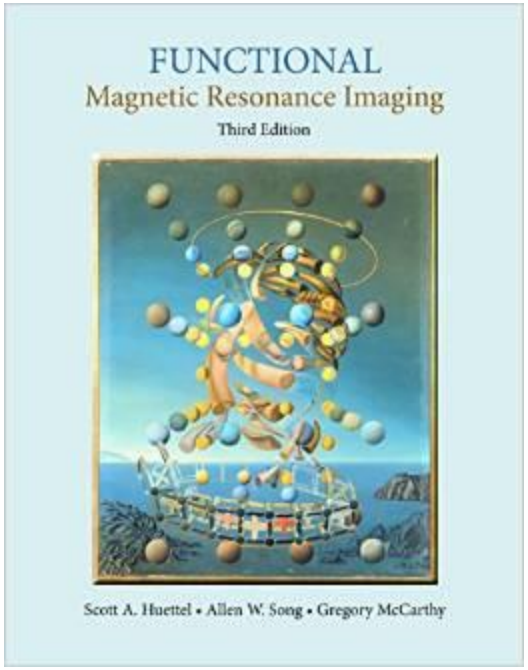
Quality Assurance & Pre-Processing in fMRI

吳建德

台灣大學 職能治療學系

References

劉鶴齡 教授

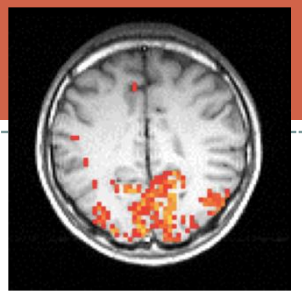


Huettel, Song & McCarthy, 2014

吳昌衛 教授

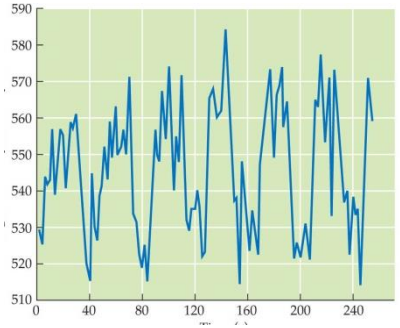
Procedures of a typical fMRI study

Hypothesis



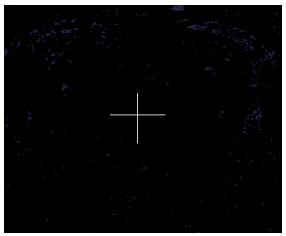
Brain activity

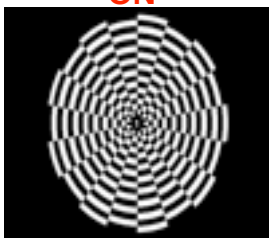
Statistical Analysis



Measured MR signal

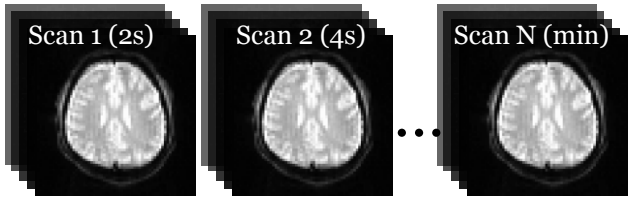
OFF ON





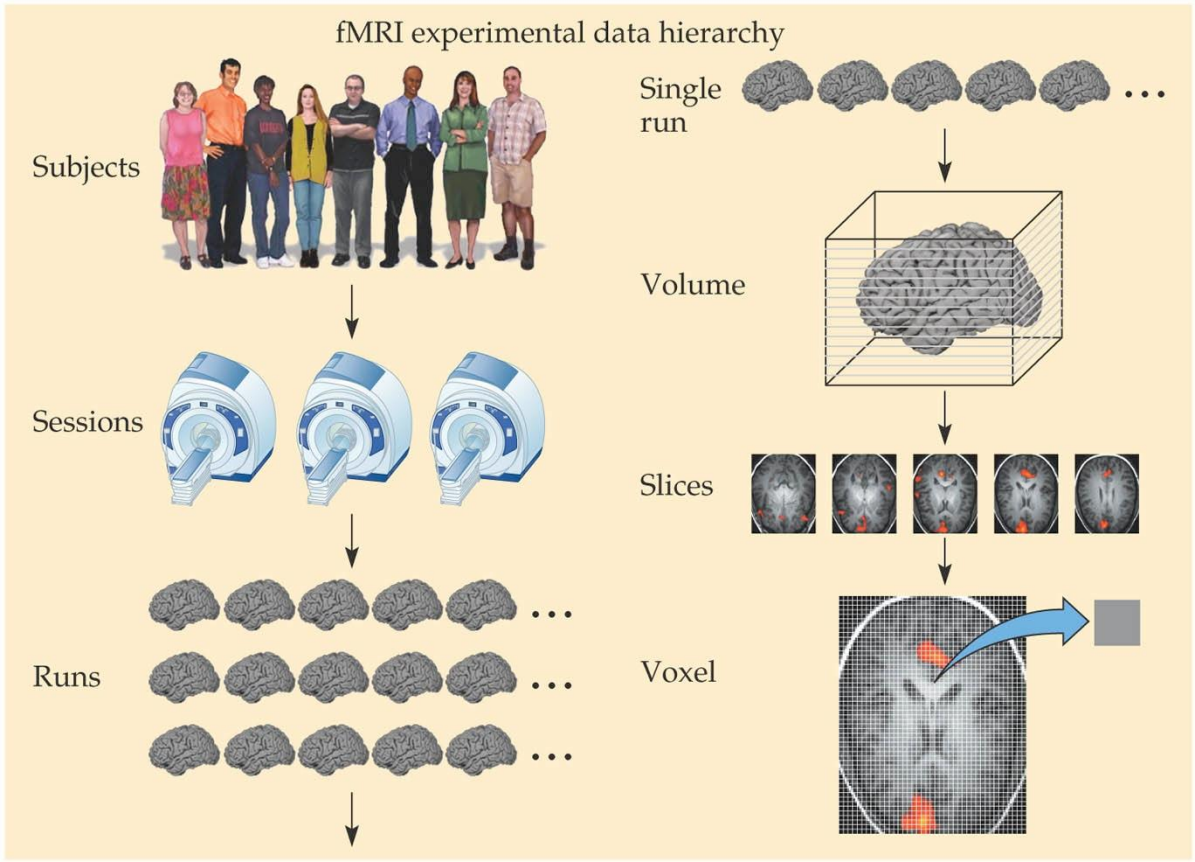
OFF ON OFF ON OFF ON OFF ON

Experimental Design



Physiological Response

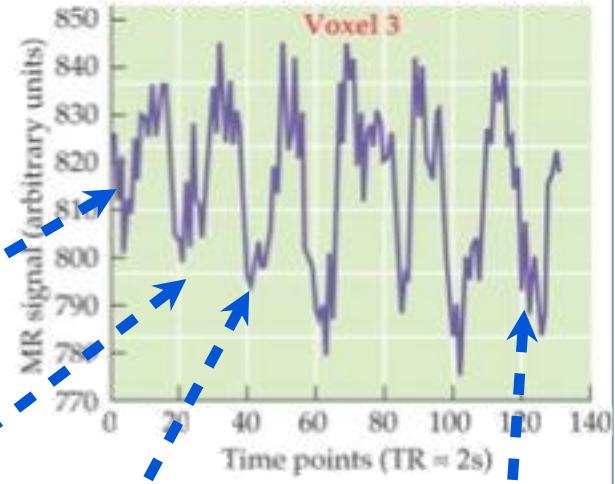
What are the DATA?

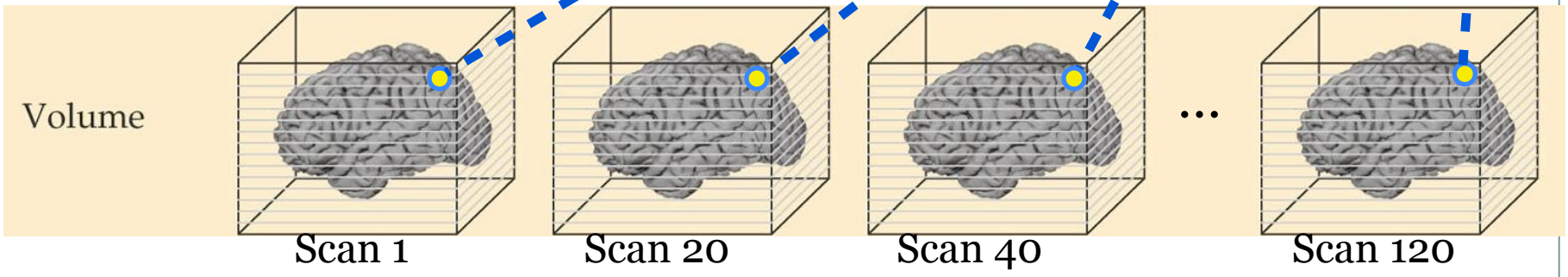


Huettel et al. ***Functional Magnetic Resonance Imaging*** 2004

DATA structure: 4 dimensions

- fMRI signal -> **(x, y, z + time)**



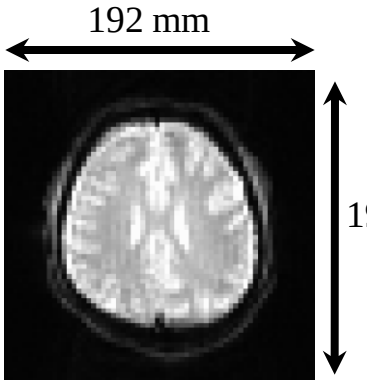


The Spatial Domain

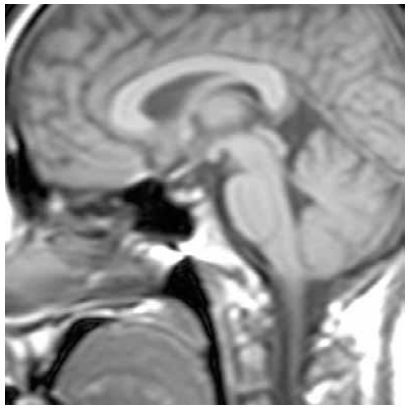
Field of view (FOV) & Matrix size (MTX)

一個volume的空間大小，決定了空間解析度

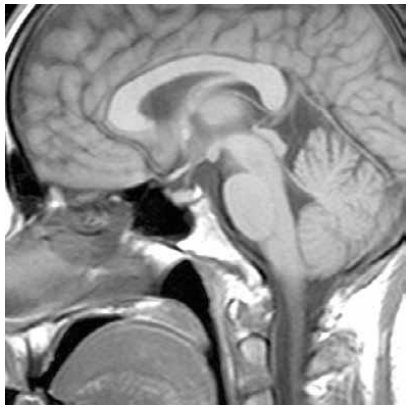
$$\text{Pixel size} = \frac{\text{FOV}}{\text{Matrix size}}$$



