Putting the Fun into Functional MRI

Peter A. Bandettini, Ph.D.

Section on Functional Imaging Methods

http://fim.nimh.nih.gov

Laboratory of Brain and Cognition

&

Functional MRI Facility

http://fmrif.nimh.nih.gov

A brief overview of the three main types of fMRI contrast

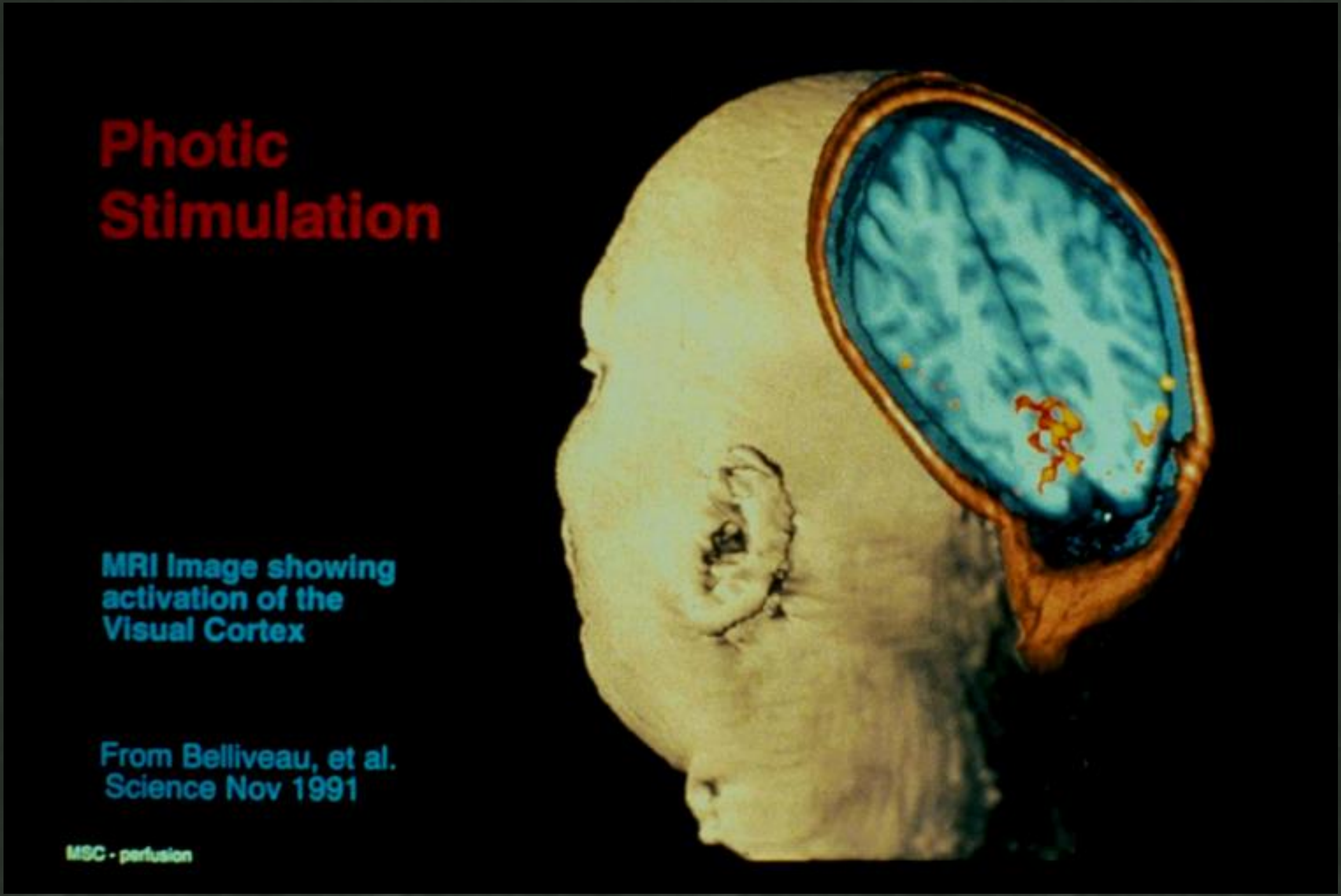
Volume

Flow or Perfusion

Oxygenation

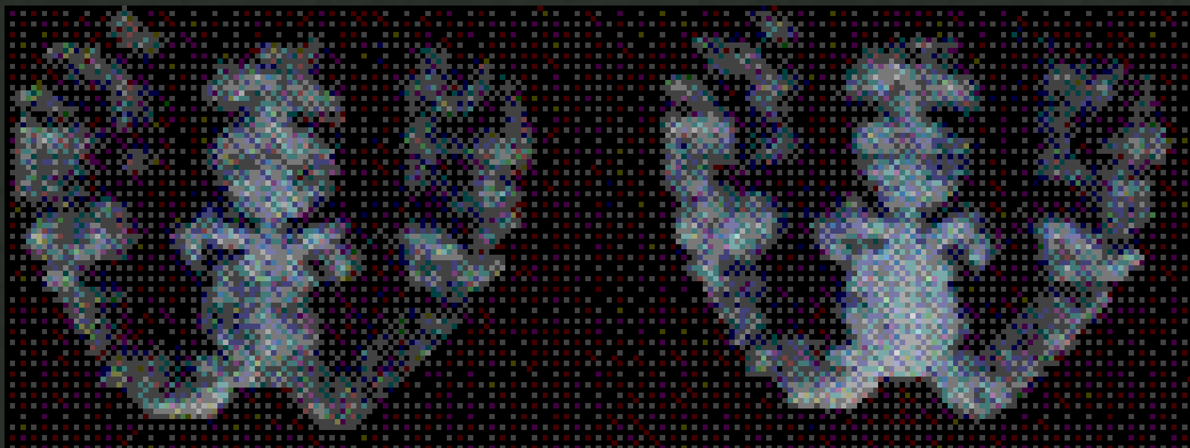
Blood Volume

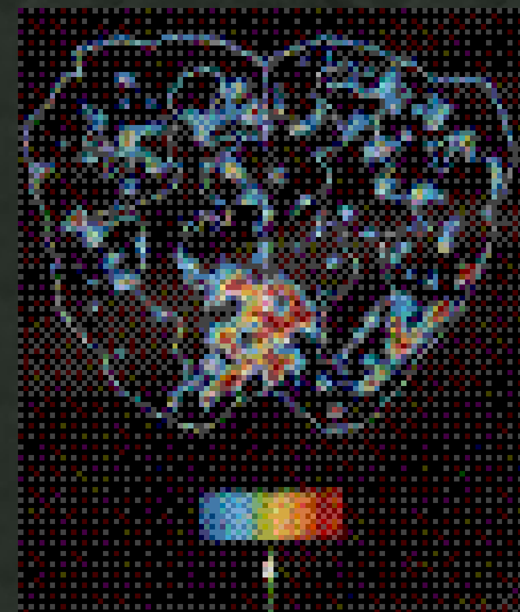
What started it all…



Blood Volume

Resting Active

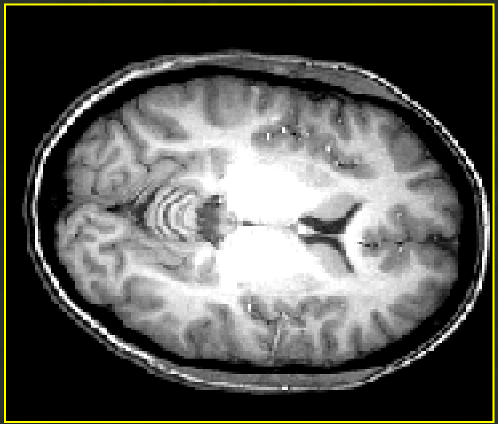




MRI vs. fMRI

MRI

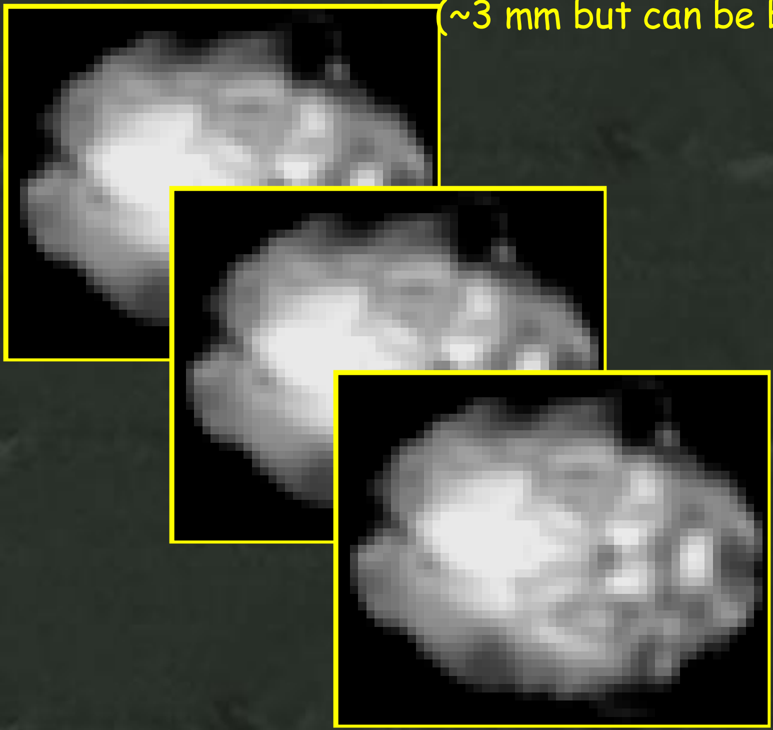
high resolution
(1 mm)



one image

fMRI

low resolution
(~3 mm but can be better)



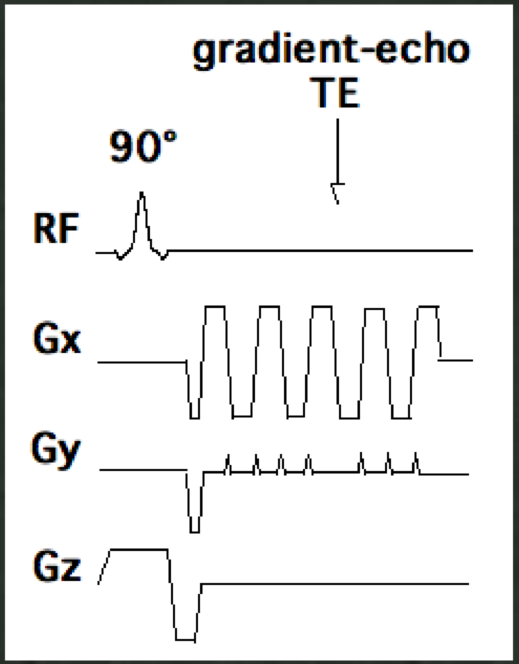
...

