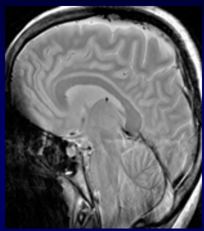
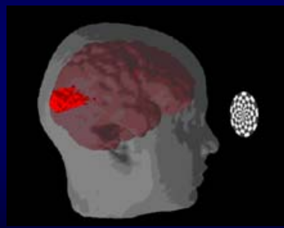
Outline

- MR Basic Principles
  - Spin
  - Hardware
  - Sequences
- Basics of BOLD fMRI
- Susceptibility and BOLD fMRI
- A few trade-offs

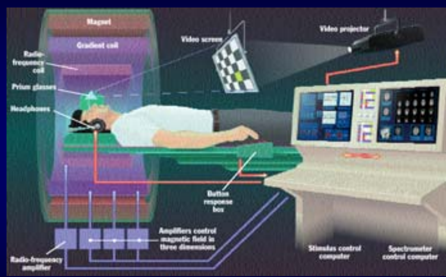


Basics of BOLD fMRI

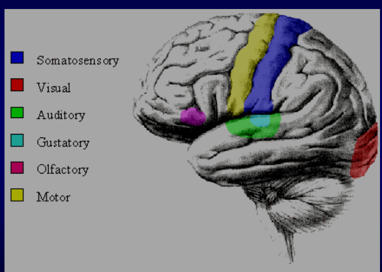


The MR room

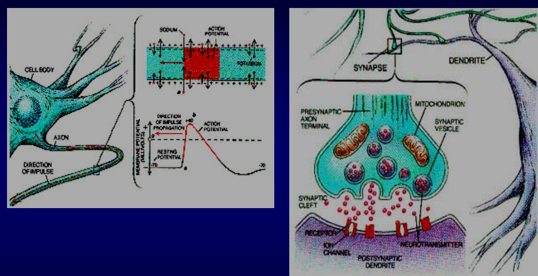
Scanner Internals



Macroscopic: Brain Systems

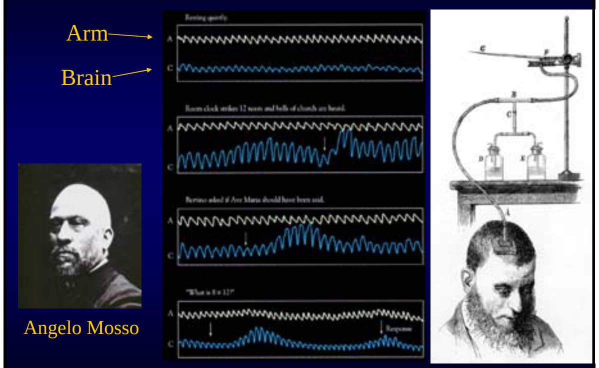


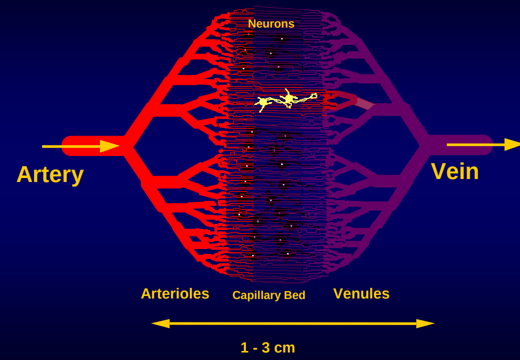
Microscopic: Neuronal Function



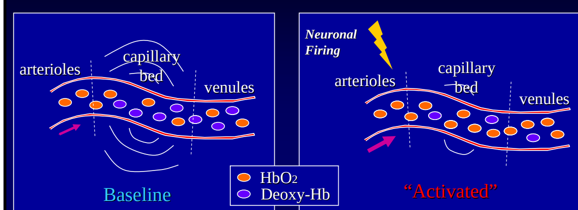
Action Potentials & Neurotransmitter Trafficking

Hemodynamic Measure of Brain Function (1881)

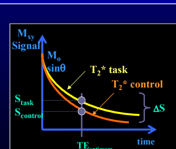




Blood Oxygen Level Dependent (BOLD)



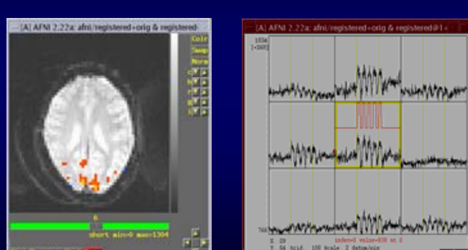
- Neural activity increases
- Blood flow increases ("reactive hyperemia")
- Deoxyhemoglobin concentration decreases
- Magnetic field homogeneity increases
- Gradient echo EPI signal increases