Example: EPI 64 x 64 → spatial resolution = 3 x 3 mm^2

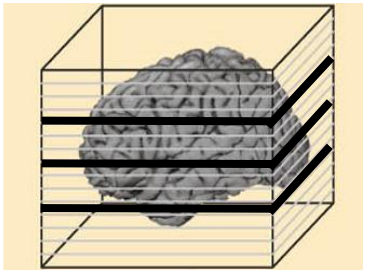


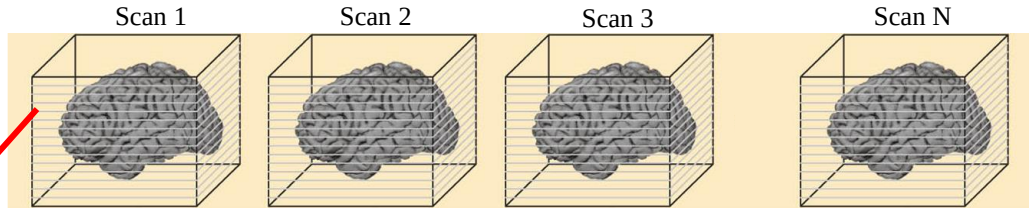
64 x 64

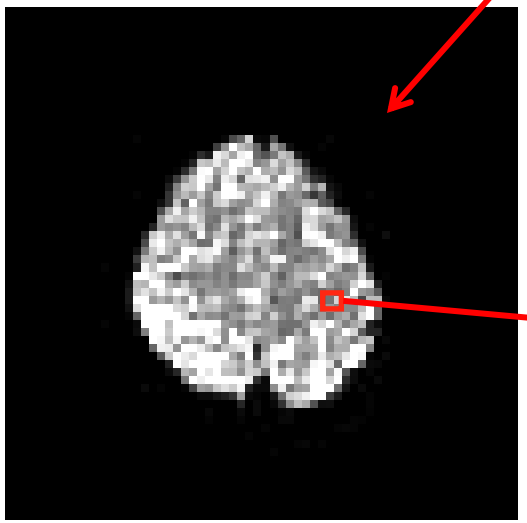


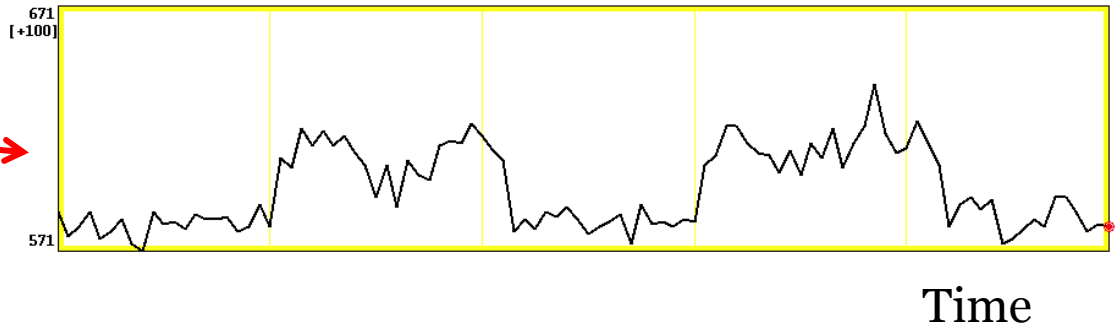
128 x 128

The Time Domain





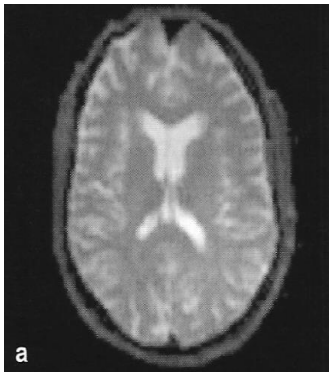


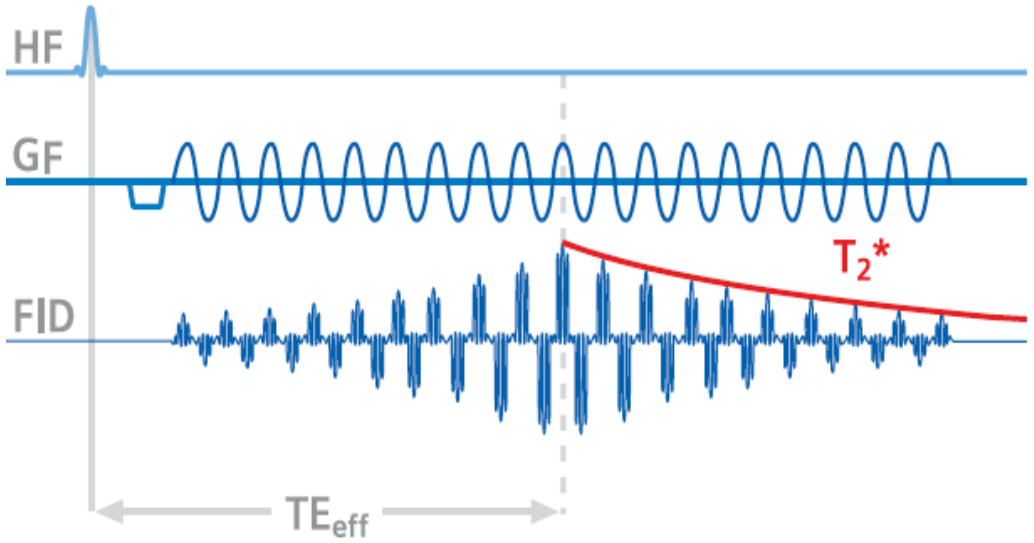


Artifacts (假影)

***Peter** Mansfield*
(1933-) UK

史上最快速成像序列(單張影像<0.1s)，卻也有最多的影像假影與麻煩…





Artifacts (假影)

❖ **N/2 Ghost**

Unmatched lines in k-space

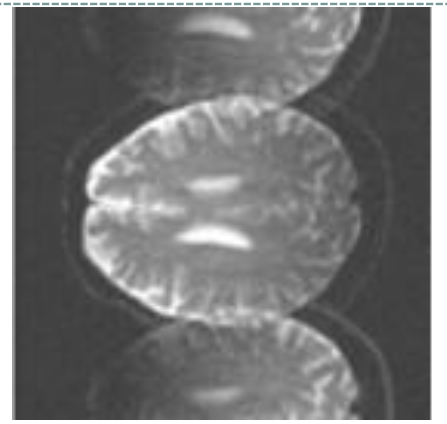
❖ **Chemical shift**

Resonance difference btw lipid / water

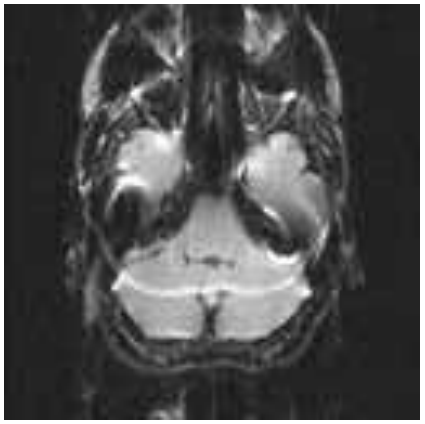
Solution:

Adjust k-space signal

Saturation pulse



N/2 ghost

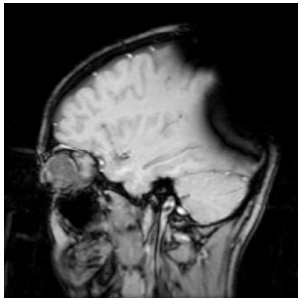


Chemical shift

Artifacts (假影)

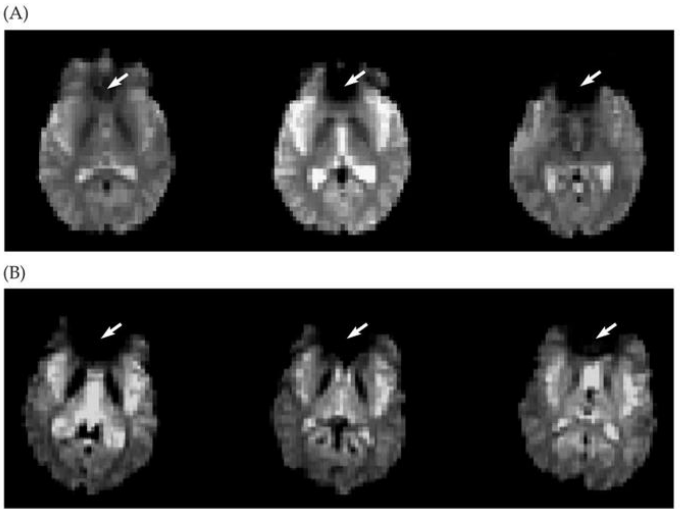
❖ **Distortion**

Susceptibility difference



❖ **Signal Drop**

significant in OFC!



Source: FSL 2010 course. ***FEAT***

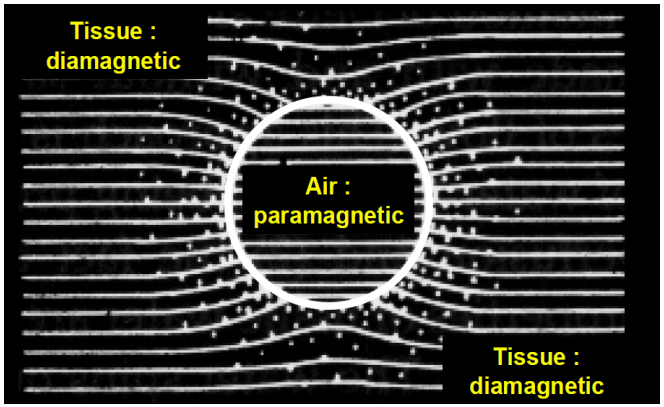
Solution:

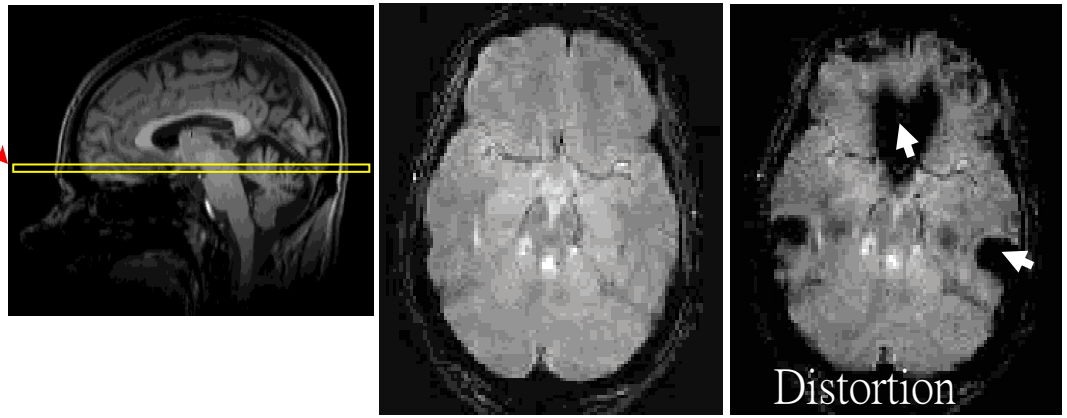
Correct using field map

Z-shim

Additional shim coil

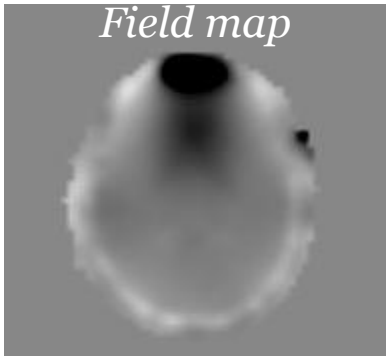
Artifacts (假影)

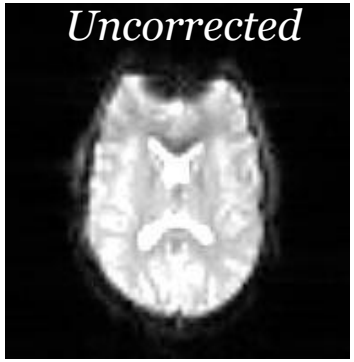


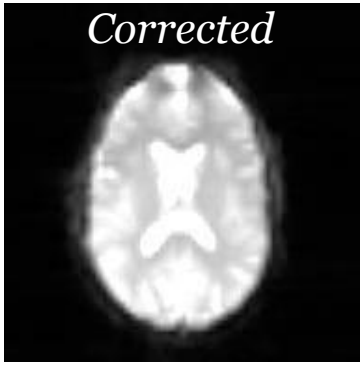


Courtesy of Prof. Karla L. Miller, Oxford University

Artifacts (假影)



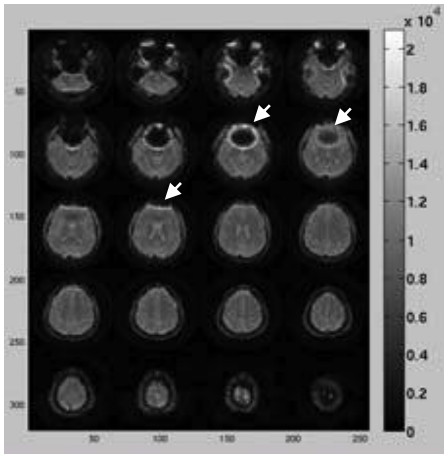




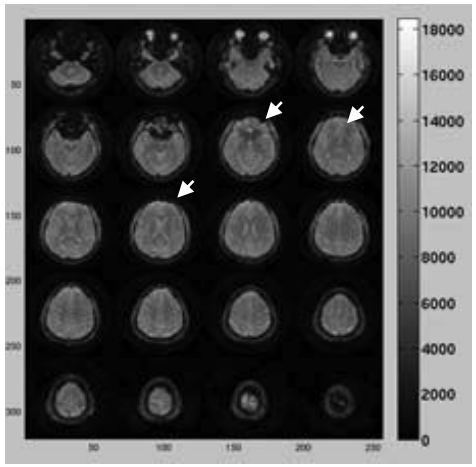
- New machine has built-in "field-map" sequences.
- Take another 1-2 min only.

- Remove part of distortion.
- Introduce slight blurring.

Before correction



After correction

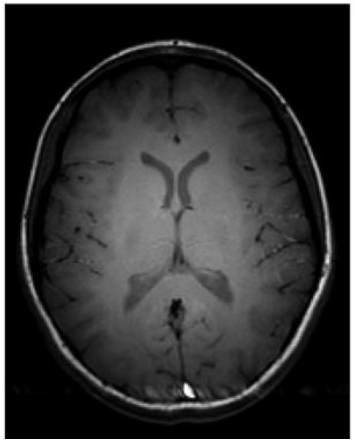


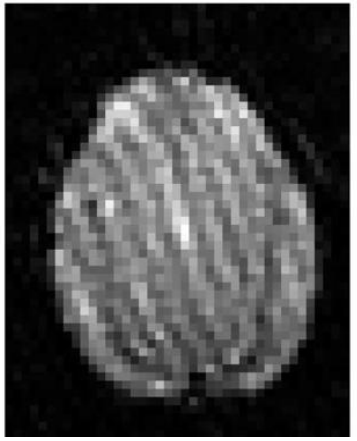
Courtesy of Prof. Ho-Ling Liu, Chang Gung University & Prof. Karla L. Miller, Oxford University

Artifacts (假影)

❖ **RF leakage**

EMI from outside frequency of FM radio



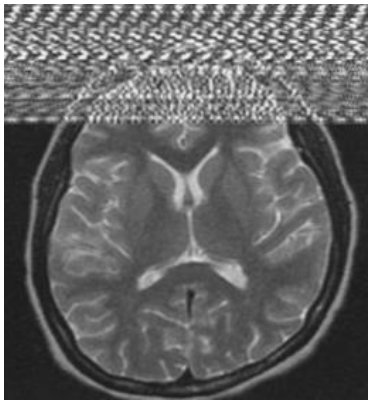


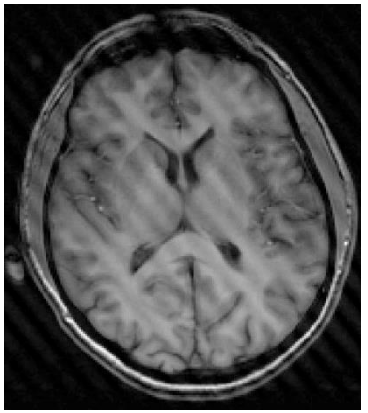
Solution:

Close the door!