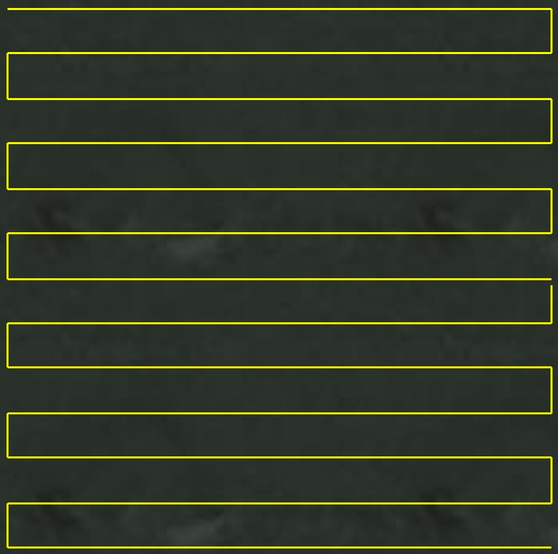
many images
(e.g., every 2 sec for 5 mins)

Single Shot Echo Planar Imaging (EPI)

EPI Readout Window

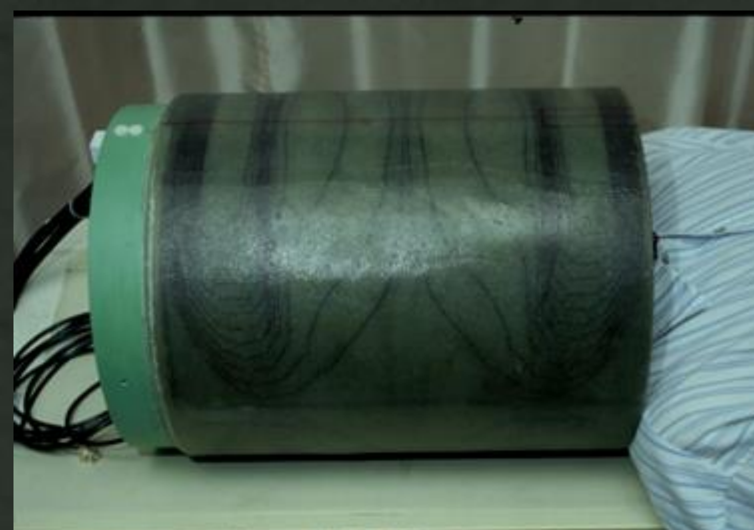
≈ 20 to 40 ms

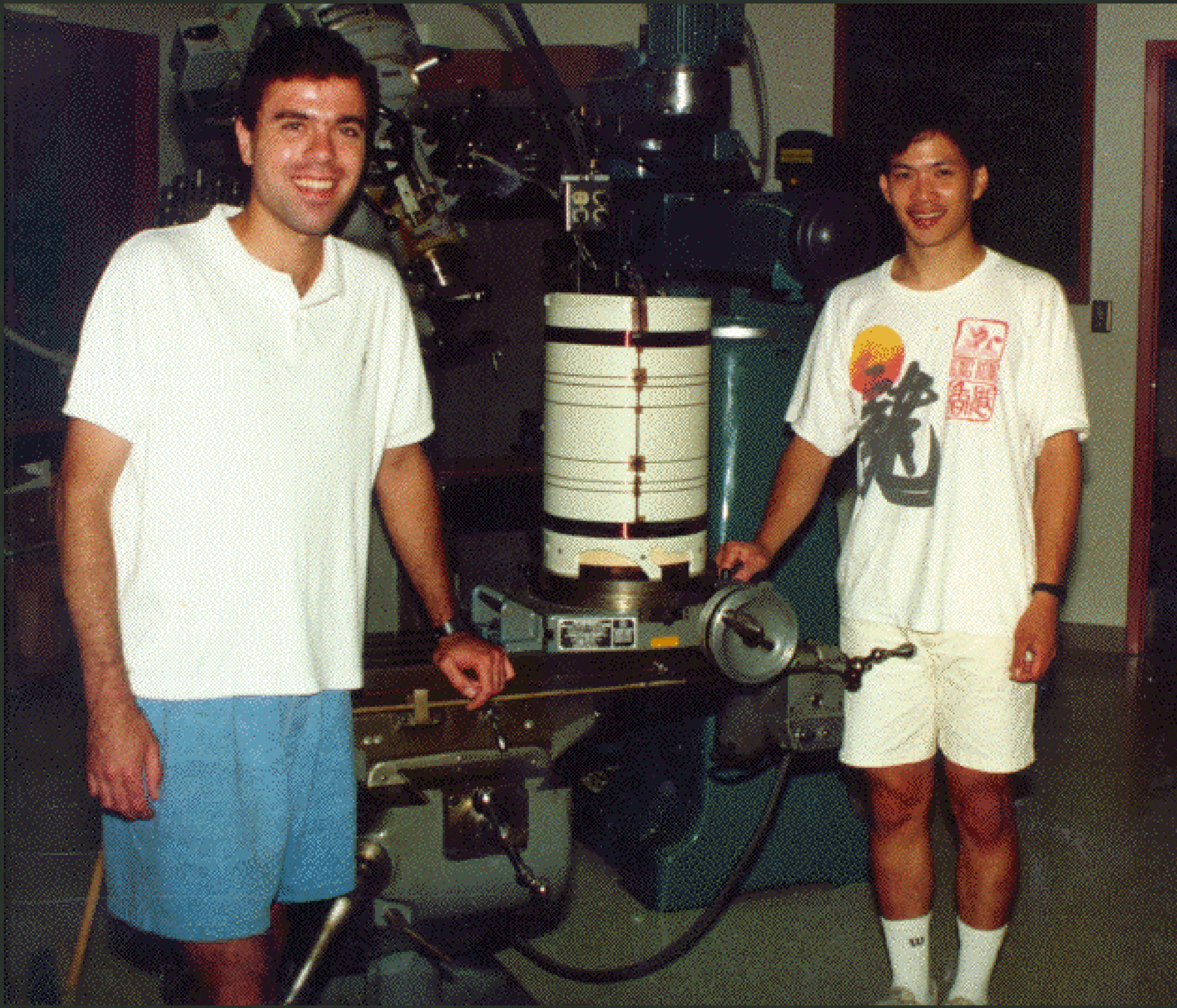




1991-1992

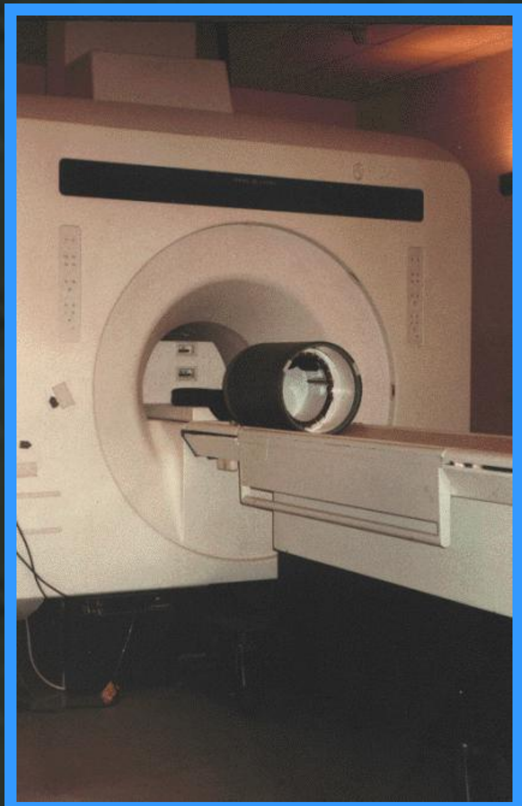
1992-1999

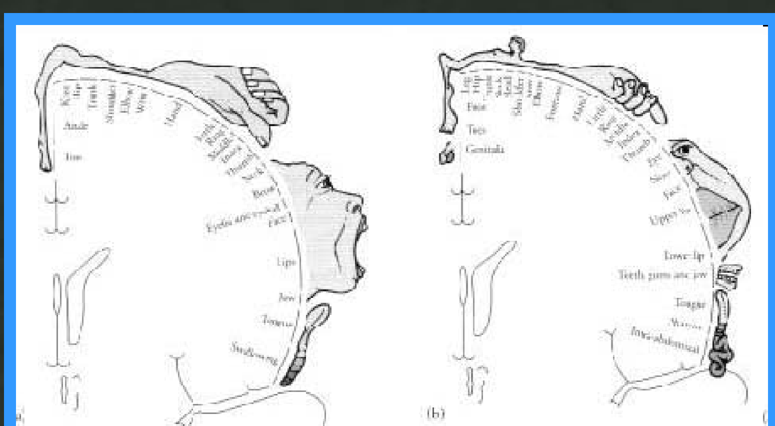


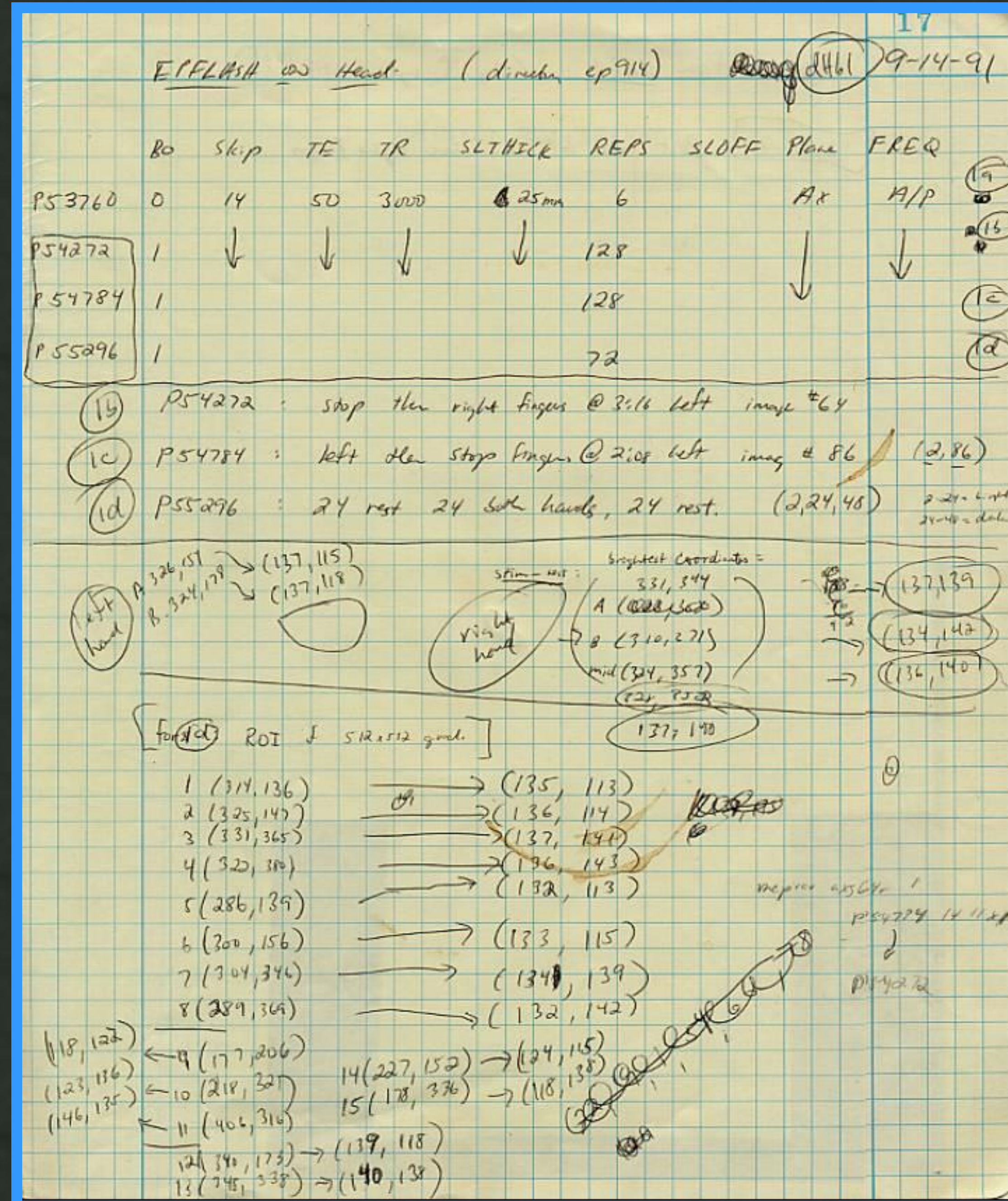


August, 1991

The fun early days of fMRI







EPFLASH ~~w~~ Head (directory ep914) d461 9-14-91

	Bo	Skip	TE	TR	SLTHICK	REPS	SLOFF	Plane	FREQ	
P53760	0	14	50	3000	25mm	6		Ax	A/P	1a
P54272	1	↓	↓	↓	↓	128		↓	↓	1b
P54784	1					128				1c
P55296	1					72				1d

1b P54272 : stop then right fingers @ 3:16 left image #64

1c P54784 : left then stops fingers @ 2:08 left imag # 86 (2,86)

1d P55296 : 24 rest 24 both hands, 24 rest. (2,24,48)

left hand A 326,151 → (137,115)
B 324,178 → (137,118)

Stim — Hit: right hand

Brightest Coordinates = 331,344
