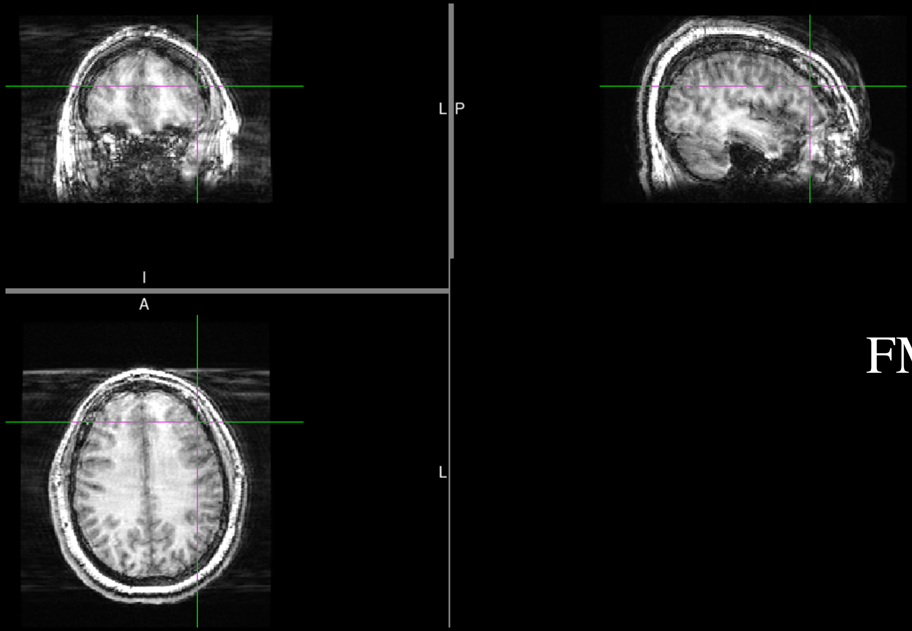
Preprocessing and artefacts



Instructor:
Luis Hernandez-Garcia, Ph.D.
Research Professor
FMRI Laboratory, Biomedical Engineering

FMRI analysis in broad strokes

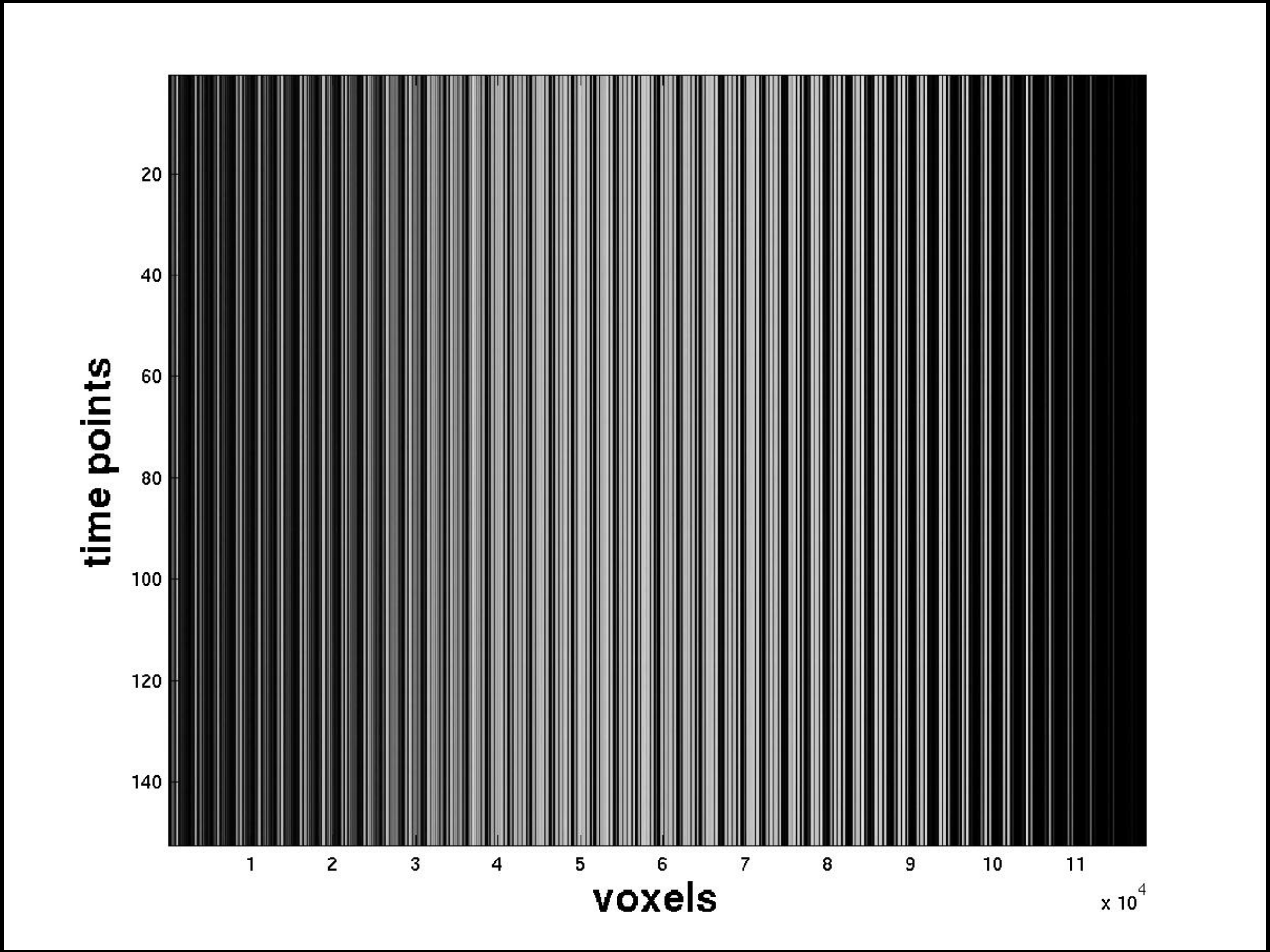
1. Formulate a 4D model of activation.
2. Examine the time-series at **every voxel** : Fit your model to the data.
   1. Does the model fit?
   2. Make some statistical images
3. Compare statistical images between subjects, groups ….

Typical data arrangement

- One 3D image per time point
- Most popular: NIFTI format (.nii)
  - header information
  - the image itself
  - (It's almost the same as AVW or Analyze format)
- Useful to read all the data as a matrix
  - Rows = time
  - Columns = space (collapsed to 1 dimension)

  (… or vice versa)

Example



time points
20
40
60
80
100
120
140
1
2
3
4
5
6
7
8
9
10
11
voxels
x 10^4

Implicit Assumptions in Analysis

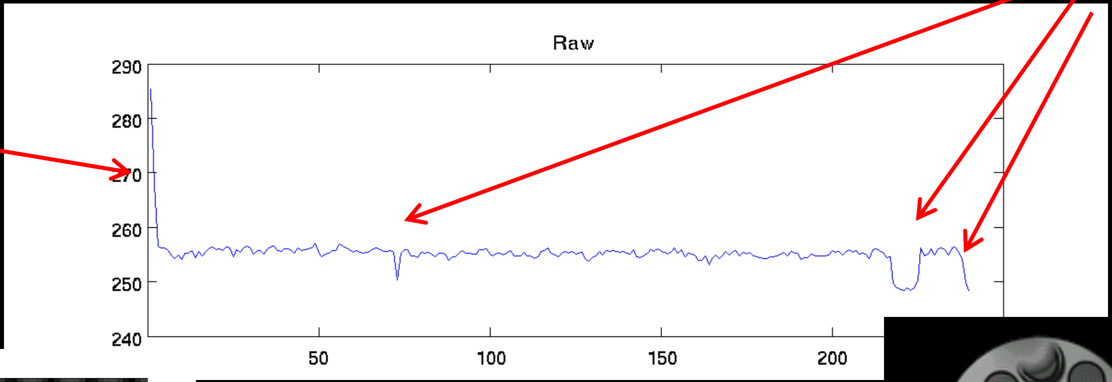
- Each Voxel contains a time series from that voxel ONLY
- All voxels in a given 3D image are sampled at the same time
- All brains are morphologically identical
- Paradigm is the SOLE SOURCE of variance in the time series.
- The image corresponds Exactly to the to the anatomy

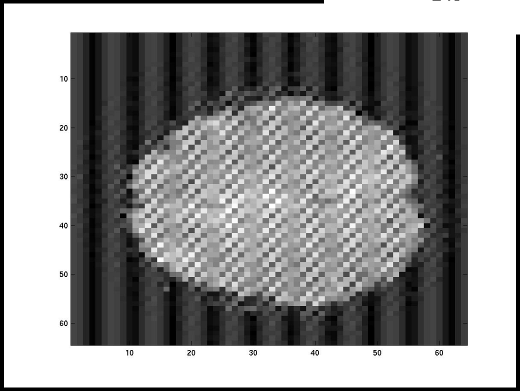
Wishful Thinking!

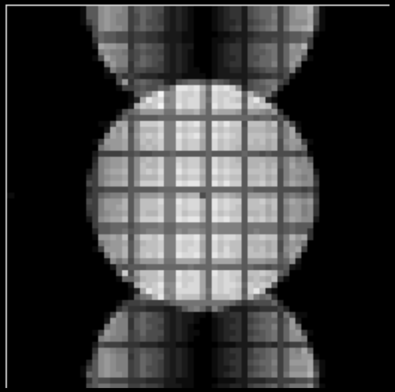
The harsh reality

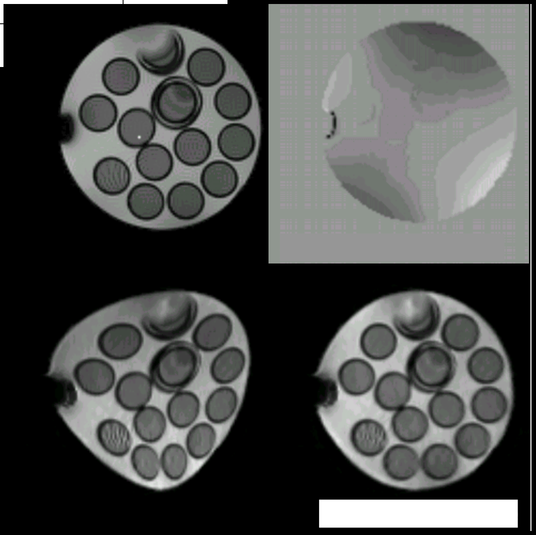
Scanner spiking issues

T1 settling time









Courtesy of Derek Nee

Lecture Goals

- Understand the following confounds in fMRI and what corrections exist
  - Slice Timing effects (temporal shifting)
  - Movement (rigid body realignment)
  - Physiological Artifacts: respiration and heart beat (regression filters)
  - Electronic Noise (filters and autoregressive models)
  - Morphology (non-linear warping)
  - Image distortions (susceptibility, ghosting, off-resonance)

Lecture Goals (II)

As a side effect, you will be introduced to signal and image processing concepts:

1. Linear transformations
2. Basis functions
3. Sampling, re-sampling, interpolation
4. Optimization, cost functions
5. other side effects include drowsiness, nausea

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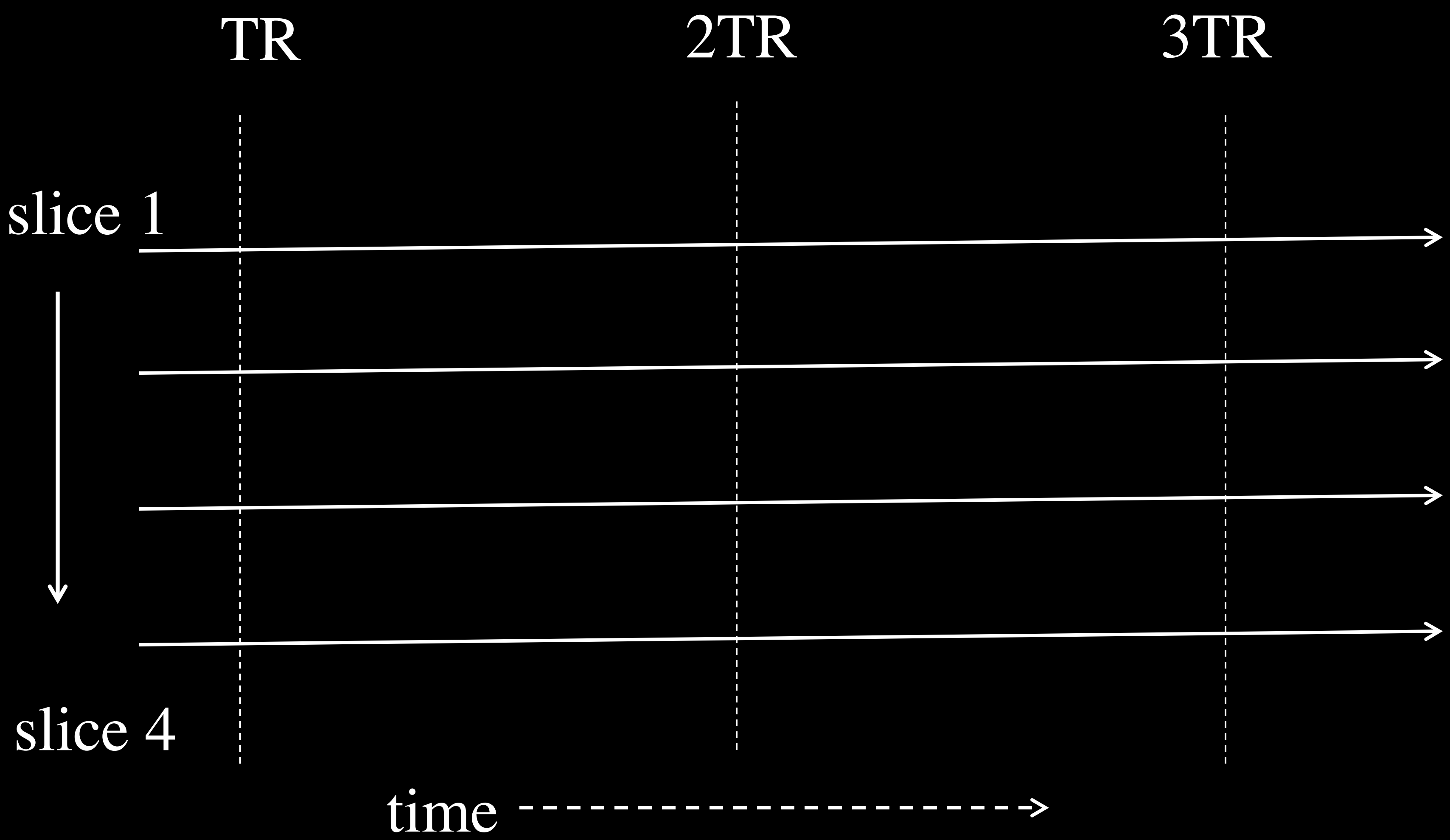
Timing Errors

- MR images are typically collected one slice at a time (exceptions: 3D imaging, multi-band imaging)
- The slices can be collected sequentially or interleaved. This is also true in Multi-band imaging.
- Delay between slice excitations is typically

$$= TR \,/\, (num.\ slices)$$

- Therefore, the time series are time-shifted differently in each slice

FMRI data "layout"



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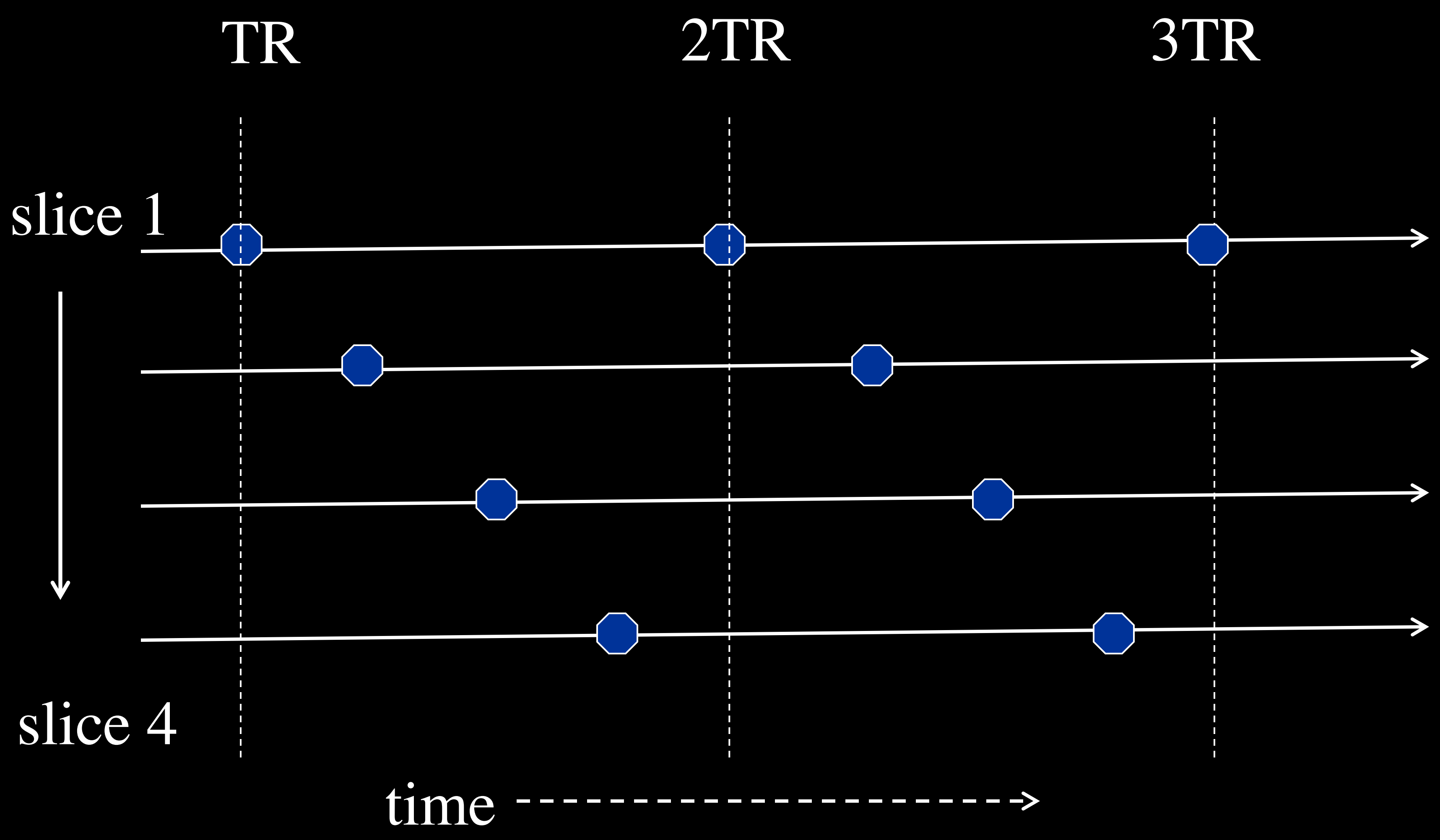
Acquisition



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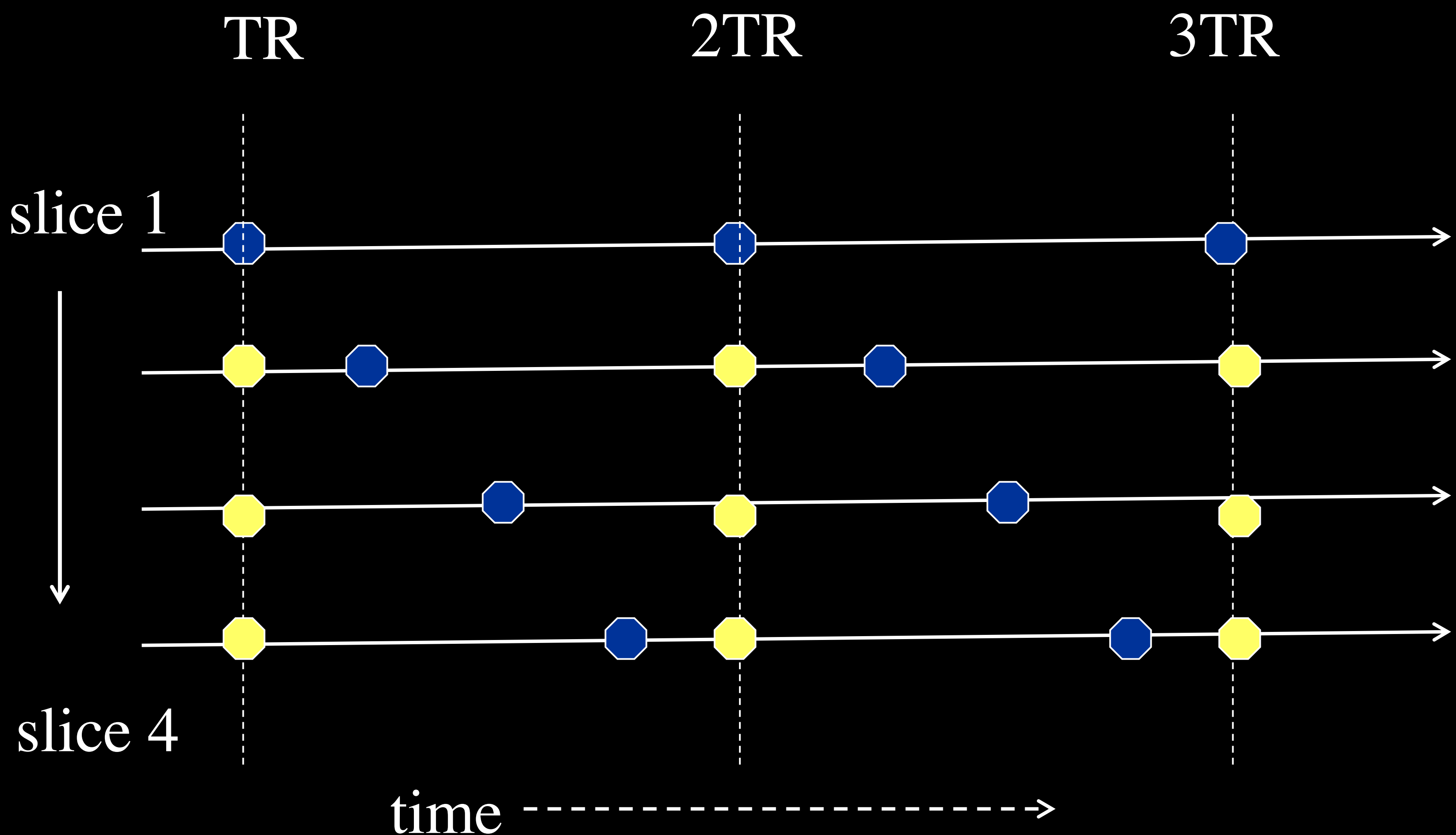
Acquisition



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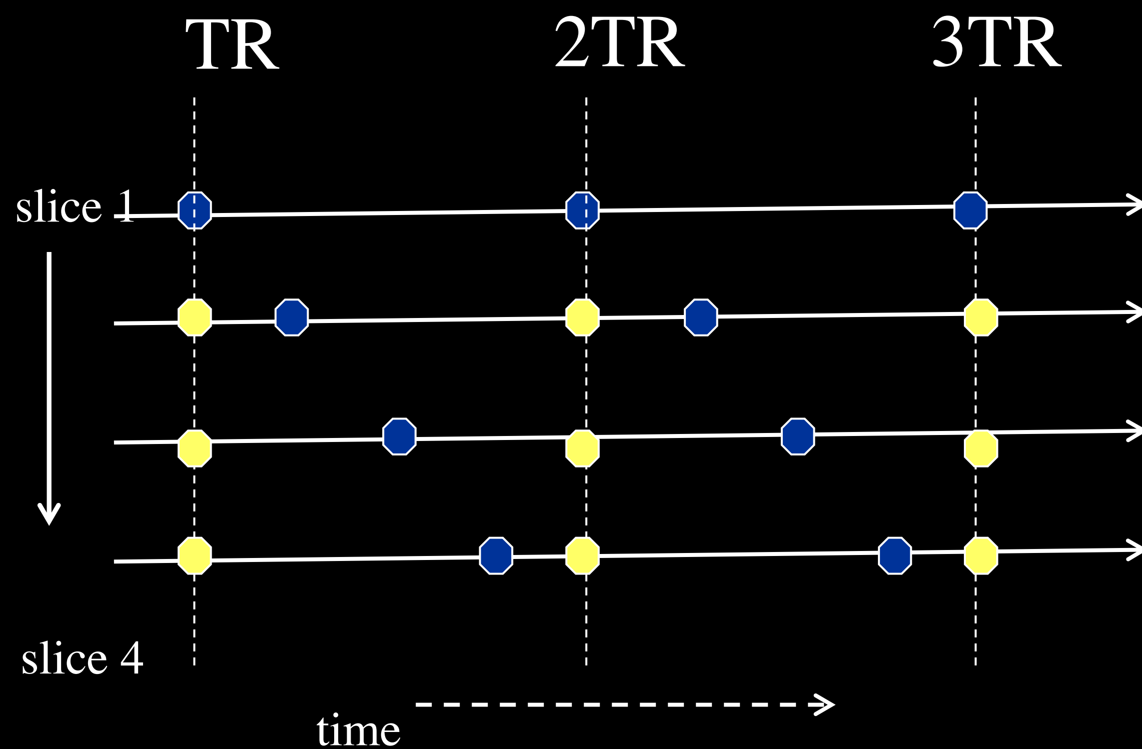
Sampling Error in Time

Sampling Error in Time

so shift it back!