RF shielding

Check the cables





Artifacts (假影)

❖ Motion

Controllable motion (yes/no)

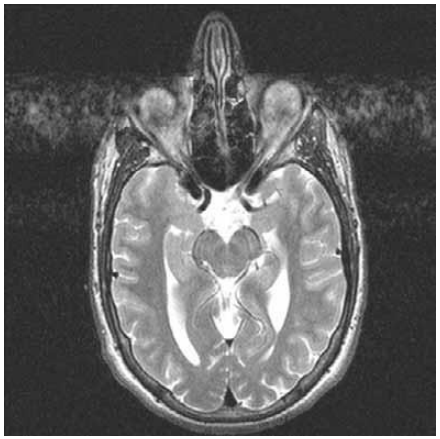
Periodic motion (breath, cardiac pulse, eye movements) causes multiple objects

Solution:

Minimize controllable motion

Record periodic motion for correction (e.g. RETROICOR)

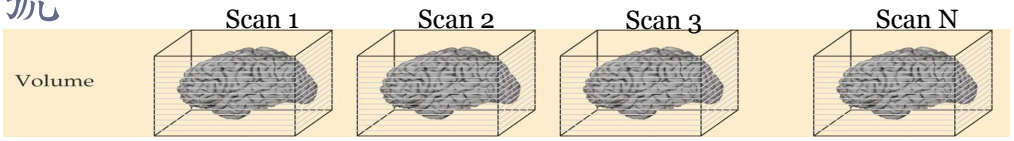
Respiration

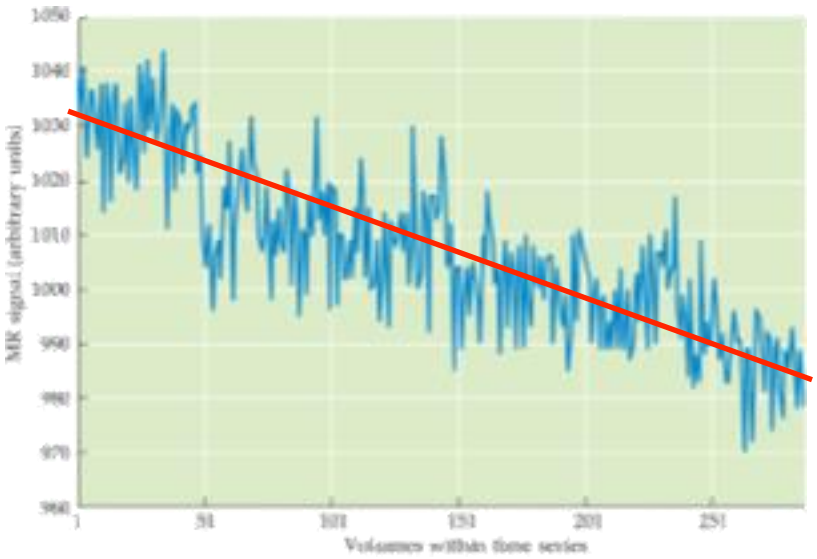


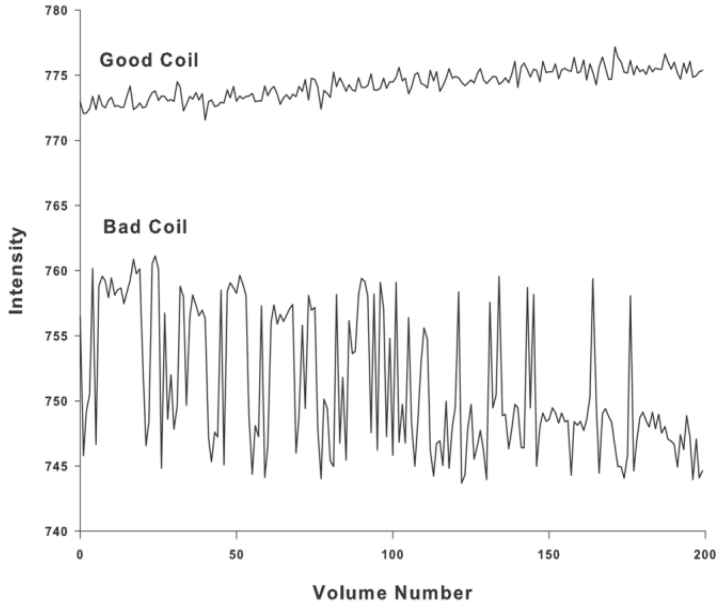
Eye-movement

Signal Instability

- fMRI是動態訊號
  - ✓ 重點在時間
  - ✓ 時間上的訊息要有足夠的穩定性
  - ✓ 可是有的時候連MRI機器本身都不是那麼穩定…





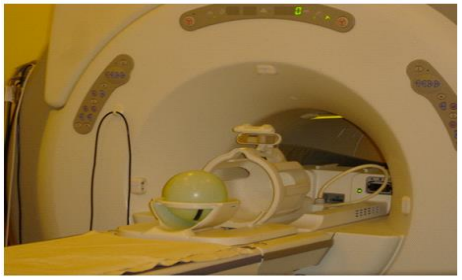


Friedman & Glover ***J Magn Reson Imaging*** 2006

fMRI stability protocol

Gary Glover
Stanford Radiology

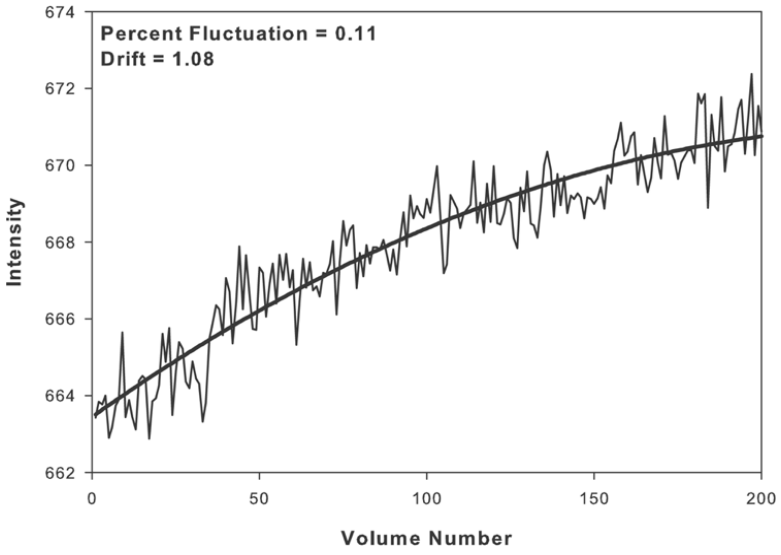
- **穩定度測試**
  - Use phantom test
  - lasting for 198 time points
  - **Drift** (<1%)
  - **Fluctuation** (P2P < 1%)



Stanford Criteria

17-cm spherical agar gel.

Acquisition type	EPI or spiral gradient echo recalled
Scan plane	Humans: axial oblique (AC-PC line) Phantom: straight axial
Field of view	22 cm
Slices	27, 4-mm-thick, 1-mm interslice gap
TR	2000 msec
TE	30 msec (3 T/4 T), 40 msec (1.5 T)
Flip angle	90 degrees
Bandwidth	≥ ± 100 kHz
Matrix	64 × 64
Number of volumes collected	For QA: 200 + optional warmup volumes
Scan time	6.67 minutes



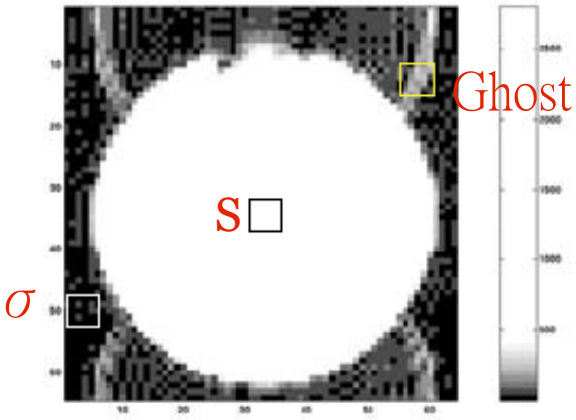
Friedman & Glover ***J Magn Reson Imaging*** 2006

Signal to Noise Ratio (SNR)

- 2 Types of SNR
  - Spatial SNR (MRI)
  - Temporal SNR (fMRI)

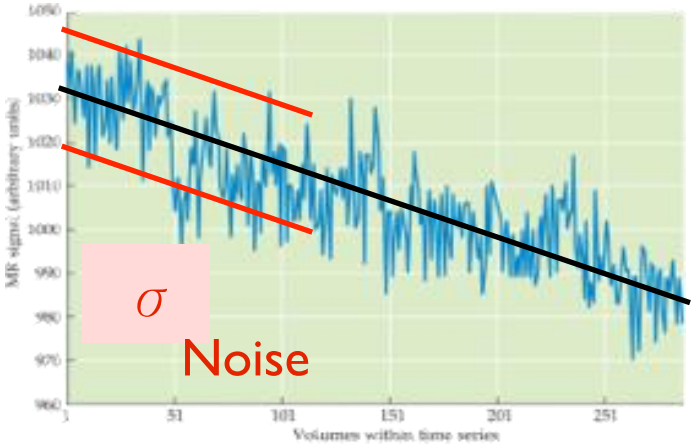
信雜比 $SNR = \frac{S}{\sigma}$ 影像強度 / 雜訊

Spatial SNR



SNR_0=115, SGR=33 (3x3x6 mm^3)

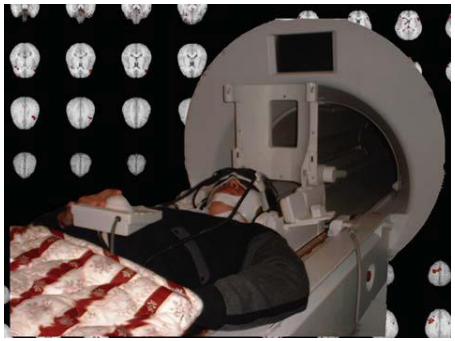
Temporal SNR



SNR=51.5, p2p=4.3%

Stimulation devices

- fMRI要進行很多刺激呈現



- 要用MRI相容系統(很貴!)

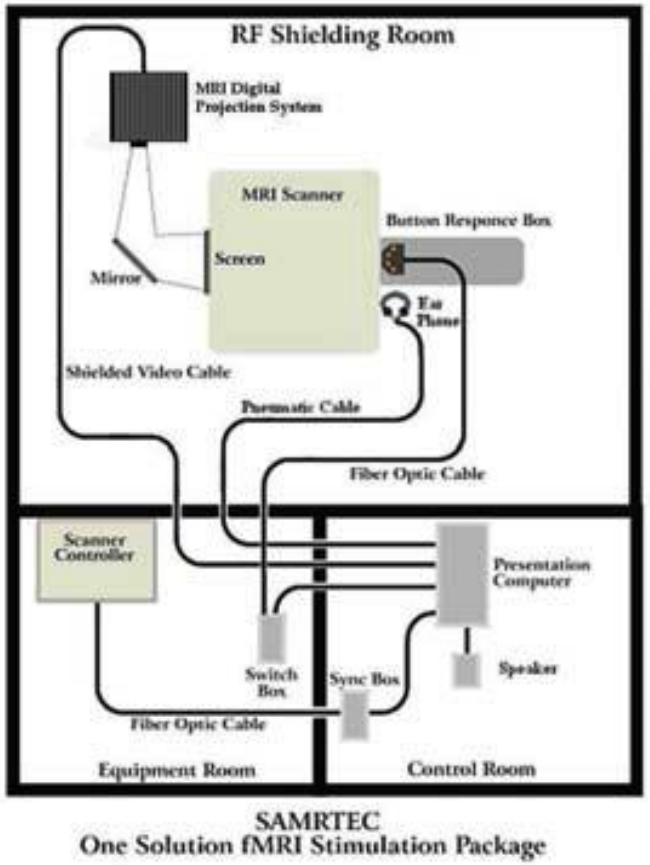
  Projector, goggle, eye tracker

  Headset, Response pad, physiological monitor

  要用光纖或透過屏蔽板連接

- 但是…

  它們會不會對fMRI影像信號產生干擾?



SAMRTEC
One Solution fMRI Stimulation Package

Courtesy of Prof. Ho-Ling Liu, Chang Gung University

Stimulation devices

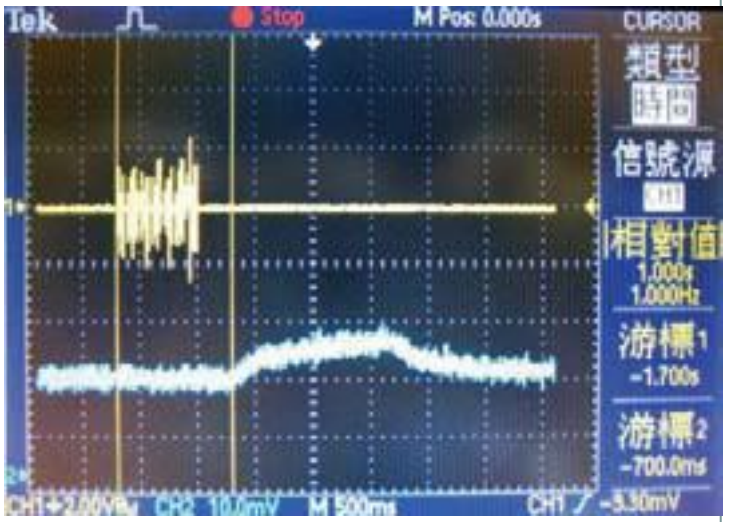
- 配戴fMRI週邊設備進行掃瞄有可能產生信號延遲或影像假影

- 視覺刺激：

  信號反應是否即時? 顯示畫面對比與亮度是否符合需求? 是否會在影像上產生假影?

- 聽覺刺激：

  聲音信號反應是否即時? 頻率是否受到影響?



Ex. The computer delivers a 1-s delay between 700-ms auditory and 1000-ms visual stimuli.