A (333,360)
B (310,271)
mid (324,357)
(137,140)

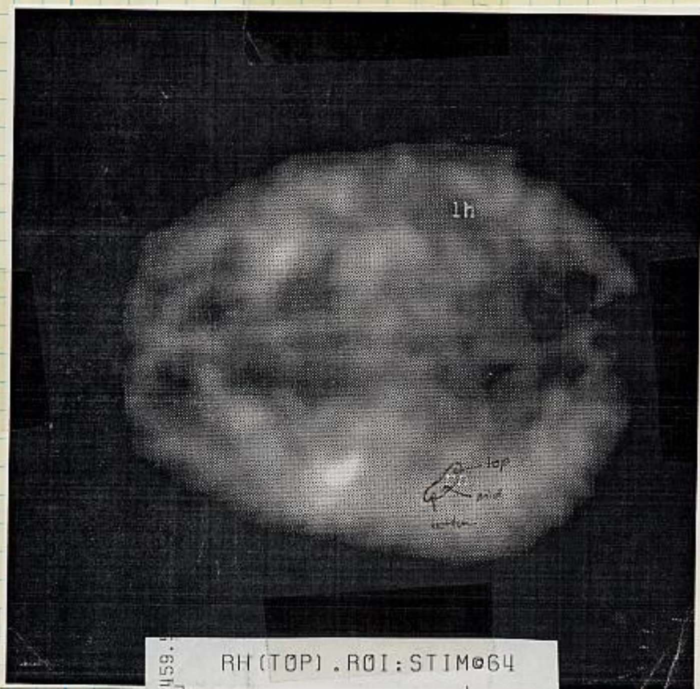
(137,139) (134,142) (136,140)

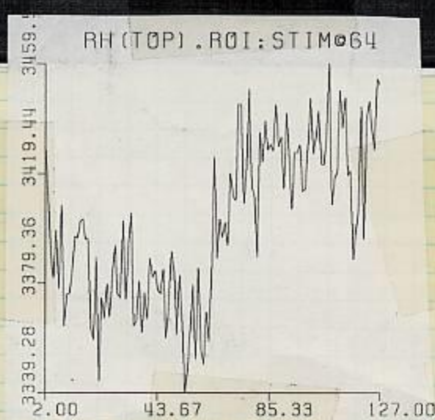
[for 1d ROI of 512x512 grid]

1 (314,136) → (135, 113)
2 (325,147) → (136, 114)
3 (331,365) → (137, 141)
4 (320,380) → (136, 143)
5 (286,139) → (132, 113)
6 (300,156) → (133, 115)
7 (304,346) → (134, 139)
8 (289,369) → (132, 142)
(118,122) ← 9 (177,206)
(123,136) ← 10 (218,327)
(146,135) ← 11 (406,316)
12 (340,173) → (139, 118)
13 (345,338) → (140, 138)
14 (227,152) → (124,115)
15 (178,336) → (118,138)

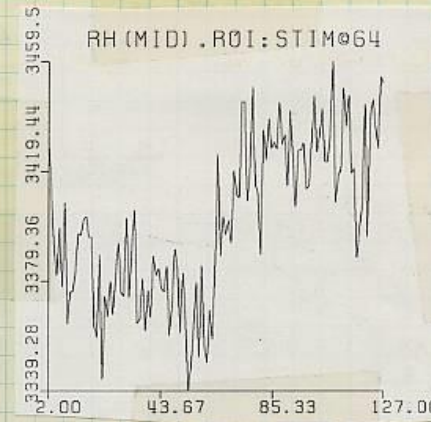
9-16-91 Results from dHb1 (sig ↑ upon stim?!!)

Experiment 1 Rest until 63 then move right fingers

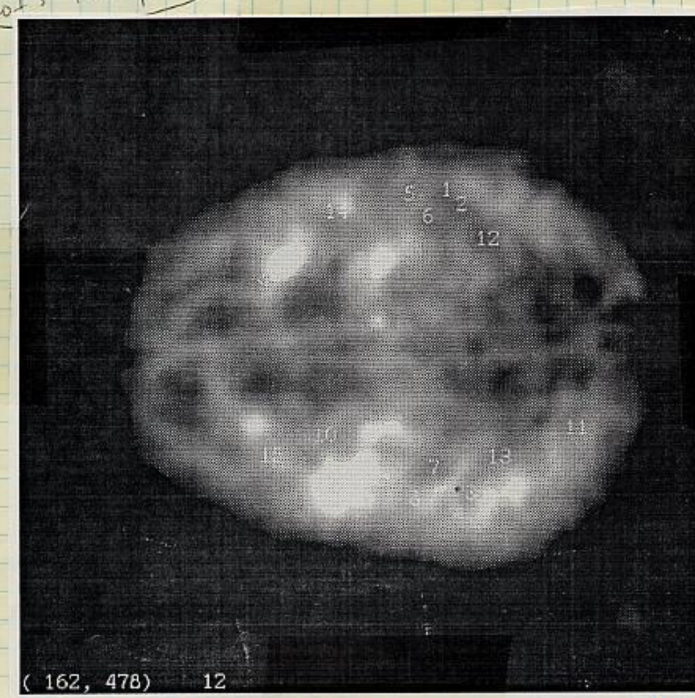




9-16-91



RoI's from p17



9-16-91

Finally, ~~a~~ difference image in which

the average of the first 64 images (no movement)
is subtracted from the last 64 images (movement of right hand.)