Hemodynamic Response Properties

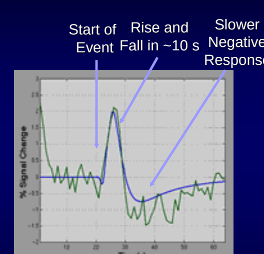
- Magnitude of signal changes is quite small
  - 0.5 to 3% at 1.5 T (or smaller)
  - Too small to see in individual images
  - Always considering differences or time-course changes in image intensity
- Response is delayed and quite slow (~10 seconds)
  - Extracting temporal information is tricky, but possible
  - Even short events have a rather long response

Blood Oxygen Level Dependent (BOLD) Contrast Activation

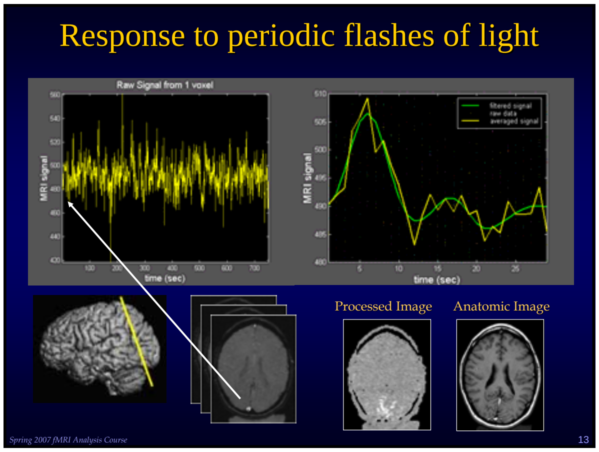


Time-Course Response in fMRI

- Brief neuronal events can elicit a (positive) blood flow and oxygenation response.
- Reponses to events as brief as 50 ms have been recorded.