Courtesy of Prof. Ho-Ling Liu, Chang Gung University

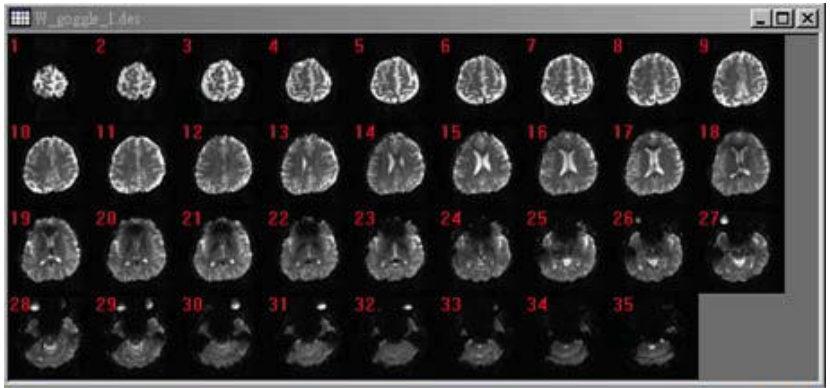
Stimulation devices

- with goggle vs. without goggle

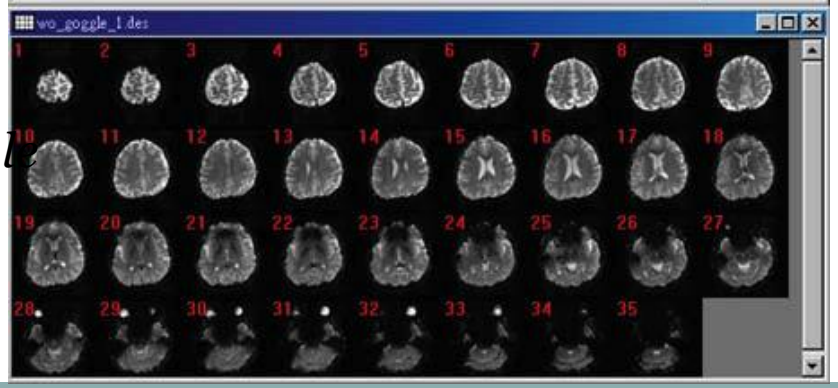
  整體SNR下降

  局部區位產生假影（要注意!）

with goggle
SNR=279.4



without goggle
SNR=371.4



Courtesy of Prof. Ho-Ling Liu, Chang Gung University

Stimulation devices

- with headset vs. without headset

  整體SNR下降

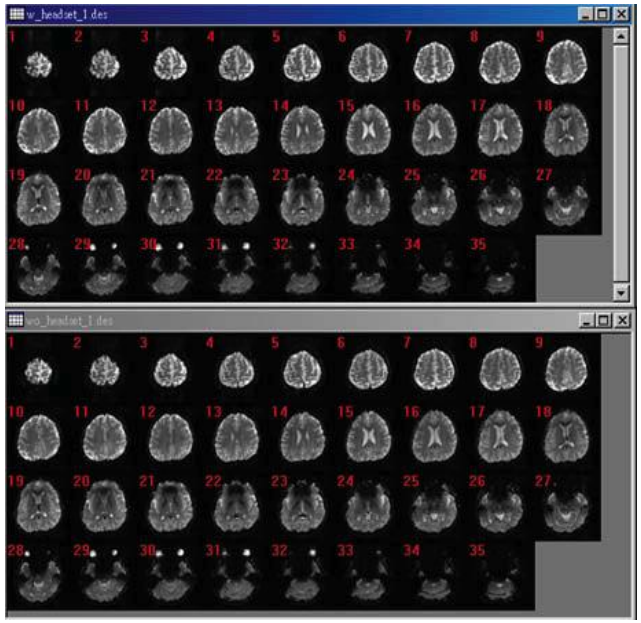
  局部區位產生假影（要注意!）

noise

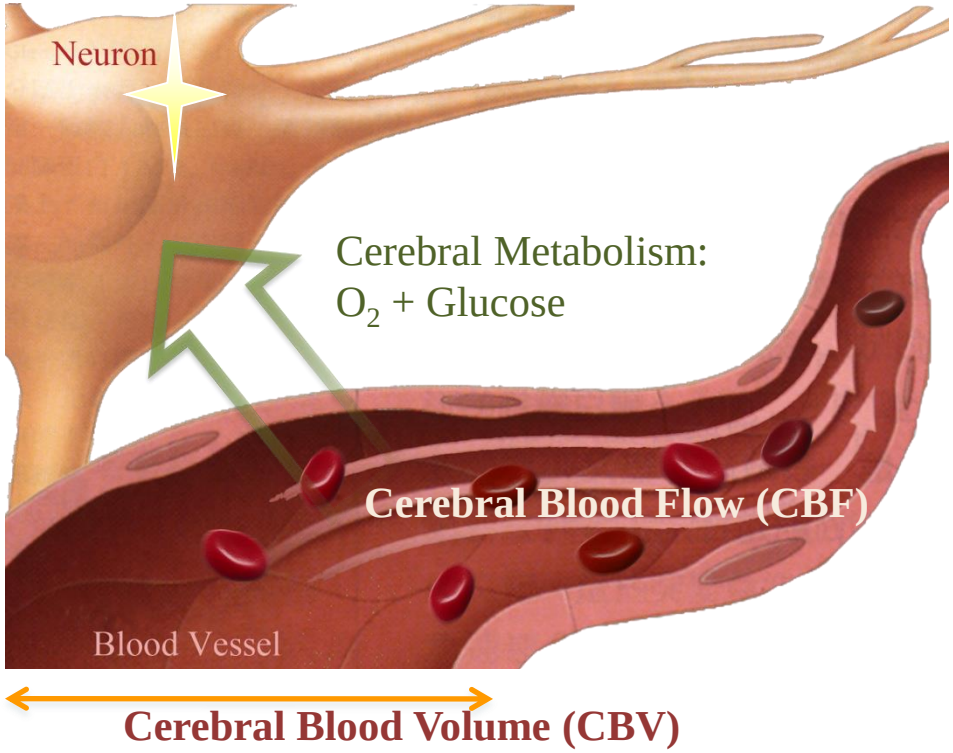
image

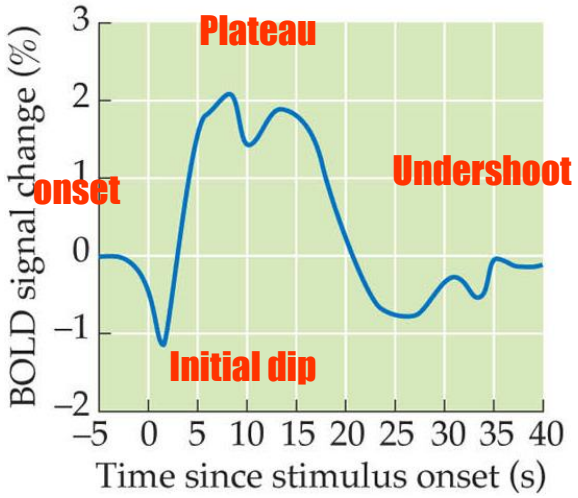
with headset
SNR=208.4

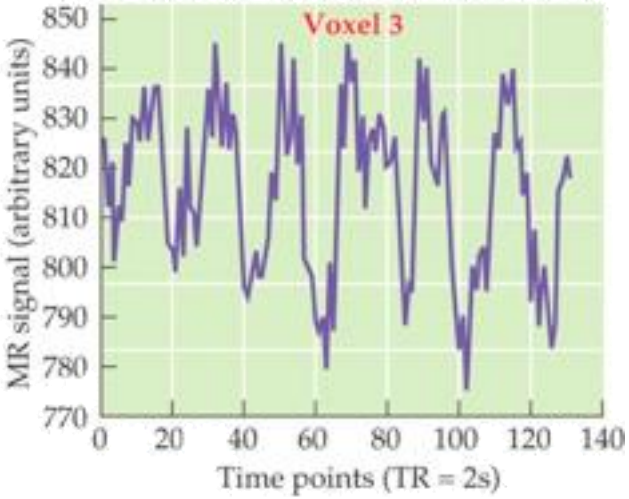
w/o headset
SNR=235.3



Functional contrast-to-noise ratio (CNR)

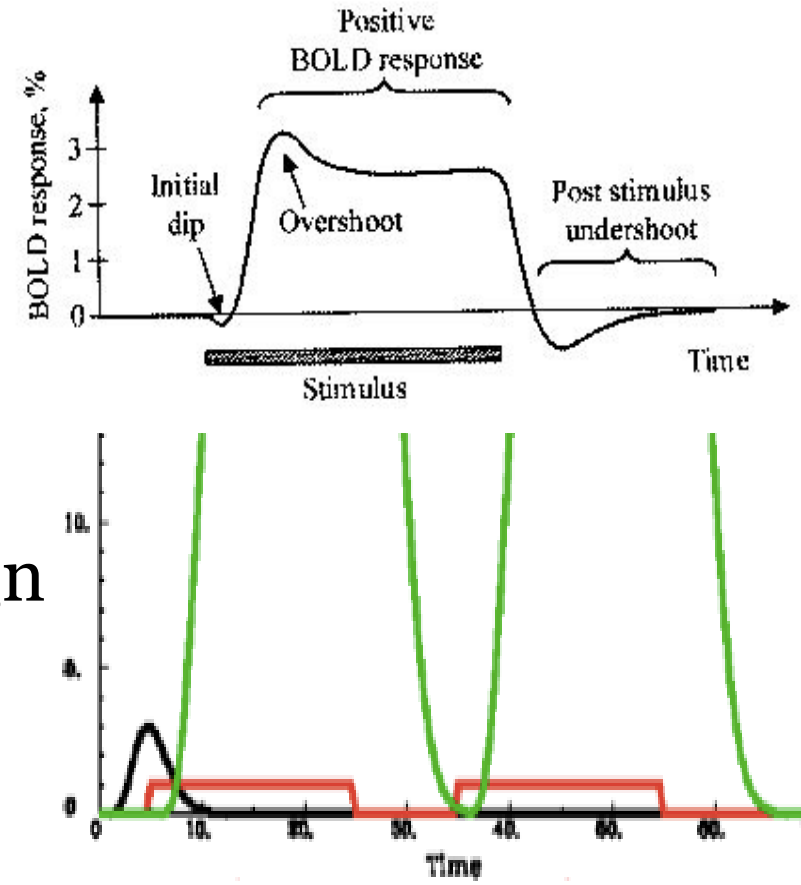






Functional contrast-to-noise ratio (CNR)

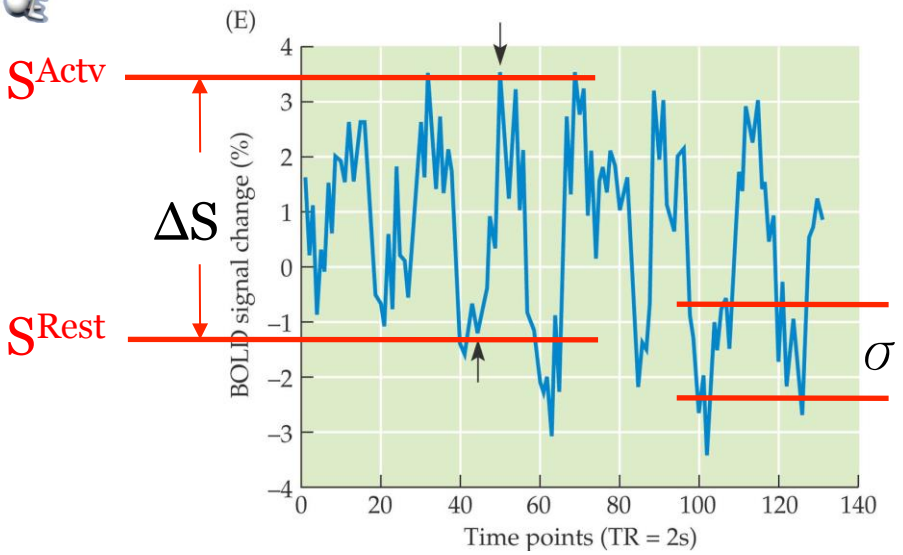
- Ideal response of fMRI signal to single stimulu
  - Delay: 1-2 sec
  - Rise time: 4-5 sec
  - Fall time: 4-6 sec
- Convolution with design
  - r(t) = h(t) ⊗ d(t)
  - Linearity assumption
    - Not precisely correct!



Functional contrast-to-noise ratio (CNR)

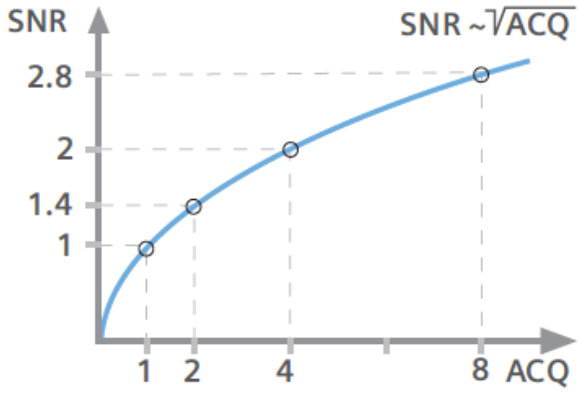
- Signal Change (SC)

$$\frac{\Delta S}{S} = \frac{S^{Actv} - S^{Rest}}{S^{Rest}}$$



- Signal-to-Noise Ratio (SNR)

$$SNR = \frac{S^{Rest}}{\sqrt{\sigma_T^2 + \sigma_P^2}}$$

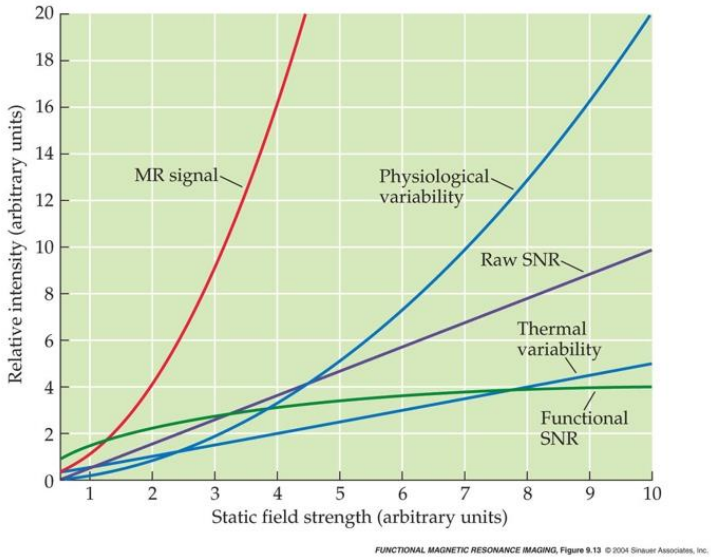


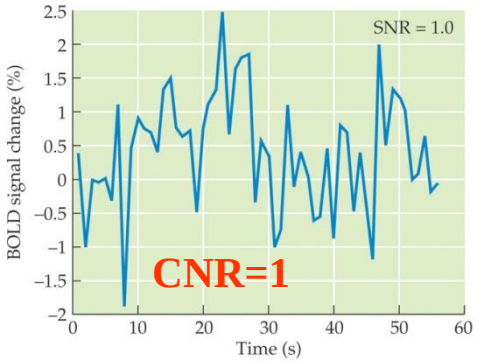
Functional contrast-to-noise ratio (CNR)