Right-Hand Movement

Axial

Thumb

Resolution.

20 cm / 64

.3125 cm

= 3.125 mm

15/20 1.5/2

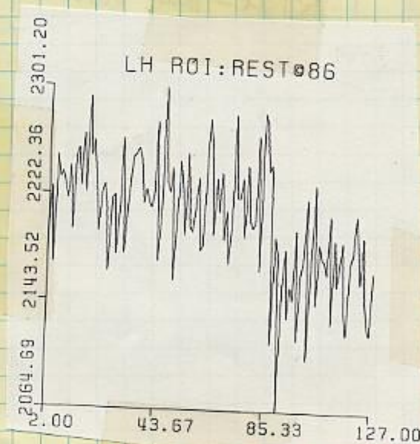
Brightest ~~spot~~ area is an indicator of largest signal increase when the ~~right~~ right hand was stimulated (fingers moved) → exactly corresponds to region of motor cortex and sensory and supplementary motor cortex as well that is associated with right hand movement.

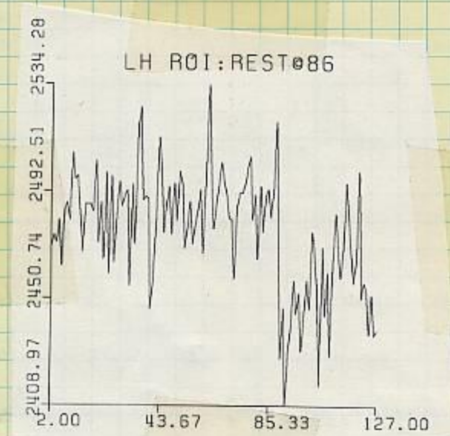
9-16-91

Results from experiment #2

Experiment #2 consisted of moving the left hand and then stopping the movement after 86 images.

LH ROI From p16

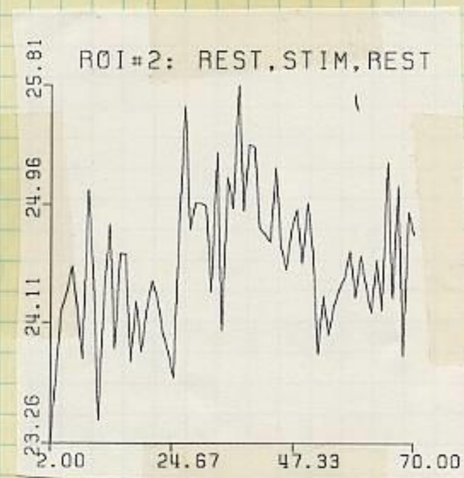




9-16-91

Experiment #3

Rest for 24 images, Move both hands for 24, then rest for 24.



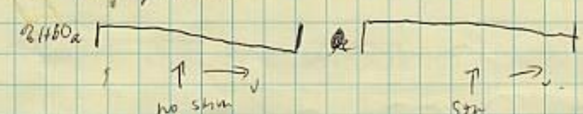
Rough Theory of What is going on here:

stim nerve tissue → move hand → ↑CO_2 ↑H^+ ↓O_2 in tissue → capillary and vein dilatation → ↑ Blood Flow → ↓% deoxy at steady state

↑ signal due to ↓ susceptibility

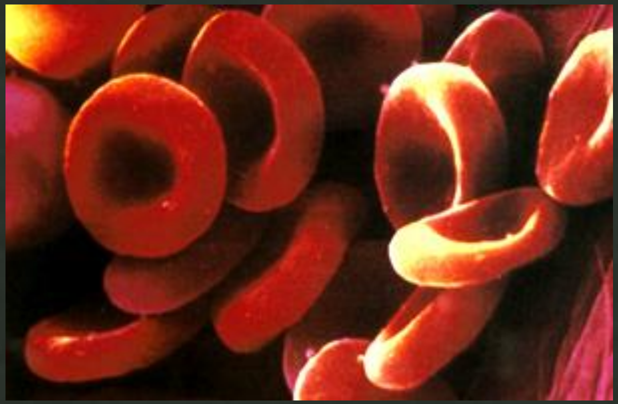
↑% deoxyHb at steady state ← decreased blood flow ← vaso constriction + cap. ← ↑O_2 ↓CO_2 ↓H^+ in tissue ← Stop stim

Question: Relationship between flow volume and bulk susceptibility in capillaries.



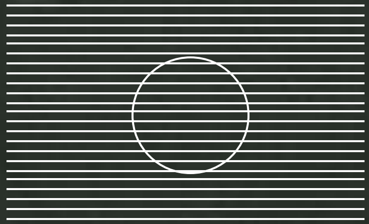
Blood Oxygenation

Oxygenated and deoxygenated red blood cells have different magnetic properties

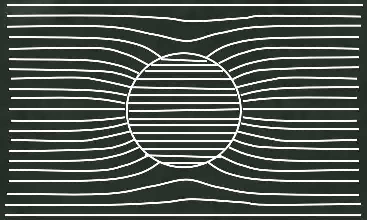


red blood cells

oxygenated



deoxygenated



L. Pauling, C. D. Coryell, *Proc.Natl. Acad. Sci. USA 22, 210-216*, **1936**.

K.R. Thulborn, J. C. Waterton, et al., *Biochim. Biophys. Acta. 714: 265-270*, **1982**.

S. Ogawa, T. M. Lee, A. R. Kay, D. W. Tank, *Proc. Natl. Acad. Sci. USA 87, 9868-9872*, **1990**.

Blood Oxygenation

Cerebral Tissue Activation

↓

Local Vasodilatation

↓

Increase in Cerebral Blood Flow and Volume → Oxygen Delivery Exceeds Metabolic Need

↓

Increase in Capillary and Venous Blood Oxygenation

↓

Decrease in Deoxy-hemoglobin

Deoxy-hemoglobin: paramagnetic
Oxy-hemoglobin: diamagnetic

↓

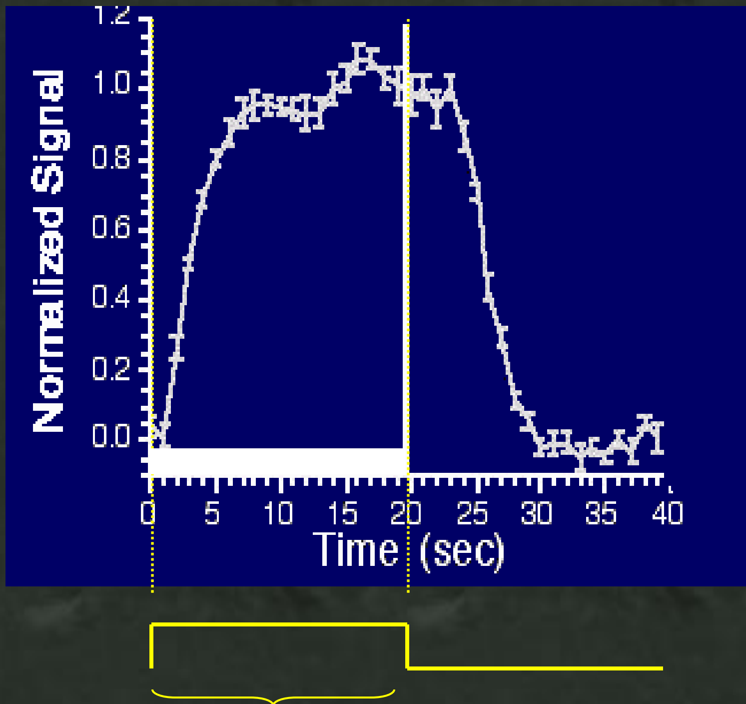
Decrease in susceptibility-related intravoxel dephasing → Increase in T2 and T2*

↓

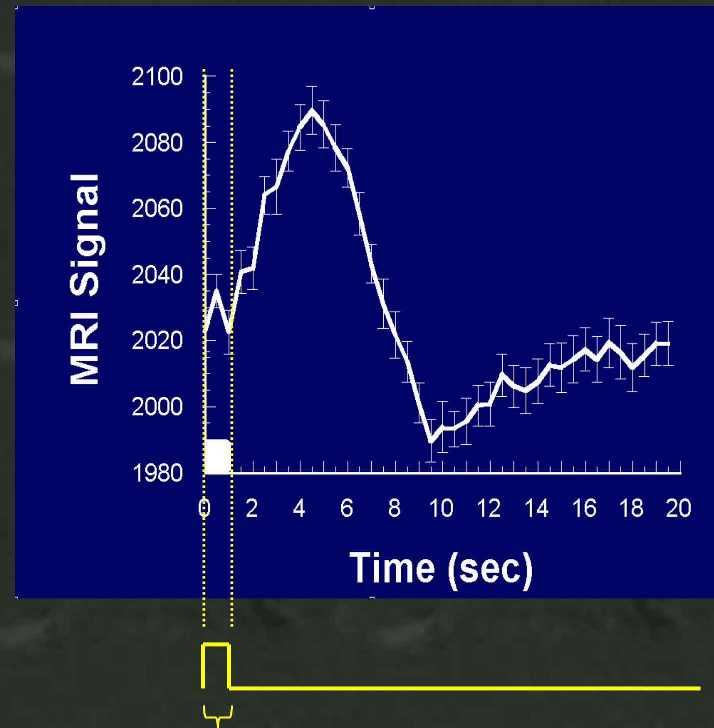
Local Signal Increase in T2 and T2* - weighted sequences