Functional MRI response to a visual stimulus of duration 2s


Response to periodic flashes of light
Raw Signal from 1 voxel
MRI signal
time (sec)
filtered signal
raw data
averaged signal
Processed Image
Anatomic Image
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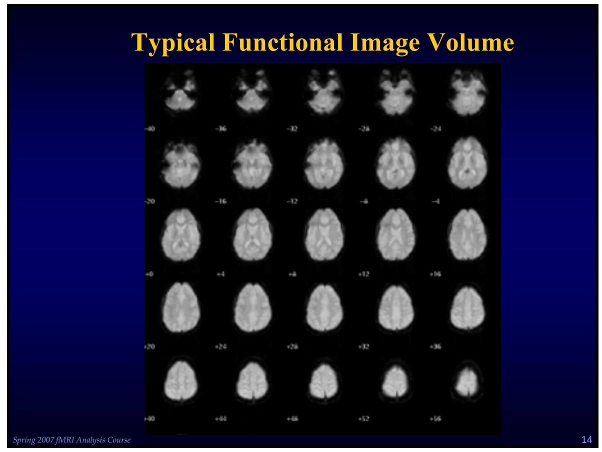
Typical Functional Image Volume
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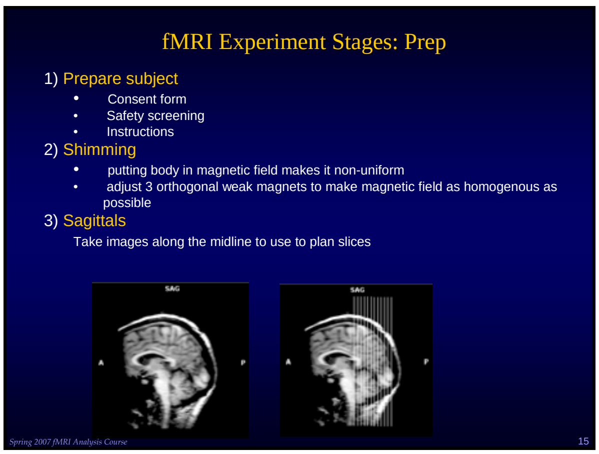
fMRI Experiment Stages: Prep
1) Prepare subject
• Consent form
• Safety screening
• Instructions
2) Shimming
• putting body in magnetic field makes it non-uniform
• adjust 3 orthogonal weak magnets to make magnetic field as homogenous as possible
3) Sagittals
Take images along the midline to use to plan slices
SAG
SAG
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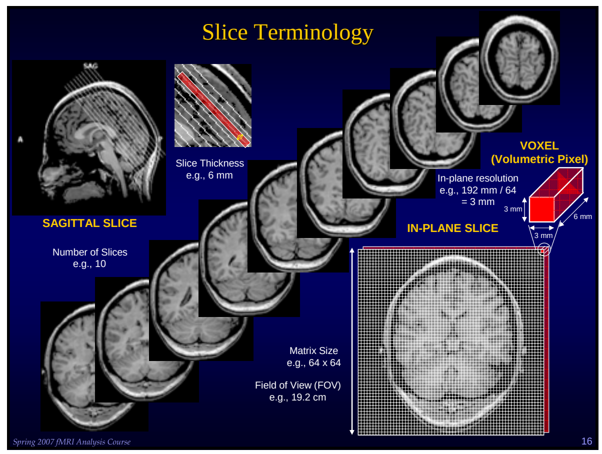
Slice Terminology
SAG
Slice Thickness
e.g., 6 mm
SAGITTAL SLICE
Number of Slices
e.g., 10
VOXEL
(Volumetric Pixel)
In-plane resolution
e.g., 192 mm / 64
= 3 mm
3 mm
6 mm
3 mm
IN-PLANE SLICE
Matrix Size
e.g., 64 x 64
Field of View (FOV)
e.g., 19.2 cm
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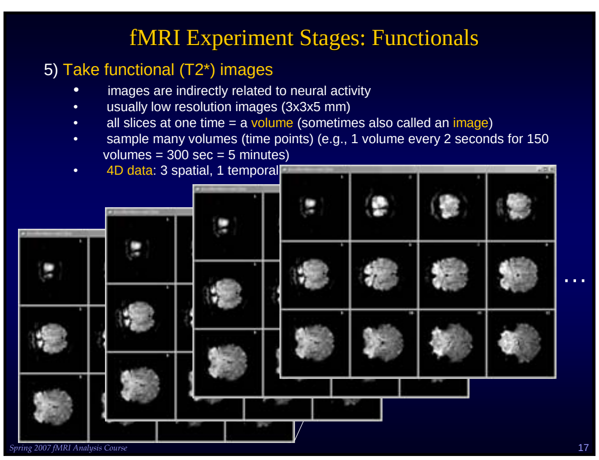
fMRI Experiment Stages: Functionals
5) Take functional (T2*) images