Interpolation / Temporal shifting

- Time shift is the same as interpolation
- Interpolation: calculate a missing data point from its neighbors
- *Interpolation = weighted average*



Interpolation = Temporal shift by a fraction of a sample

	Time domain	*Frequency Domain*
• Have:	$f(t)$	$F(\omega)$
• Want:	$f(t - \tau)$	$e^{-i\omega\tau} F(\omega)$

Temporal shifting strategy

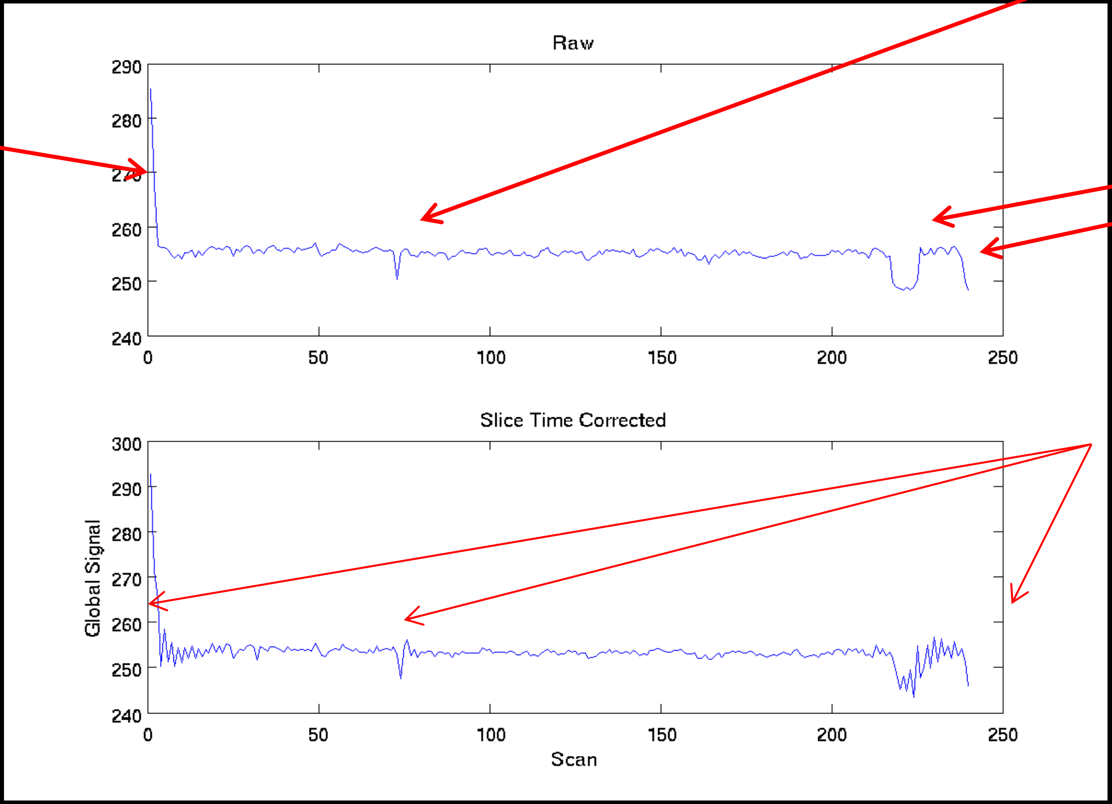
1. Fourier transform along time dimension
2. Add linear phase increment (multiply the complex data by $e^{-i\phi\omega}$)
3. Inverse Fourier transform
4. Note: this strategy uses the whole time series. Noise in one sample can contaminate the whole time course!

Interpolation side effects

Scanner spiking issues

T1 settling time

Subject movement

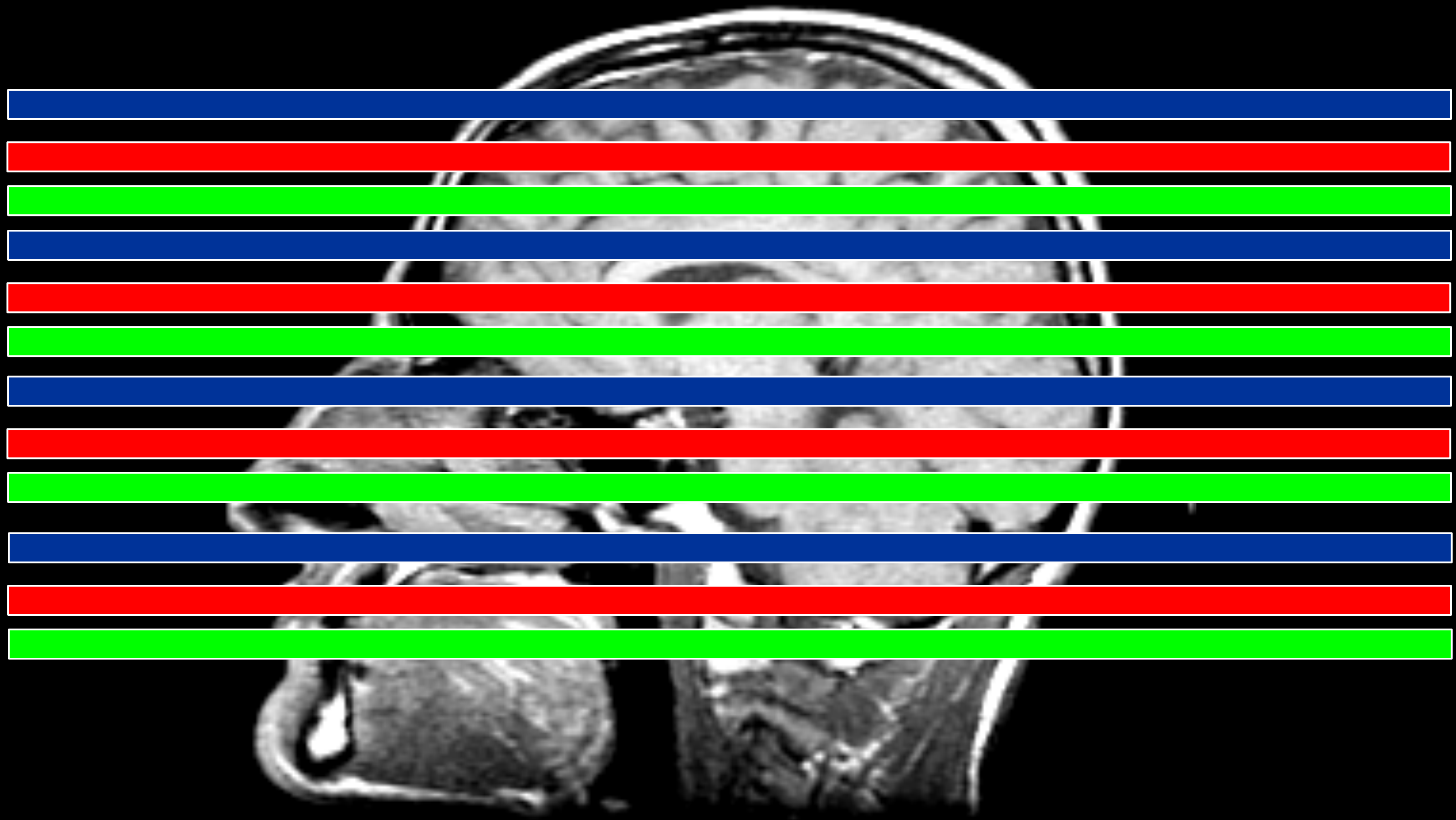


Interpolation from Slice timing correction “spreads” artifacts over time!

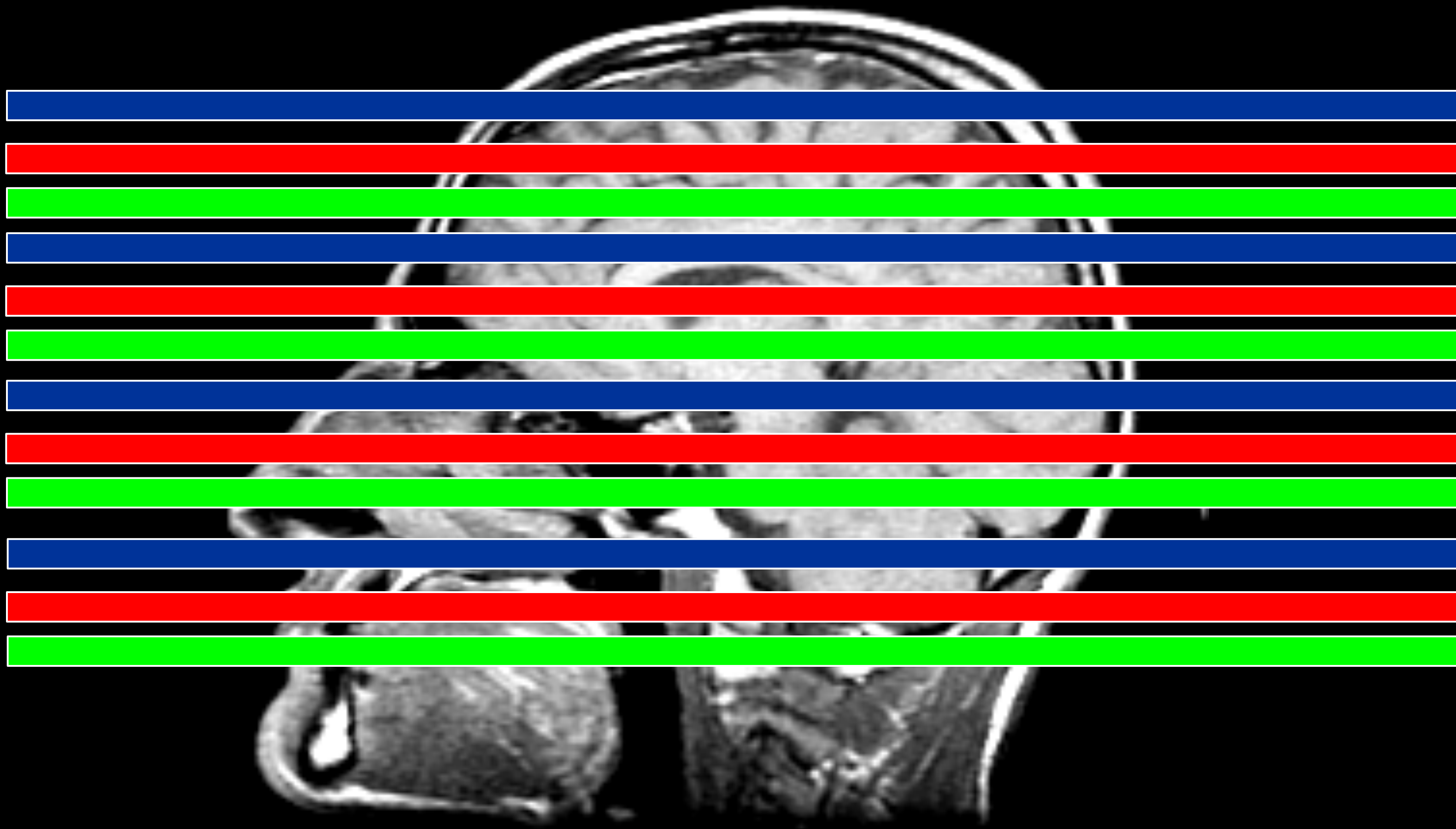
Global signal (mean over space): a good indicator of large scale changes in signal

Courtesy of Derek Nee

What about Multi-Band imaging?



What about Multi-Band imaging?



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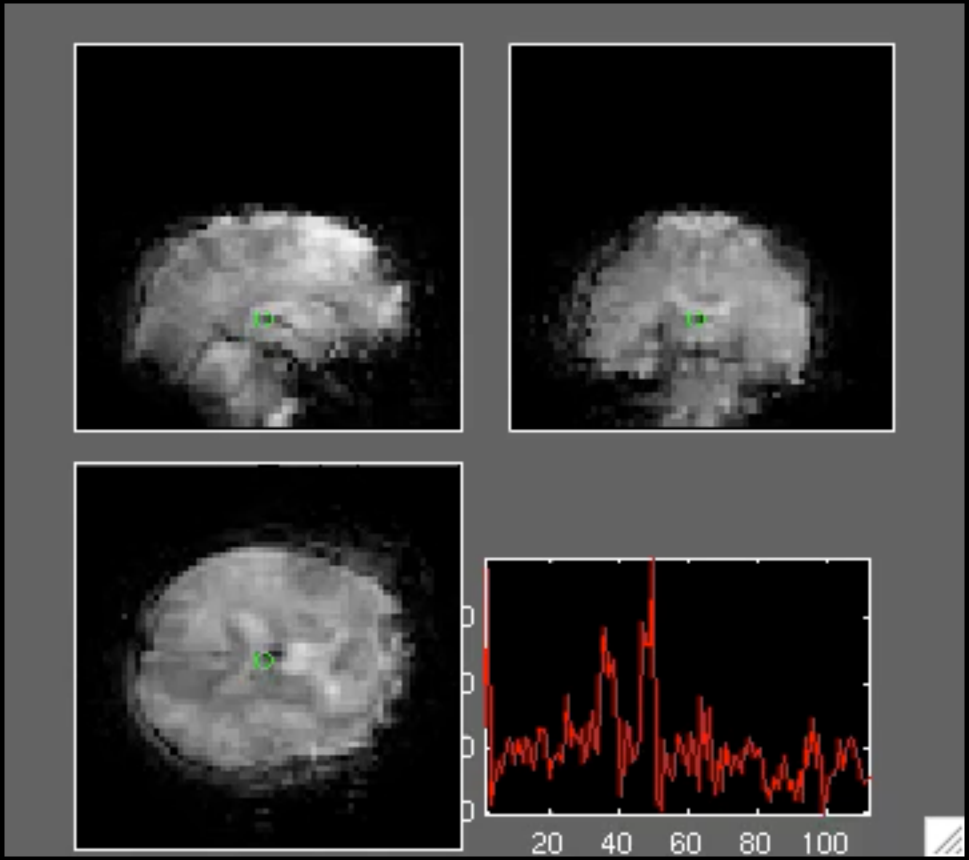
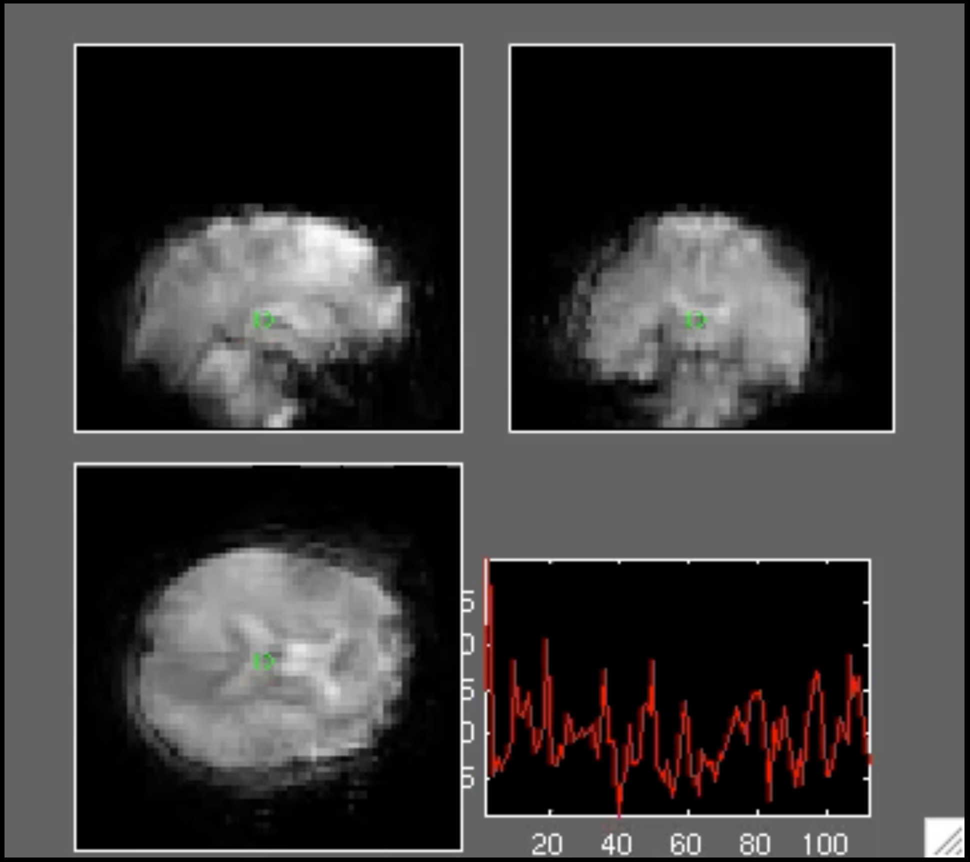
  - Morphology (non-linear warping)

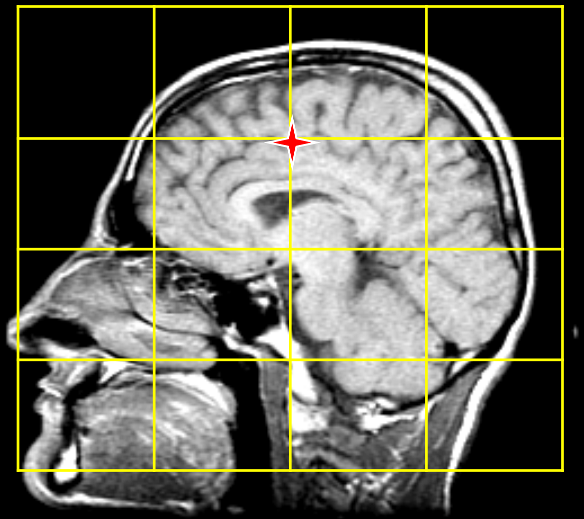
Movie: Uncorrected movement



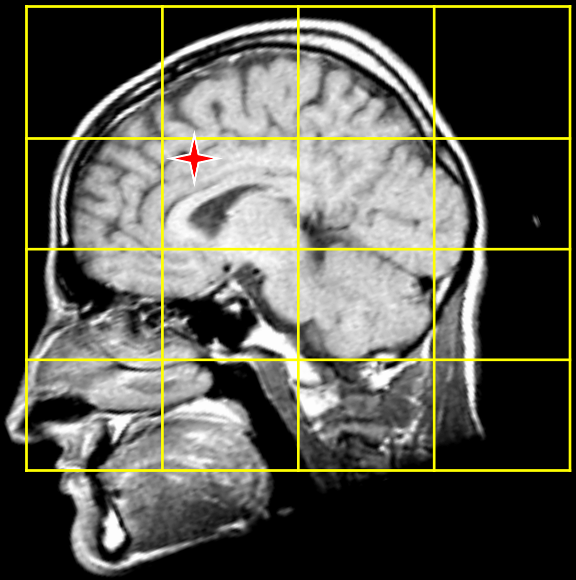
Movie: Corrected Movement



Movement

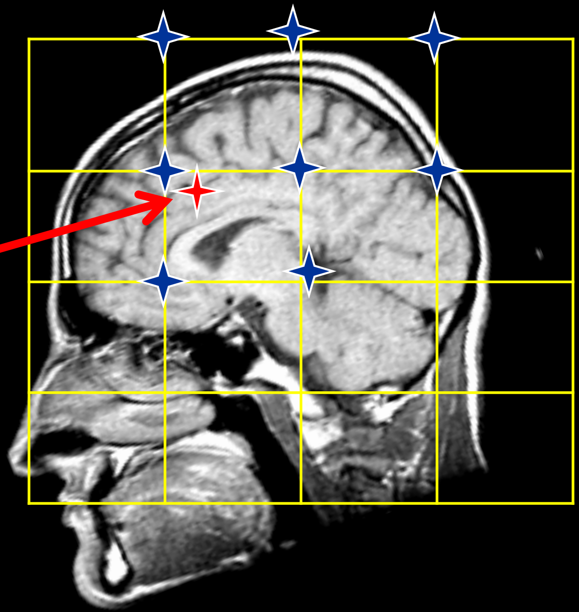


Movement



Movement

Interpolate this point from its neighbors



Resampling the image

- Think of realignment as transforming the sampling grid, rather than the image.
- Interpolation:
  - Choose weighting function (kernel):
    - Nearest neighbor
    - bi-linear, tri-linear interpolation
    - sinc interpolation

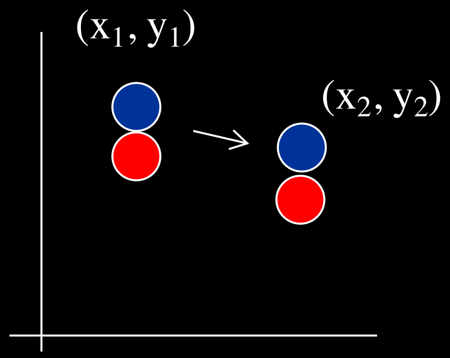
Movement: figuring out the new coordinates

In 2 Dimensions:

- shift from (x_1,y_1) to (x_2,y_2):

$$x_2 = x_1 + \Delta x$$

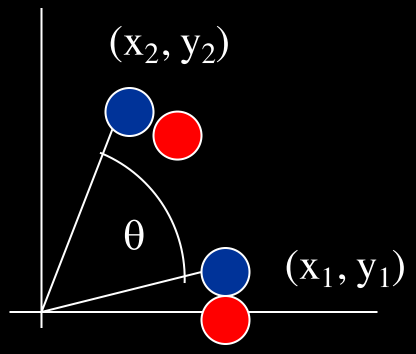
$$y_2 = y_1 + \Delta y$$



- Rotation from (x_1, y_1) to (x_2,y_2):

$$x_2 = x_1 cos(\theta) + y_1 sin(\theta)$$

$$y_2 = -x_1 sin(\theta) + y_1 cos(\theta)$$



2-D Transformation matrix

- Both Together (note that the order matters)

$$x_2 = x_1 \cos(\theta) + y_1 \sin(\theta) + \Delta x$$

$$y_2 = -x_1 \sin(\theta) + y_1 \cos(\theta) + \Delta y$$

…but let's say it with matrices:

$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) & \Delta x \\ -\sin(\theta) & \cos(\theta) & \Delta y \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

2-D Transformation matrix

$$(x_2,y_2) = \boldsymbol{A}(x_1, y_1)$$

this extends to N-dimensions too

3-D Rotation matrices

$$\begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 & 0 \\ -\sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 & 0 \\ \cos(\theta) & 1 & \sin(\theta) & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

xy plane rotation

xz plane rotation

yz plane rotation

Estimation of Movement

1. Compare the two images. How good is the match?
2. Choose a set of translations, rotations
3. Combine the six transformations matrices (linear operators) into one "rigid body" transformation

$$r_2 = A\, r_1$$

3. Resample the images at the new locations
4. Are the two images more alike (do they line up better)?
5. Repeat and search for the best matrix **A**

Comparing images: cost function

- How do you know two images match?