Blood Oxygenation

Blood Oxygenation



task



task

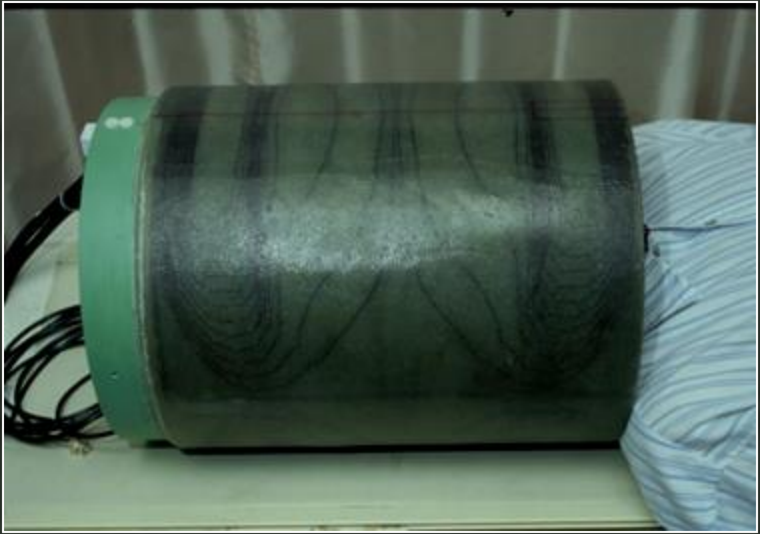
•K. K. Kwong, et al, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.

•S. Ogawa, et al., (1992) "Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proc. Natl. Acad. Sci. USA." 89, 5951-5955.

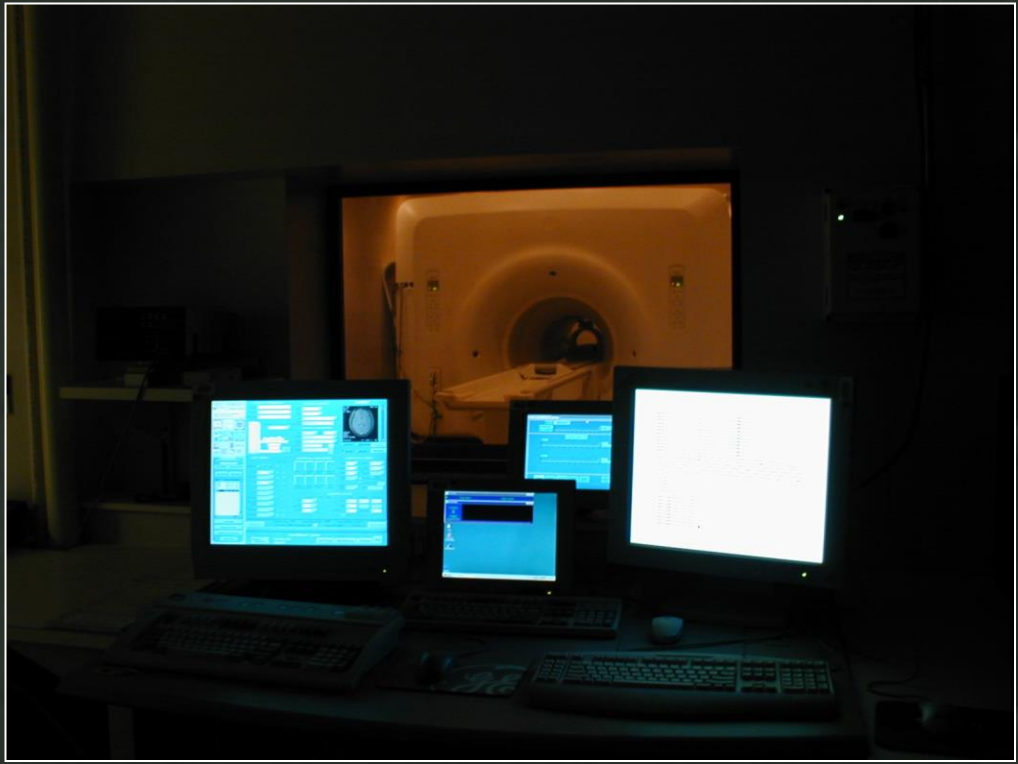
•P. A. Bandettini, et al., (1992) "Time course EPI of human brain function during task activation." Magn. Reson. Med 25, 390-397.

•Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

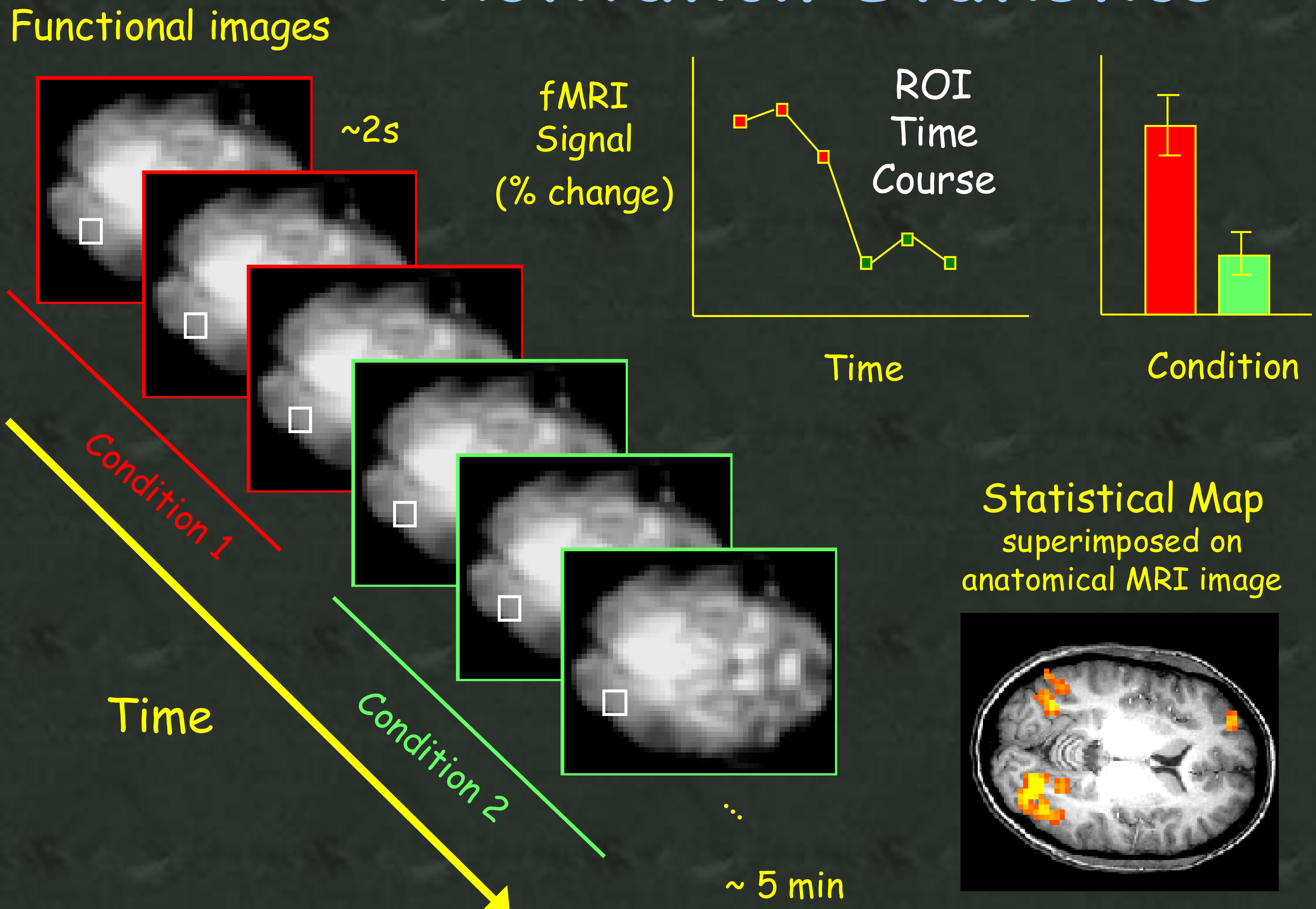
Local Gradient Coil
(low inductance)



Whole body gradients
(more powerful amplifiers)