• images are indirectly related to neural activity
• usually low resolution images (3x3x5 mm)
• all slices at one time = a volume (sometimes also called an image)
• sample many volumes (time points) (e.g., 1 volume every 2 seconds for 150 volumes = 300 sec = 5 minutes)
• 4D data: 3 spatial, 1 temporal
…
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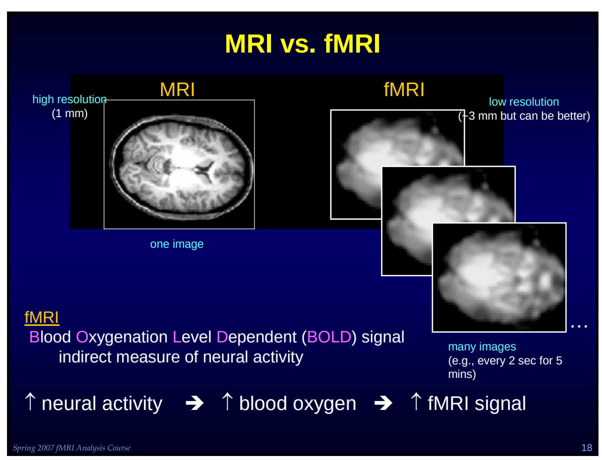
MRI vs. fMRI
high resolution
(1 mm)
MRI
one image
fMRI
low resolution
(~3 mm but can be better)
fMRI
Blood Oxygenation Level Dependent (BOLD) signal
indirect measure of neural activity
many images
(e.g., every 2 sec for 5 mins)
…
↑ neural activity ➔ ↑ blood oxygen ➔ ↑ fMRI signal
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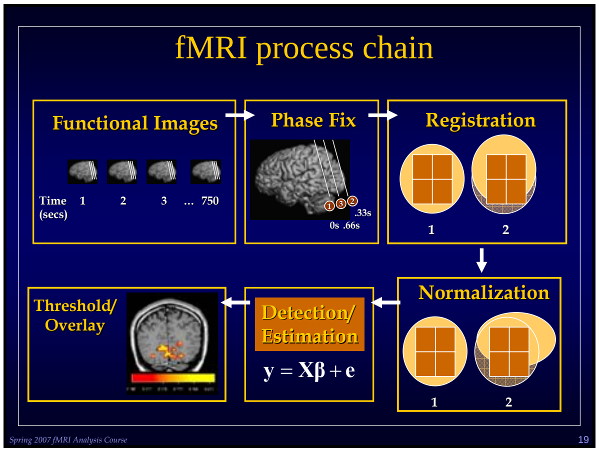
fMRI process chain
Functional Images
Time (secs)
1
2
3
... 750
Phase Fix
0s .66s
.33s
Registration
1
2
Normalization
1
2
Detection/ Estimation
y = Xβ + e
Threshold/ Overlay
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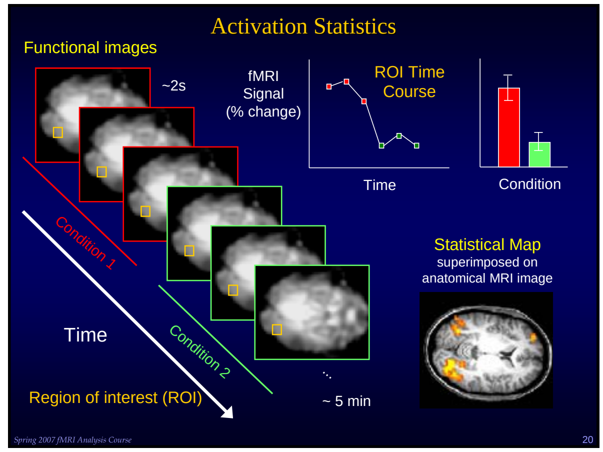
Activation Statistics
Functional images
~2s
fMRI Signal (% change)
ROI Time Course
Time
Condition
Condition 1
Condition 2
Time
Statistical Map
superimposed on anatomical MRI image
Region of interest (ROI)
~ 5 min
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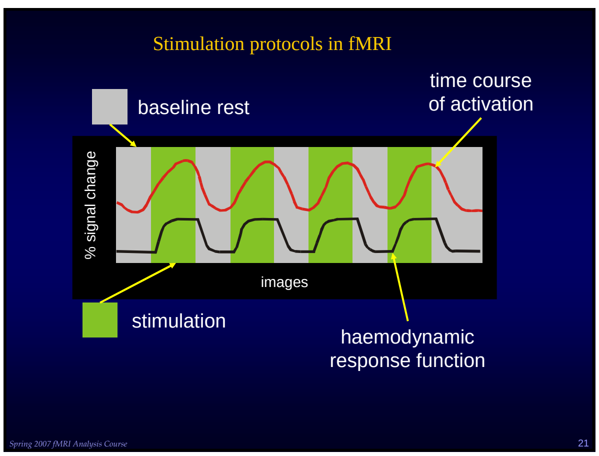
