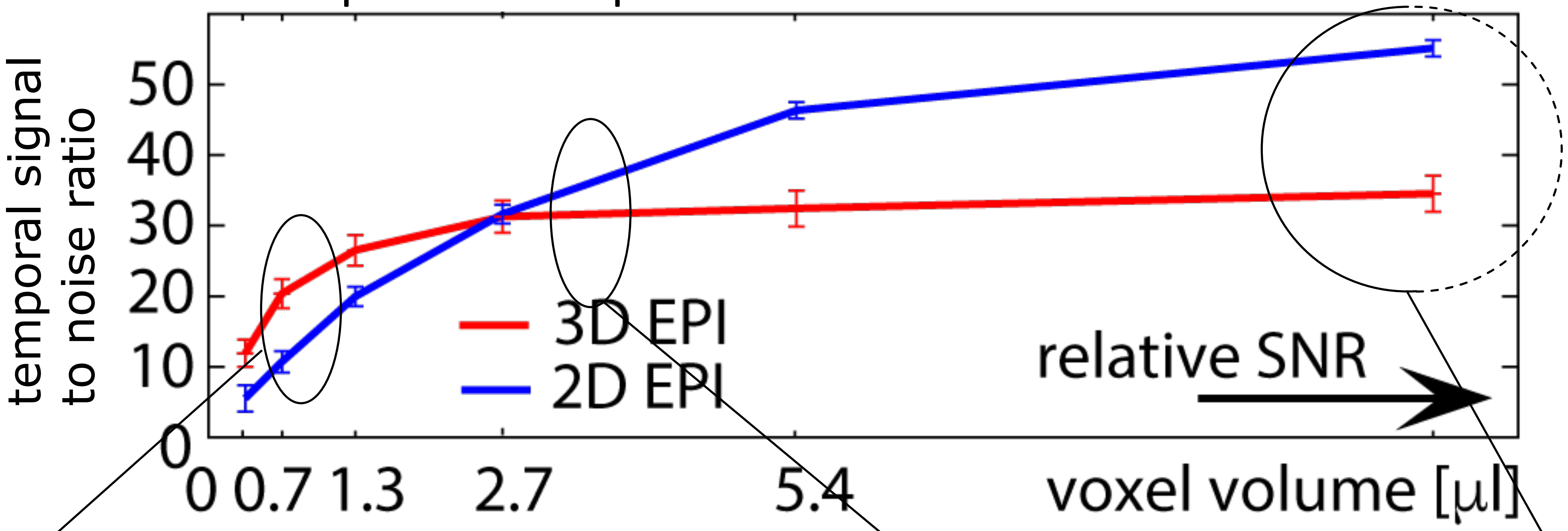


after motion correction



Slides from Laurentius Huber

The “best” pulse sequence interacts with voxel size & SNR

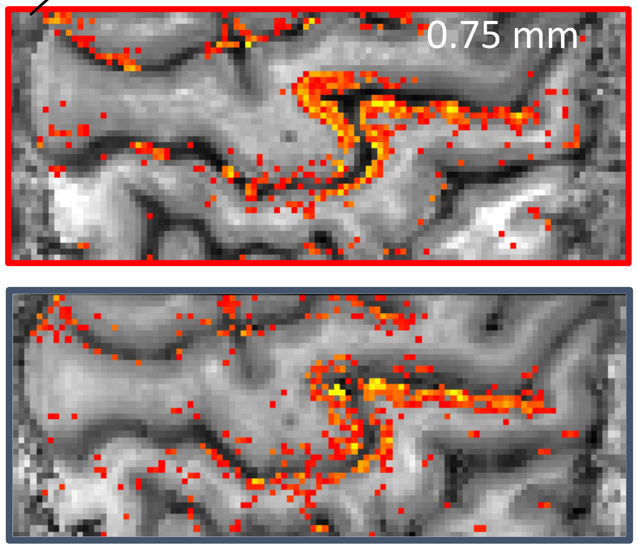


Huber et al., NeuroImage, 2016