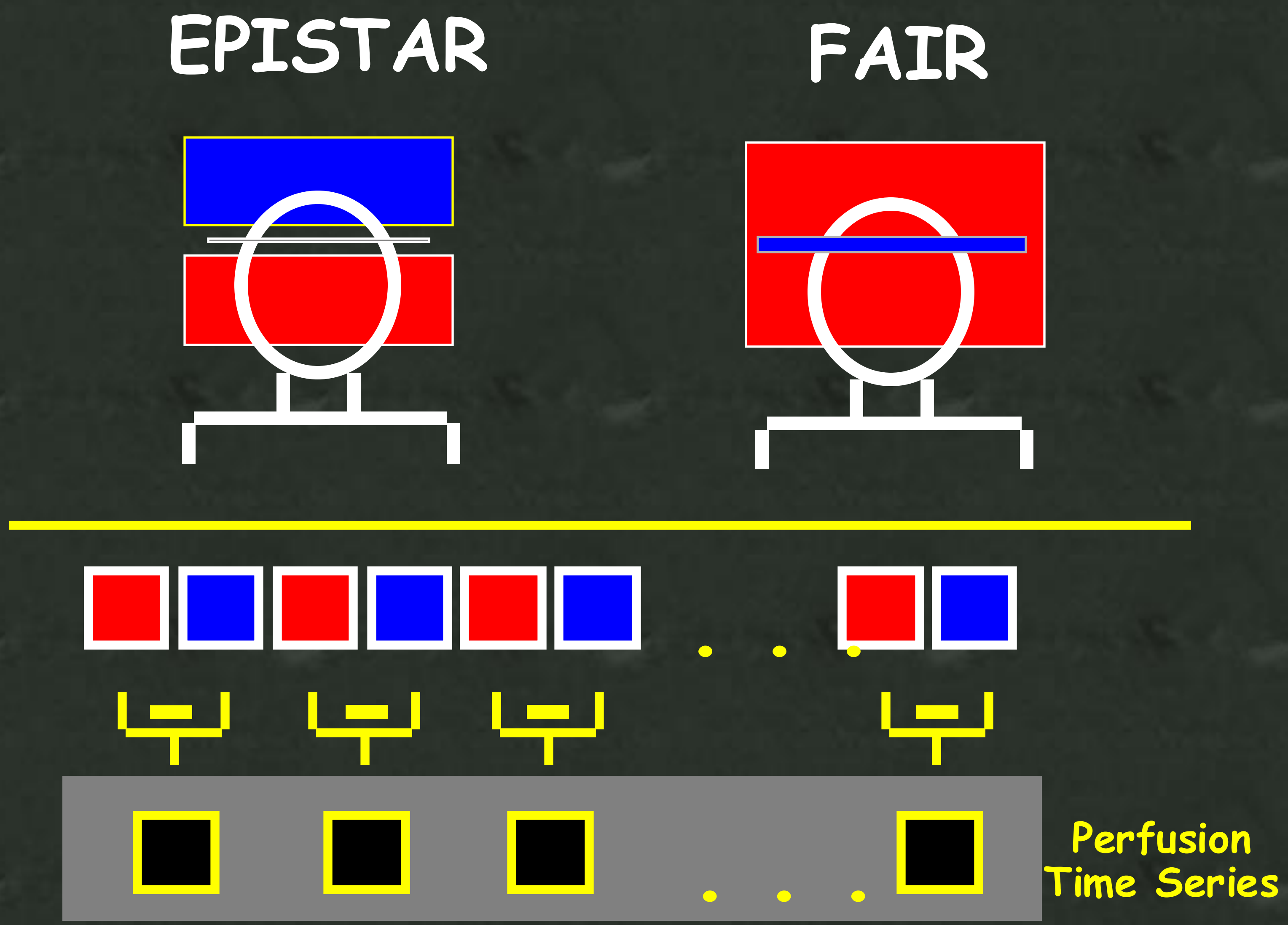


Activation Statistics

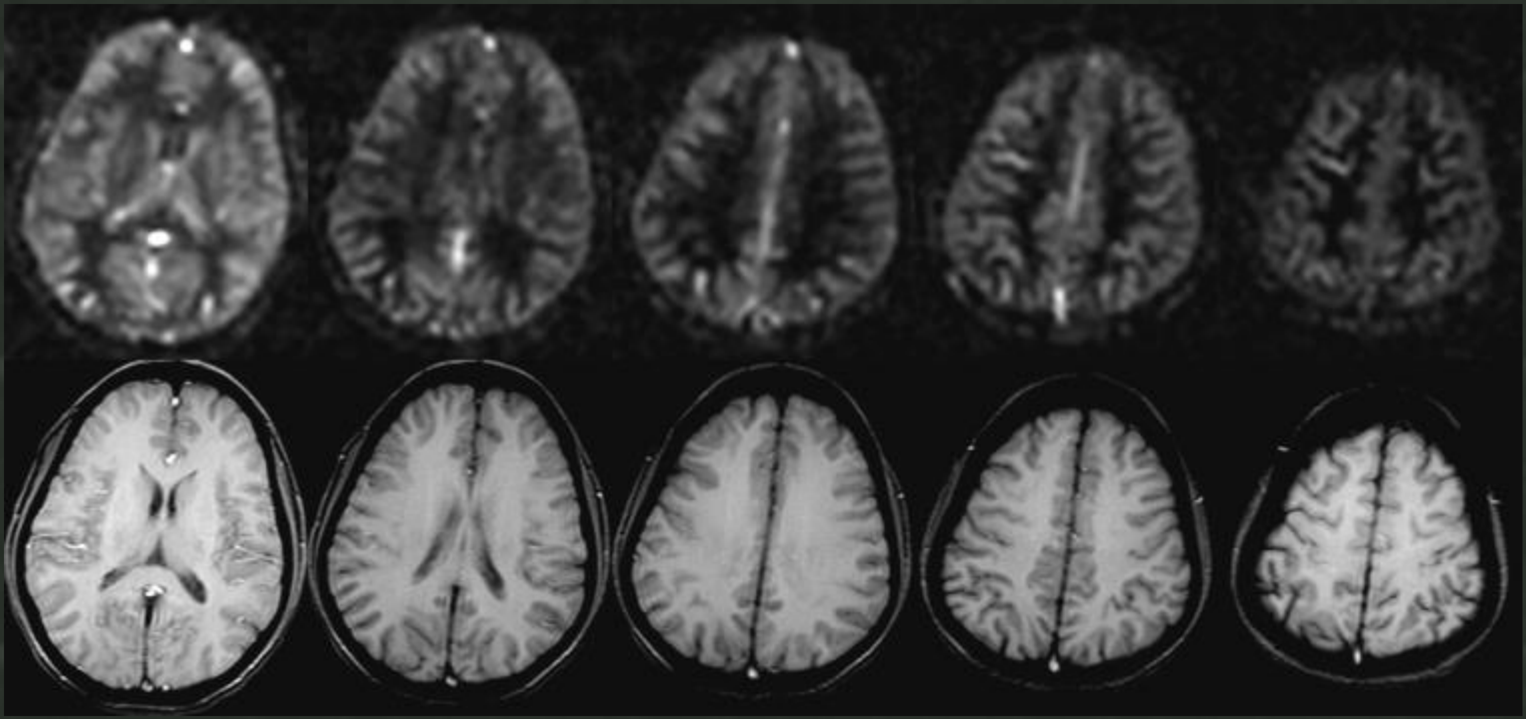


Courtesy, Robert Cox

Perfusion



Perfusion



Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) "Magnetic resonance imaging of perfusion using spin-inversion of arterial water." Proc. Natl. Acad. Sci. USA 89, 212-216.

Edelman, R., Siewert, B. & Darby, D. (1994) "Qualitative mapping of cerebral blood flow and functional localization with echo planar MR imaging ans signal targeting with alternating radiofrequency (EPISTAR)." Radiology **192**, 1-8.

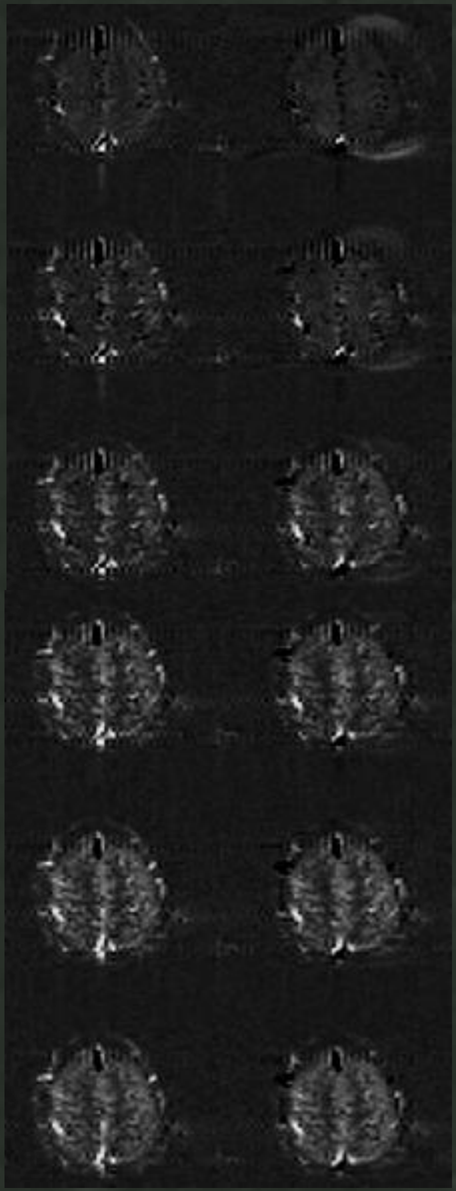
Kim, S.-G. (1995) "Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping." Magn. Reson. Med. **34**, 293-301.

Kwong, K. K. et al. (1995) "MR perfusion studies with T1-weighted echo planar imaging."Magn. Reson. Med. **34**, 878-887.