Stimulation protocols in fMRI
baseline rest
time course of activation
% signal change
images
stimulation
haemodynamic response function
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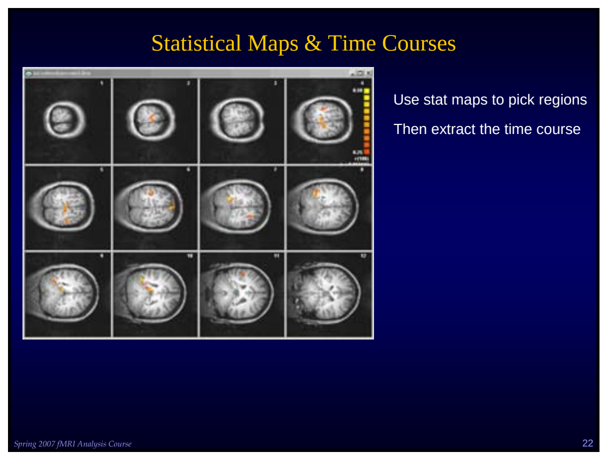
Statistical Maps & Time Courses
Use stat maps to pick regions
Then extract the time course
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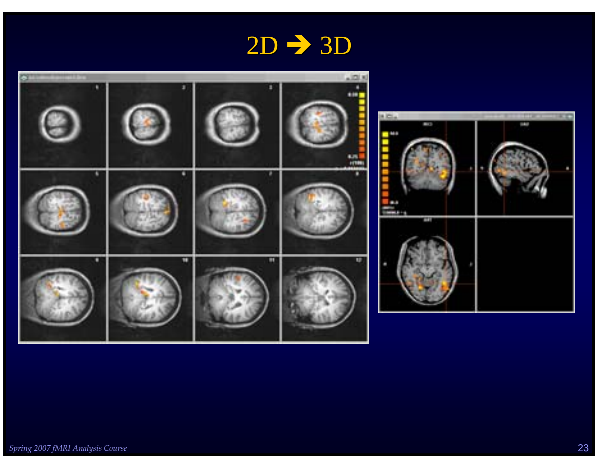
2D → 3D
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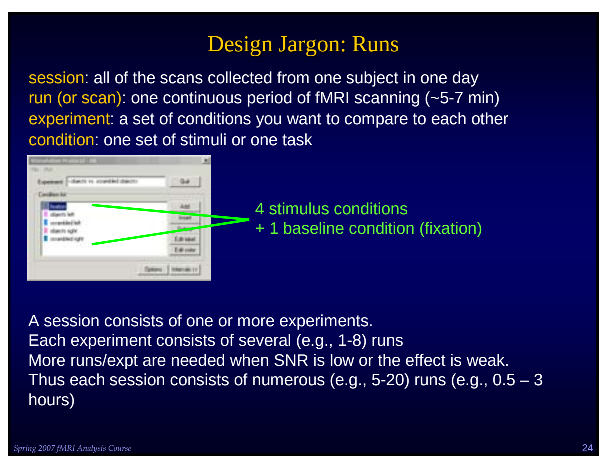
Design Jargon: Runs
session: all of the scans collected from one subject in one day
run (or scan): one continuous period of fMRI scanning (~5-7 min)
experiment: a set of conditions you want to compare to each other
condition: one set of stimuli or one task
4 stimulus conditions
+ 1 baseline condition (fixation)
A session consists of one or more experiments.
Each experiment consists of several (e.g., 1-8) runs
More runs/expt are needed when SNR is low or the effect is weak.
Thus each session consists of numerous (e.g., 5-20) runs (e.g., 0.5 – 3 hours)
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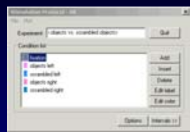
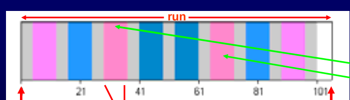
Design Jargon: Paradigm or Protocol