1. Least squares difference

$$\Sigma (I_1 - I_2)^2$$

2. Normalized correlation, correlation ratio

$$\frac{\Sigma(I_1 \ I_2)}{(Var(I_1) (Var(I_2))^{1/2}} \qquad \frac{Var(E[I_1 I_2])}{Var(I_2)}$$

3. Mutual information

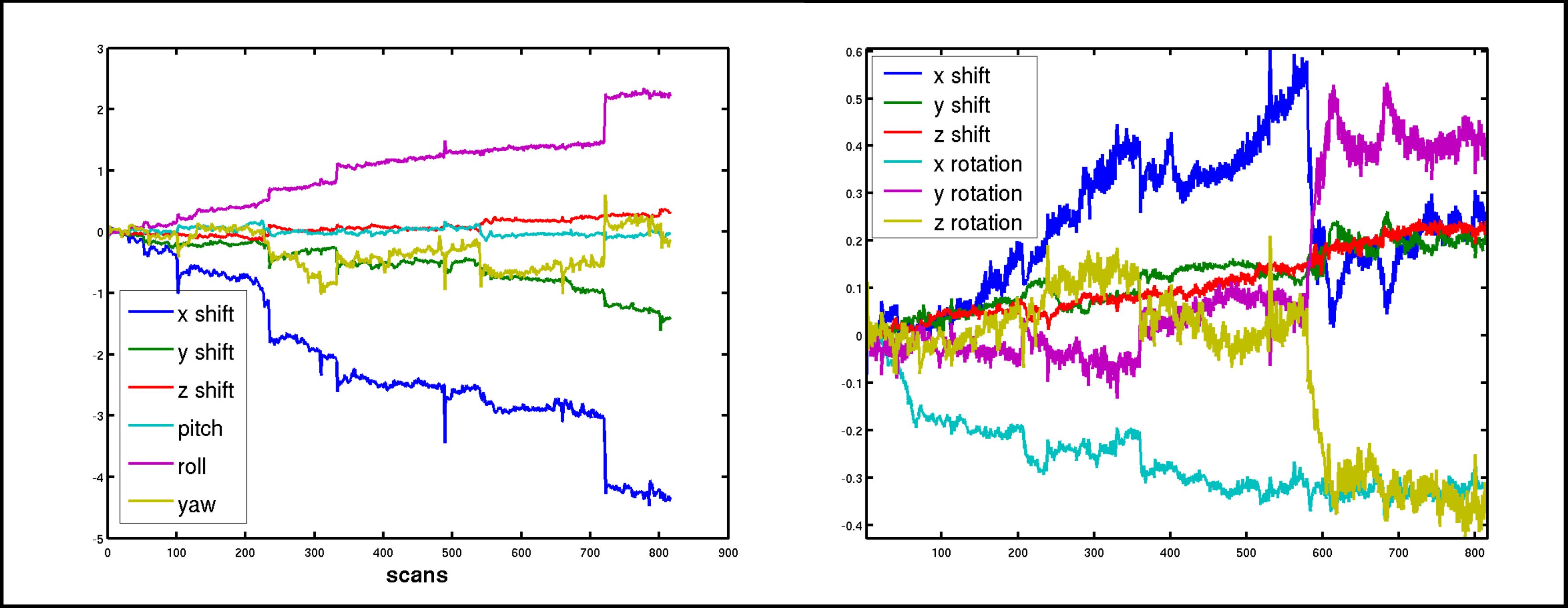
$$M(I_1,I_2) = \sum_{i,j} p(I_1,I_2) \log_2\left(\frac{p(I_1,I_2)}{p(I_1)\,p(I_2)}\right)$$

4. others ….M. Jenkinson and S.M. Smith. Medical Image Analysis, 5(2):143-156, June 2001

Search Strategies

- Least squares ($Y=X\beta$) … ?
- Steepest descent: vary parameters and compute the gradient in the cost function (error). Keep going as long as it gets better.
- There are variations on this theme:
  - simplex
  - Newton's method / gradient descent
  - Adaptive methods
  - others…

Sample Movement Parameters



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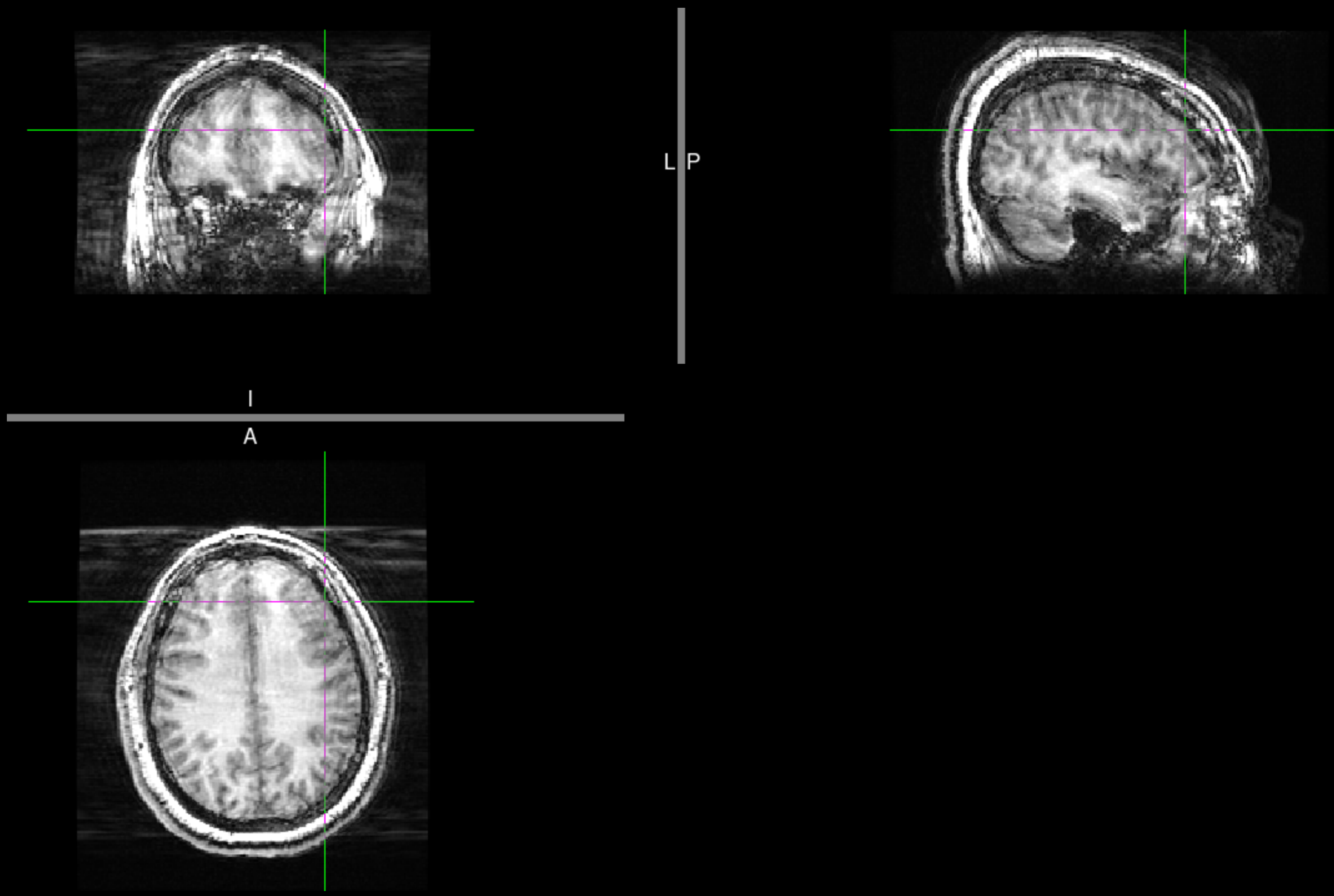
Movement Noise

- In addition to misplacing voxels, you introduce a fluctuation in signal intensity during realignment
- This is a complicated function of the movement:
  - Movement affects the k-space trajectory
  - Mixes partial volumes,
  - Interpolation methods also have an effect on intensity.

Movement Noise corrections

- Minimize movement while acquiring data whenever possible !!
- Including movement regressors as confounds: what is the physics relationship between signal intensity and movement?
  - It's Complicated
    - ... but can be approximated with first order linear relationship.
    - Higher order terms (Lund et al., 2005 NeuroImage) are extremely helpful
  - Reduces residual variance
  - If movement is correlated with task = BIG TROUBLE!

Movement Artefacts



Lecture Goals

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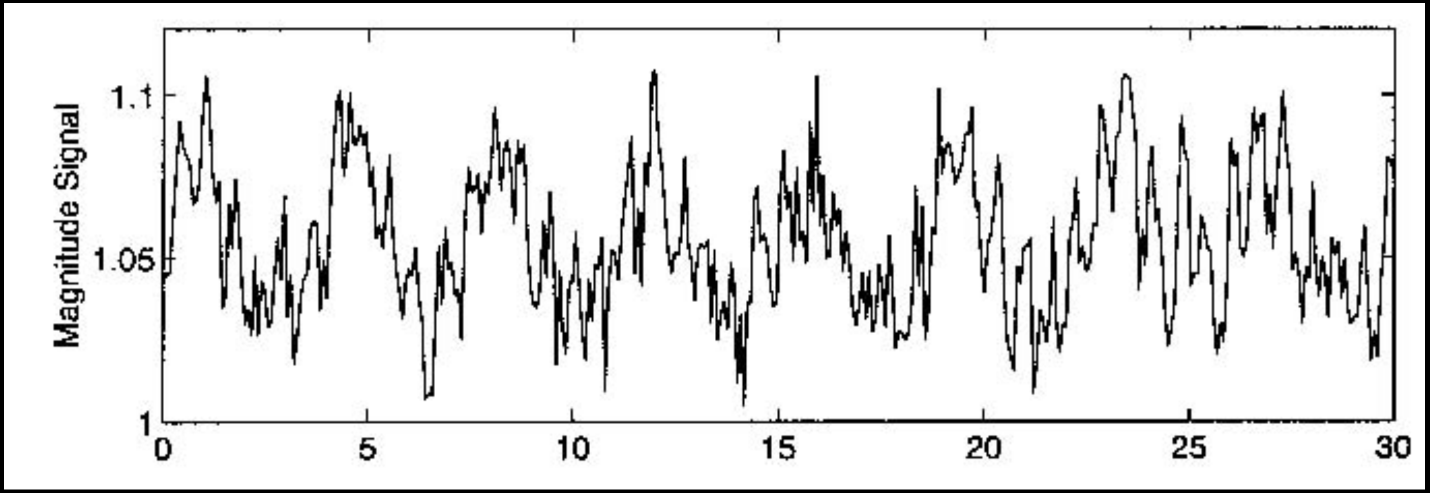
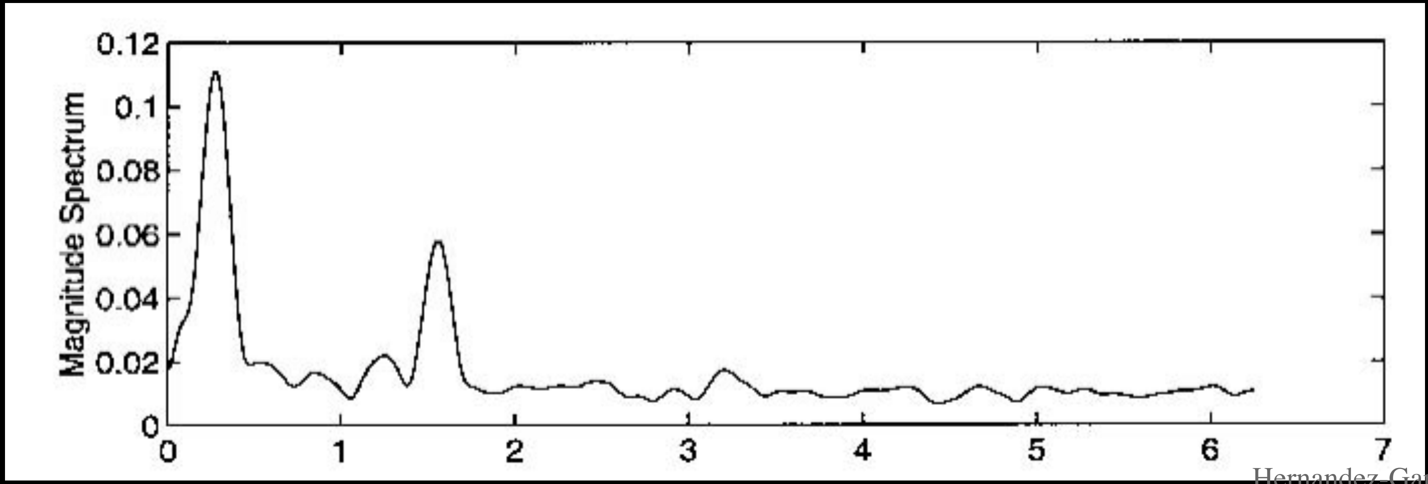
Physiological oscillations



Time domain



frequency domain

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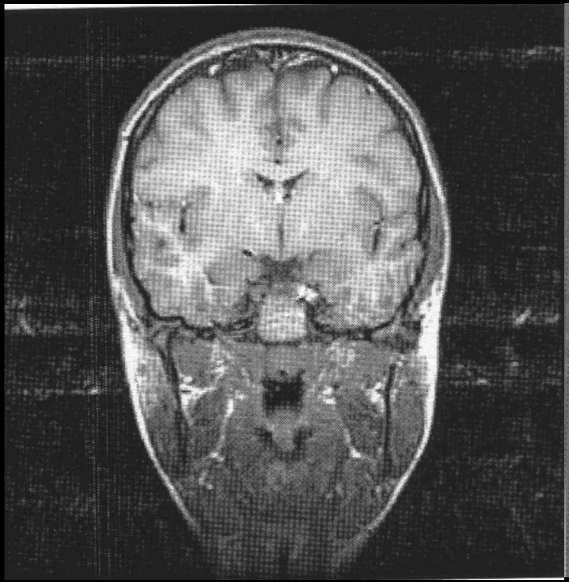
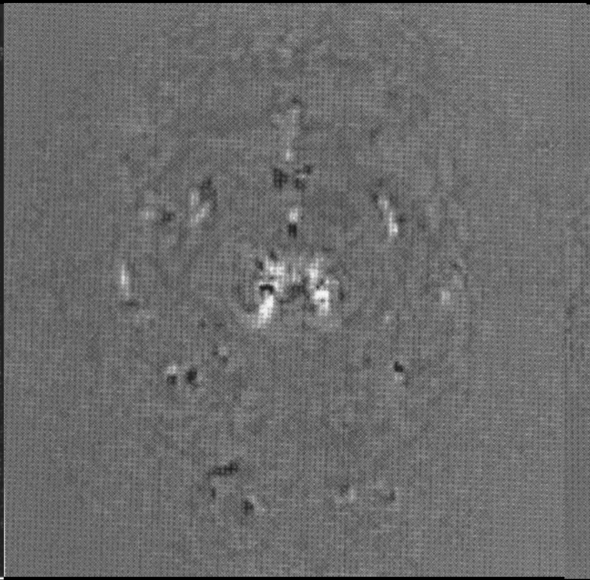
courtesy of Douglas Noll

Cardiac and Respiratory Variance

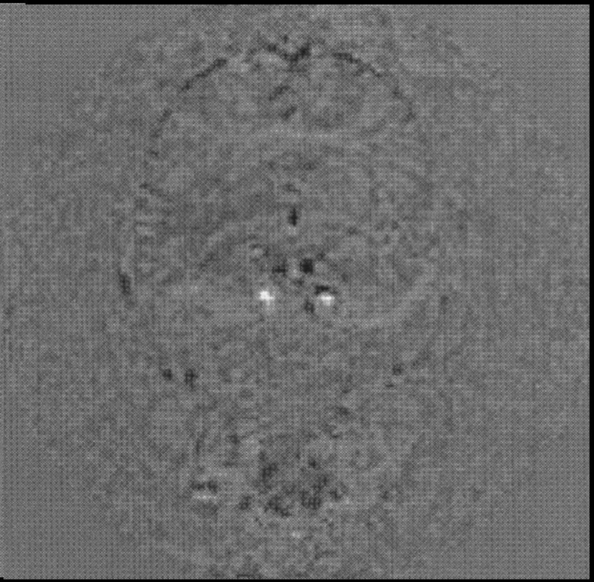
anatomy



Residual Variance w/o Physio correction



Residual Variance w/ Physio correction



Data courtesy of Scott Peltier

Cardiac Noise

- Blood flow is pulsatile -> changes blood volume, and velocity.
- How blood flow affects the MR signal:
  - Flow enhancement (incoming spins have not received any RF , fully relaxed -> more signal)
  - Flow void (sometimes spins flow so fast through the plane that they don't see the RF pulse, or they flow out before they can be encoded -> less signal)
  - Flow induced displacement (additional phase acquired because of in-plane movement -> distorted/displaced signal, ghosting)

Reduction of cardiac effects during Acquisition

- Use a smaller flip angle - reduces flow enhancements and voids.
- Use flow "spoilers" to remove vascular signals.
  - (A pair of balanced gradient pulses, a.k.a. "crushers", makes moving spins get out of phase with each other and cancel, but the stationary spins come back into focus and their signal remains.)
- Use fast acquisition (single shot) to reduce ghosting.
- "Cardiac Gating"

Reduction of cardiac artifacts after acquisition

- Digital Filters …
- Measure cardiac waveform and include in analysis as a confound.
- Note: watch out for aliasing!!
  - heartbeat > 1 Hz
  - If TR = 1 sec. -> Nyquist frequency < 0.5 Hz
  - SMS speeds up sampling rate – reduces aliasing.

Respiration

- Air and Tissue difference in magnetic susceptibility (χ) : Distortion of B_0 field
- Chest movement changes the shape of the B_0 field.
- Resonant frequency changes slightly
  - (Recall that $\omega_0 = \gamma B_0$)
- Blood Pressure and CBF change slightly with respiration
  - pulsation of arteries -> CBV
  - pCO2 -> CBF

Corrections for Respiration

- Fast image acquisition (single shot)
- Record Respiratory waveform and use as a confound. (Note- sometimes it's correlated with task of interest)
- "Notch" or "band-stop" Filters
- Aliasing is not as much of a problem as in cardiac fluctuations, but might still interfere with design
  - Respiration ~ 0.08 Hz
  - BOLD ~ from 0.01 to 0.05 (broad)
  - typical Nyquist frequency < 0.5 Hz

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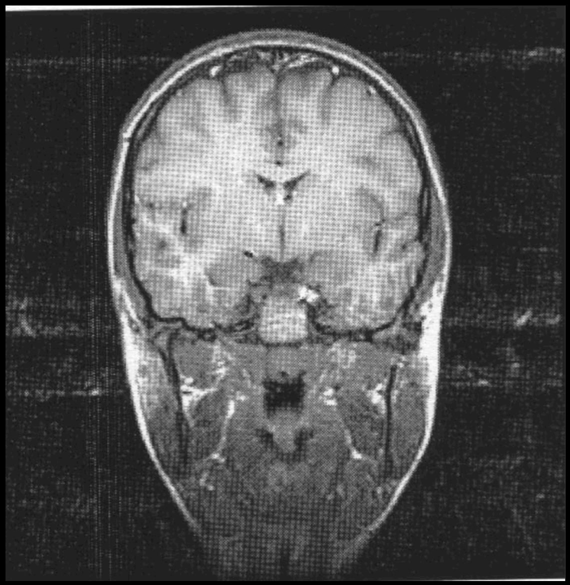
Definitions

Signal to Noise Ratio(SNR) :
Ratio of the amount of Signal to the standard deviation of the noise



Contrast to Noise Ratio (CNR):
Ratio of Difference in signal between two "things" to the standard deviation of the noise

Signal Intensity in MRI

- The signal is proportional to M and V, where:
  - V = $\Delta x\ \Delta y\ \Delta z$ is the voxel volume
  - M is the intensity of the magnetization vector.
- Proton Density and B0 determine the size of the spin populations, I.e. - magnitude of M
- Acquisition timing also affects the observed Signal

$$\rho(1 - e^{-TR/T1})e^{-TE/T2}$$

Thermal Noise

- Not related to the NMR phenomenon but from random thermal fluctuations.
  - Present with or without B_0, RF, Gradients
- Uniform spectral density: “white noise”.
- Comes from the whole body – amount of noise depends on the amount of the body to which the receive coil is sensitive.

Thermal Noise in MRI

- The noise/pixel in a 2D image is:

$$\sigma_n^2 = \frac{1}{N_x N_y}\frac{\sigma}{\Delta t} \propto \frac{1}{N_x N_y \Delta t} = \frac{1}{T_{A/D}}$$

  where:
  - N_x and N_y are the number of samples in the *x*- and *y*-directions
  - σ is the std. dev. of the inherent noise in the system
  - Δt is the sampling time (faster sampling allows more noise into the system), and
  - $T_{A/D}$ is the total time the signal is sampled … (includes number of averages)

Signal to Noise Ratio

- The *SNR* is then:

$$\boxed{SNR \propto \frac{signal}{\sigma_n} \propto m_0 V \sqrt{T_{A/D}}}$$

- Comments:
  - SNR is proportional to Volume (V)
  - SNR is proportional to magnetization ($m_0 \propto B_0$)
  - Better SNR for longer acquisitions ($T_{A/D}$)

Resolution Penalty

- Suppose we wished to double the spatial resolution: from 3 x 3 x 5 mm^3 to 1.5 x 1.5 x 2.5 mm^3
  - Voxel volume decreases by a factor of 8

$$\boxed{SNR \propto V \sqrt{T_{A/D}}}$$

- Based on this expression, $T_{A/D}$ must increase by 8^2 = 64 in order to maintain the same SNR
  - The number of averages might have to increase by 20-30 fold to get $T_{A/D}$ to 64

Image SNR vs. Temporal SNR

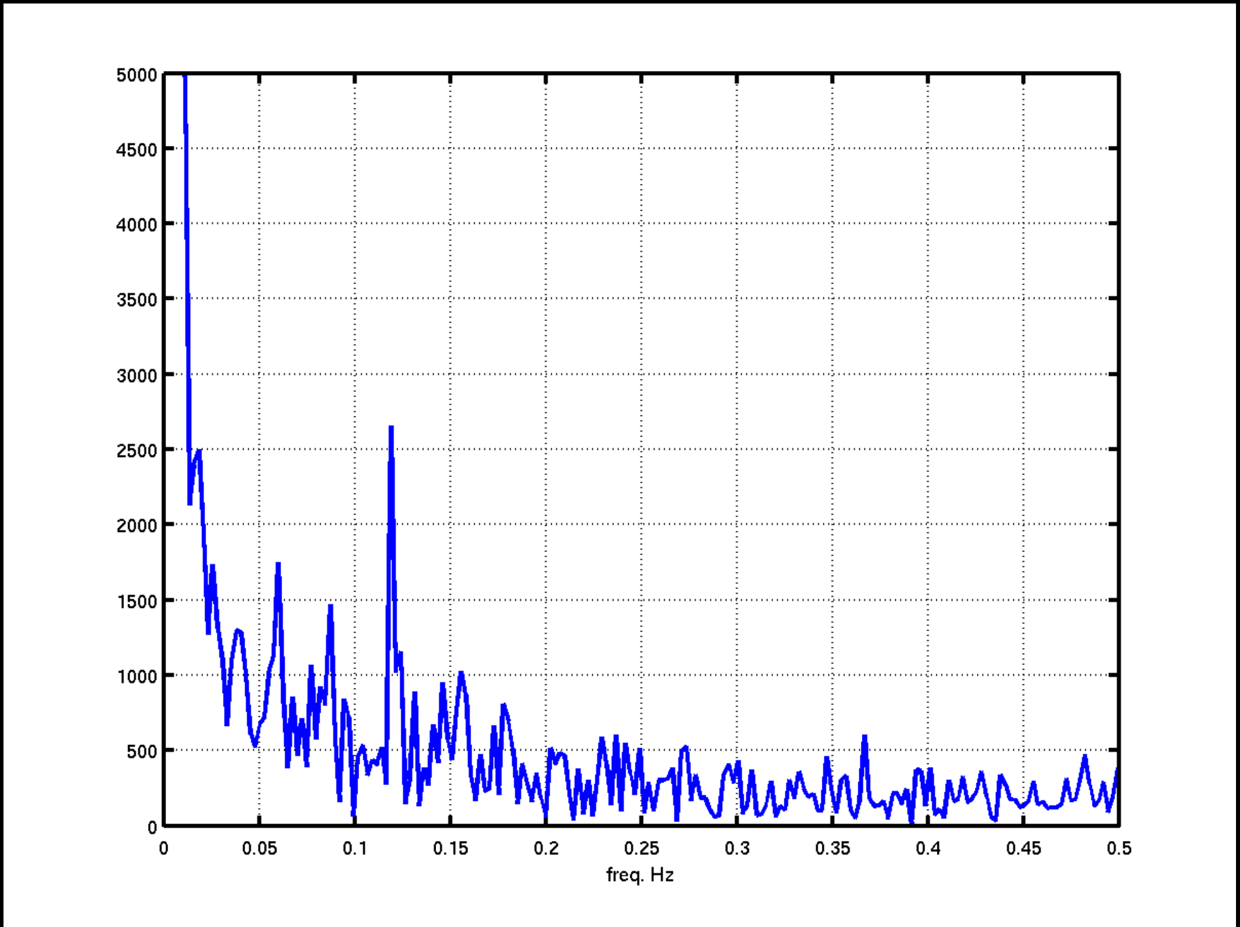
- There are two main kinds of SNR that we look at :
  - **Image SNR** – dominated by thermal noise
  - **Temporal SNR** – includes thermal noise, but also includes temporal fluctuations (respiration, cardiac, drifts, trends, equip instabilities, etc., etc.)