Perfusion

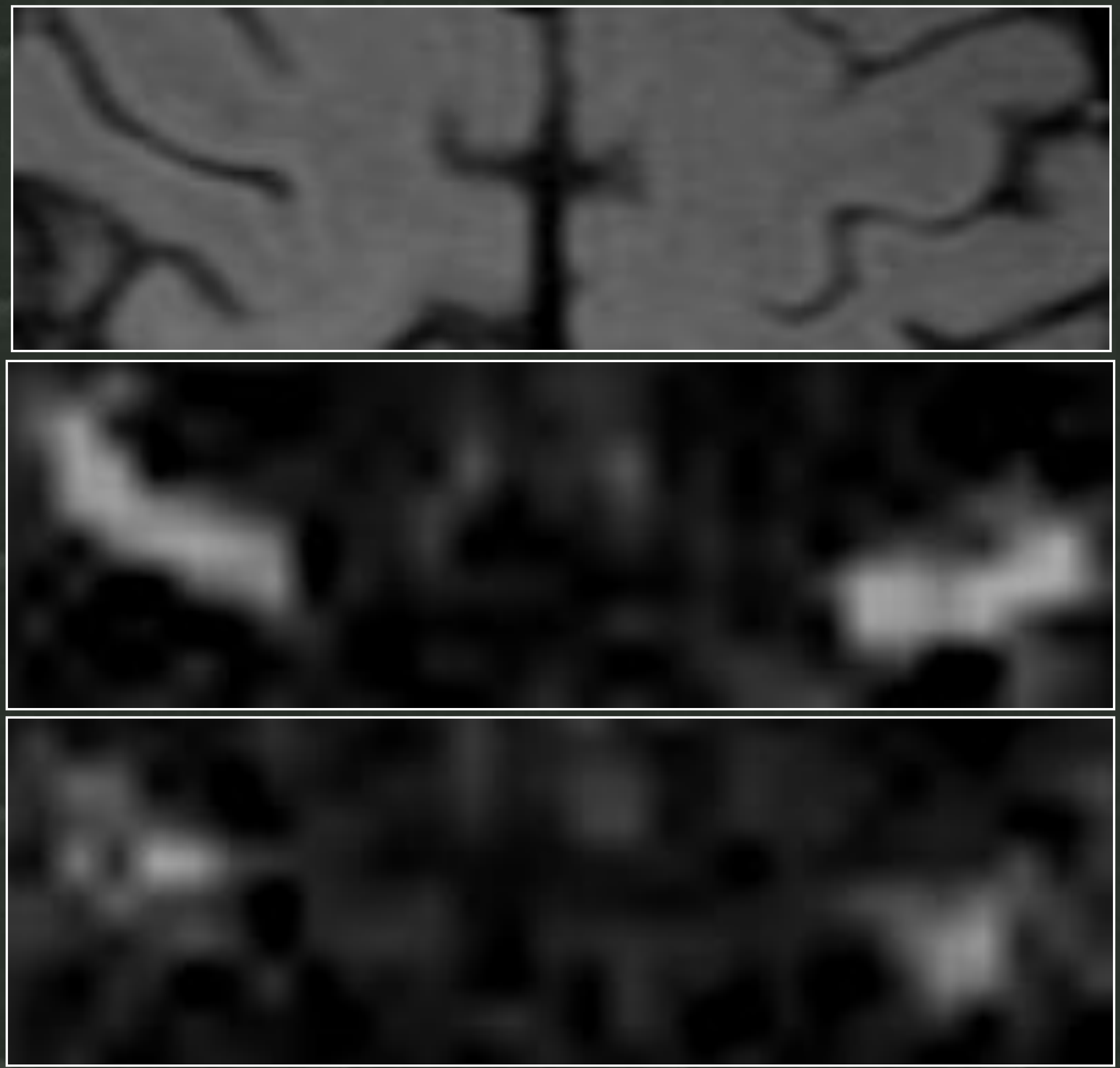
TI (ms)
200
400
600
800
1000
1200

FAIR EPISTAR



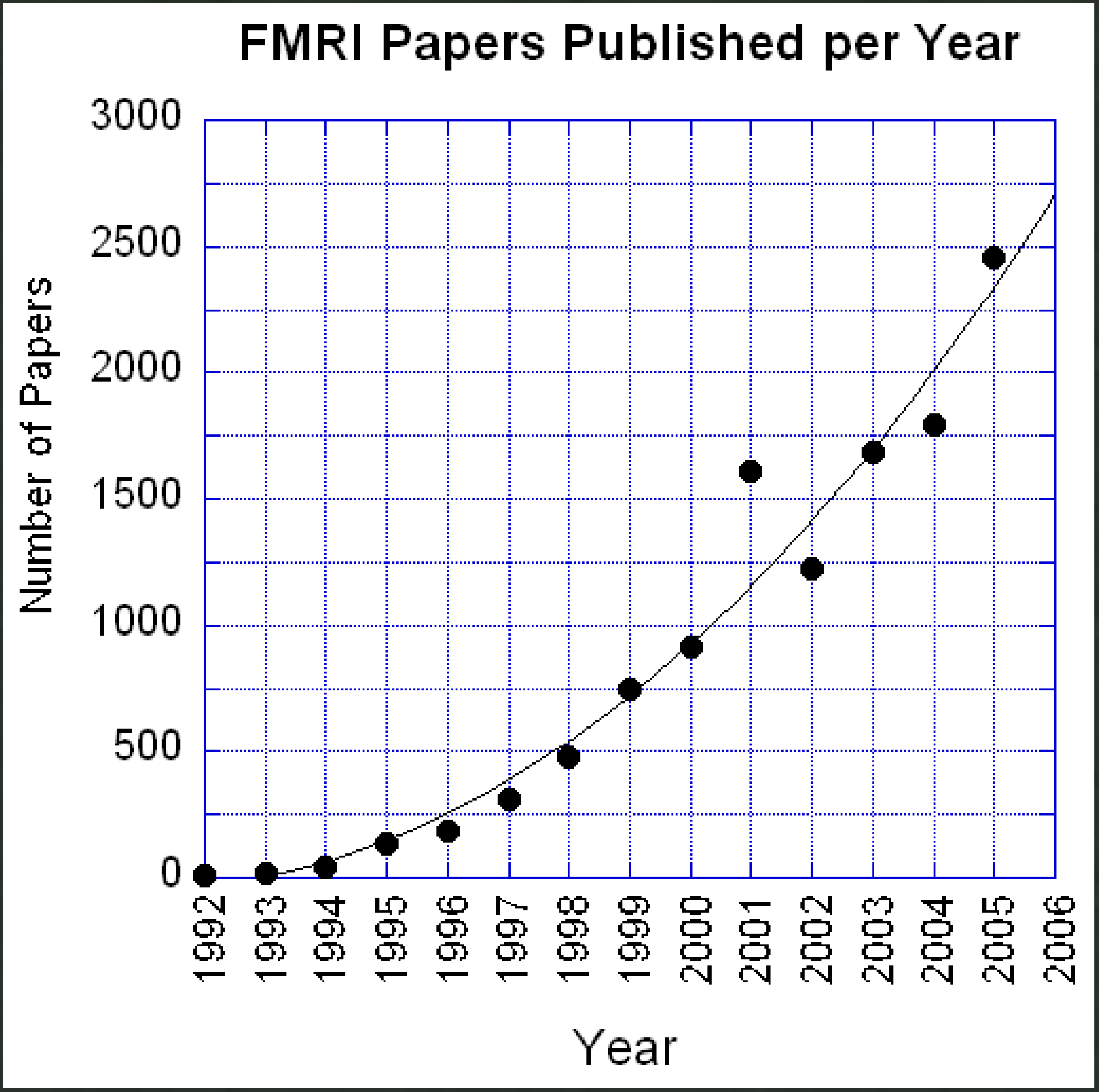
Perfusion

Simultaneous BOLD and Perfusion

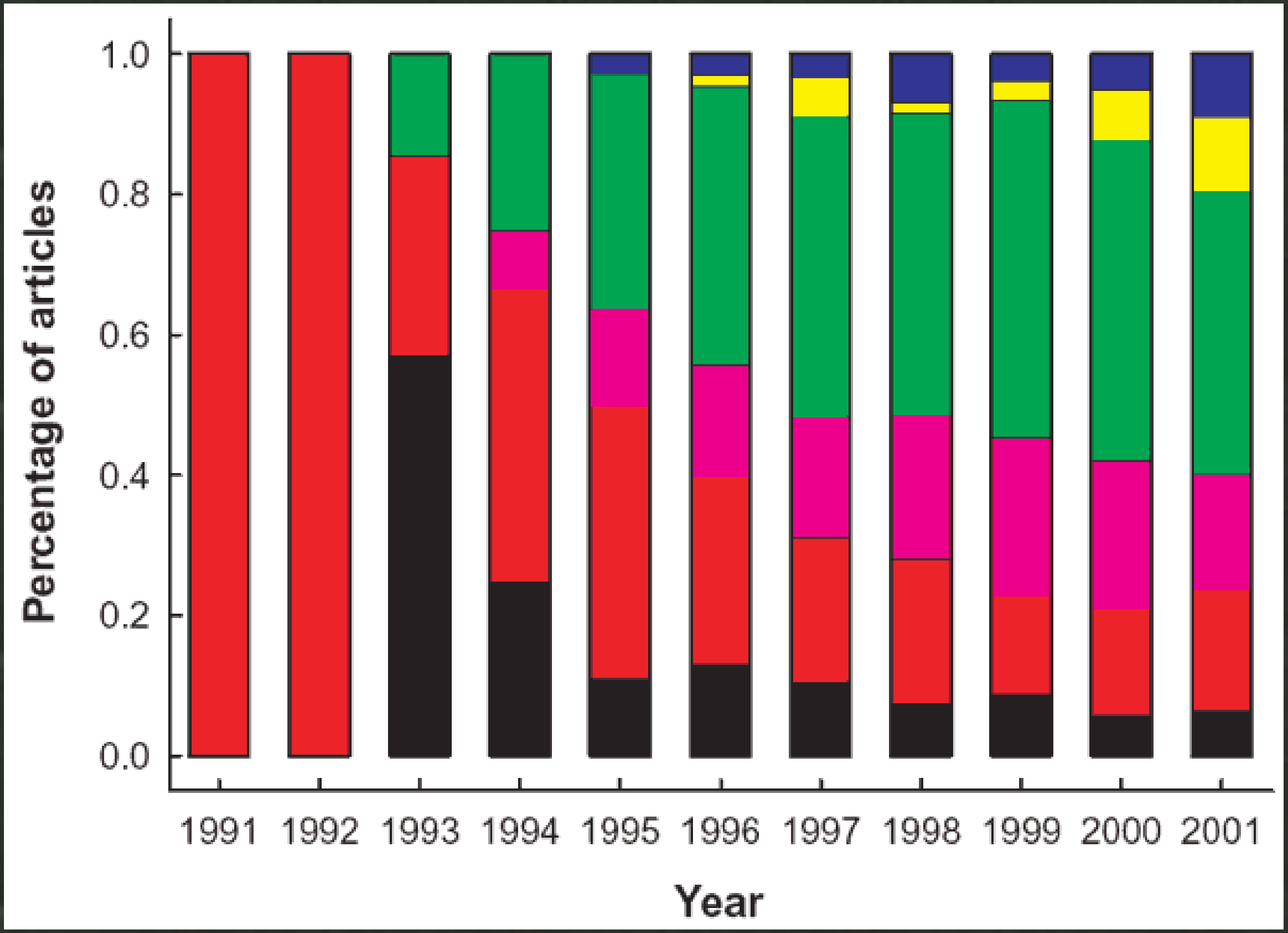


BOLD

Perfusion