paradigm (or protocol): the set of conditions and their order used in a particular run



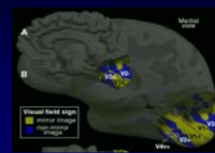
epoch: one instance of a condition
first “objects right” epoch
second “objects right” epoch

volume #1 (time = 0)
epoch 8 vol x 2 sec/vol = 16 sec
volume #105 (time = 105 vol x 2 sec/vol = 210 sec = 3:30)

Time

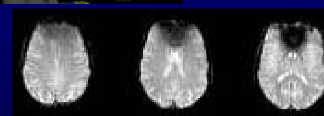
Susceptibility in MR

The good.

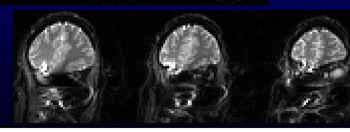


All susceptibility effects increase with Bo field

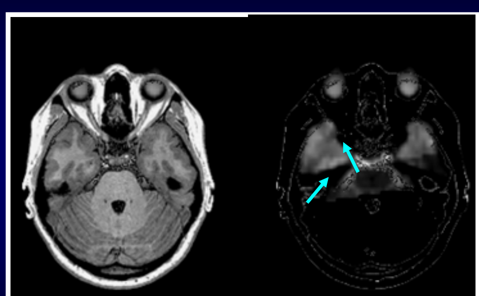
The bad.



The ugly.

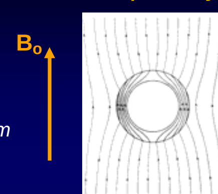


Susceptibility in Temporal Lobes



What is the source of susceptibility?

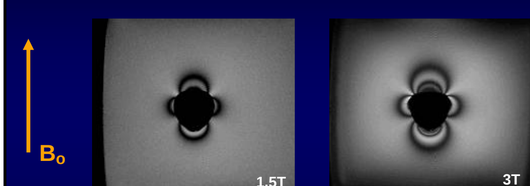
The magnet has a spatially uniform field but your head is magnetic…



Pattern of B field outside magnetic object in a uniform field…

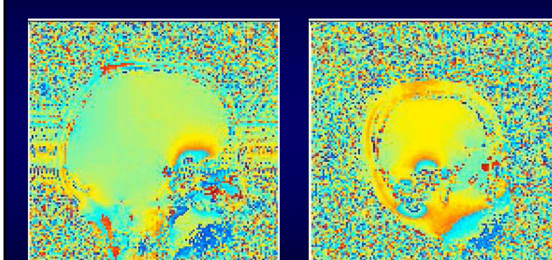
1) deoxyHeme is paramagnetic
2) Water is diamagnetic ($\chi = -10^{-5}$)
3) Air is paramagnetic ($\chi = 4 \times 10^{-6}$)