- Temporal SNR is most important for fMRI
  - We detect task related signal changes over time

“1/f” noise and drift

- Temporal Noise in FMRI is typically thermal white noise plus “1/f” noise.
- 1/f noise is more cumbersome (also more interesting?)
  - General Linear Model solvers assume independence
  - 1/f noise means autocorrelation (dependence)
- Contributing sources:
  - equipment instability (heating)
  - Physiological fluctuations
  - temperature drift
  - Neuronal changes

Drift and 1/f noise



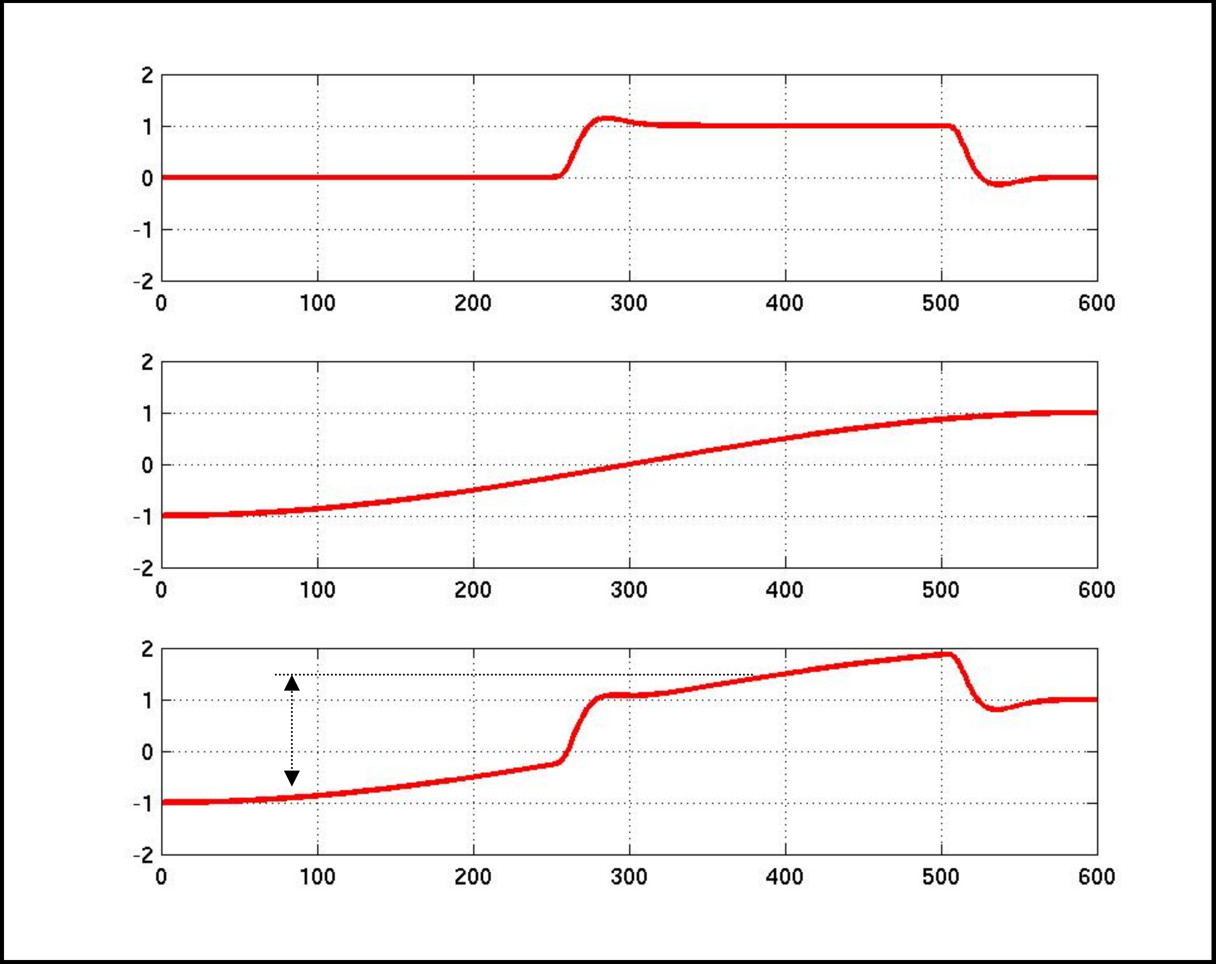
Why do we care so much about 1/f noise?

- Slow paradigms: Activation is CONFOUNDED by 1/f effects.
  - drug effects
  - basal state
  - session effects
  - …

- Friston, K., Josephs, O., Zarahn, E., Holmes, A., Rouquette, S., and Poline, J.-B. (2000). To smooth or not to smooth? *NeuroImage*, 12:196-208.

- Wang J. **Aguirre** GK. Kimberg DY. Roc AC. Li L. Detre JA. Arterial spin labeling perfusion fMRI with very low task frequency. *Magnetic Resonance in Medicine. 49(5):796-802, 2003 May.*

Slow drifts as confounds



Fixes to 1/f

- Make the task design at higher frequency and filter lower frequencies out.
- Use something else:
  - T2* mapping
  - ASL
  - Others ... (VASO)

  both use pairs of adjacent images and subtract out the drift.
- Model the drift with an Auto-regressive model and remove it as a confound. (more on this next week)

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Spatial Normalization: Correcting for Morphological "Noise"

- Morphology varies over a lot over subjects
- Additionally, different brains may be organized differently (e.g- language, handedness…)
- We have to work under the assumption that brains are "close enough" to each other.
- Maybe there is some sort of transformation that we can do to a brain to make it match some "canonical" brain.
- This transformation is not "rigid-body" (ie- varies over the object - produces warp)

Spatial Normalization: Correcting for Morphological "Noise"

- Warp all subjects' images so that they match a template (*canonical* brain) that is the "paragon of braininess".
  - MNI templates
  - Talairach and Tournoux
  - Many other specialized ones …
- Main approaches to warping:
  - higher order affine transformations that include skewing terms
  - deformation fields (non-linear warping) .We'll focus on this latter one.

Non-linear warping

- Objective: find a transformation that will minimize the difference (Error) between the template and the object.

$$Error = \Sigma_{pixels} (I_1 - I_2)^2 + R$$

(note we could also use the same cost functions as with realignment - correlations, MI, …)

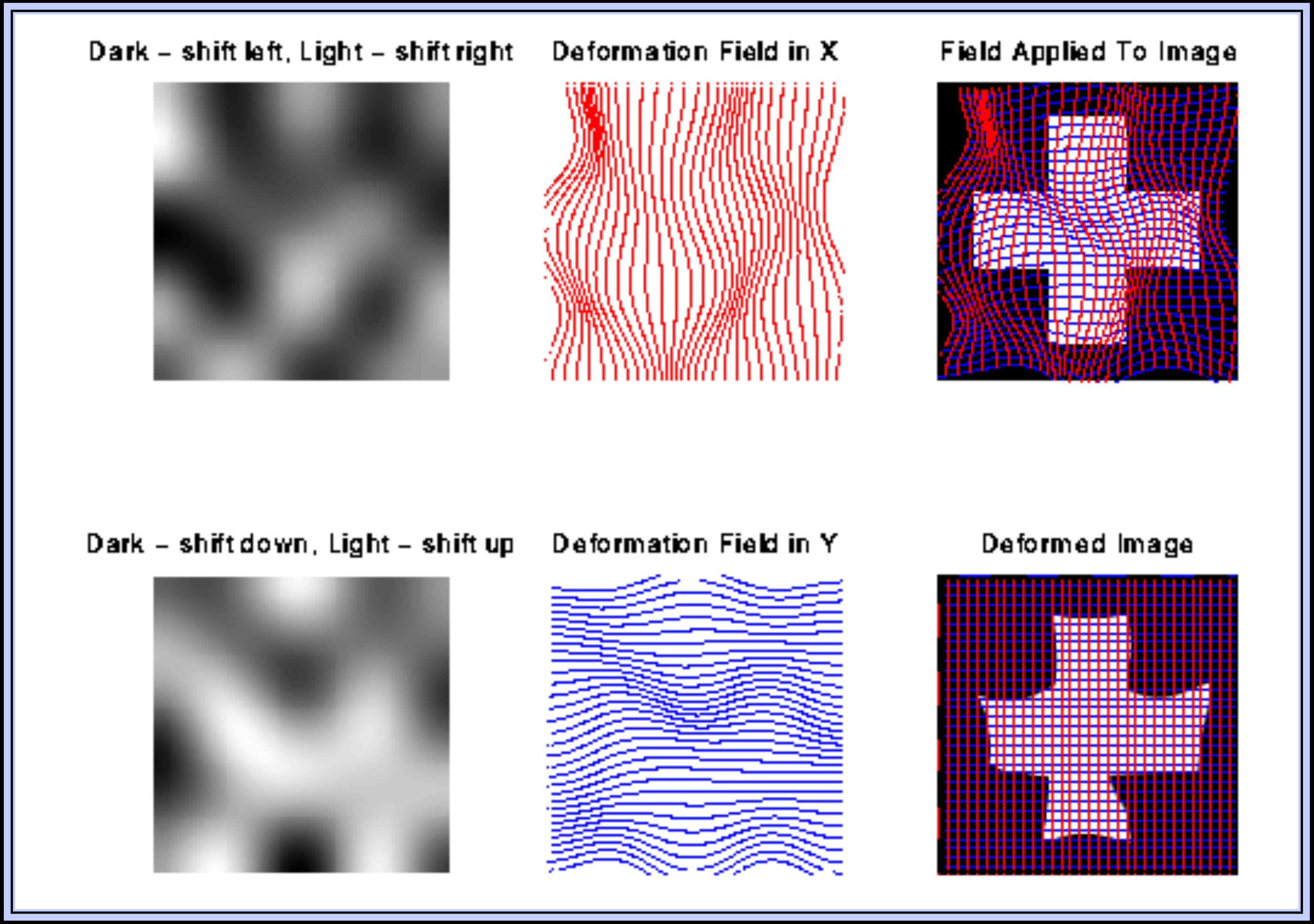
R is a "regularization" term, typically a spatial derivative to penalize roughness.

Non-linear warping

- Different from “Rigid Body” transformations
- Let the transformation be made up of a ***different shift at each location.***
- Assume this amount of shift (warp) is a smooth and continuous function over the 3D space we’re working on. Let’s call it

$$s = W(r)$$

Sample deformation field



Slide from SPM website

Non-linear warping

- Approximate the *warp*() function as a series. Could be Taylor series, Fourier, Euler, ….etc. (It turns out that Discrete Cosine Transforms are particularly good for this application.)

$$W(\mathbf{r}) = \Sigma_i\, a_i \cos(\omega_i\, \mathbf{r})$$

- Find the first few coefficients a_i to approximate the *warp()* function in *each* direction (x,y,z shift).

(This means that there are three, 3D, warping functions to find)

A SERIES of unfortunate ...

Everything is
a sum of
polymonials

This tea
is cold...

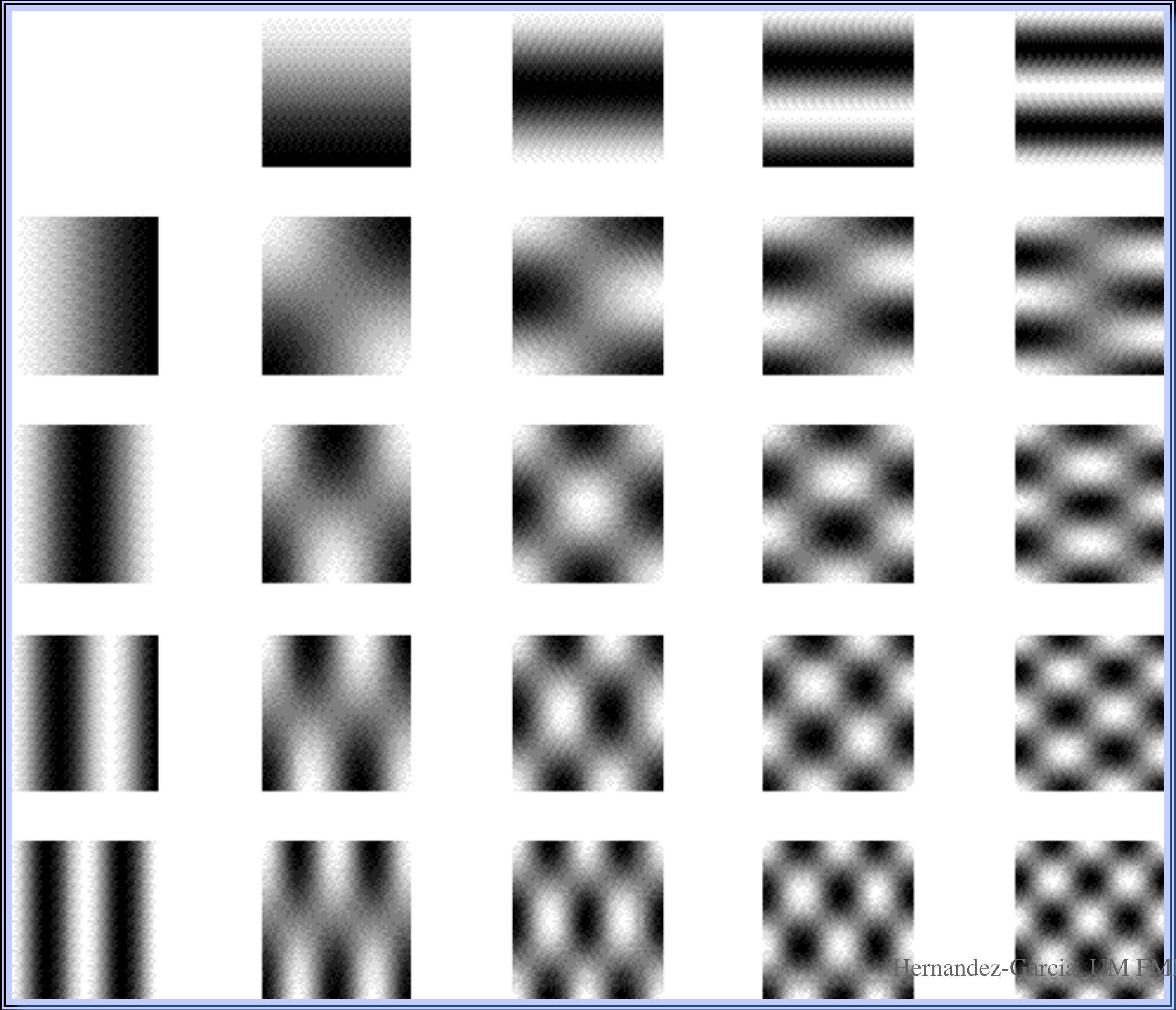
Brook Taylor
1715

Everything is
a sum of
sinusoids

I hope they
don’t chop off
my head ...

Jean-Baptiste
Joseph Fourier

Basis Functions



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Non-linear warping

- Finding the coefficients is again an optimization problem…
- Strategies: least squares, Gauss-Newton, simplex, gradient descent, genetic algorithms, neural networks
- … Just minimize the cost function.

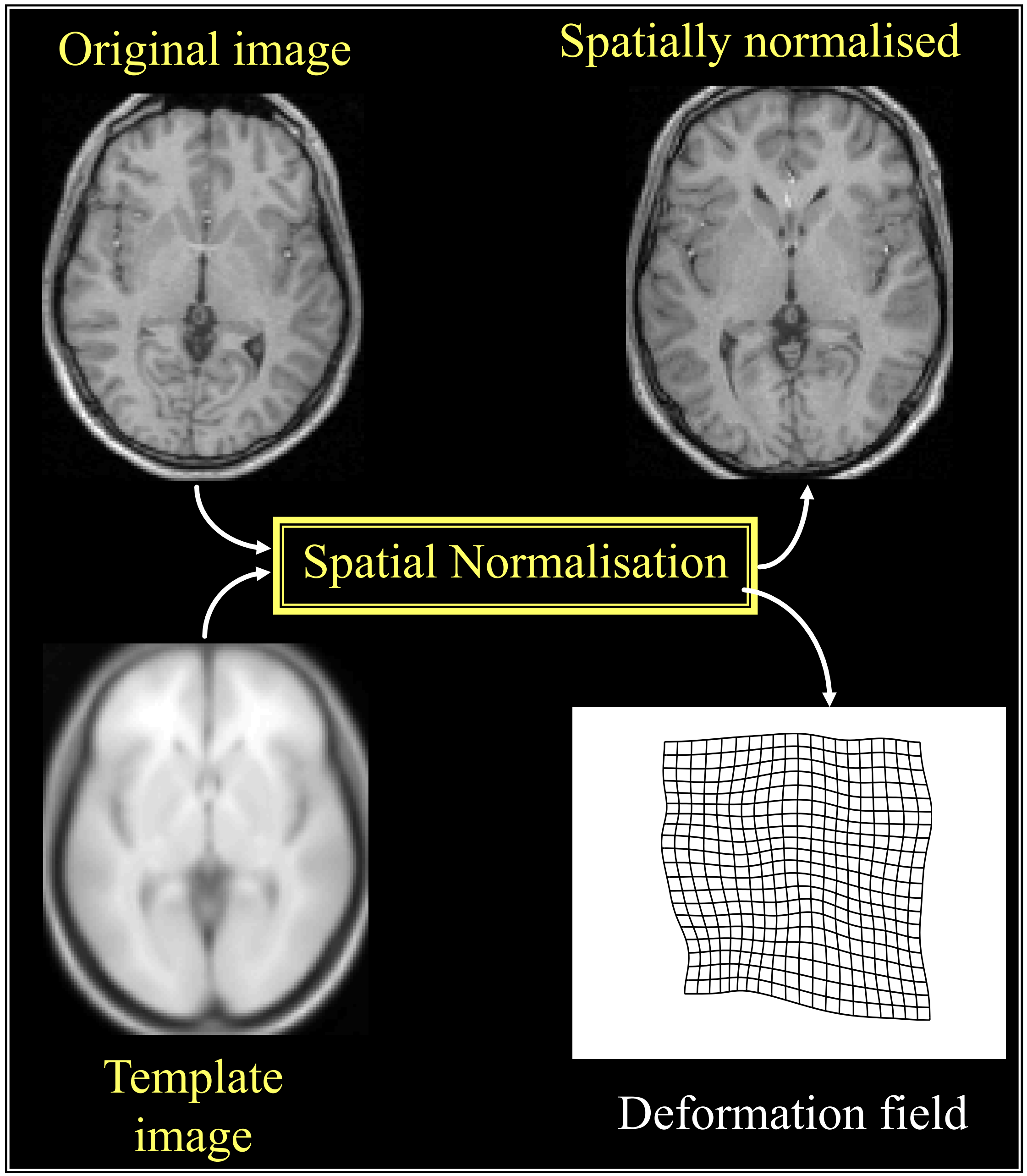
Spatial Normalisation

Determine the spatial transformation that minimises the sum of squared difference between an image and a linear combination of one or more templates.

Begins with an affine registration to match the size and position of the image.

Followed by a global non-linear warping to match the overall brain shape.

Uses a Bayesian framework to simultaneously maximise the smoothness of the warps.



slide from SPM website?

Normalization References

Friston et al (1995): *Spatial registration and normalisation of images*.
Human Brain Mapping 3(3):165-189

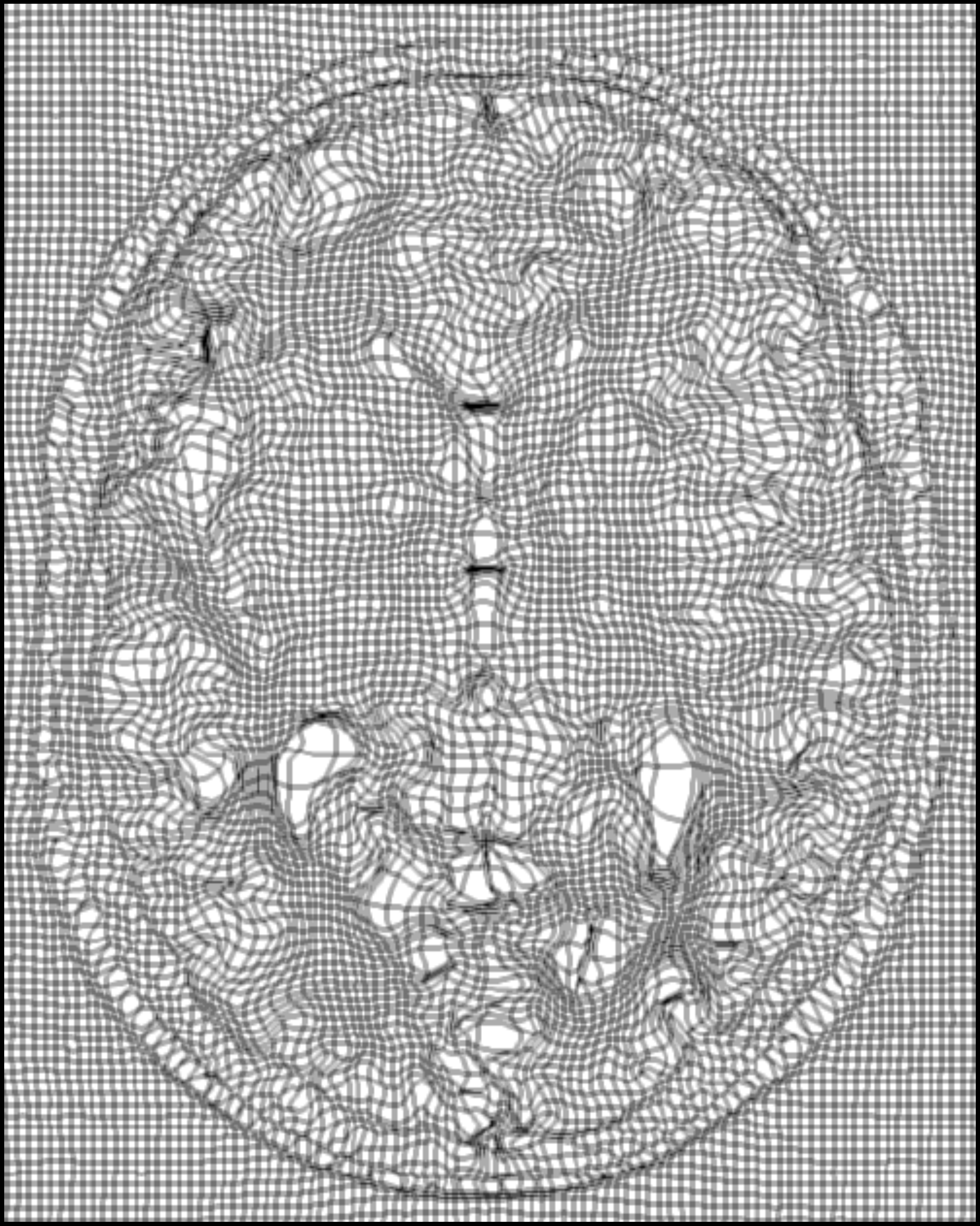
Ashburner & Friston (1997): *Multimodal image coregistration and partitioning - a unified framework*.
NeuroImage 6(3):209-217