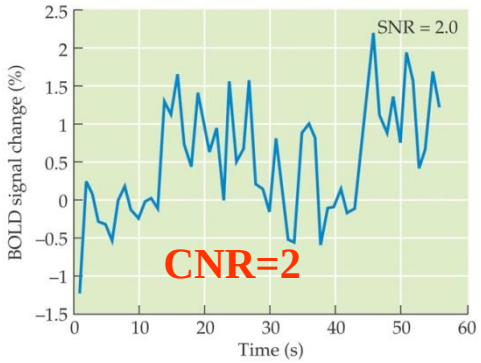
- Contrast-to-Noise Ratio (CNR) or *Functional SNR*

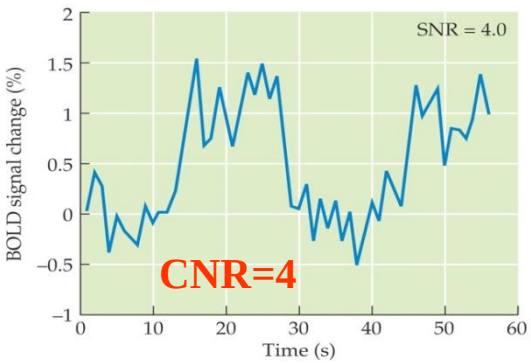
$$CNR = SC \times SNR = \frac{\Delta S}{\sigma}$$

2% 100





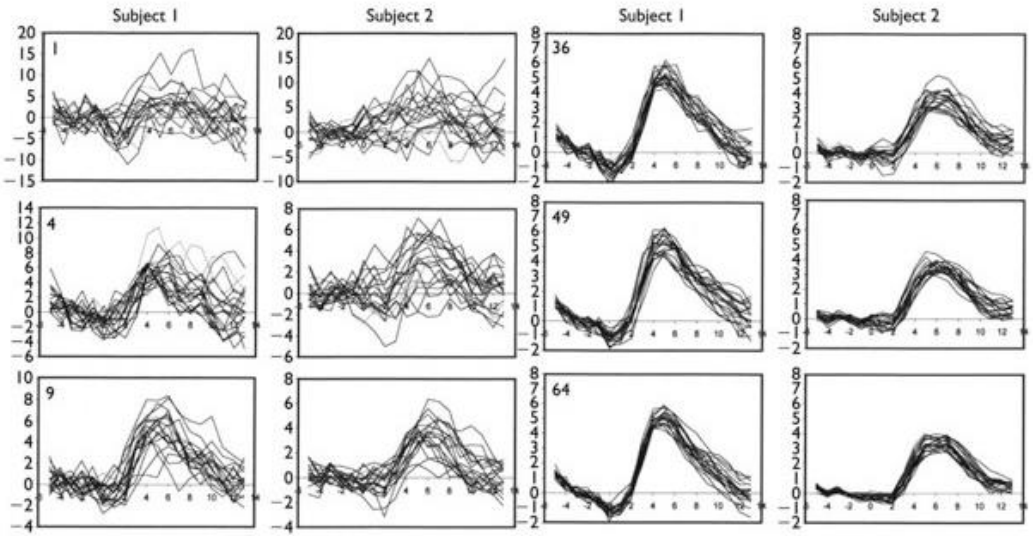


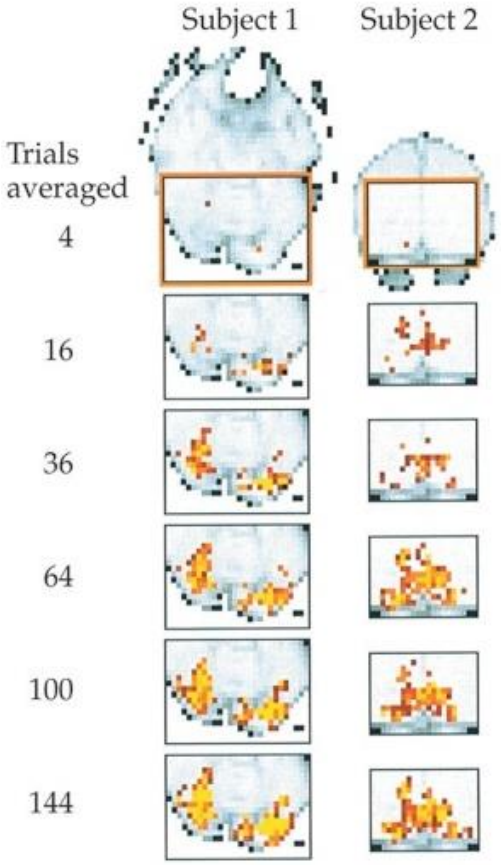


Increasing functional CNR

- **Trial Number ⇑**

Trade-off: ACQ time & Task effect





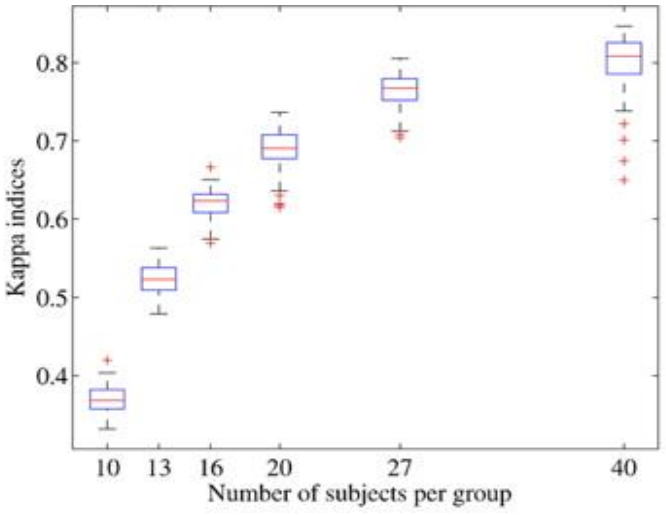
Increasing functional CNR

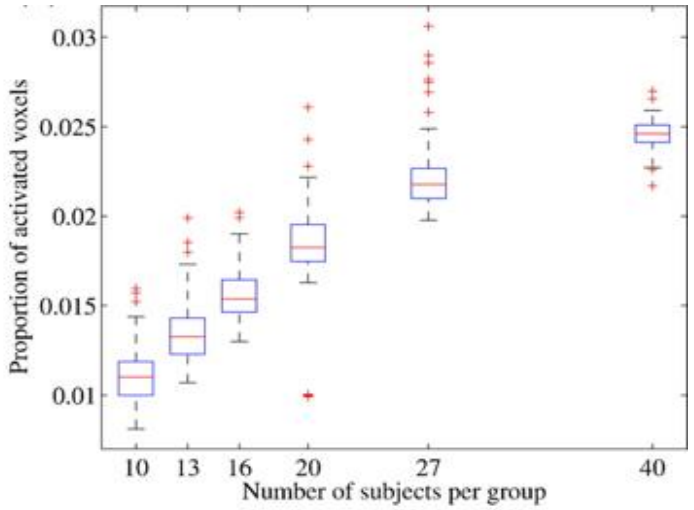
- **Subject Number ⇑**

  For reliability, N=20 is a minimum requirements.

  Preferably, N>27

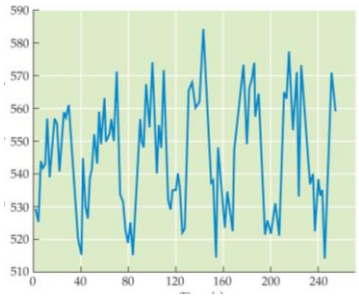
  Based on *auditory & motor* activity!

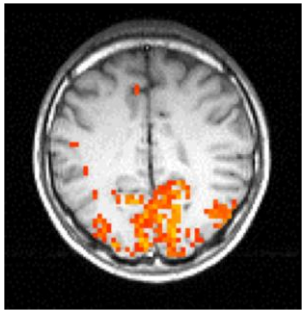




Thiroin et al. ***Neuroimage*** 2007

fMRI PreProcessing





Experimental Design

Image Acquisition

Quality Assurance

Preprocessing

Before we can really get the fancy results...

SPM procedure

Statistical Tests

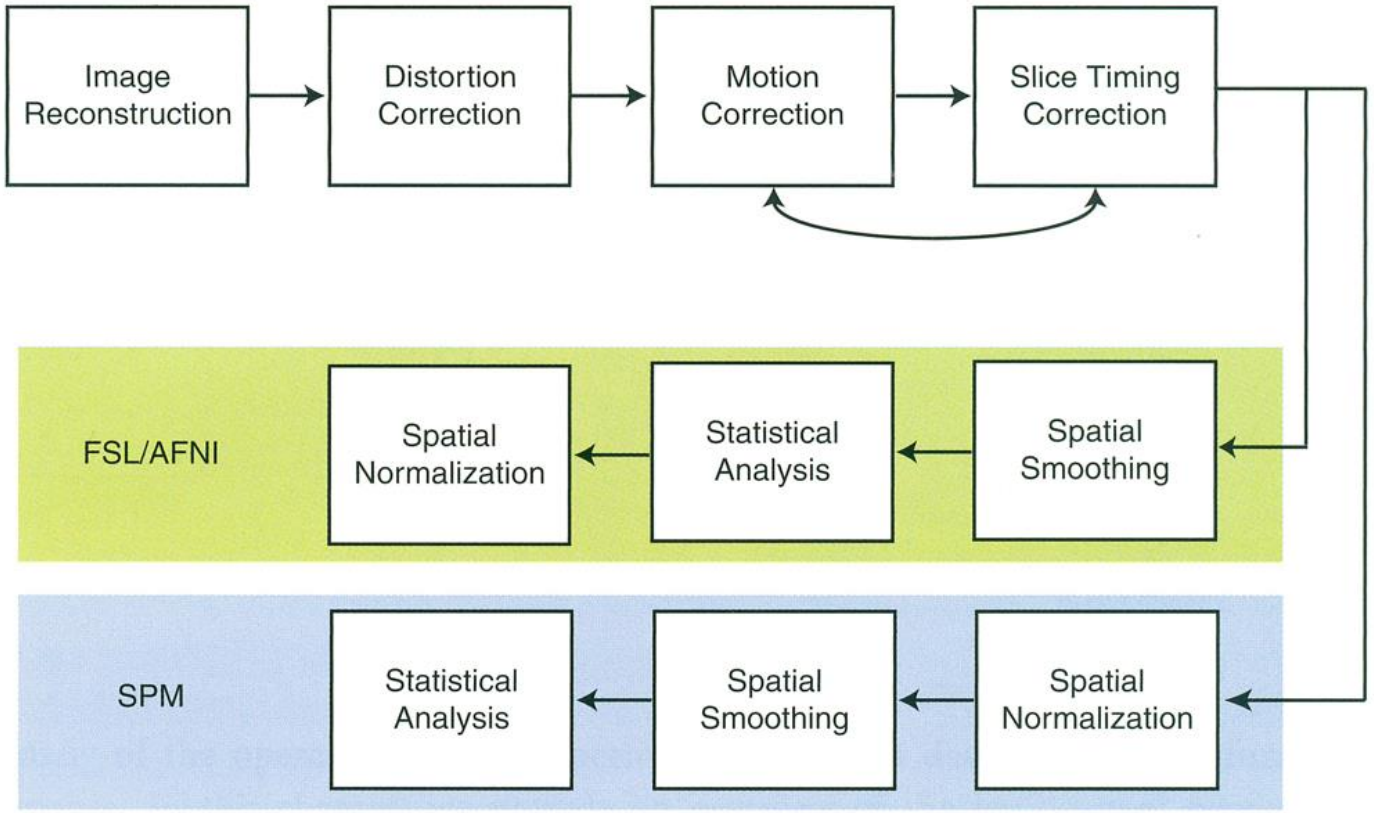
1st-level t-test/correlation/regression (GLM)