SMS wins in physiological noise dominated regime

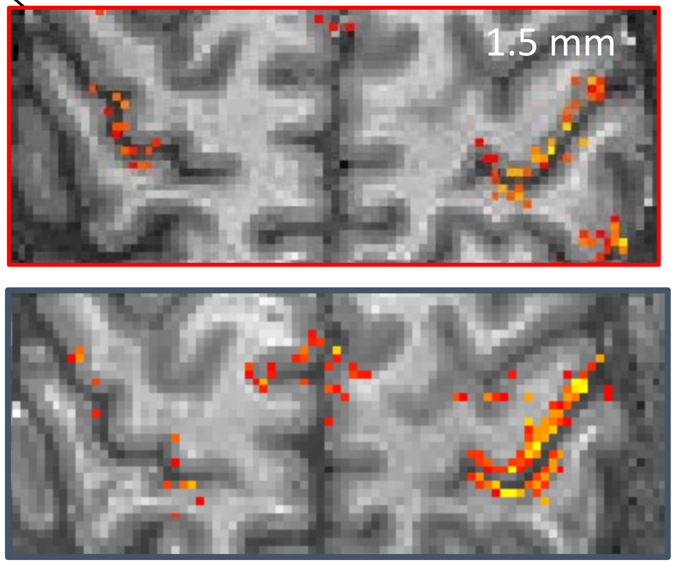
3D EPI

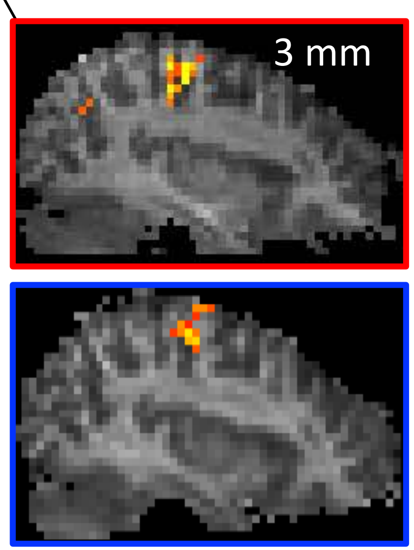
2D SMS



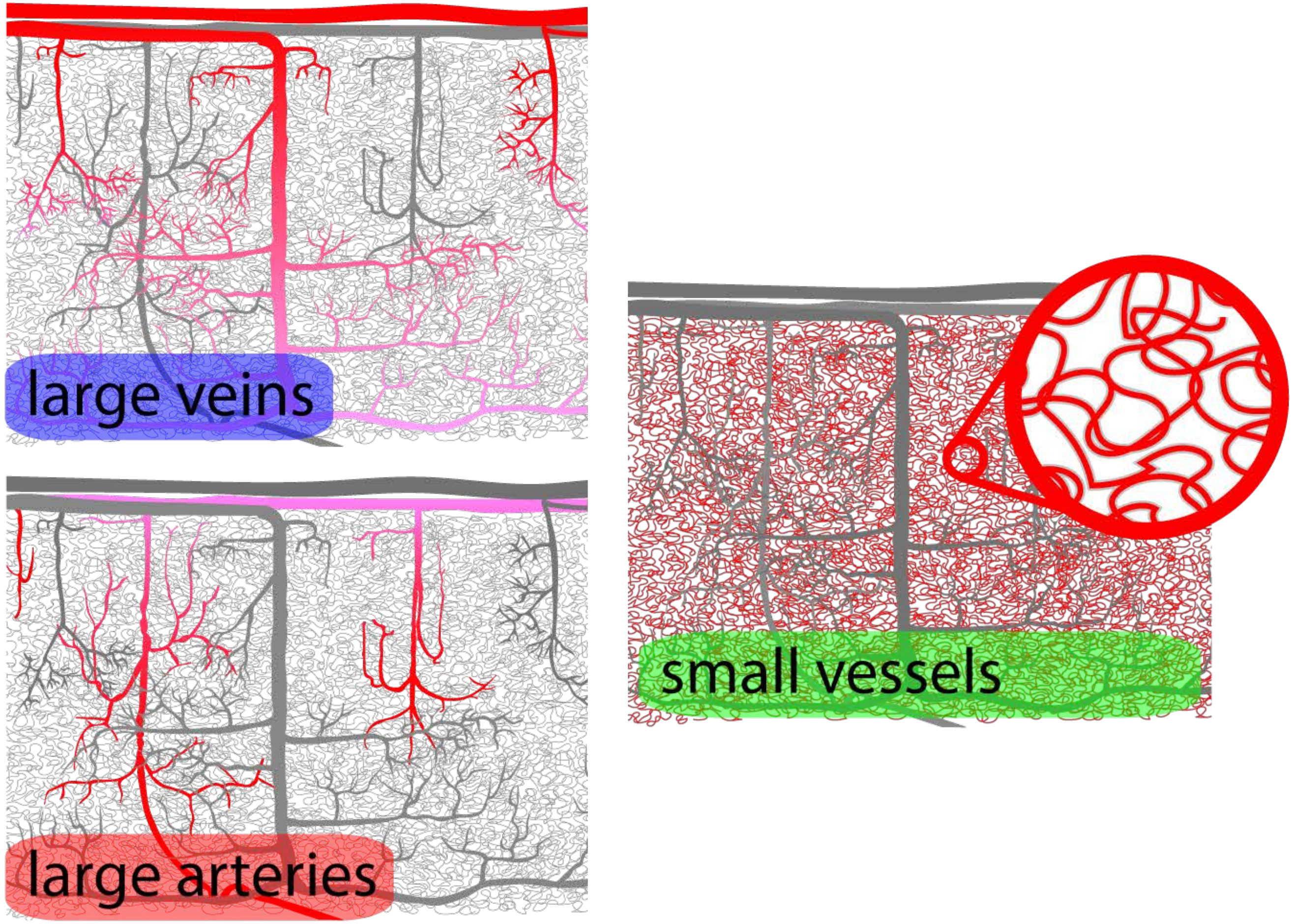
SMS is challenged in thermal noise dominated regime]