Collignon et al (1995): *Automated multi-modality image registration based on information theory*.
IPMI' 95 pp 263-274

Ashburner et al (1997): *Incorporating prior knowledge into image registration*.
NeuroImage 6(4):344-352

Ashburner et al (1999): *Nonlinear spatial normalisation using basis functions*.
Human Brain Mapping 7(4):254-266

Ashburner & Friston (2000): *Voxel-based morphometry - the methods*.
NeuroImage 11:805-821

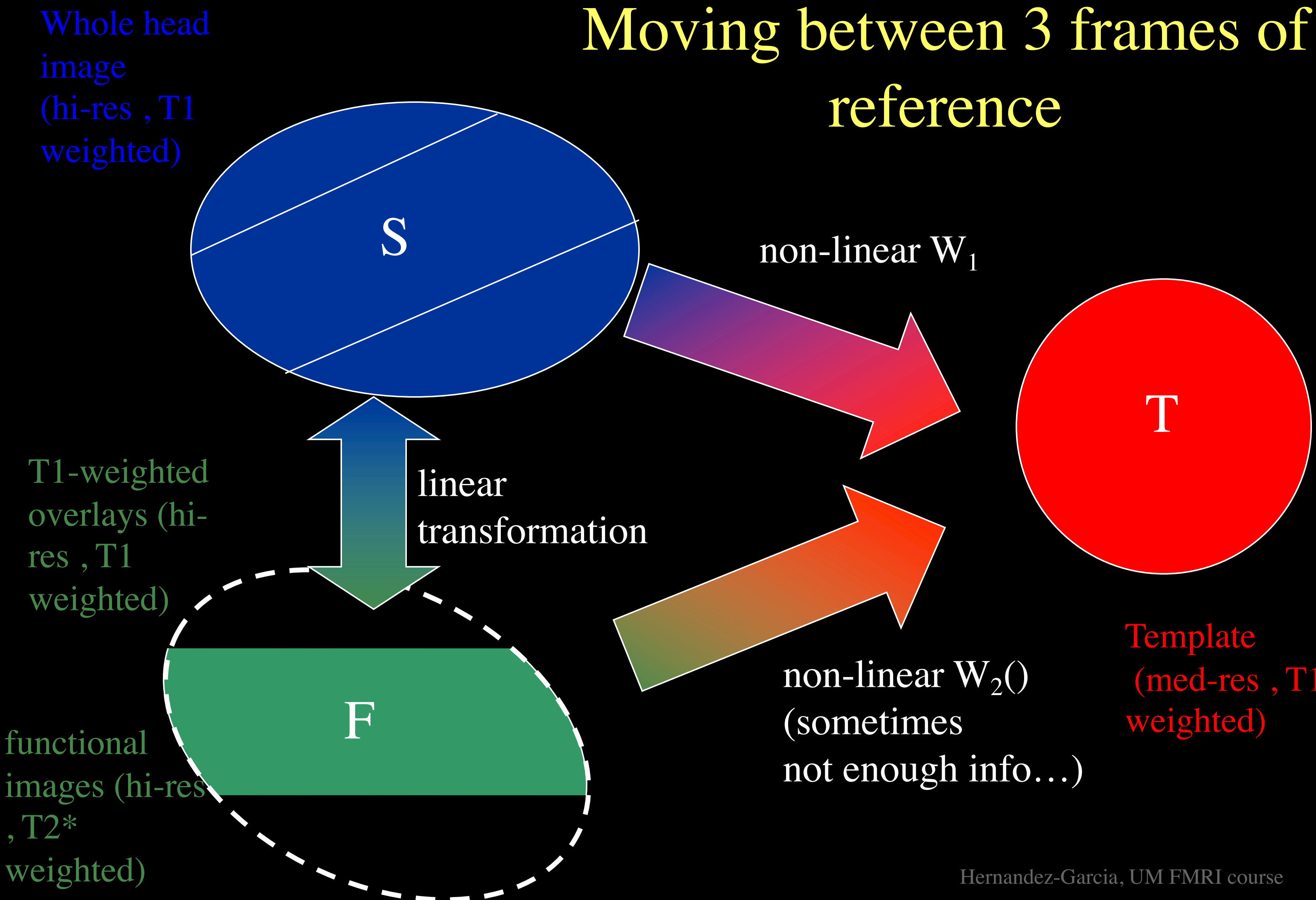


slide from SPM website?

Practical aspects of spatial normalization

- Resolution , contrast , Field Of View can be different between template and functional images.
- Useful to collect additional images to use in the search for the deformation fields, then apply the resulting deformations to the functional images.

Practical Normalization Path: Moving between 3 frames of reference



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Typical Normalization path

1. Register whole brain to overlay.

   $e = (F - AS)^2$, find A that minimizes e

2. Warp the transformed whole brain image into template

   $e = (T - W_2(AS))^2$, find W_2 that minimizes e

3. Use the same warping parameters to warp the functional maps. The end result is:

   W_2F

S = whole brain image
F = functional image
T = template image

Segmented Normalization

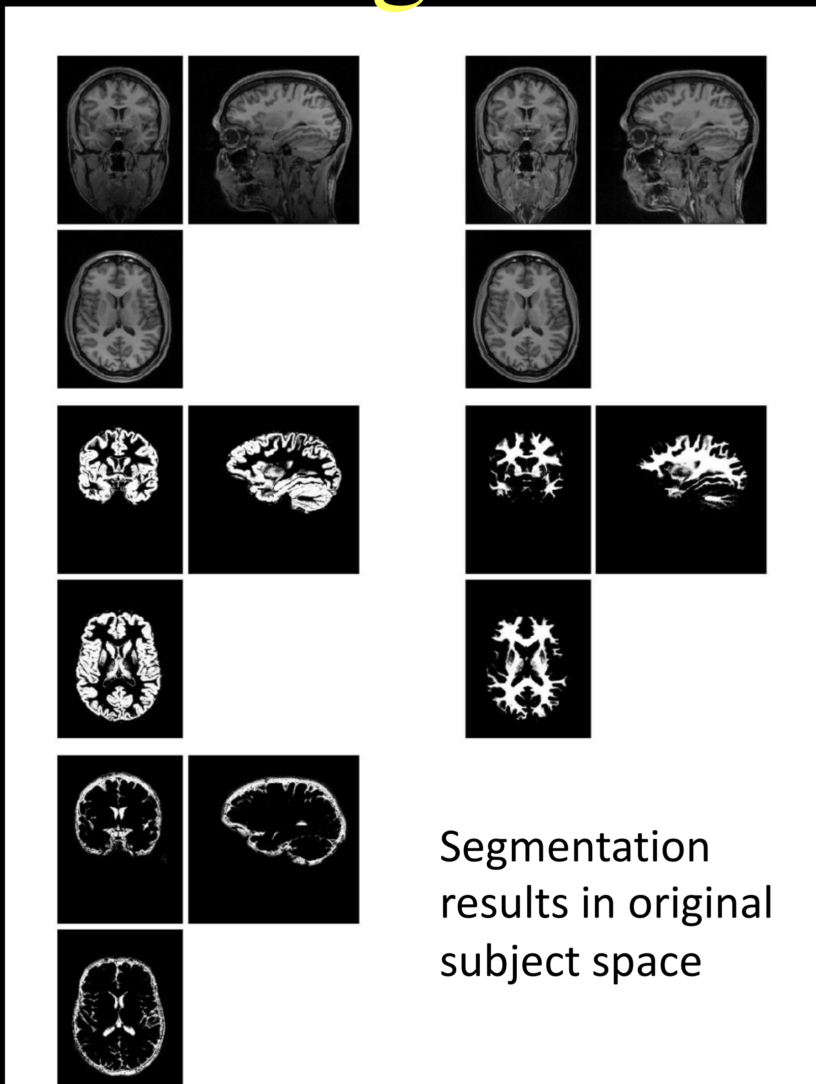
- Warping and Normalization algorithms have evolved considerably. Many variants and strategies motivated by morphometry studies (e.g. Brain Voyager).
- Knowledge of brain structure (e.g. grey matter, white matter, CSF) can improve the normalization process
- Strategy: partition the brain into GM, WM, and CSF and then performs a more "informed" normalization on the resulting partitions

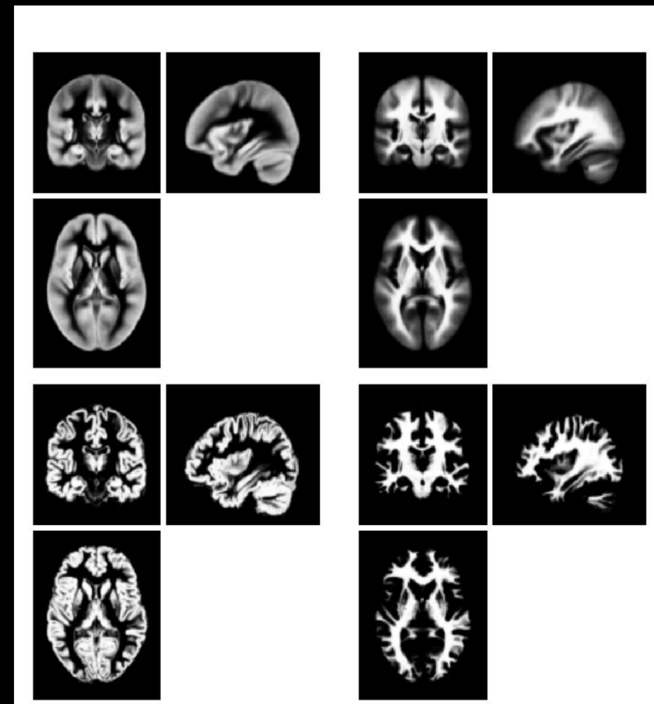
Courtesy of Derek Nee

Segmented Normalization

1. Use clustering algorithm to calculate intensity distributions of grey matter, white matter, and CSF (additional clusters for eyes and scalp too)
2. Normalize resultant segments to template
3. Significant improvements in normalization

Segmented Normalization





Tissue probability maps

Normalized tissue maps

Courtesy of Derek Nee

Lecture Goals

- Understand the following confounds in fMRI and what corrections exist
  - Slice Timing effects (temporal shifting)
  - Movement (rigid body realignment)
  - Physiological Artifacts: respiration and heart beat (regression filters)
  - Electronic Noise (filters and autoregressive models)
  - Morphology (non-linear warping)
  - Image distortions (susceptibility, ghosting, warping)

When things actually go wrong

- Up to now we have explored the charming features of the FMRI signals… They are expected to be there.
- Now we'll look at a whole other set of complications that are not present in a consistent way.

Unwanted Things that can happen to the MR signal

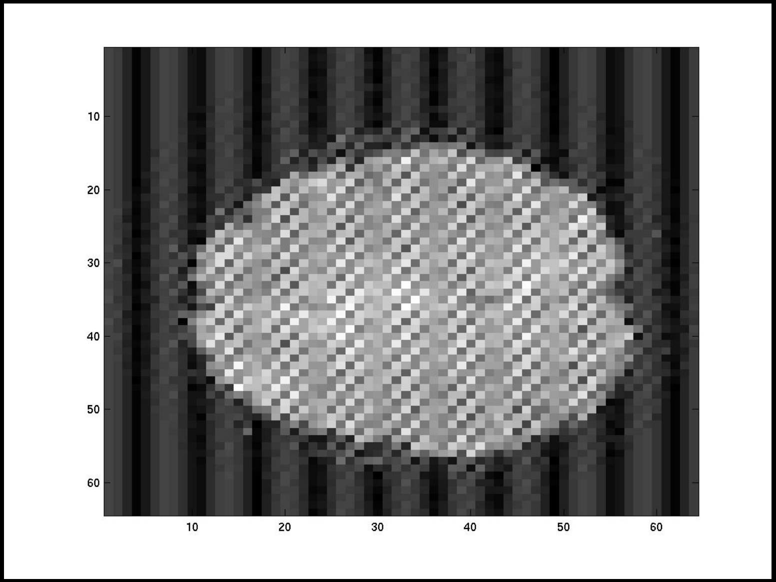
- Addition of "junk"
  - Coherent at different frequencies
  - Incoherent (spikes)
- Multiplication (modulation) by "junk"
  - Unwanted frequency shifts
  - Unwanted Phase shifts

What do these do to the image?
(Think Fourier Transform)

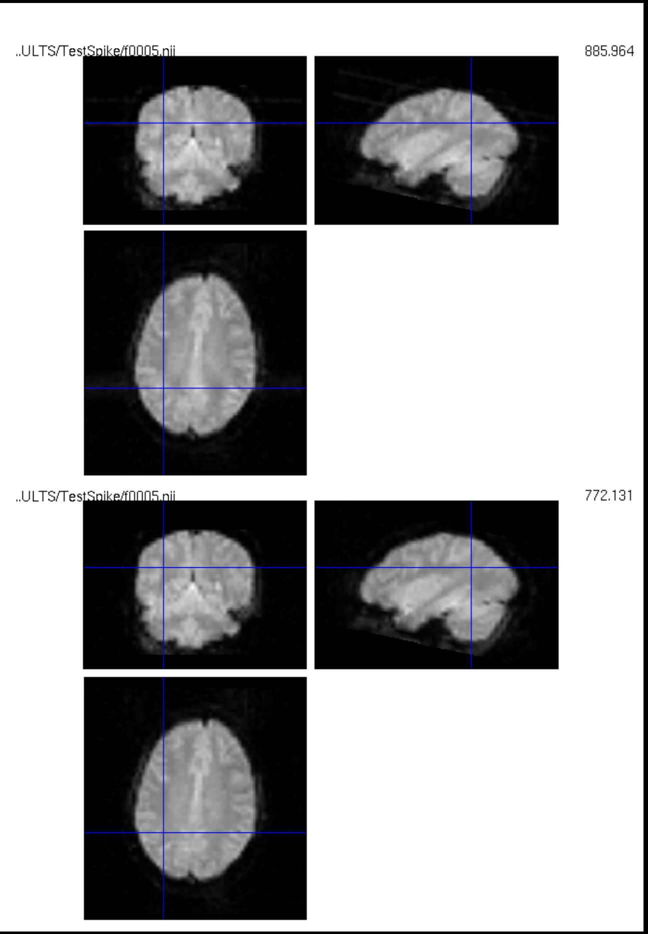
White Pixel Artifact

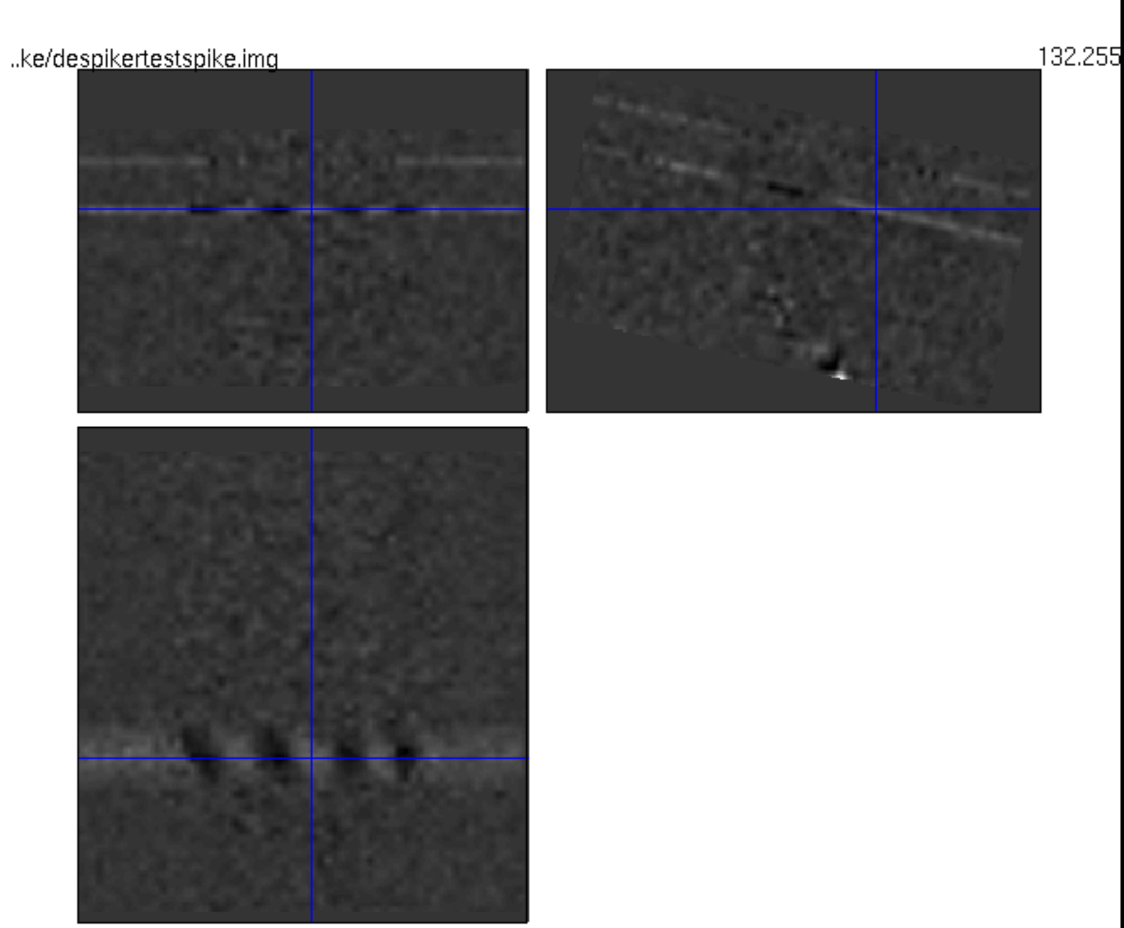
(added junk)

- Caused by a noise spike during acquisition
- Spike in K-space <--> sinusoid in image space



Not Always Easy to See…





Top image has spikes, bottom does not

Difference of the two images

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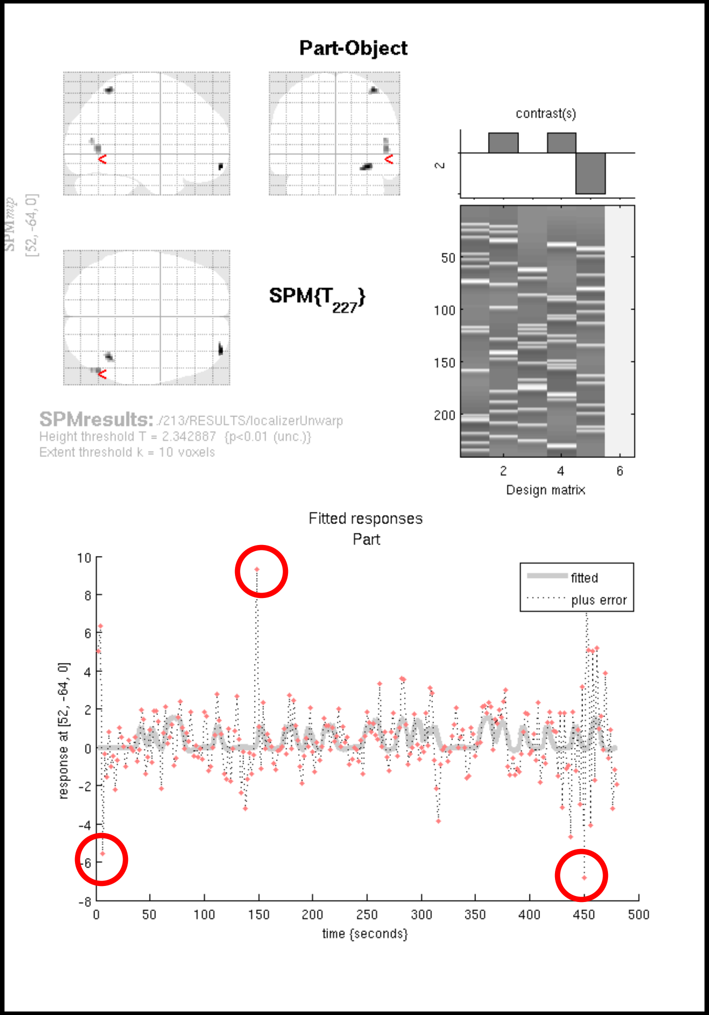
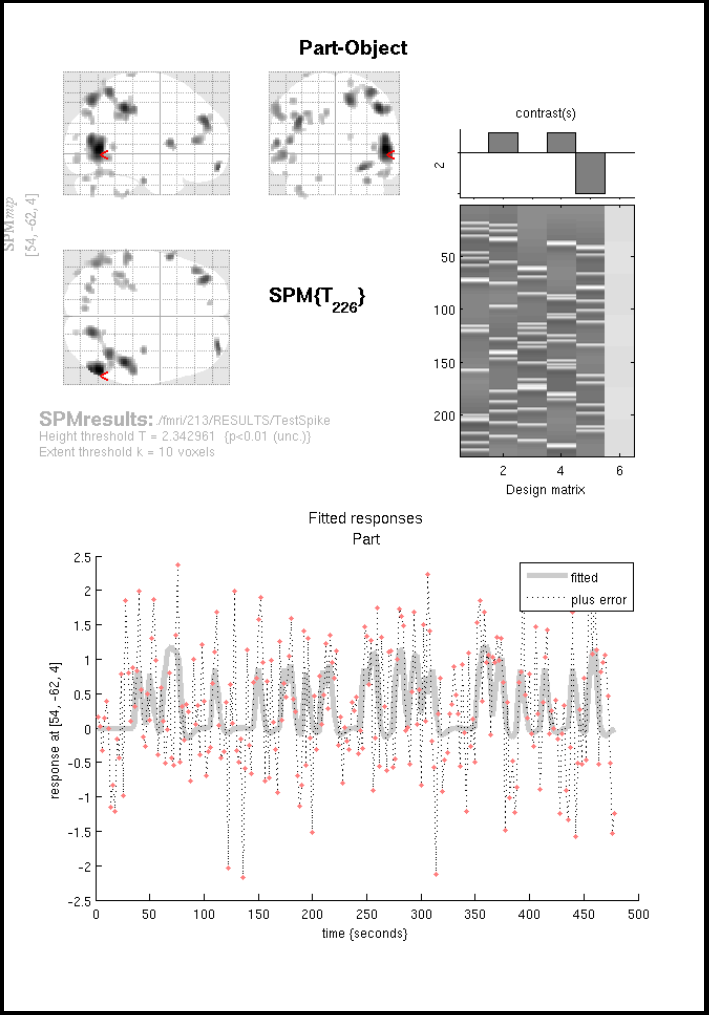
Courtesy of Derek Nee

Spikes In Results - Corrected



Deviations from -8 to 10



Deviations from -2.5 to 2.5

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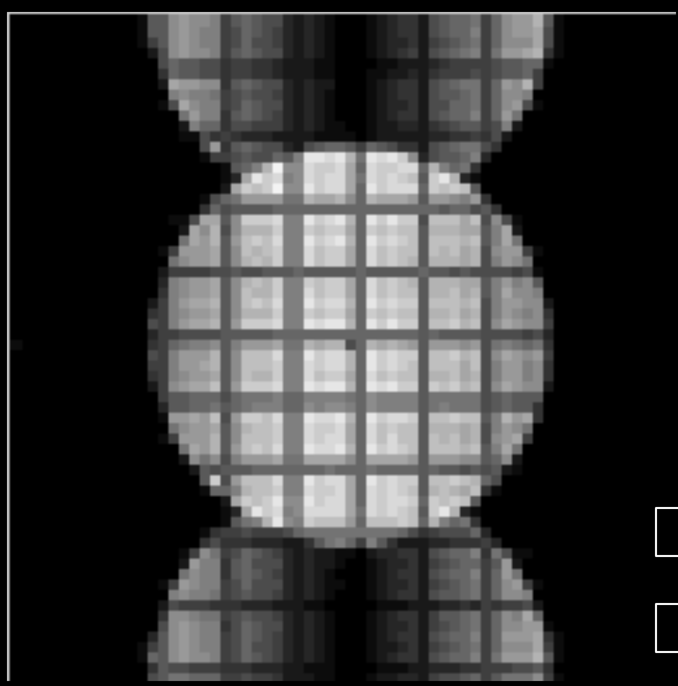
Courtesy of Derek Nee