Group Analysis

2nd-level analysis

Poldrack et al. ***Neuroimage*** 2008

Preprocessing Procedures



Poldrack et al. ***Handbook of Functional MRI*** 2011

Motion Correction

QA

Realign-ment

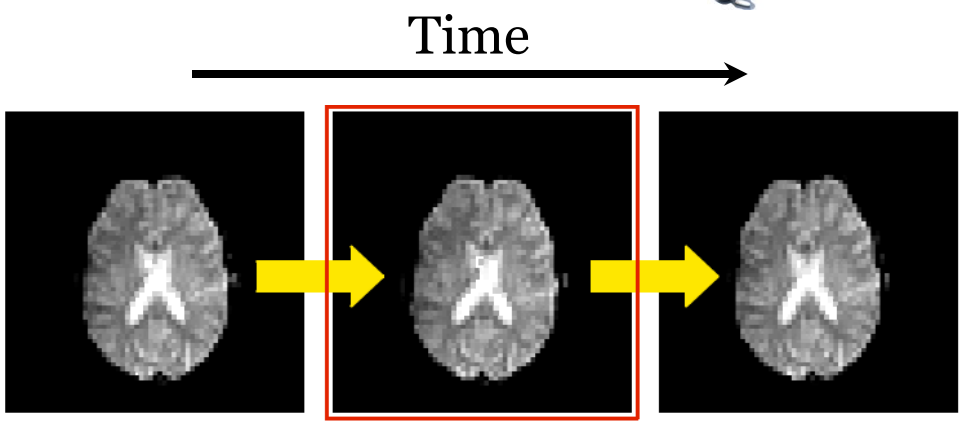
Slice timing

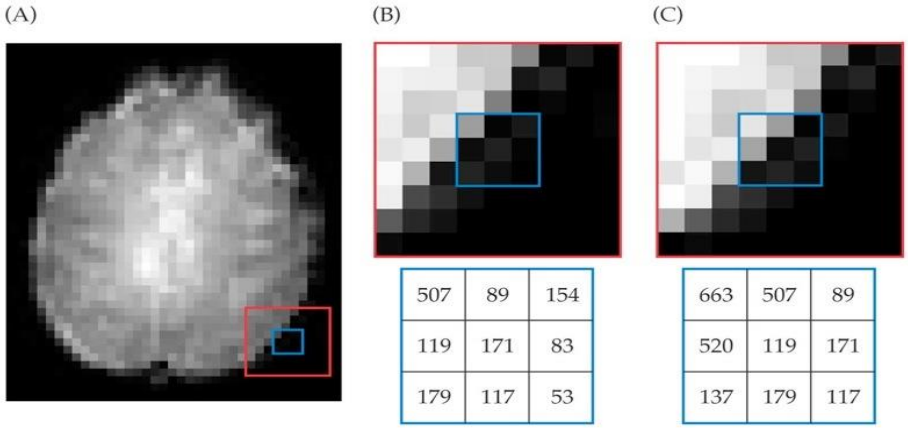
Coregist ration

Normali zation

Smooth

Segment ation



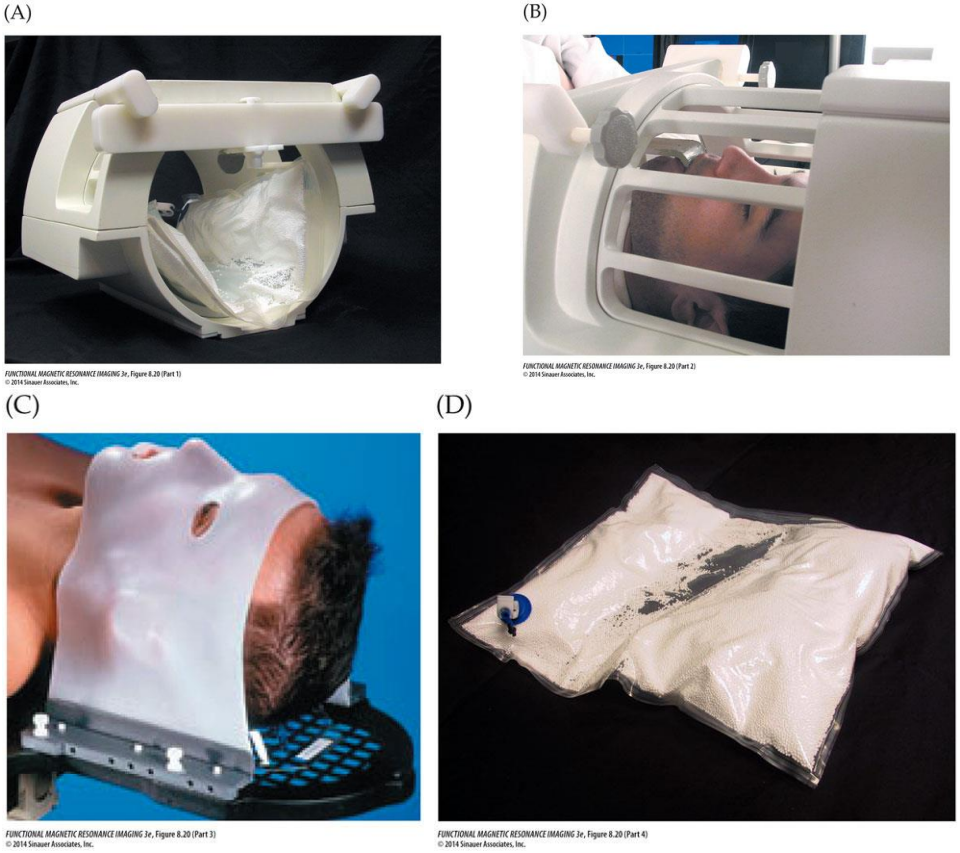


Huettel SA et al. ***Functional MRI*** 2014

- People do move in MRI
- General assumption:
  - each voxel should be located at the same point in acquisition.
  - **even w/ padding, slight motion is possible!**

$$\Delta S = (663-507)/507 = 30\%$$

Motion Correction

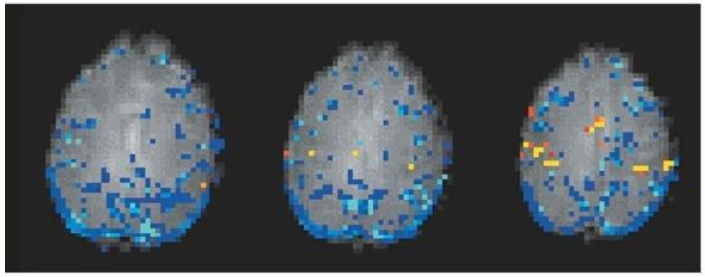


- **Motion** causes strong artifacts in MRI!
- Even worse in fMRI

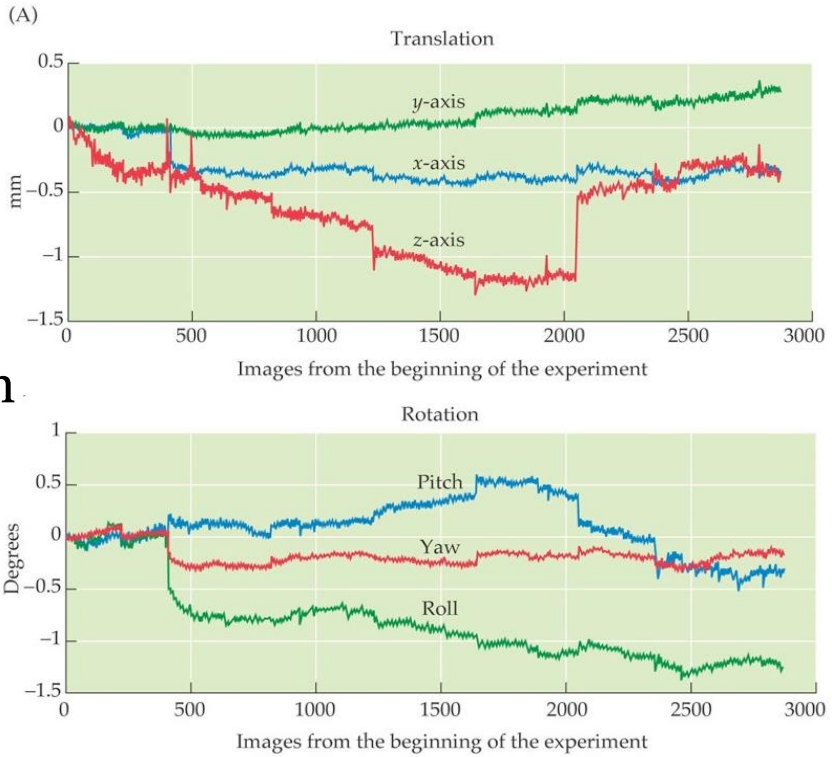
  ~ 1-mm motion may cause 30% signal change >> BOLD signal!
- Mandatory immobilization!

Huettel SA et al. ***Functional MRI*** 2014

Motion Correction



← If you don't do motion correction, esp. for task-related motion



- *Solution:*
  - Realign to a **common reference** (you pick one)
    - **Rigid-body** transformation (3 translations + 3 rotations)
    - Estimate / Write (SPM)
      - check if correction is good enough.

Huettel SA et al. ***Functional MRI*** 2014

Motion Correction

QA

Realign-ment

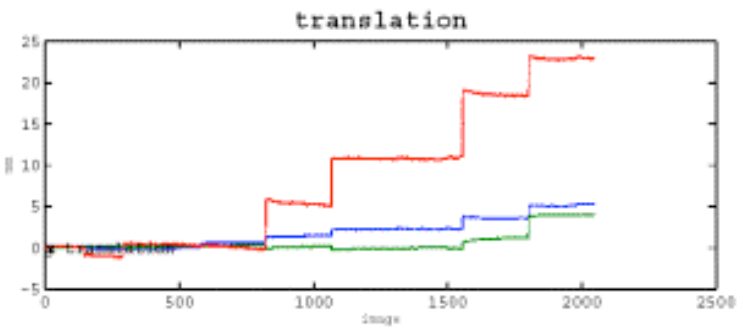
Slice timing

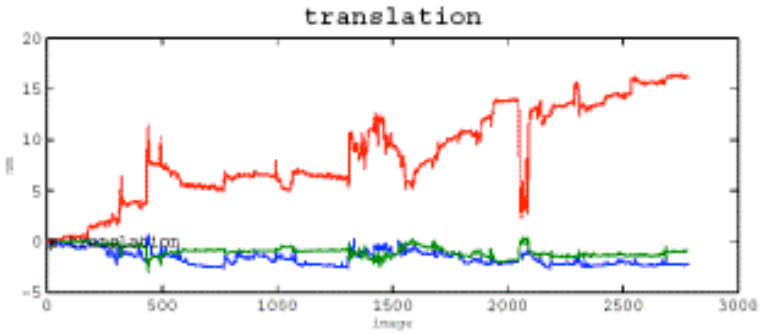
Coregist ration

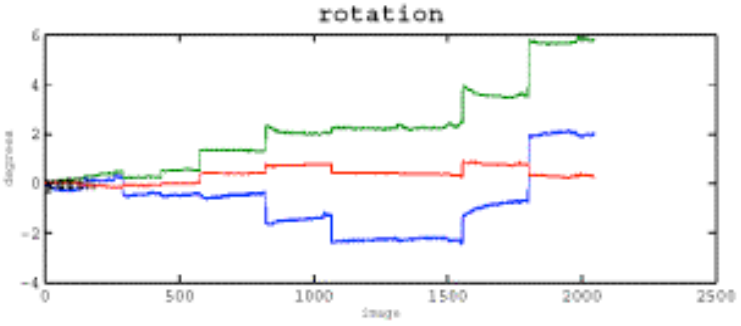
Normali zation

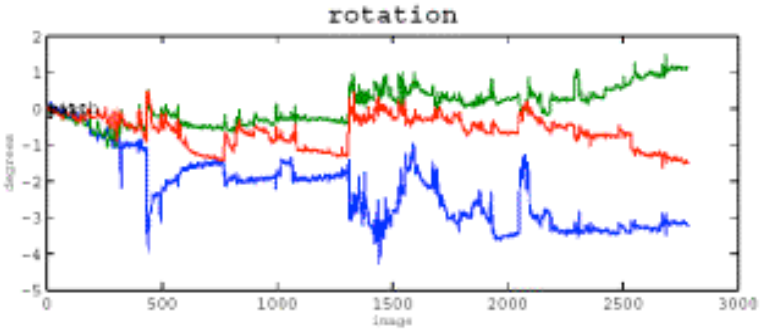
Smooth

Segment ation









Catastrophe…

Motion Correction

QA

Realign-ment

Slice timing

Coregist ration

Normali zation

Smooth

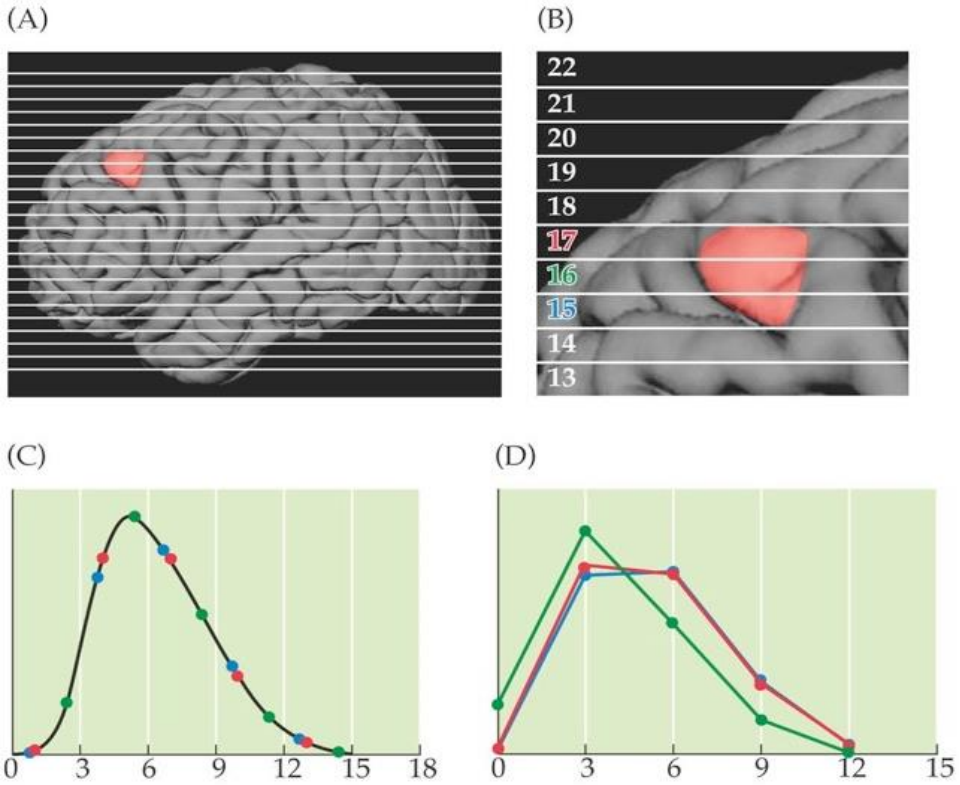
Segment ation

masking were disabled. The statistical analysis model included covariates for the global CBF variation and translational motion of the head. Extracerebral voxels were masked and statistical parametric maps (SPM's) were computed. First, the periods without penile stimulation were divided into periods when penile erection was present (Post-Stimulation) or when the penis was flaccid (Flaccid), defined as <10% of the maximum penile circumference. Average translational scan-to-scan movement was in the sub-millimeter range, average rotational scan-to-scan movement was less than 3 degrees in most subjects and always less than 6 degrees. Greater head motion was often recorded at the transition between the stimulation and non-stimulation periods. Five perfusion images (representing 33 s) were separately modeled and excluded from the analyses to remove confounding head motion at the time of maximum arousal and ejaculation. Comparisons were made between the Stimulation and

Slice timing correction

- Interleaved
  - ✓1-3-5-2-4

for less RF cross-talk



- *Problem:*

Adjacent slices are acquired at half-TR-away in timing

Error in timing estimation!