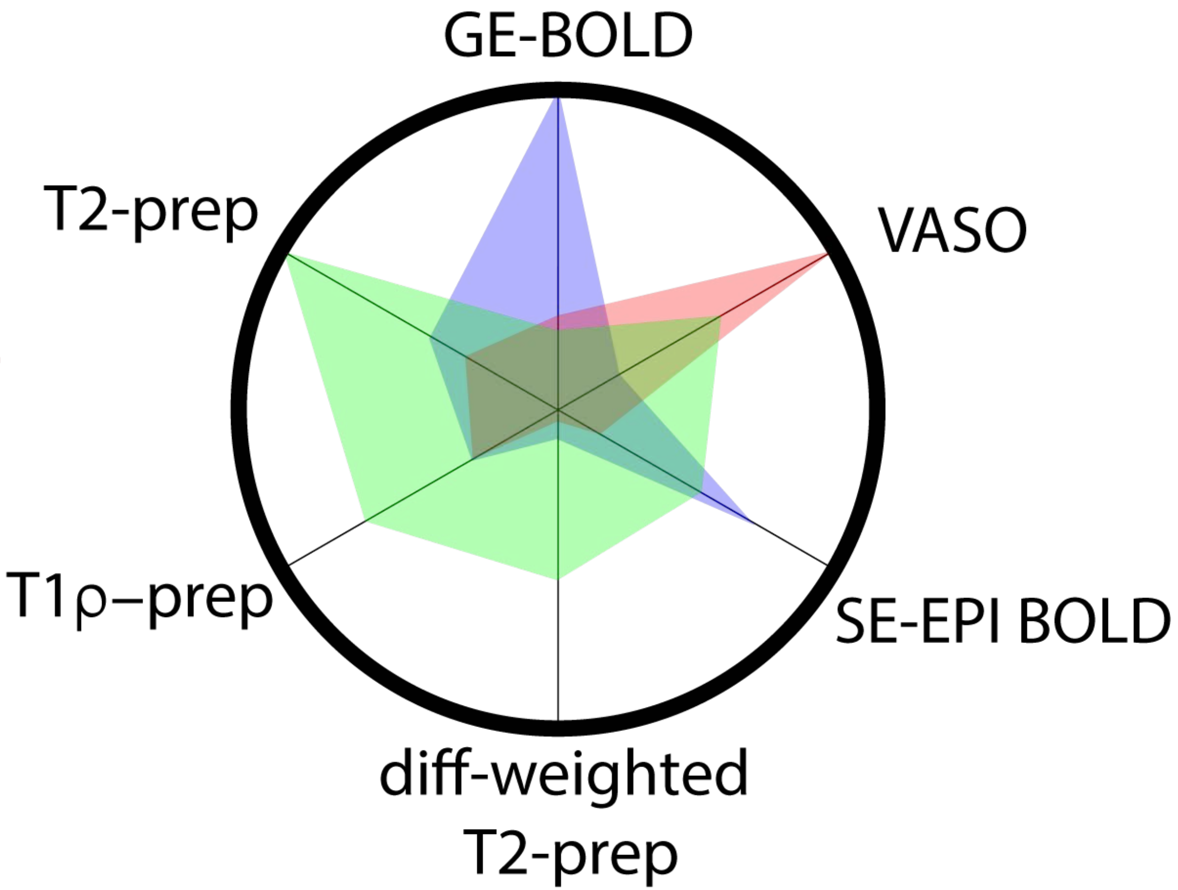
see poster #3605





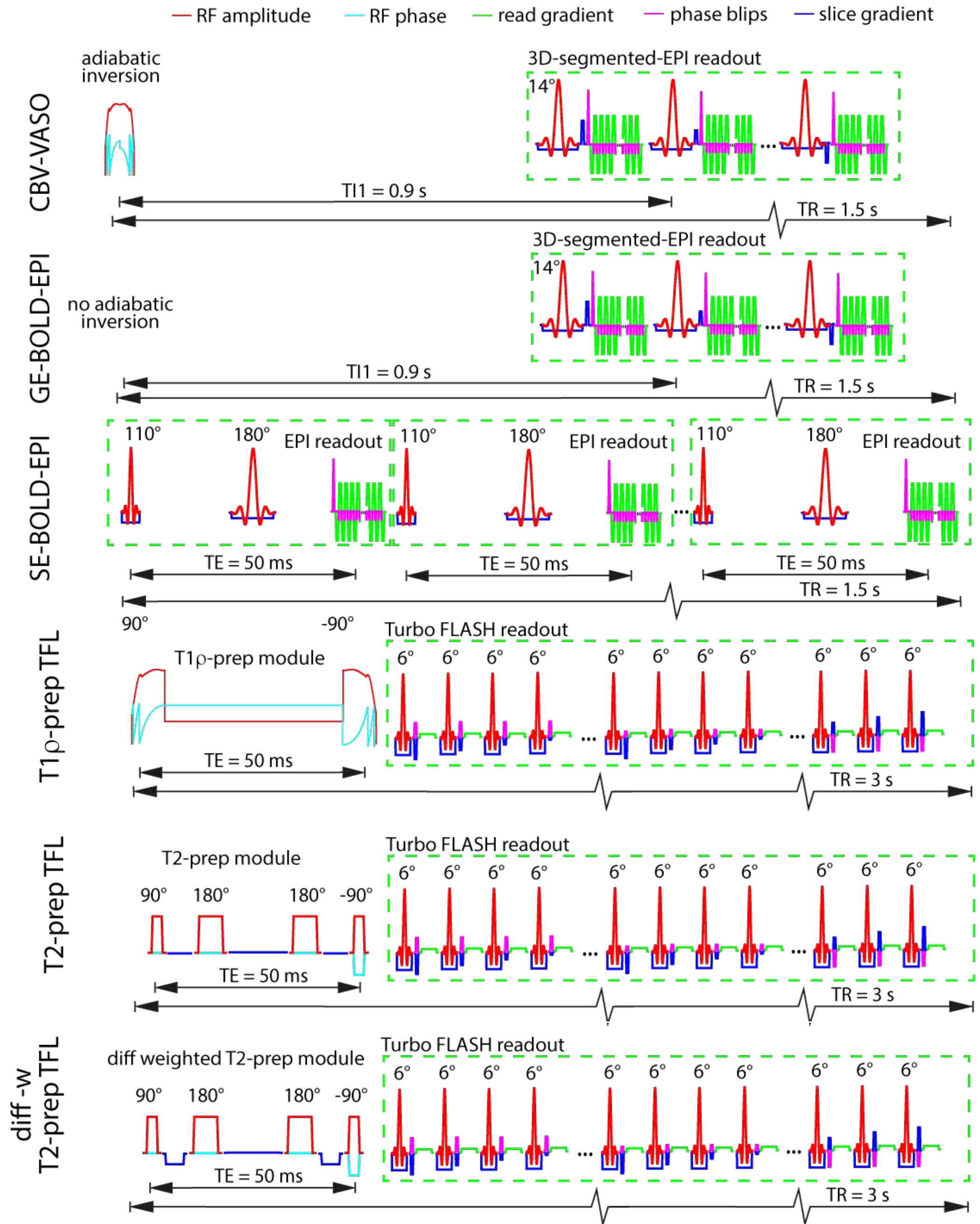
Pulse sequences contrasts



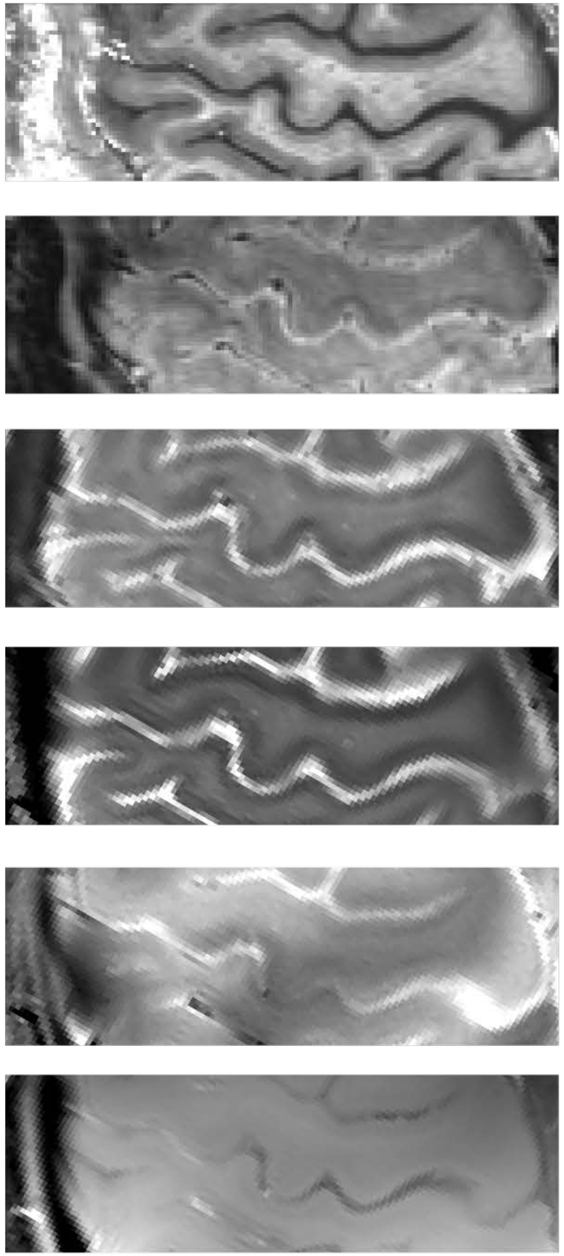


Images from Laurentius Huber
graphical depiction of review articles [Uludaĝ and Blinder 2017] and [Huber et al., 2017]
drawn based on Duvernoy, 1981 Brain Res

Parameters and Pulse Sequences



MRI contrast



[Lu, 2003]
[Huber, 2014]

CMRR C2P
[Auerbach, 2013]

[Rane, 2013]