Despiking

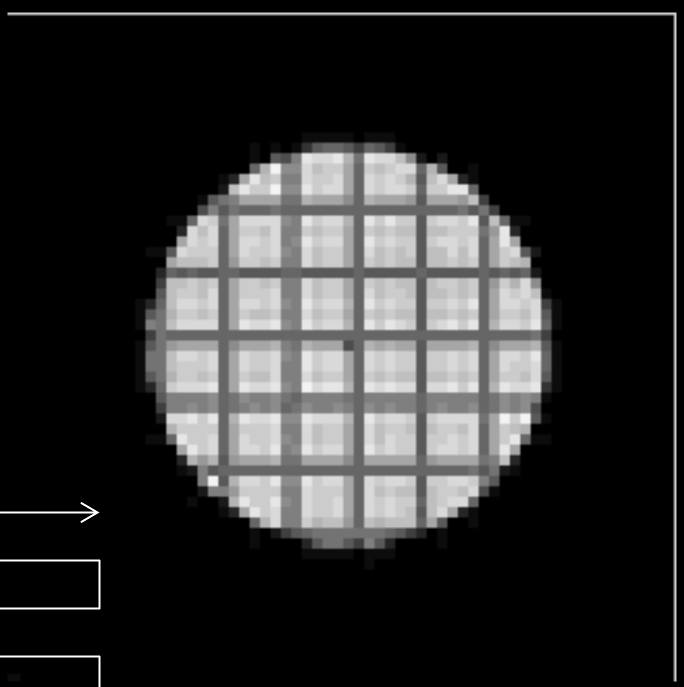
- How do I know if I have a problem?
  - Look for large changes in global signal
  - Difference images to make spikes more visible
  - Look for large deviations from predicted response
- How do I fix it?
  - Treat the artifacts as early as possible, either in k-space or in voxel-space before other preprocessing steps have been applied
  - Replace spike with interpolation of neighbors

Ghosting

(modulation by junk)



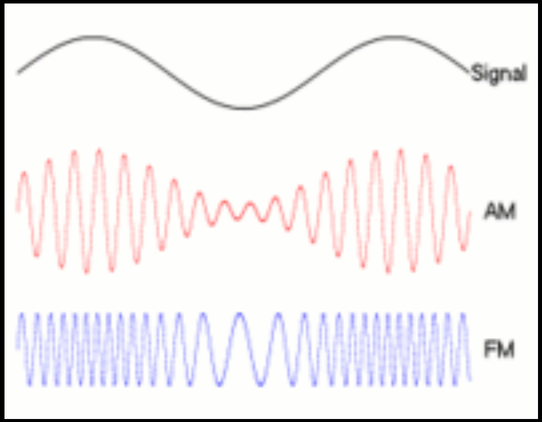
K-space sampling



Courtesy of P. Jezzard

Modulation

(…just when you thought you were done with high school trigonometry!)



$$\begin{aligned} \sin\alpha\cos\beta &= \frac{\sin(\alpha+\beta)+\sin(\alpha-\beta)}{2} \\ \cos\alpha\cos\beta &= \frac{\cos(\alpha+\beta)+\cos(\alpha-\beta)}{2} \\ \sin\alpha\sin\beta &= \frac{\cos(\alpha-\beta)-\cos(\alpha+\beta)}{2} \end{aligned}$$

$$f(t)\sin\omega_0 t \quad \overset{\mathcal{F}}{\Longleftrightarrow} \quad \frac{i}{2}[F(\omega+\omega_0)-F(\omega-\omega_0)]$$

Modulation

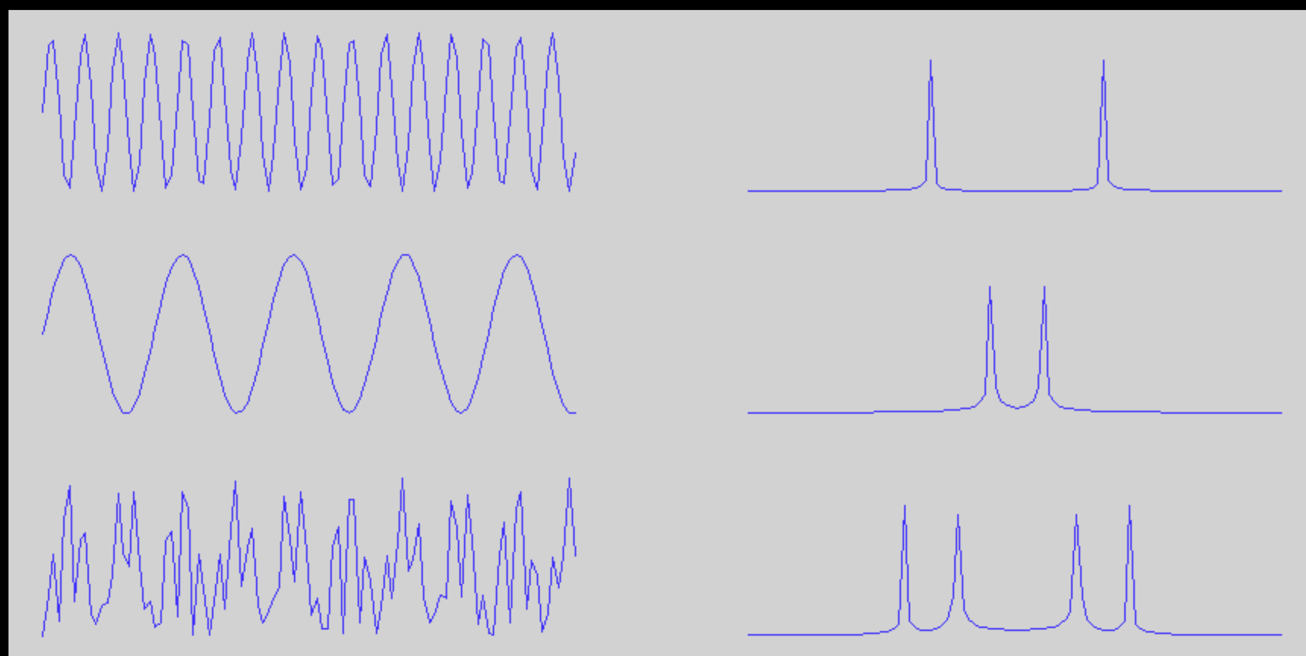
(…just when you thought you were done with high school trigonometry!)

Time domain Frequency Domain

A(t)

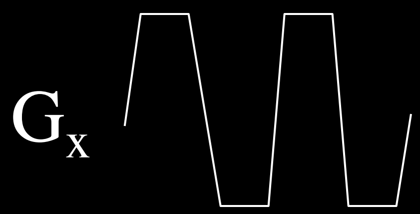
B(t)

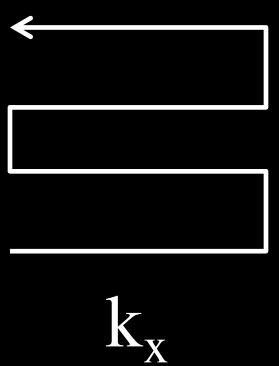
A(t)* B(t)



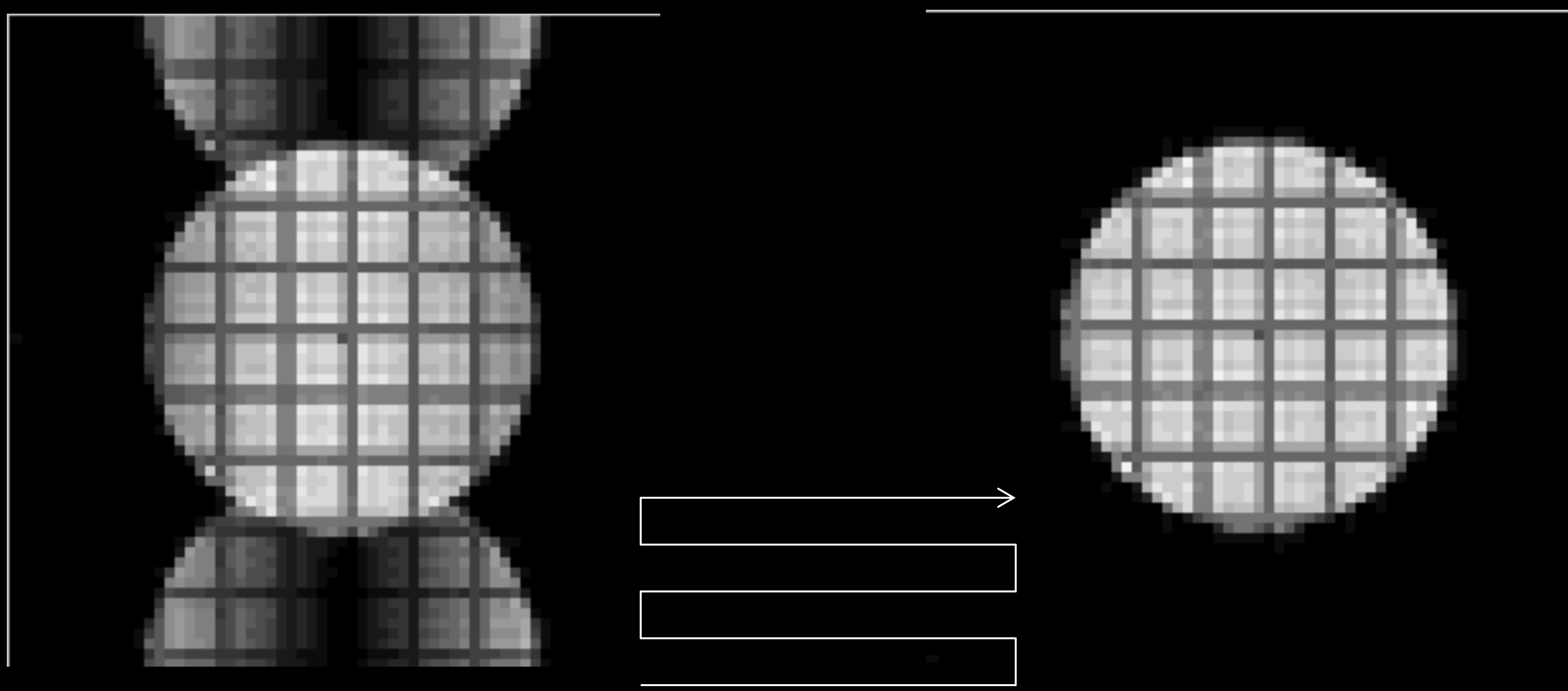
EPI Nyquist ghost

- Caused by phase-error every other line of k-space (hardware problem - e.g.- sometimes the gradient coils are not well balanced)
- This means k-space data are **modulated along one axis** by artefact
- Artefact is oscillation at the Nyquist frequency.
- Solution can be easy:
  1. add a little bit of phase to alternate lines of k-space and reconstruct.
  2. See it the ghosting gets better or worse.
  3. Repeat until fixed.





EPI Nyquist Ghost



K-space sampling

Courtesy of P. Jezzard

Off-resonance effects

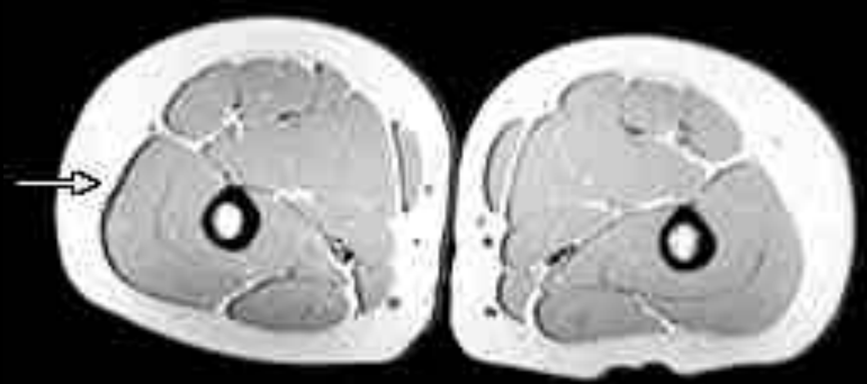
(frequency shifts)

- Recall:

$$\omega_0 = \gamma B_0$$

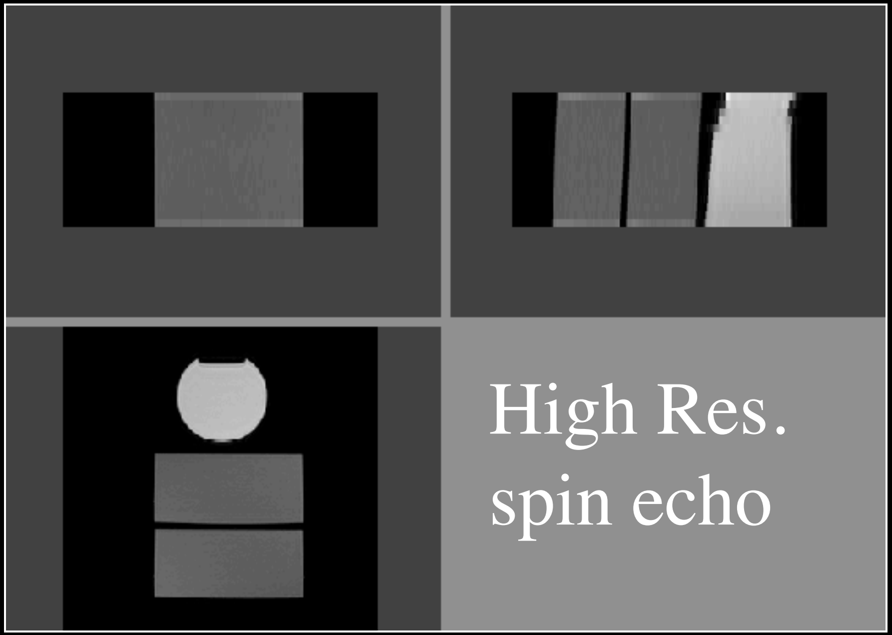
- **Chemical shift**: fat protons have a different gyromagnetic ratio, and hence resonant frequency (3.5ppm away from water)
- **Field distorsions:** produce the same effect (changes in B_0 instead of change in γ). Both result in a change of ω_0 in a particular region

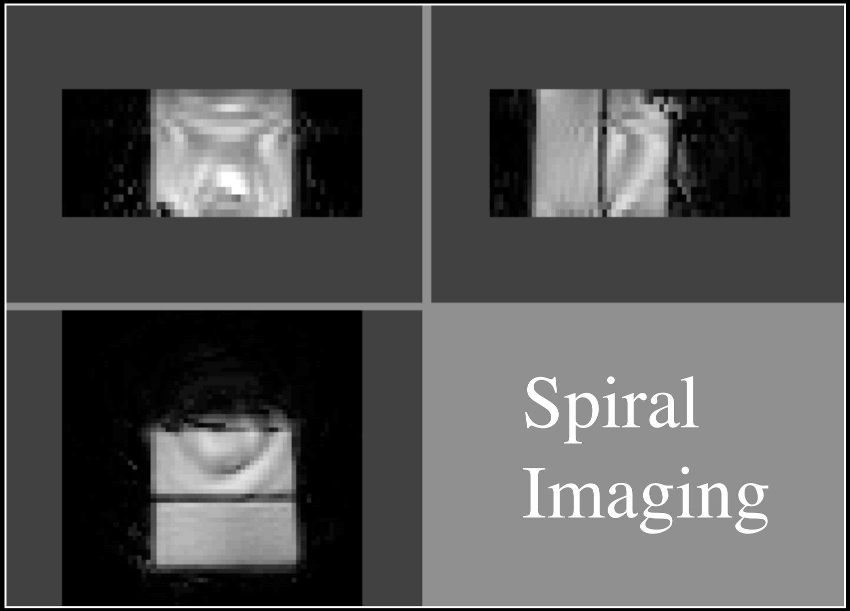
Examples of Chemical Shift Artifact

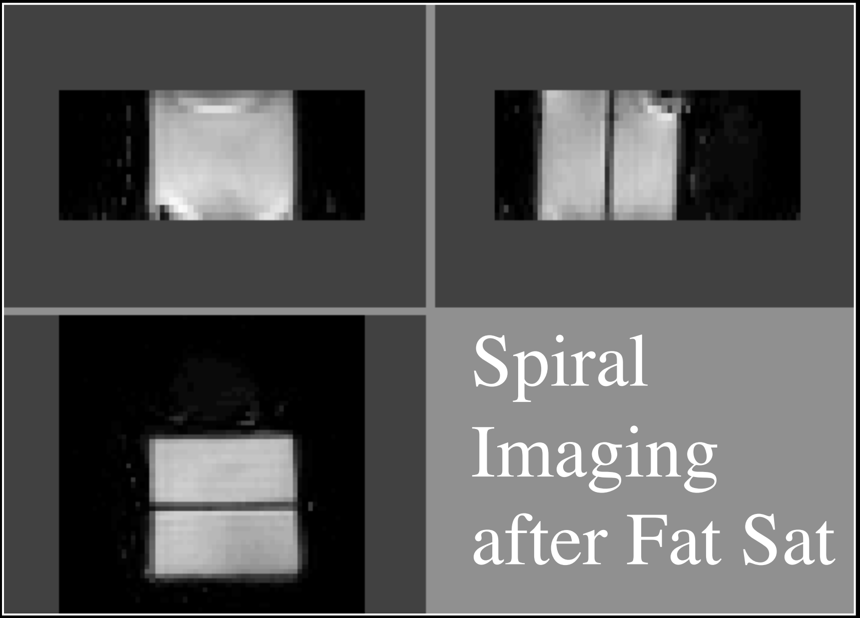


Images from: Hornak, http://www.cis.rit.edu/htbooks/mri/chap-11/chap-11.htm

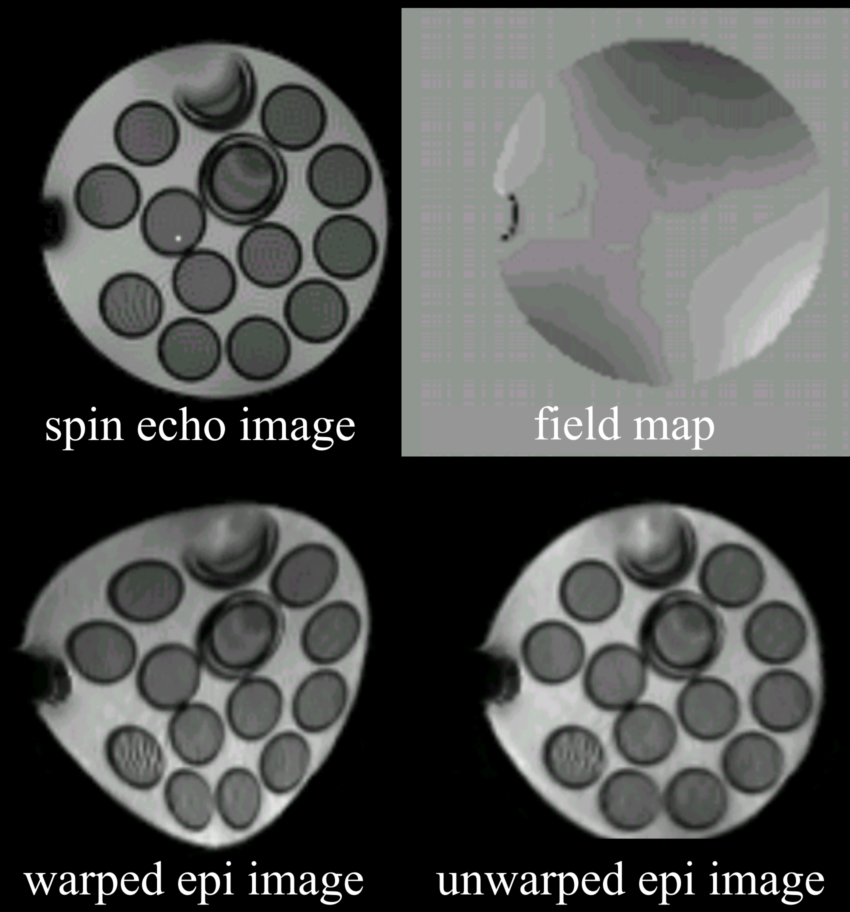
Chemical Shift Artifact (spiral imaging example)







Geometric Distortions



Jezzard and Balaban, MRM 34:65-73 1995

Geometric Distortion

- Caused by Bad "shim" and/or non-linear gradients.
  - The gradient you want is not always the gradient you get.