Susceptibility effects occur near magnetically dis-similar materials

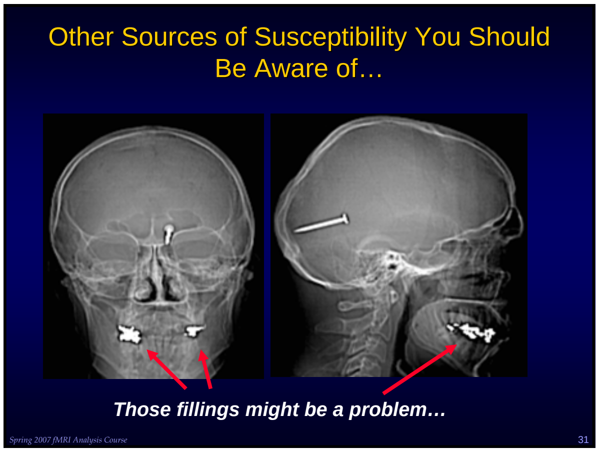


Ping-pong ball in H_2O:
Field maps (ΔTE = 5ms), black lines spaced by 0.024G (0.8ppm at 3T)

B_o map in head: it’s the air tissue interface…



Sagittal Bo field maps at 3T


Other Sources of Susceptibility You Should Be Aware of…
Those fillings might be a problem…
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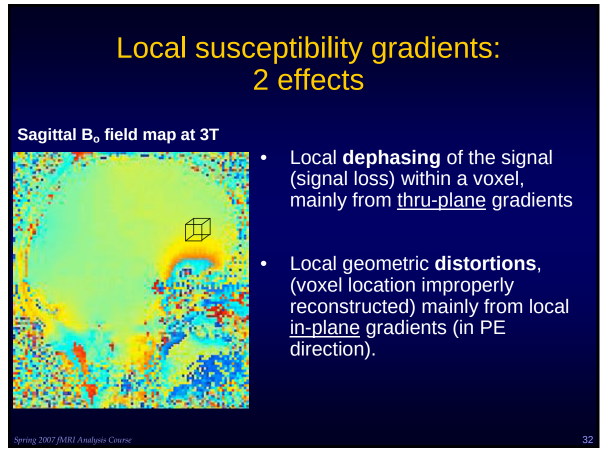
Local susceptibility gradients:
2 effects
Sagittal B_o field map at 3T
• Local **dephasing** of the signal (signal loss) within a voxel, mainly from thru-plane gradients
• Local geometric **distortions**, (voxel location improperly reconstructed) mainly from local in-plane gradients (in PE direction).
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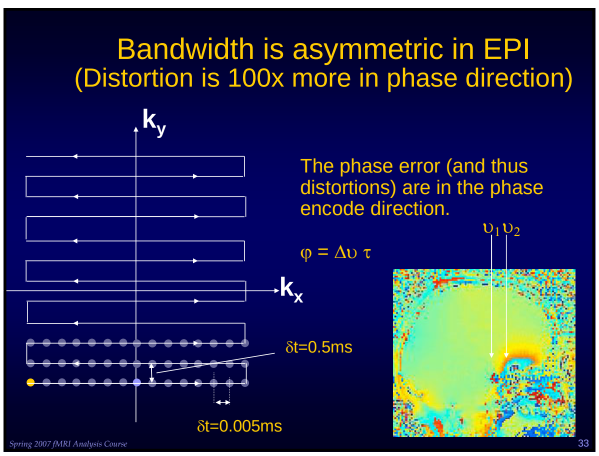
Bandwidth is asymmetric in EPI
(Distortion is 100x more in phase direction)
k_y
k_x
The phase error (and thus distortions) are in the phase encode direction.
$\varphi = \Delta\upsilon\ \tau$
$\upsilon_1 \upsilon_2$
δt=0.5ms
δt=0.005ms
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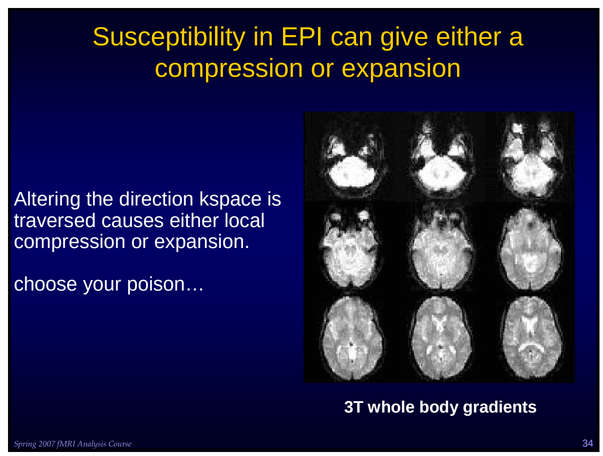
Susceptibility in EPI can give either a compression or expansion
Altering the direction kspace is traversed causes either local compression or expansion.
choose your poison…
3T whole body gradients
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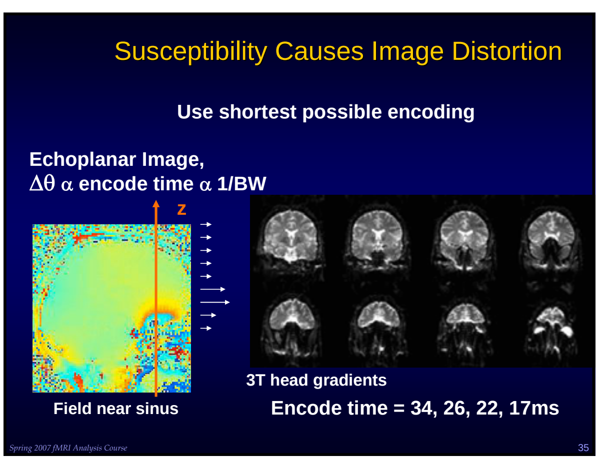
Susceptibility Causes Image Distortion
Use shortest possible encoding
Echoplanar Image,
$\Delta\theta\ \alpha$ encode time α 1/BW
z
Field near sinus
3T head gradients
Encode time = 34, 26, 22, 17ms
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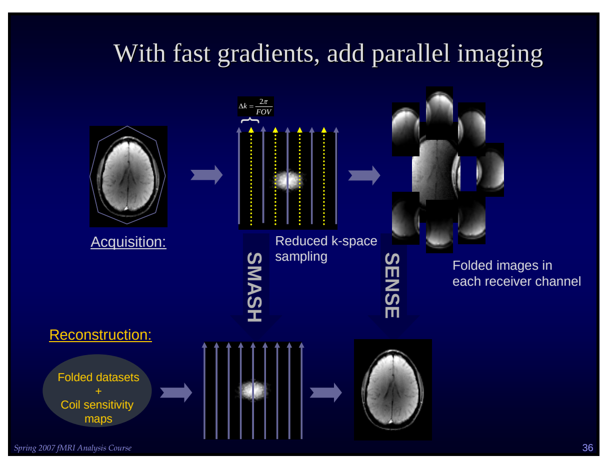
With fast gradients, add parallel imaging
Acquisition:
Reduced k-space sampling
SMASH
SENSE
Folded images in each receiver channel
Reconstruction:
Folded datasets
+
Coil sensitivity maps
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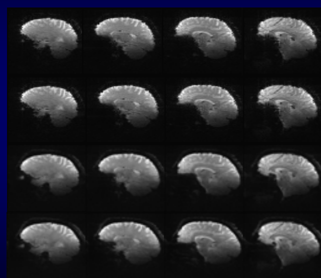
3T MAGNETOM Allegra

ss EPI PAT



Single shot TE = 30 ms

Conventional 64x64

with PAT x2 64x64

with PAT x2 128x128

with PAT x2 192x128

4 channel tx/rx array coil
MAGNETOM Allegra. Courtesy Bruker Medical and USA Instruments.

What can you do?

- Good shimming (first & second order)
- Thinner slices (Drawback: Takes more to cover the brain)
- Shorter TE (Drawback: BOLD contrast is optimized for TE = T2*local)
- "Z-shimming" Repeat measurement several times with an applied z gradients that rewind the dephasing, Pick the right gradient afterward on a pixel by pixel basis. (Drawback: multi shot or longer encode). *Yang et al. MRM 39 p402, 1998.*
- Use special RF pulse with built-in prephasing in just the right places. (Drawback: long RF pulse, pre-phasing differs from person to person) *Glover et al. Proceed. ISMRM p298, 1998.*
- The "mouth shim" paramagnetic material in roof of mouth. *Wilson, Jenkinson, Jezzard, Proceed. ISMRM p205, 2002.*
- Distortion correction based on a measured field map (drawback: cannot recover signal dropout or fully correct "overlapping" intensities)
- Multi-shot imaging methods (drawback: more motion sensitive)
- Fancy pulse sequences (best to have local physicist): 180 degree refocusing pulses to reverse distortion (GRASE)/Multiple refocusing pulses… single-shot FSE, U-Flare