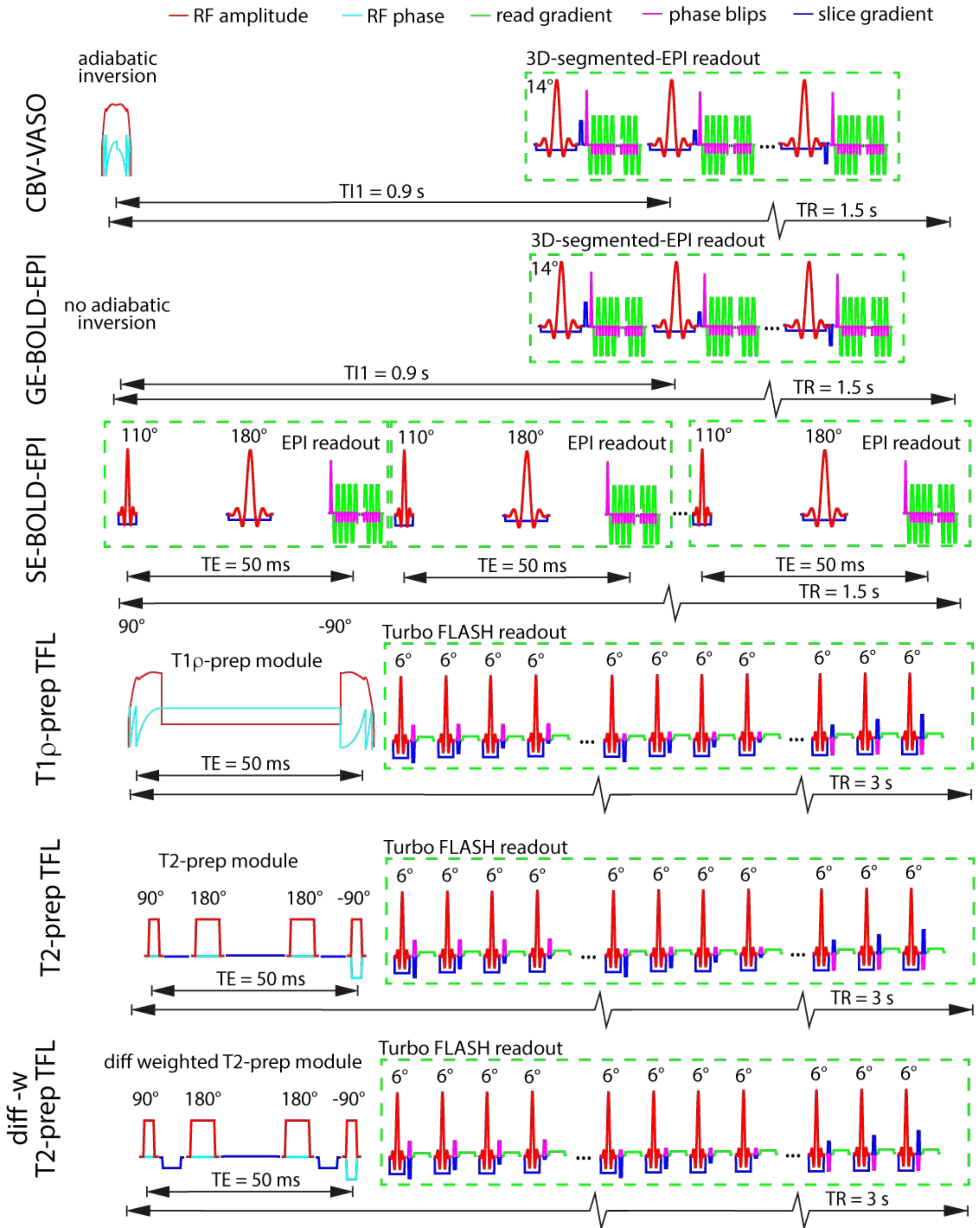
[Hua, 2014]

[Duong, 2003]