- Solutions:
  1. Correct using field maps.
     1. Measure B_0 map
     2. calculate how much extra phase is due to the inhomogeneity,
     3. remove "bad" phase from data (not easy)
  2. correct by warping the image to match an undistorted one

(NB – These work to a point. Sometimes you can't separate signals that have been pushed together by the artifact:

You can't recover signal from voxels where all the signal is gone completely)

Distortions are usually "errors" or unexpected terms in the Signal Equation

$$S(t) = \int m(x,y,z) e^{i2\pi(k_x(t)x + k_y(t)y + k_z(t)z)} dx \cdot dy \cdot dz$$

$$k_x(t) = \frac{\gamma}{2\pi}\int_o^t G_x(\tau)d\tau \quad + \text{junk}$$

$$k_y(t) = \frac{\gamma}{2\pi}\int_o^t G_y(\tau)d\tau \quad + \text{junk}$$

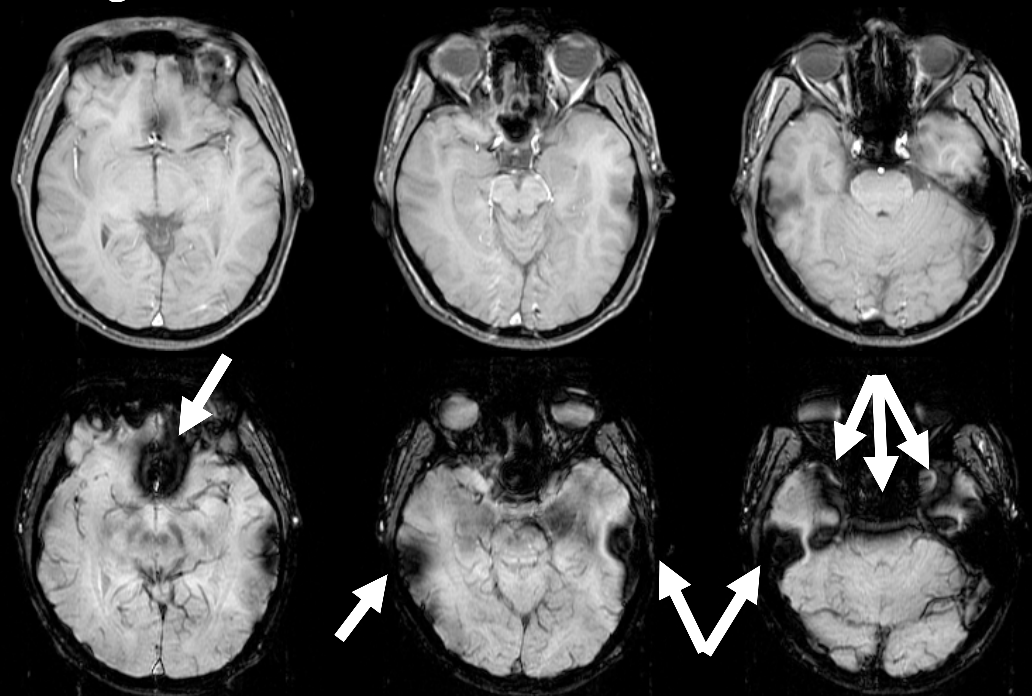
$$k_z(t) = \frac{\gamma}{2\pi}\int_o^t G_z(\tau)d\tau \quad + \text{junk}$$

Susceptibility Artifacts

- Off-resonance artifacts caused by adjacent regions with different magnetic Susceptibility
- **BOLD** signal requires susceptibility weighting… but this also leads to image artifacts

No Susceptibility Contrast

High Susceptibility Contrast



Hernandez-Garcia, UM FMRI course

courtesy of Douglas Noll

Magnetic Susceptibility

- Amount of Magnetization of a material produced in response to a magnetic field

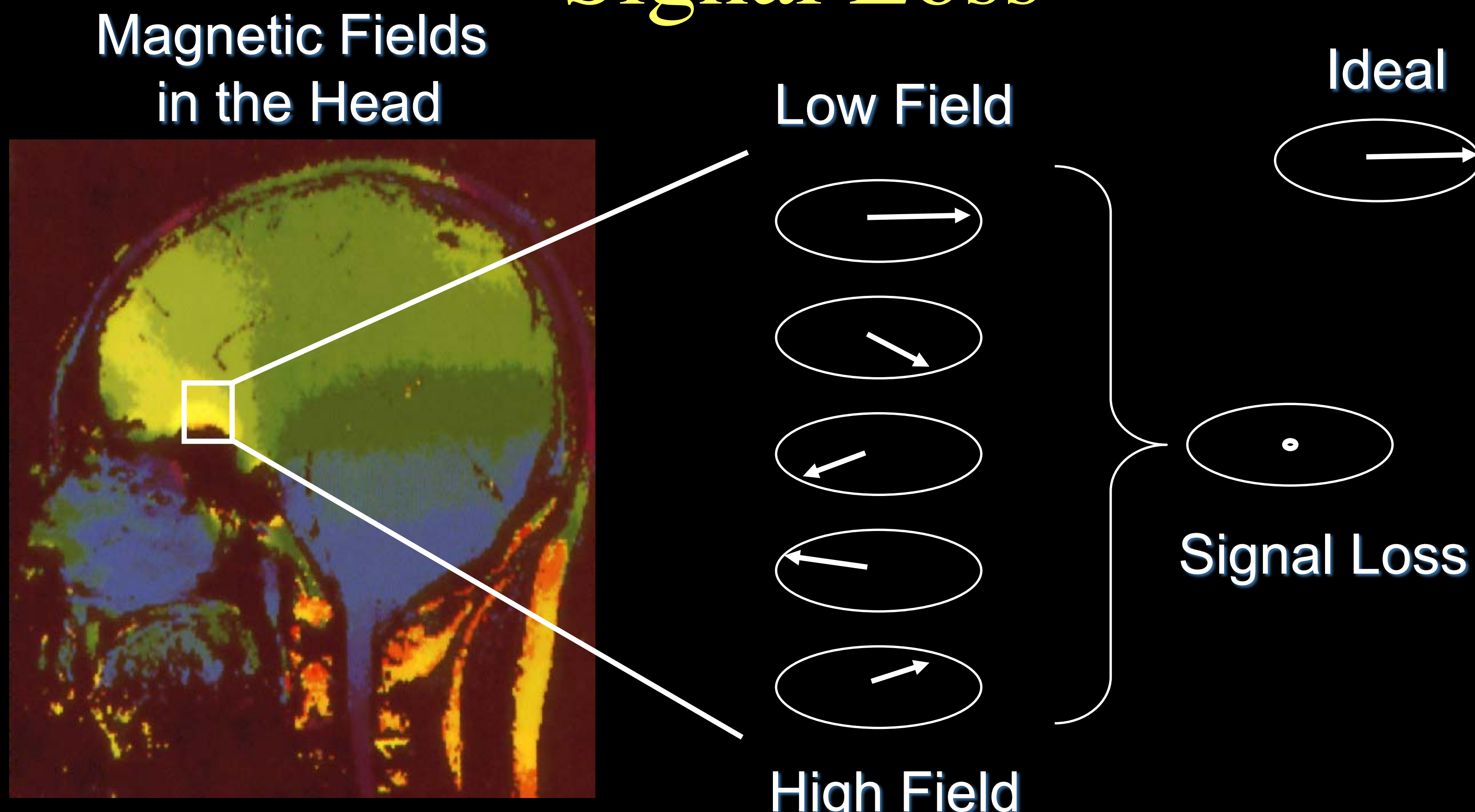
$$M = \chi H$$

- Field gets distorted by this magnetization

$$B = \mu_0 H + \chi \mu_0 H$$

- Gets worse with higher field scanners!

Susceptibility can produce Signal Loss



Li et al. Magn. Reson. Med. 36:710 (1996)

courtesy of Douglas Noll

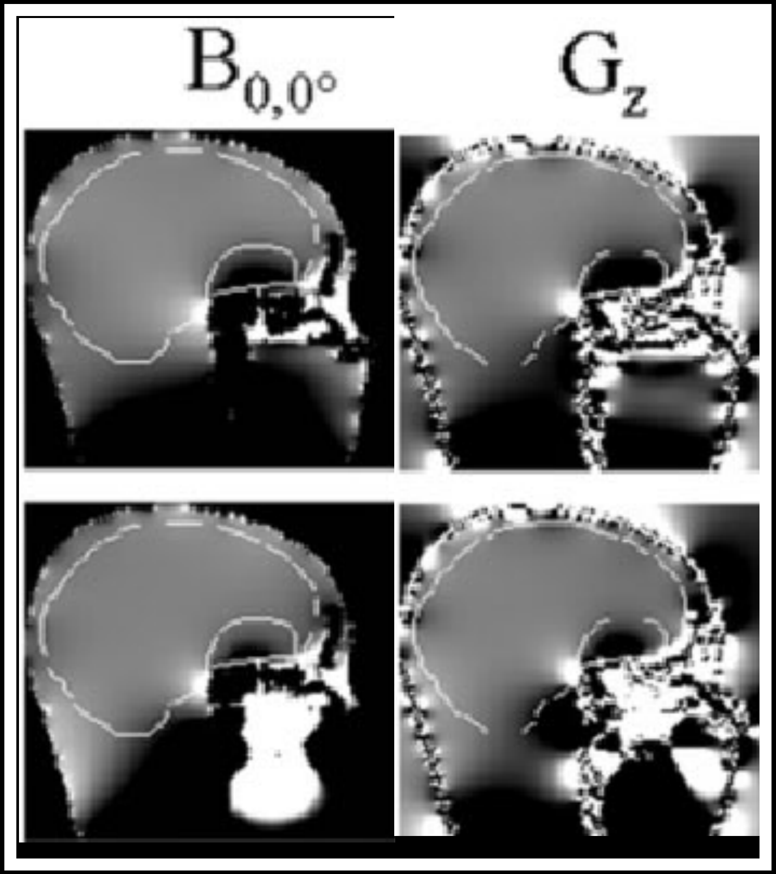
Susceptibility Artifacts

- Local gradients Challenges:
  - If severe: Lots of different phases within a voxel. Result is destructive interference: signal loss.
  - If they are more gentle: skewing of the k-space trajectory in different voxels)
- Solutions: Lots of tricks you can do, to fix it, but they all have an associated cost in time, SNR, computation, hardware ...
  - Choose acquisition parameters such that the artifacts are minimized … simplest, usually best!
  - Parallel imaging
  - Z-shimming, active shims
  - Forward-model, iterative reconstructions

Intra-oral Diamagnetic Shims

- Shimming by 1st, 2nd and 3rd order shims provides only modest field correction

- Magnetic field can be made more uniform through the use of intraoral shims made of diamagnetic materials



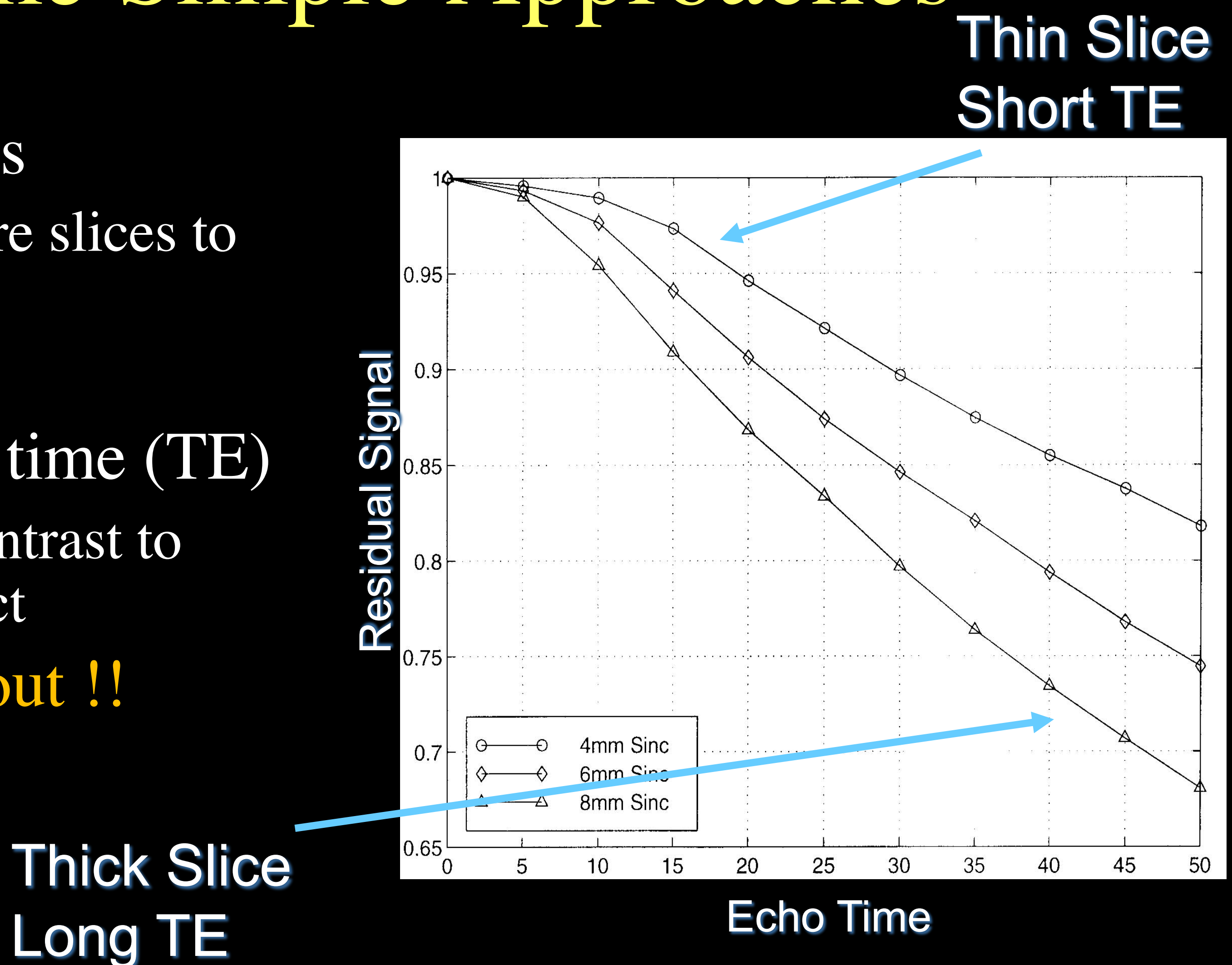
(Wilson & Jezzard P *MRM* 50:1089-94, 2003)

Why are some images affected by off-resonance, but not others?

- Spin Echoes refocus spins that get out of phase
- Gradient Echoes do not
- Major factors:
  - How much time you allow the effect to accumulate – echo times, readout time
  - How much variation in the magnetic field within the excited volume – slice thickness, shim

Some Simple Approaches

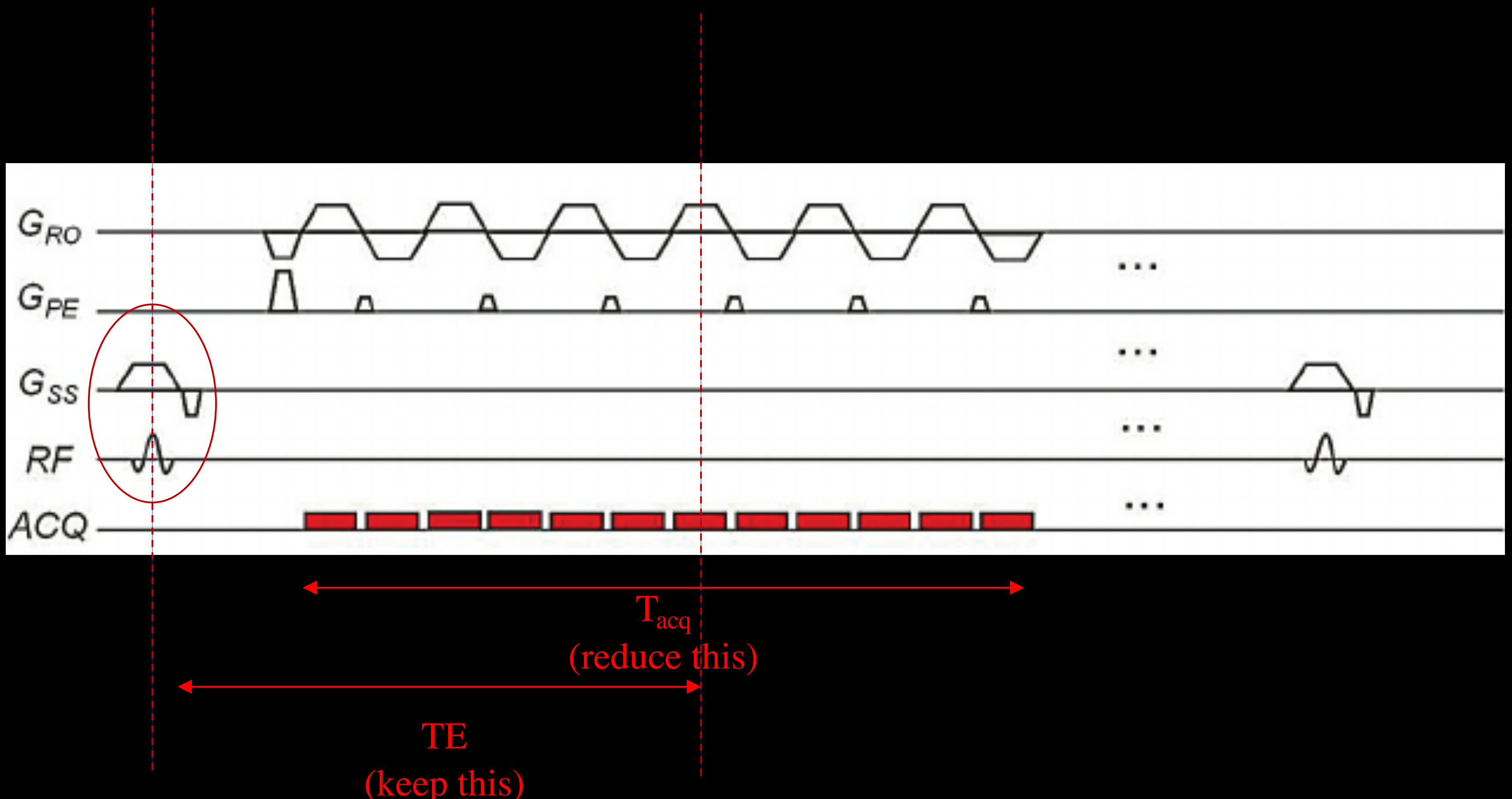
- Thinner slices
  - Slower, more slices to cover head
  - Lower SNR
- Shorter echo time (TE)
  - Reduced contrast to BOLD effect
- Shorter readout !!



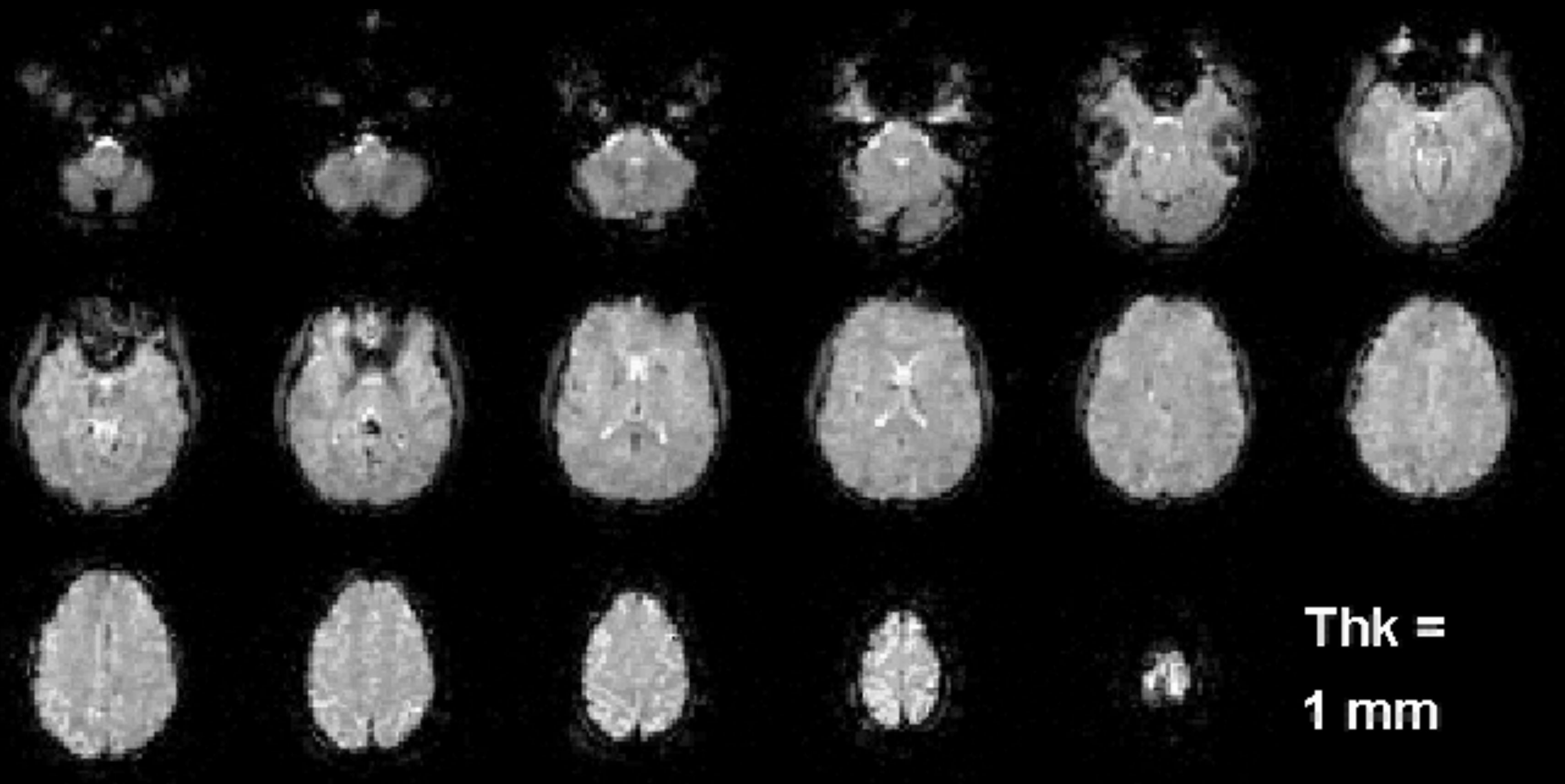
Hernandez-Garcia, UM FMRI course

courtesy of Douglas Noll

EPI pulse sequence



Signal Loss vs. Slice Thickness
(movie)

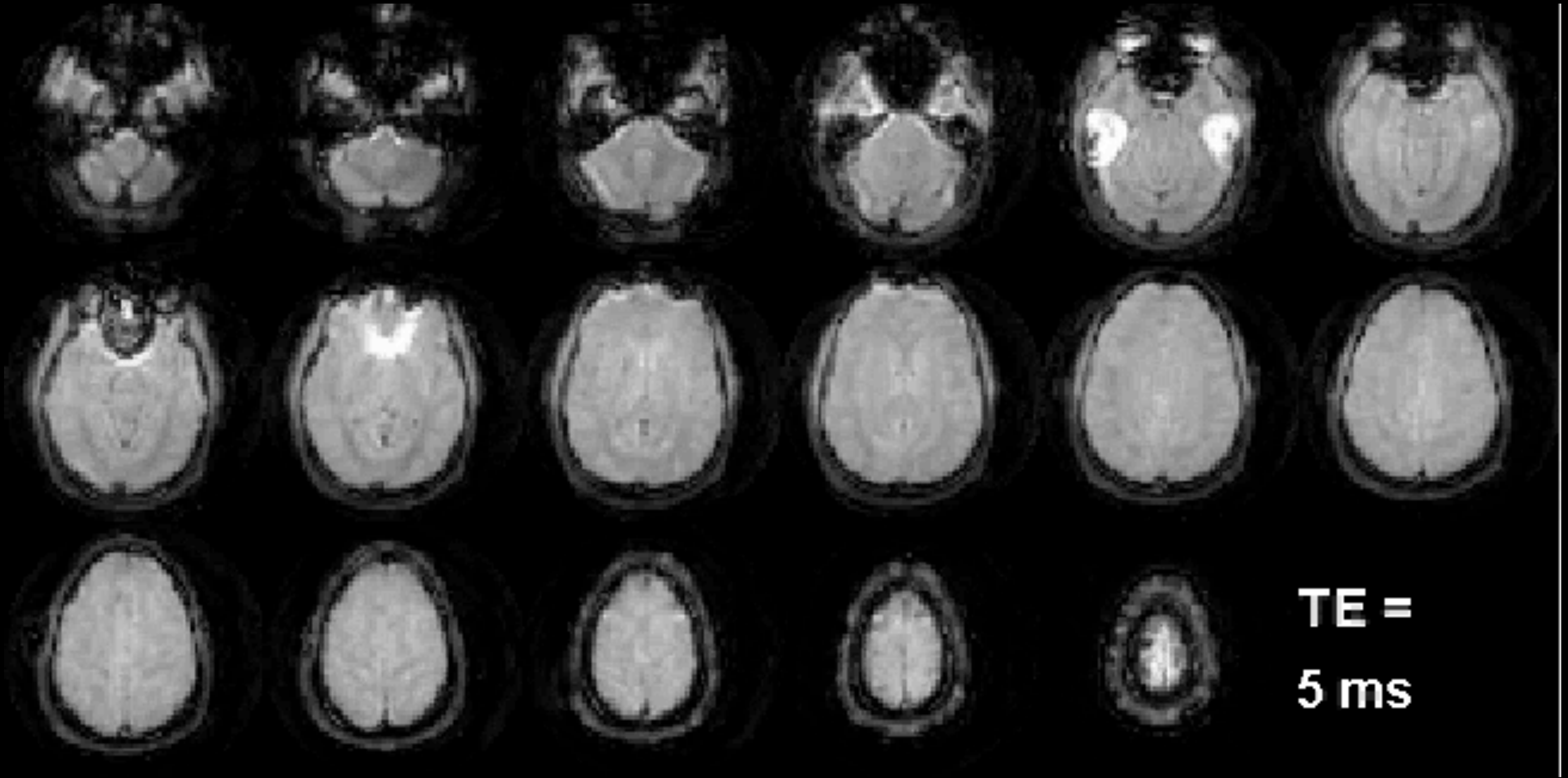


TE = 25 ms, 20 ms Single-Shot Spiral Acquisition

Hernandez-Garcia, UM FMRI course

courtesy of Douglas Noll

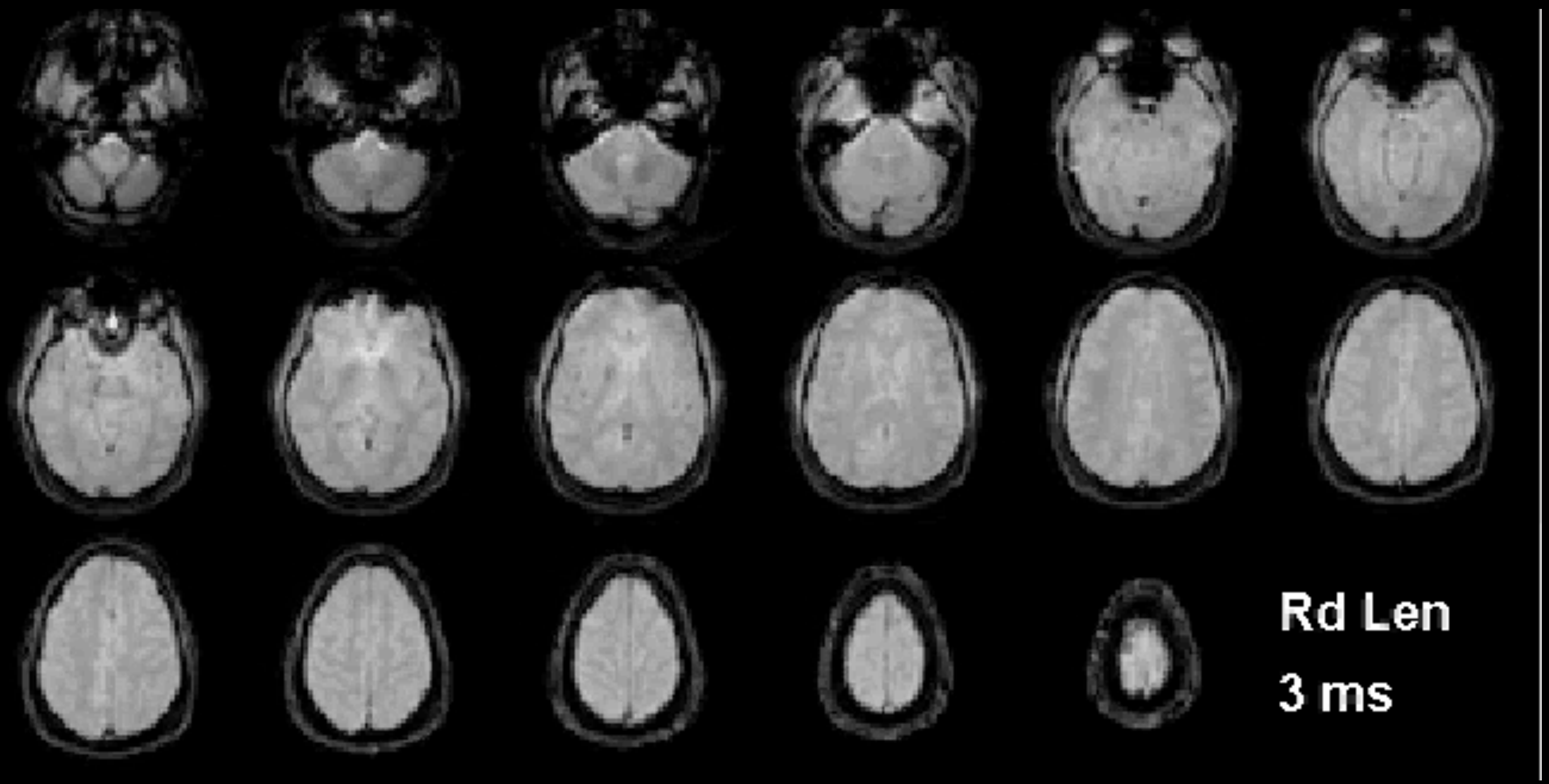
Signal Loss vs. TE (movie)