Single-shot Gradient Echo EPI

- Parameters you can choose
  - TR
  - Slice thickness/gap
  - Number of slices/slice acquisition order
  - TE
  - Bandwidth
  - Matrix size
  - Field of view
  - Flip angle
- All of these parameters can be appropriately applied over a wide range of values

TR (repetition time)

- Determines how much magnetization is allowed to recover before it is knocked over again by the next rf pulse
- From a pure signal strength perspective, waiting for very long TR's (5 seconds +) allows for maximal signal-to-noise (SNR)
- Noise is MR dominated by physiologic noise (not thermal noise)
- Requires many images in both conditions to reliably distinguish activation (which requires shorter TR's)
- fMRI can be performed as fast as TR=100ms
- Bottom line: use as short a TR as you can

Flip Angle

- A given flip angle will maximize the SNR (Ernst Angle)…at long TR's (> 3s) this is 90 degrees
- This angle is dependent upon the TR
- Incorrect angles may sensitize your BOLD scans to in-flow artifacts (bad) [Lu et al, NeuroImage 17, 943–955 (2002)]
- Bottom line: For TR of 1-2s, a flip angle of around 60-70 degrees is optimal

$$\theta = \cos^{-1}\left(\exp\left(TR/T_1\right)\right)$$

Comparison of Ernst Angles (Maximize SNR) and Optimal Angles (Maximize CNR) at Different TR Values Based on Numerical Simulations of the Pure Parenchyma Voxel

TR (ms)	Ernst angle (deg)	Optimal angle (deg)	Difference (deg)
500	52	40	12
1000	68	54	14
1500	77	64	13
2000	82	71	11
2500	85	76	9
3000	87	80	7

Number of slices

- Separate slices in EPI are typically squeezed into a TR interval
- Many factors influence # of slices that fit in a TR
  - Length of TR
  - TE (determines center of blue box)
  - Matrix size (determines length of blue box)
  - Bandwidth (determines length of blue box)
- Bottom line: collect as many slices as you can

So far

- Long TR maximized SNR
- Short TR maximizes fMRI stats
- Long TR provides many slices
- Short TR provides few slices

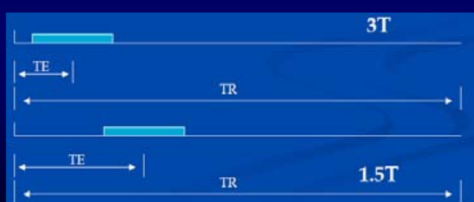
- The above suggests imaging only brain regions of interest (to minimize slices)
- But processing decisions also play a role
  - Whole brain data is much easier to spatially normalize
  - Motion correction works best with thin slices
  - In general TR's between 1s and 2s are not too bad

Slice Thickness

- SNR in MRI is proportional to voxel volume (thinner slices -> less SNR)
- Thinner slices reduces partial volume effects
- Thinner slices reduces through-plan dephasing
- What is the size of the structure of interest?
- Isotropic voxel size is preferred

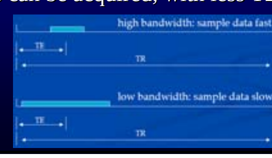
TE (echo time)

- Optimum TE is shorter at high field (say 30ms at 3T versus 50ms at 1.5T)
- Shorter TE reduces signal loss due to field inhomogeneities, but also reduces BOLD effect



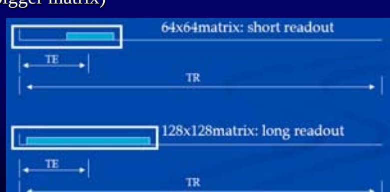
Bandwidth

- Rate at which points are sampled (the echoes are digitized)
- High bandwidth implies a high sampling rate
  - Sampling of the order of 128 kHz
  - 128kHz/64matrix = 2000Hz/pixel
- Noise is proportional to sampling rate
- High bandwidth means faster data acquisition (and more slices can be acquired, with less T2 blurring)



Matrix Size

- Matrix size impact everything
  - Increasing matrix size decreases voxel size and thus SNR
  - Increasing matrix and FOV maintains constant voxel size, but increases N and therefore increases SNR
  - Intravoxel dephasing reduced somewhat with smaller voxels (bigger matrix)



Field of View (FOV)

- Voxel size determined by field of view and matrix size

$$\Delta x = \frac{FOV_x}{N_x} \qquad \Delta y = \frac{FOV_y}{N_y}$$

- FOV=200mm/64 matrix = 3.125mm voxel dimension

- Recall SNR proportional to voxel volume