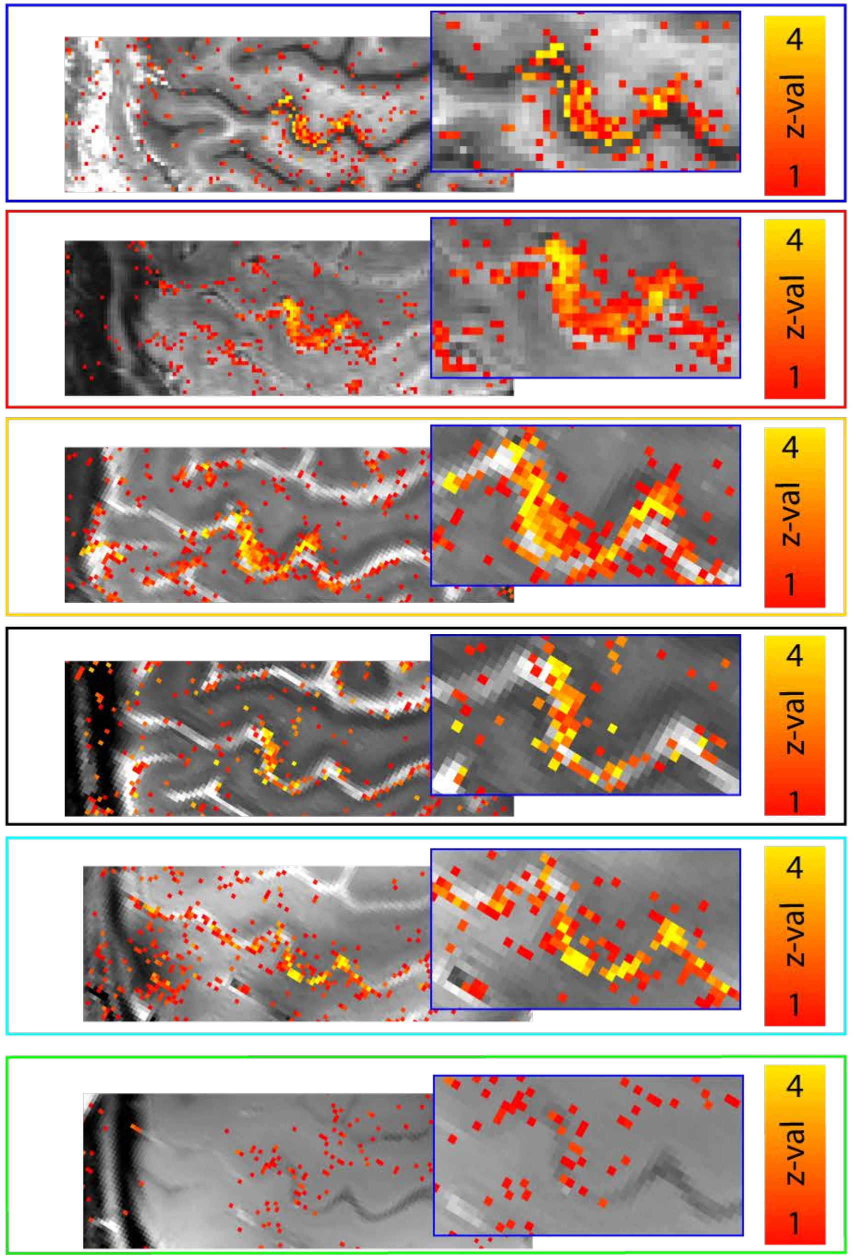
Images from Laurientius Huber

[Huber et al., ISMRM, 2017]