Huettel SA et al. ***Functional MRI*** 2001

Slice timing correction

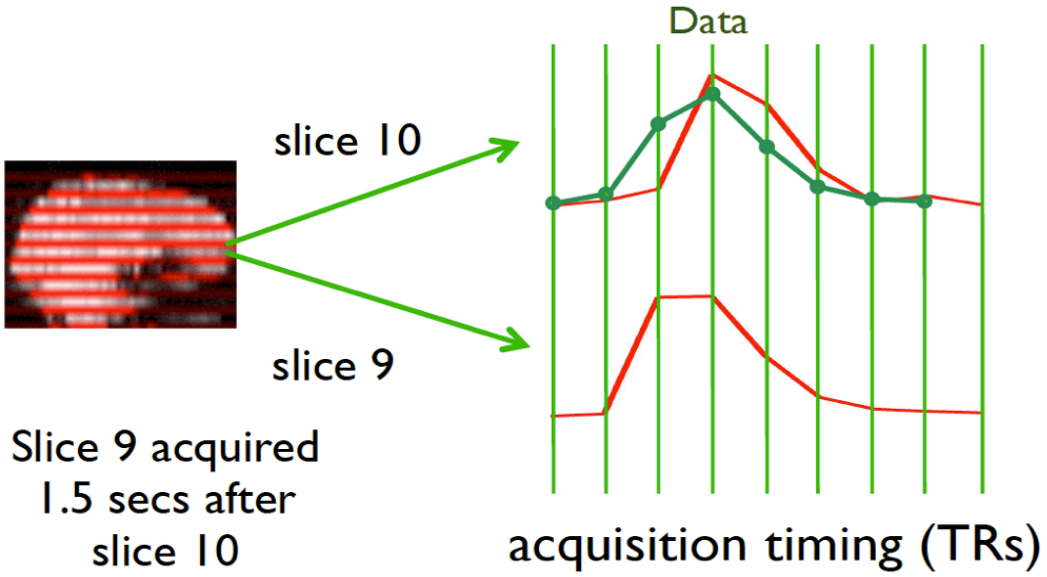
Problem:

- Adjacent slices are acquired at half-TR-away in timing

Solution:

- shifting the time delay
- interpolation

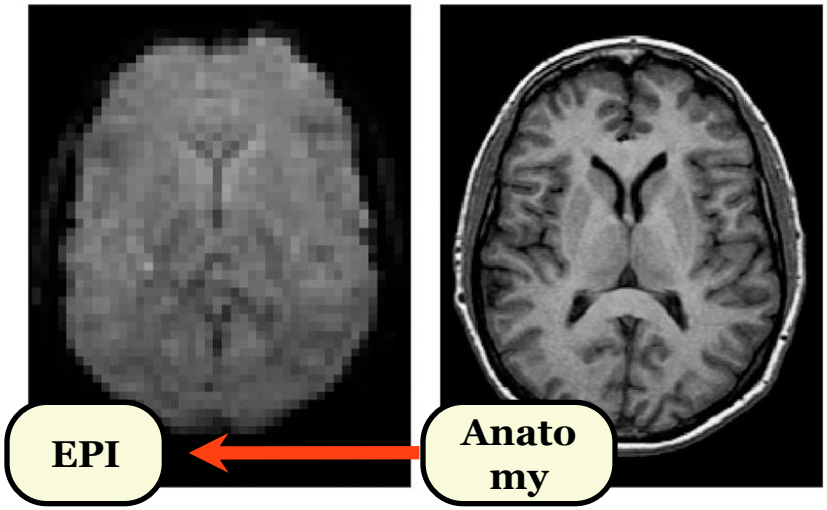
especially significant in Event-related design



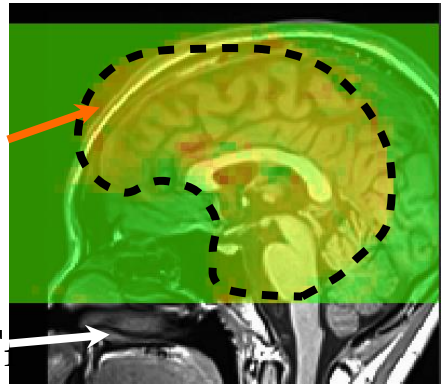
Source: FSL 2010 course. ***FEAT***

Coregistration

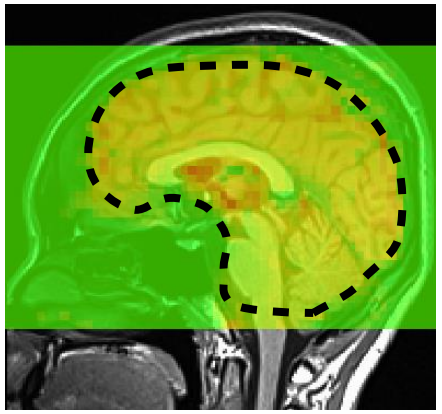
- **Anatomical image** (T_1w) should match **EPI images**
  - T_1w → EPI



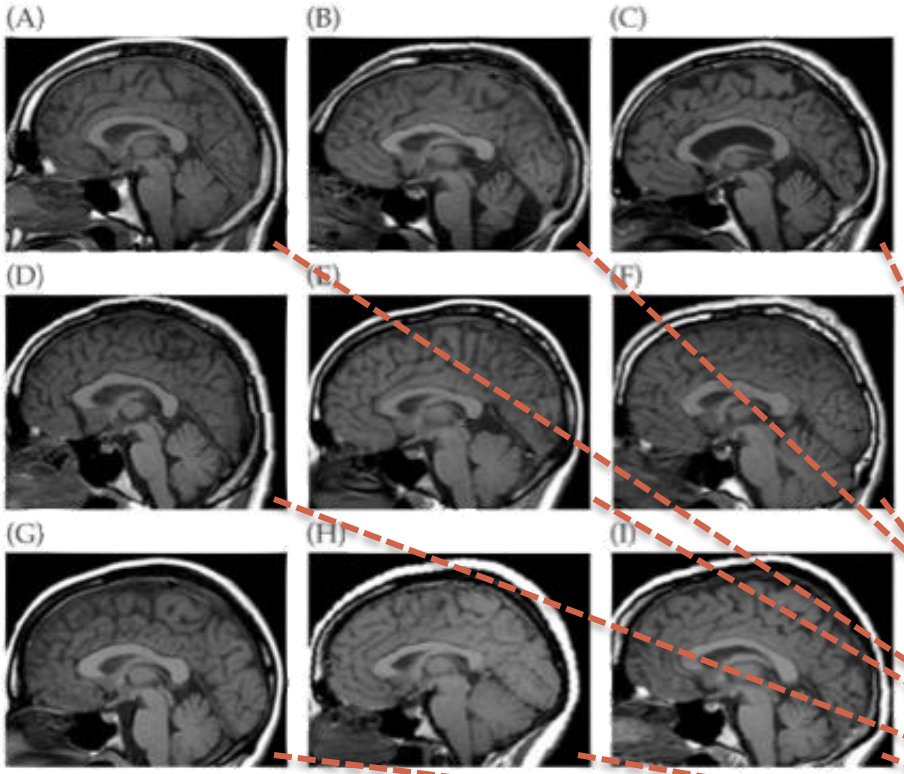
Un-coregistered



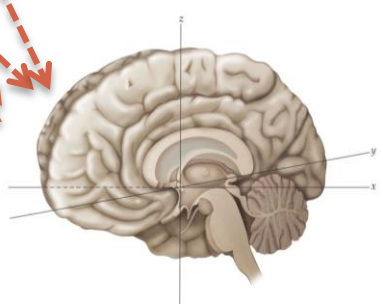
Coregistered



Normalization



- Everybody has different kinds of brain shape.
- To conduct Group Analysis, individual has to be transformed into a **template** (standard) **space**.



Huettel SA et al. ***Functional MRI*** 2001

Normalization: templates

- ***Standard Templates***
  - ✓ **Talairach**

    single French subject
  - ✓ **Montreal Neurological Institute (MNI)**

    152 normal westerns

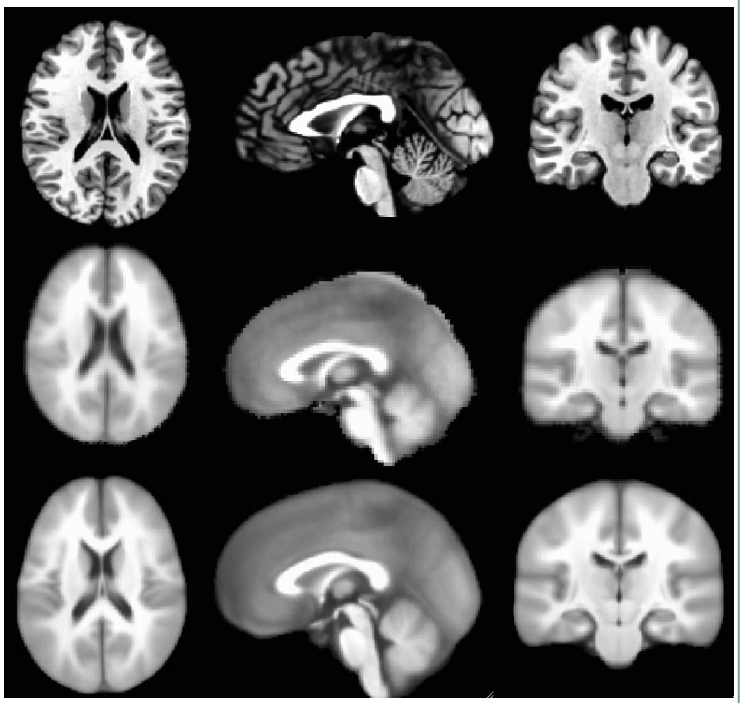
    http://www.bic.mni.mcgill.ca/
  - ✓ **International Consortium for Brain Mapping (ICBM)**

    452 normal westerns

    http://www.loni.ucla.edu/
  - ✓ **Asian templates**

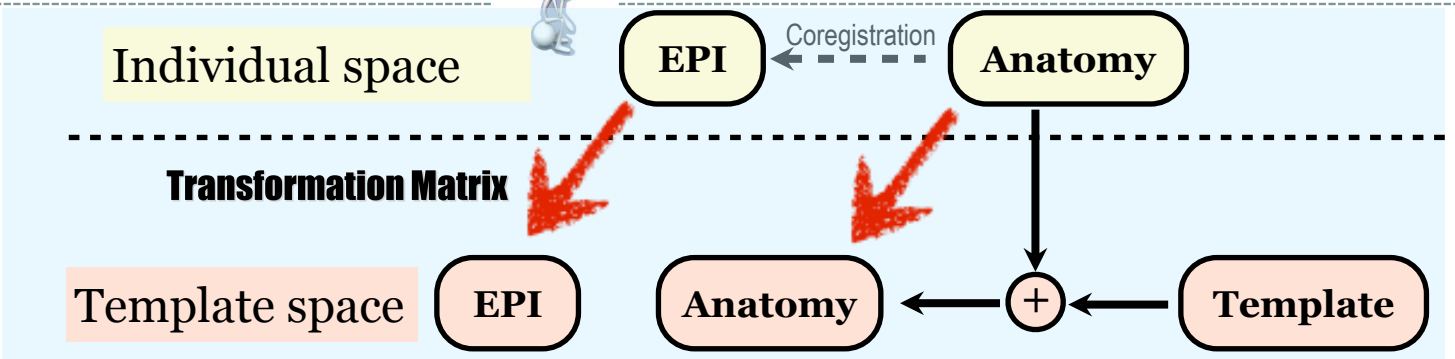
    NTU

    Singapore

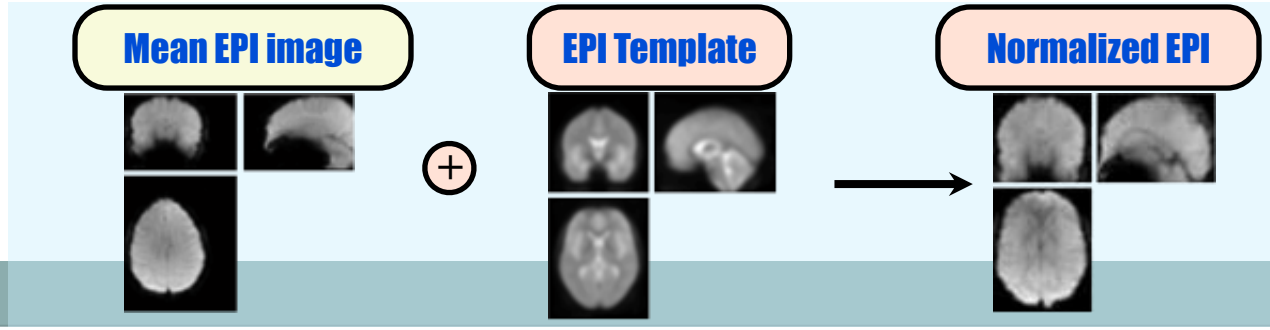


MNI to Talairach Conversion (Yale University)
http://www.bioimagesuite.org/Mni2Tal/index.html

Normalization



- For correcting brain disparity b/w subjects
- Affine (rigid body) transformation
  - Estimate: form Transformation Matrix
  - Write: apply TM to functional data

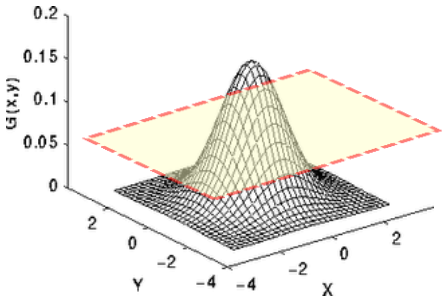


Spatial Smoothing

- Apply a 3D convolution with a Gaussian kernel

Full-width-half maximum (FWHM)

$$FWHM = 2\sigma\sqrt{2\ln(2)}$$



Weights

0.1	0.3	0.4	0.3	0.1
0.3	0.6	0.8	0.6	0.3
0.4	0.8	1.0	0.8	0.4
0.3	0.6	0.8	0.6	0.3
0.1	0.3	0.4	0.3	0.1

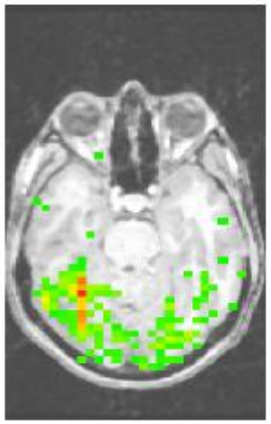
FWHM

1. **To increase SNR**
2. **To reduce stat. comparison**

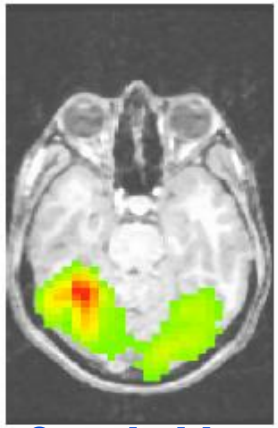
- Remove noise (small activations)
- Blurring (reduce spatial resolution)

Optimal size of Smooth:

~1.5x original voxel size



Original unsmoothed data



Smoothed data (FWHM = 8mm)

Source: AFNI 2011 course.