Thickness = 4 mm, 20 ms Single-Shot Spiral Acquisition

courtesy of Douglas Noll

Susceptibility Distortions from Long Readouts (movie)



TE = 10 ms, Thickness = 4 mm, Spiral Acquisition

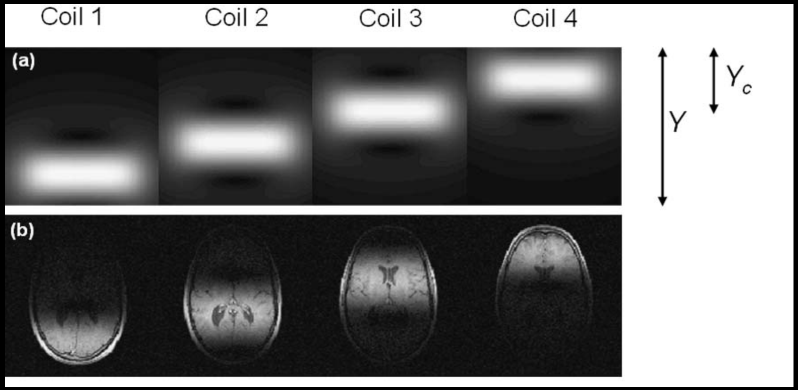
courtesy of Douglas Noll

Reducing Readout Length

- Hardware limits: we can only go so fast!
  - Gradient strength limited by peripheral nerve stimulation
  - Head gradients would be one approach
  - … but there are still hardware limits!
- Parallel imaging (e.g. SENSE) can reduce readout duration
  - More coils collecting less data per coil.
  - How much data can we skip, and calculate from coil sensitivity?
- Compressed sensing
  - How much data can we skip, and calculate from prior information?

Parallel Imaging

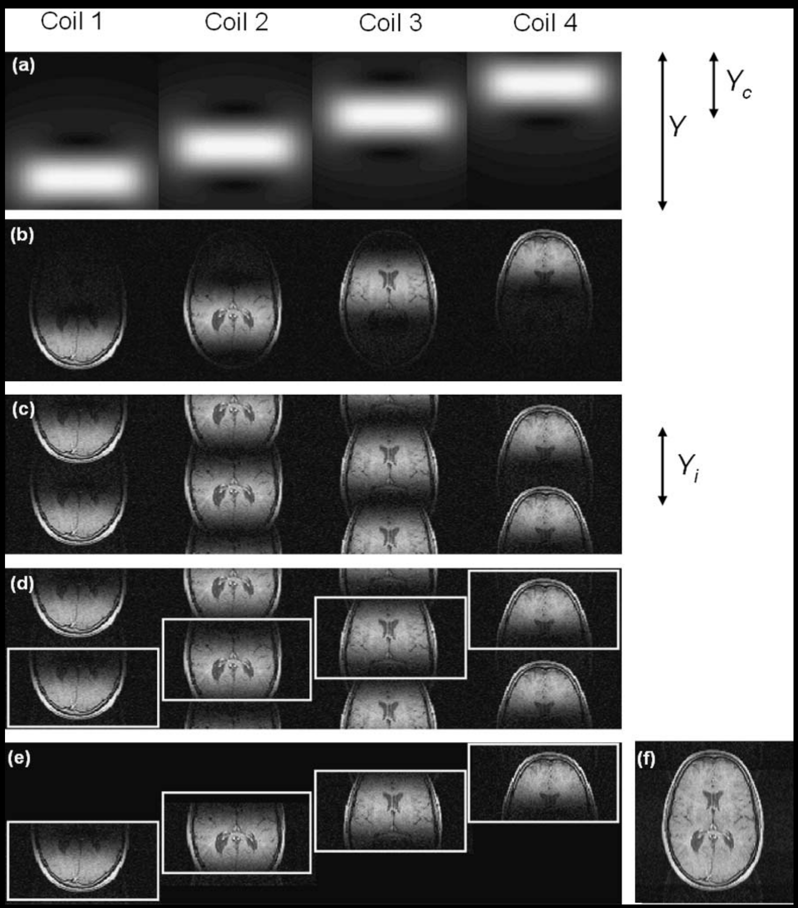
(see Blaimer et al " Topics in MRI, 15, 4, 2004" for review article)



PILS

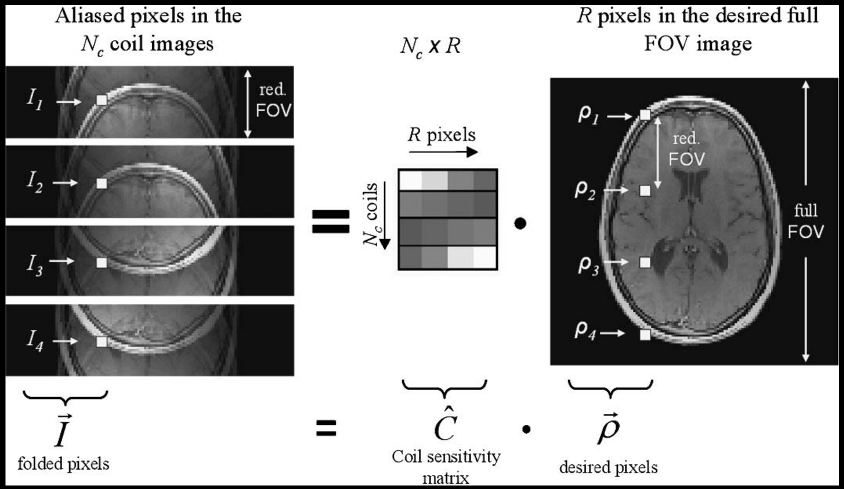
Parallel Imaging

(see Blaimer et al " Topics in MRI, 15, 4, 2004" for review article)



PILS

SENSE



$$C^{-1}I = \rho$$

GeneRalized Autocalibrating Partially Parallel Acquisitions (GRAPPA)

Mark A. Griswold,[1*] Peter M. Jakob,[1] Robin M. Heidemann,[1] Mathias Nittka,[2] Vladimir Jellus,[2] Jianmin Wang,[2] Berthold Kiefer,[2] and Axel Haas

1. Collect undersampled image time series with multiple coils.

2. Collect **some** of the missing data (just once).

3. Calculate interpolation kernel using the multi-coil fully sampled data

4. Interpolate the missing k-space data from the existing data and the interpolation kernel

Deshmane, Anagha & Gulani, Vikas & Griswold, Mark & Seiberlich, Nicole. (2012). Parallel MR imaging. Journal of magnetic resonance imaging : JMRI. 36. 55-72. 10.1002/jmri.23639.

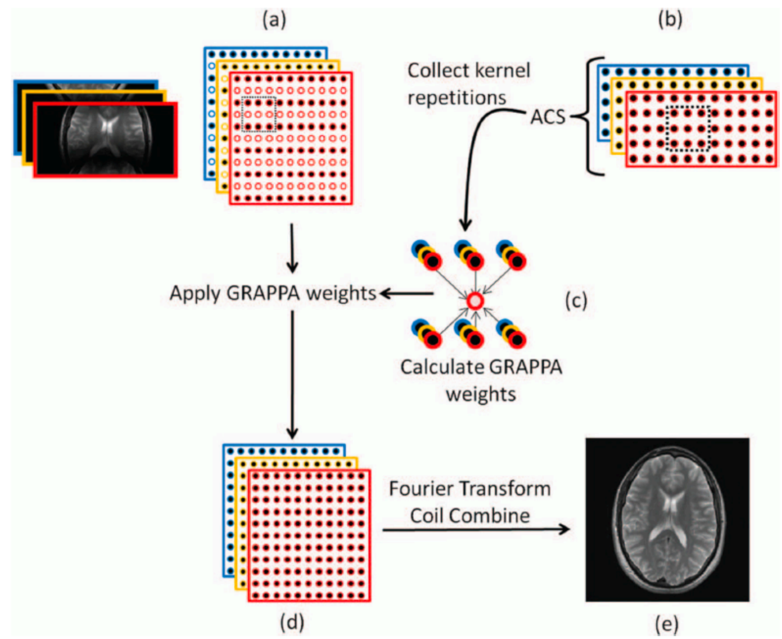
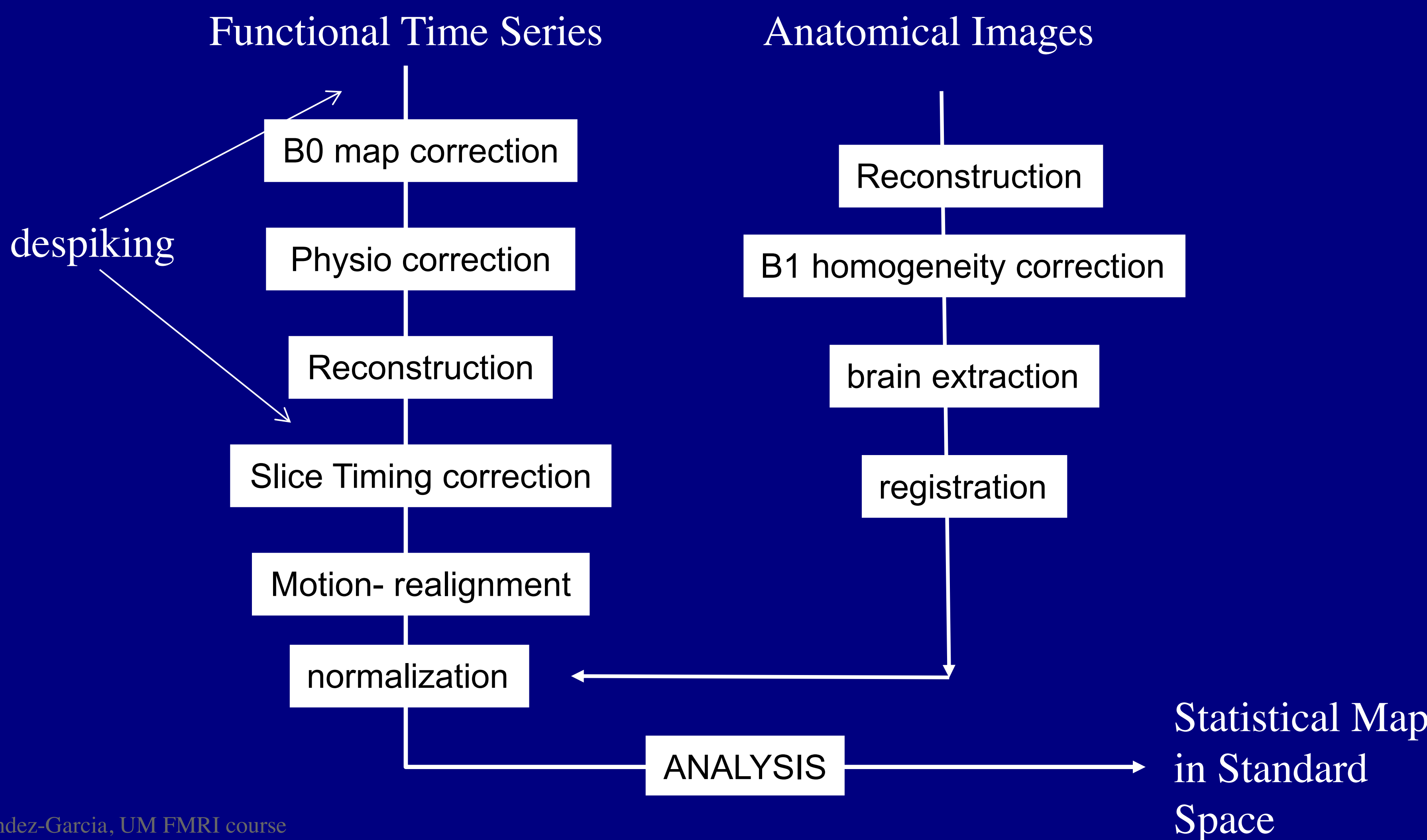


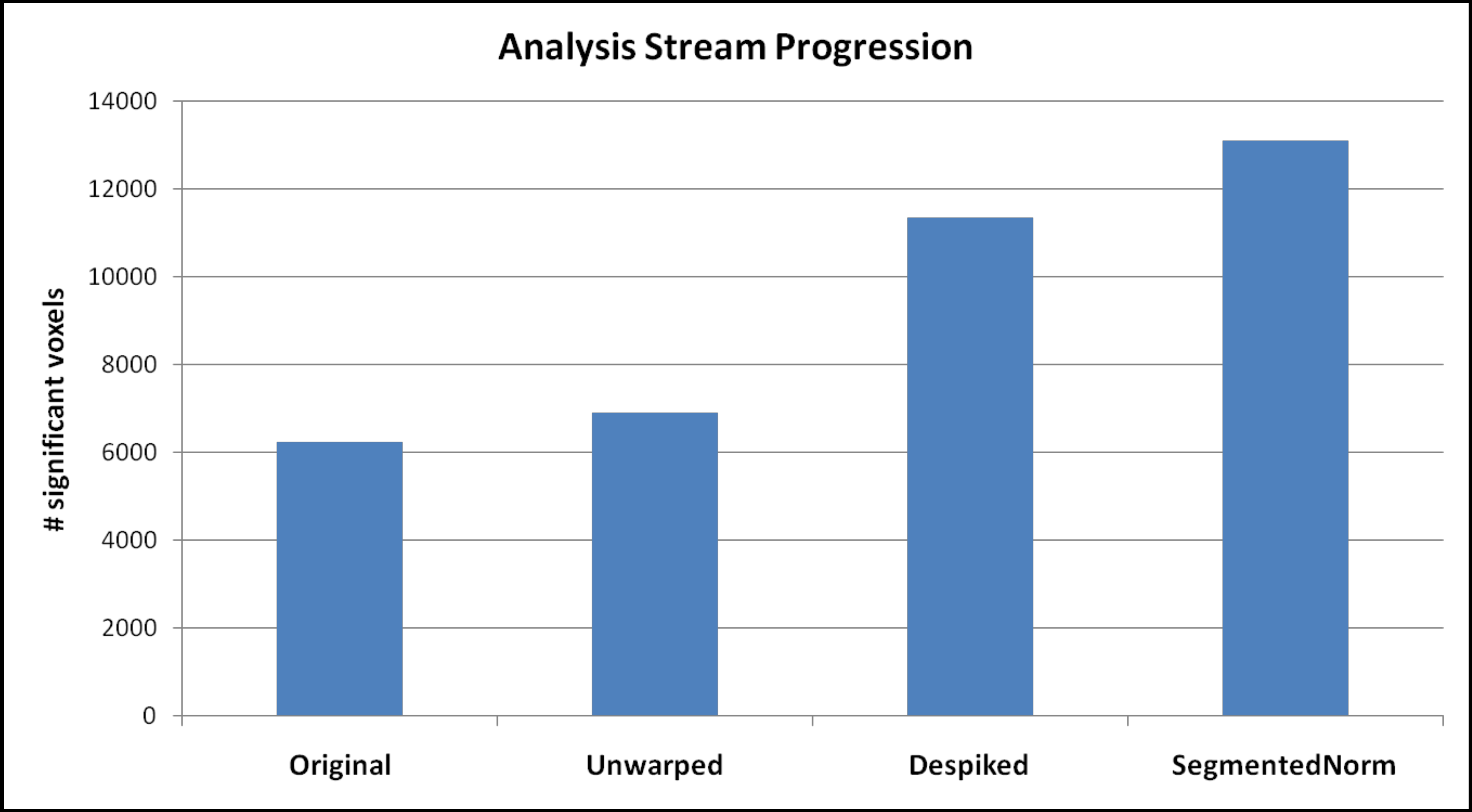
Figure 9.

a: Undersampled *k*-space data are collected from each coil, where the different coils are shown with different colors. The kernel (outlined by the dotted black box) consisting of some source points (solid circles) and target points (empty circles) defines the neighborhood of *k*-space points that will be used for the GRAPPA reconstruction. **b:** Additional data (auto-calibration signals, or ACS) are collected, usually near the center of *k*-space. **c:** The repetitions of the kernel through the ACS region are used to calculate the GRAPPA weights. **d:** The GRAPPA weights are then applied to fill in the missing *k*-space data from each coil to produce fully sampled single-coil data. e: The Fourier transform is used to obtain single-coil images, which are then combined to form a reconstructed full-FOV image. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Putting it all together :



How important is pre-processing?



Hernandez-Garcia, UM FMRI course

Courtesy of Derek Nee

Appendix ...

Local interpolation (use a few neighbors at a time)

- Multiplication in frequency = Convolution in time
- Instead of the Frequency domain phase shift, calculate a **weighted average** of a few neighbors neighbors
  - Weights are determined by the **sinc()** function
  - Prevents local errors from affecting the whole time series
  - Can be faster
  - Can build filters onto the sinc function.
- Drawbacks:
  - ringing artifacts if not enough points are used,
  - Too slow if too many points are used in window.

Does it matter how we interpolate?

- Alternatives to the sinc() function:
  - Nearest Neighbor
  - Linear , Bilinear, Trilinear …Polynomial
- They can all be shown to be some sort of weighted average : a convolution with a different kernel … different properties
- They are all approximations based on some assumptions about the function. Sinc is most accurate as long as enough data are used.
- These concepts also apply to image interpolation, resampling, etc.

"Localized" interpolation: the long version

The digitized signal in frequency domain

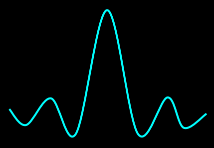
$F(\omega)\ e^{-i\omega\tau}$ $rect(\omega)$

$rect(\omega)$

The signal in time domain

$f(\ t\ ) * sinc(t - \tau)$

$sinc(t) = sin(t)\ /t$



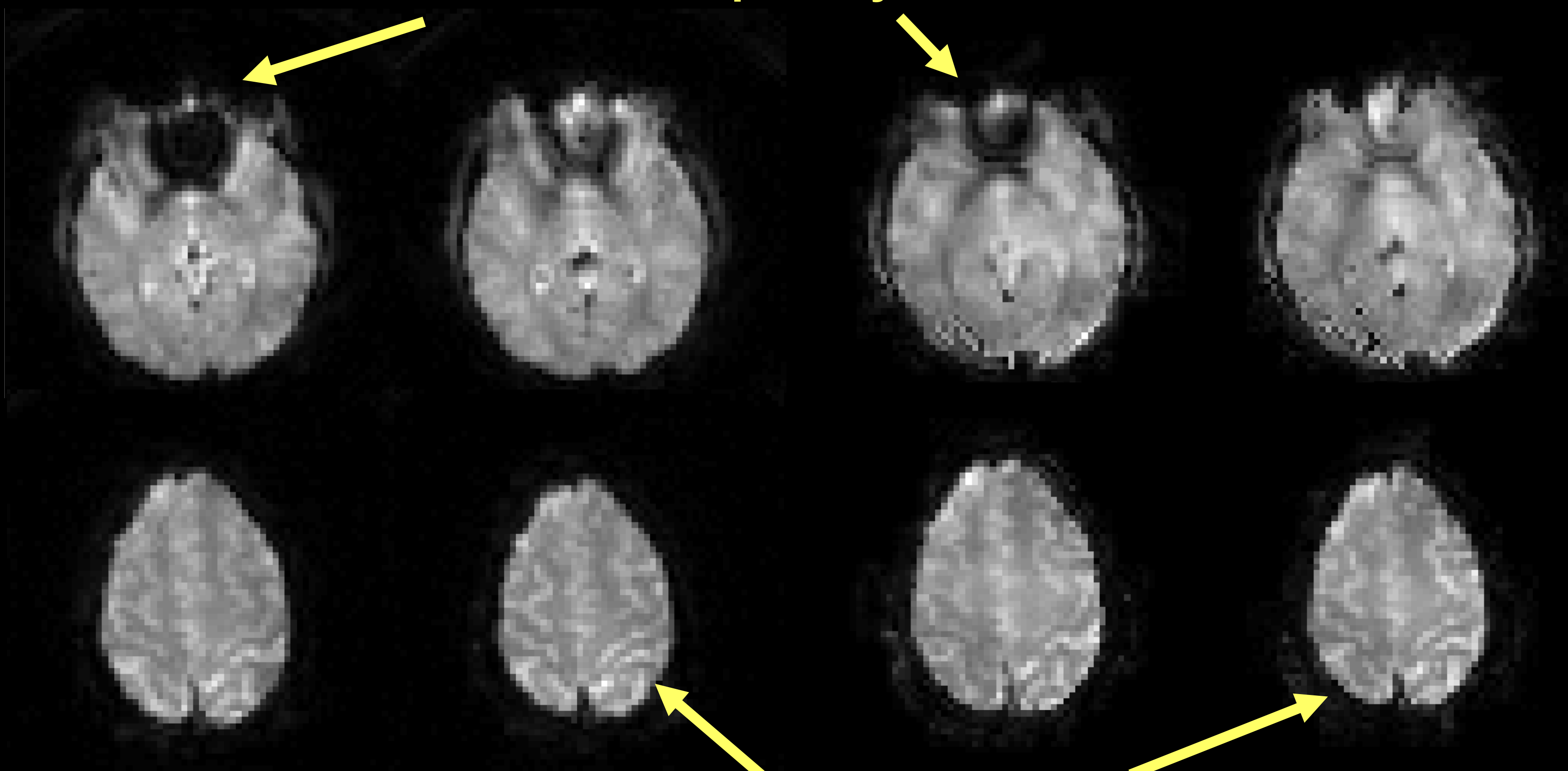
Convolution:

$f[n]*g[n] = \Sigma_k\ f[k]\ g[n-k]$

Spiral SENSE – Results

Head Coil **4-Channel SENSE Coil**

Reduced Susceptibility Artifact



Excellent Detail

courtesy of Douglas Noll