Parameters and Pulse Sequences

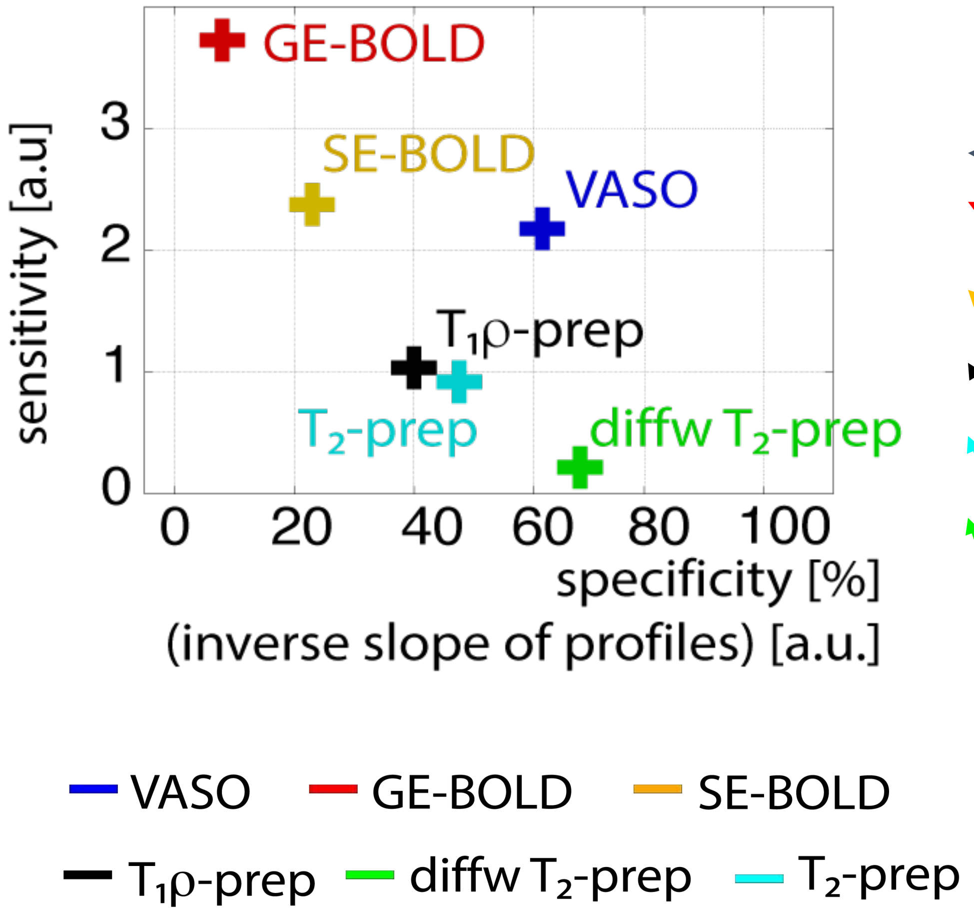


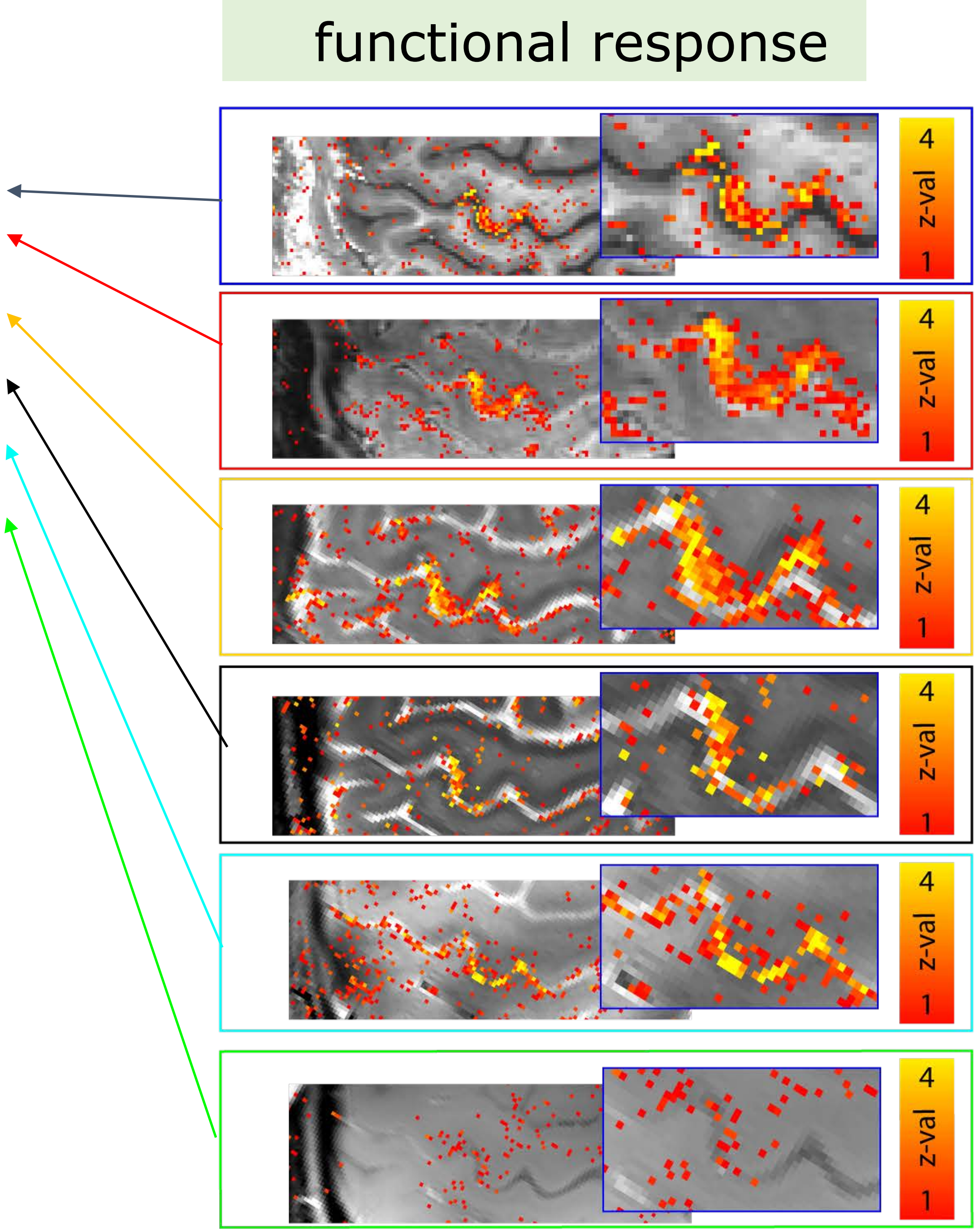
Functional Response



Images from Laurentius Huber

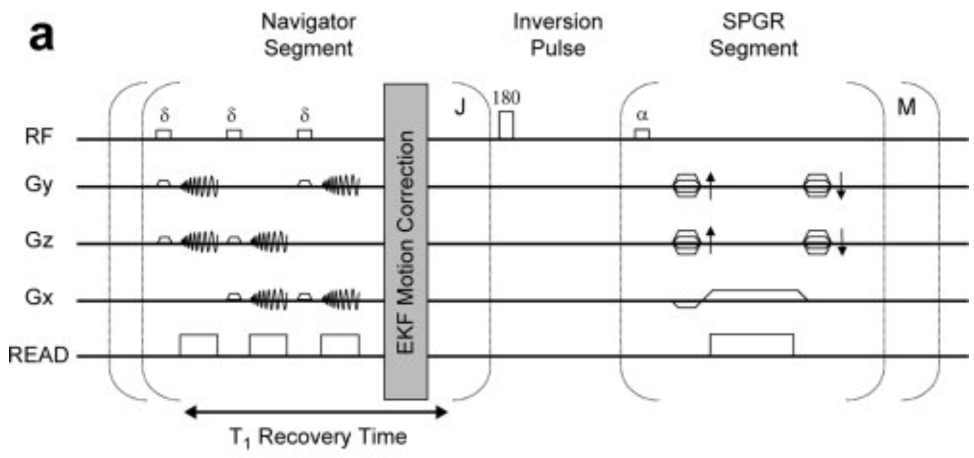
Parameters and Pulse Sequences



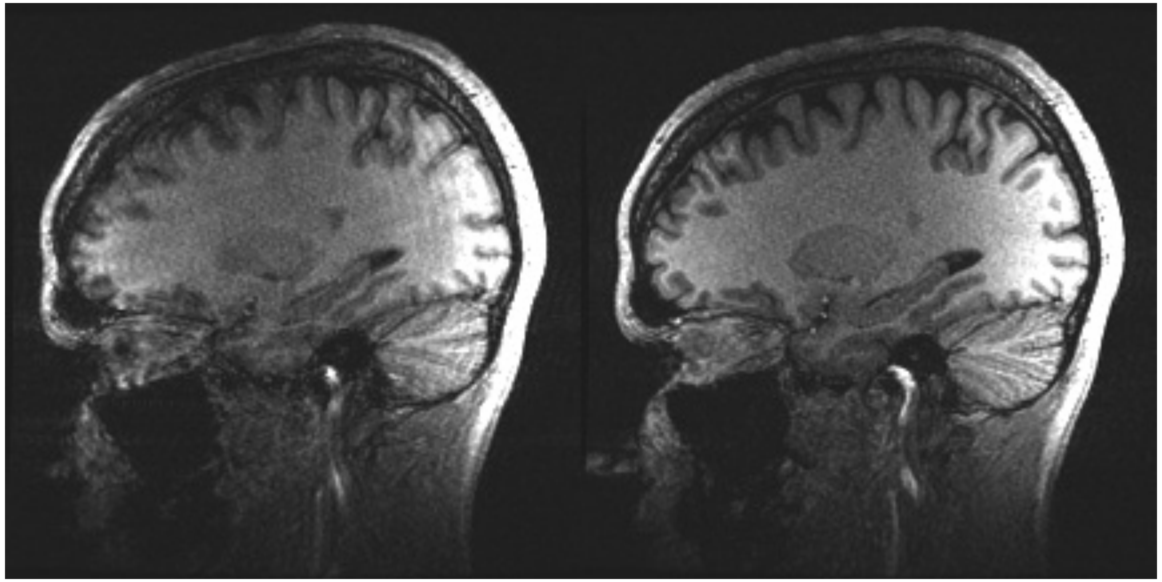


Images from Laurientius Huber
[Huber et al., ISMRM, 2017]

Real time motion correction during data collection



MPRAGE anatomical image



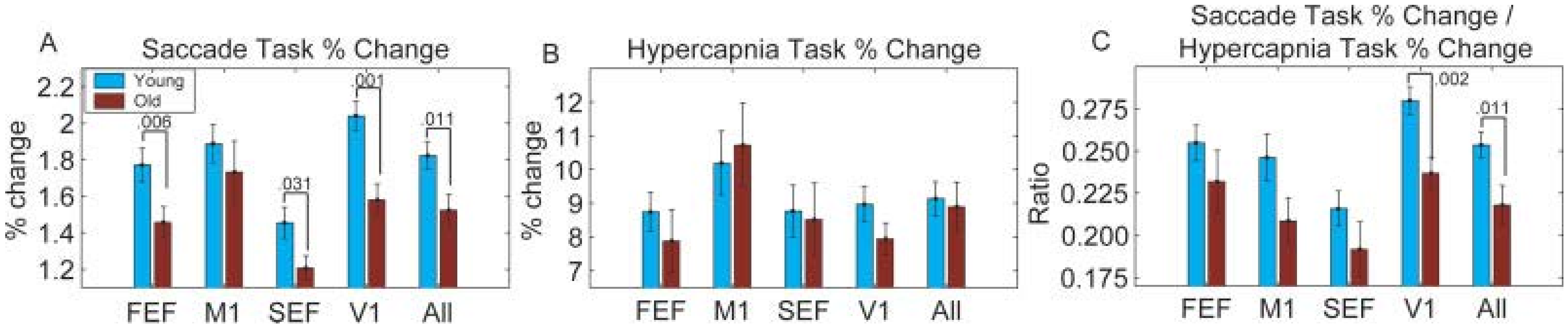
Without PROMO

With PROMO

Images from Vinai Roopchansingh

Calibration or Baseline scans

Collecting an additional scan that helps correct for subject-specific systematic variation



Handwerker, Gazzaley, et al 2007

- Other examples are simple tasks, enriched gas breathing, baseline CBF, standard deviation of resting scans
- Good sanity checks and may be useful
- These can take scanner time away from studying the effects of interest, which has limited their popularity
  - Relatively few clinically interesting studies use them

Summary

- Noise from many sources will always exist in fMRI data
- The more you understand noise sources and what acquisition decisions affect them, the better you can control for noise in acquisition and correct for noise in post-processing

Acknowledgements

Laurentius Huber

Ben Inglis

Vinai Roopchansingh

Bob Cox

Peter Bandettini

Laurentius Huber is giving several presentations that focus on layer sensitive fMRI, reducing acquisition noise, and VASO

Oral presentation NOT in the program
In Tuesday session on High resolution fMRI via multiband (SMS) acquisition: opportunities and limitations, Ballroom AB, 8:40-9:00AM

Posters: 3540 & 3605