Spatial Smoothing

QA

Realign-ment

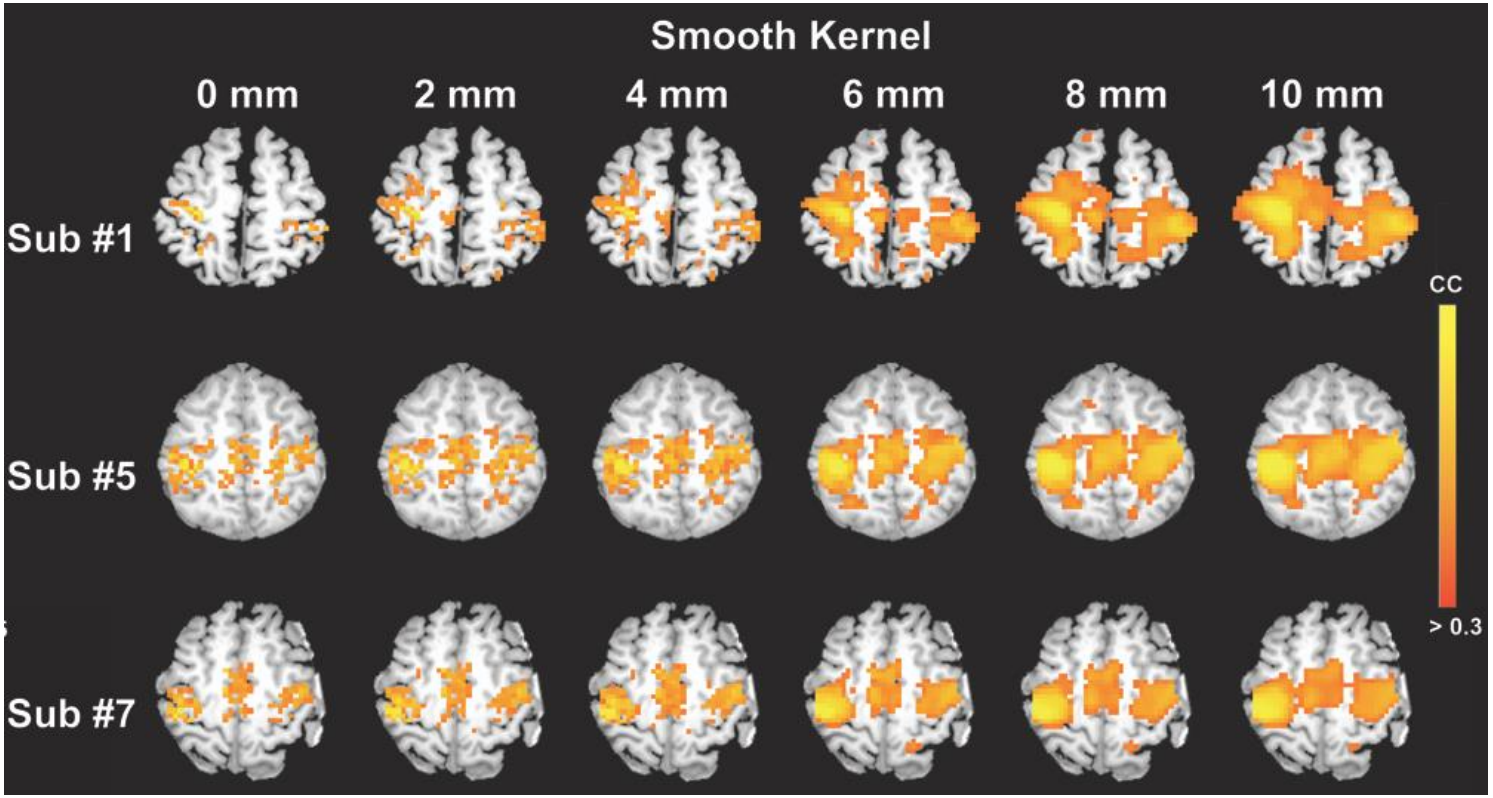
Slice timing

Coregist ration

Normali zation

Smooth

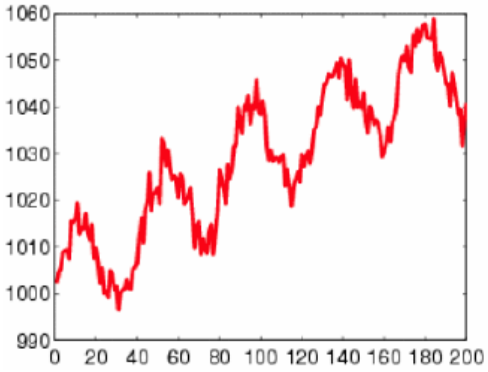
Segment ation

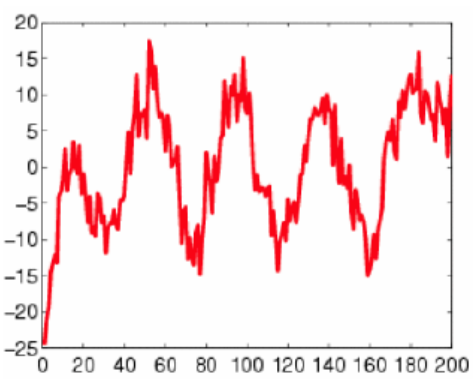


Wu et al. ***Brain Connectivity*** 2011

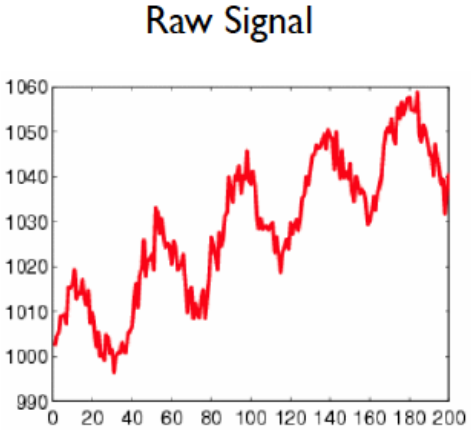
Temporal Filtering

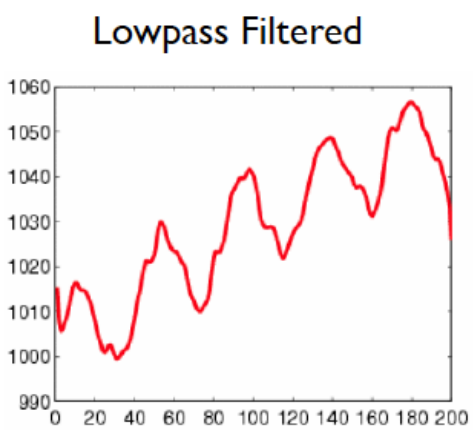
- ❖ High-pass filter
  - remove linear trend





- ❖ Low-pass filter
  - smoothing signal





Temporal Filtering

QA

Realign-ment

Slice timing

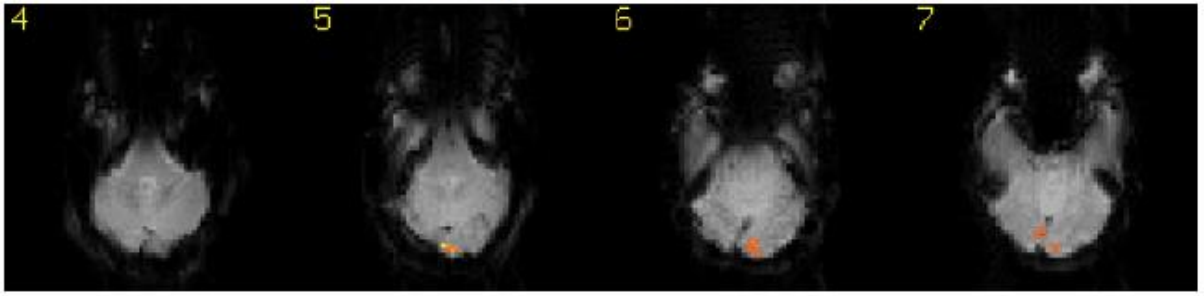
Coregist ration

Normali zation

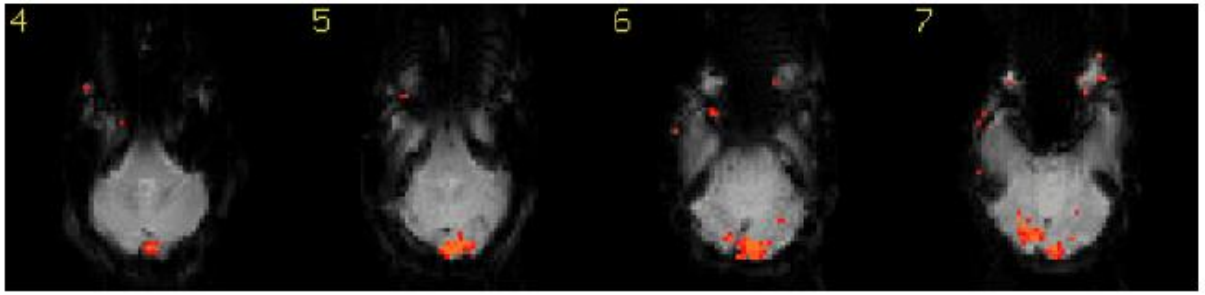
Smooth

Segment ation

No Temporal Filtering



Highpass Temporal Filtering

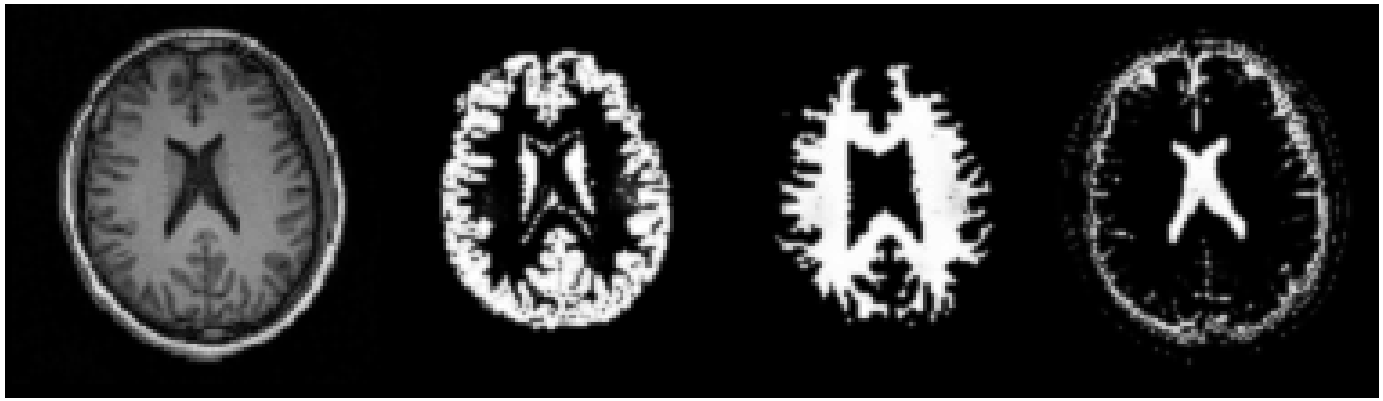


Don't remove the task frequency!

Segmentation

- Classifies different **anatomical divisions** in the brain
- Not related to functional data, but useful to generate masks for global covariates. (for resting-state fMRI)

Anatomy **Gray matter** **White matter** **CSF**



Take Home Message I

- Acquired MR images may contain several **artifacts**

  Worst case: throw away garbage datasets.

  Doesn't matter, summon **EE/medical physics** experts

Take Home Message II

- **Preprocessing** summary

(no necessary to include them all):

Slice-Timing Correction	Get consistent acquisition timing
Motion Correction (Realignment)	Get consistent anatomical coordinates
Coregistration (EPI - T1)	Get consistent anatomy btw Anat. & Func.
Normalization	Get consistent anatomy btw subjects
Spatial smoothing	Reduce σ_T and Increase power
Temporal filtering	Reduce physiological noise σ_P in frequency