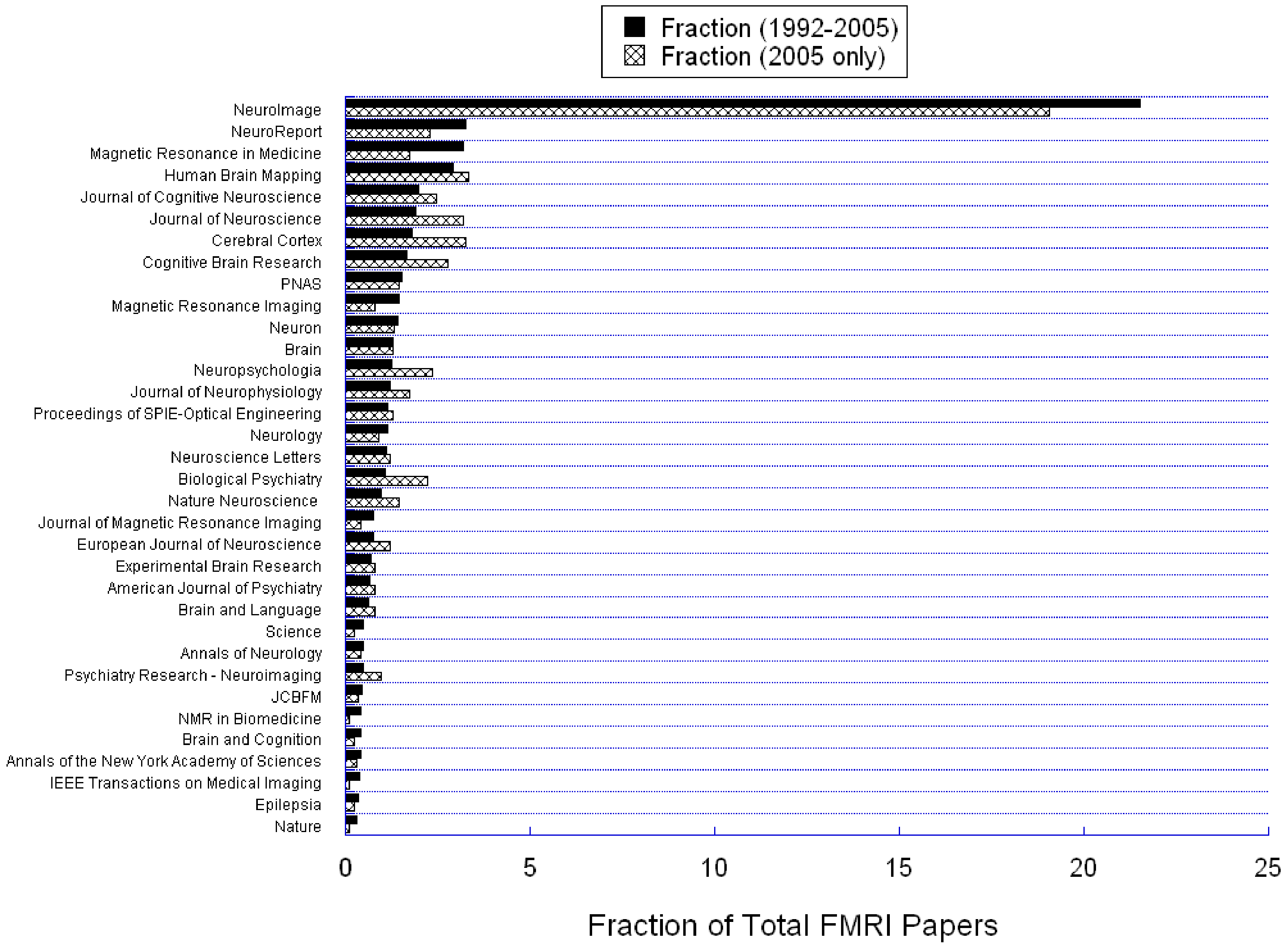
"fMRI" or "functional MRI"

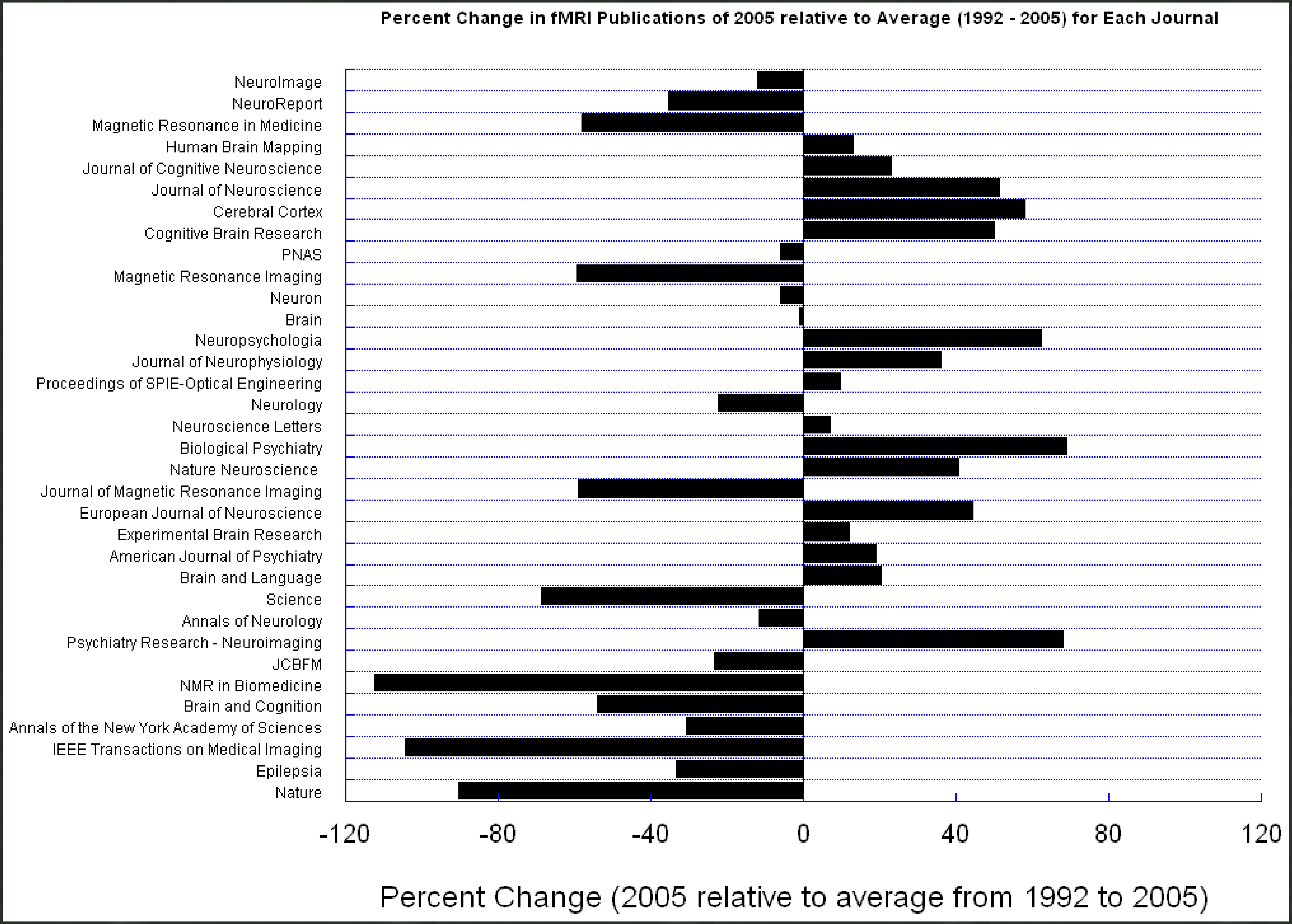


Motor (black)
Primary Sensory (red)
Integrative Sensory (violet)
Basic Cognition (green)
High-Order Cognition (yellow)
Emotion (blue)

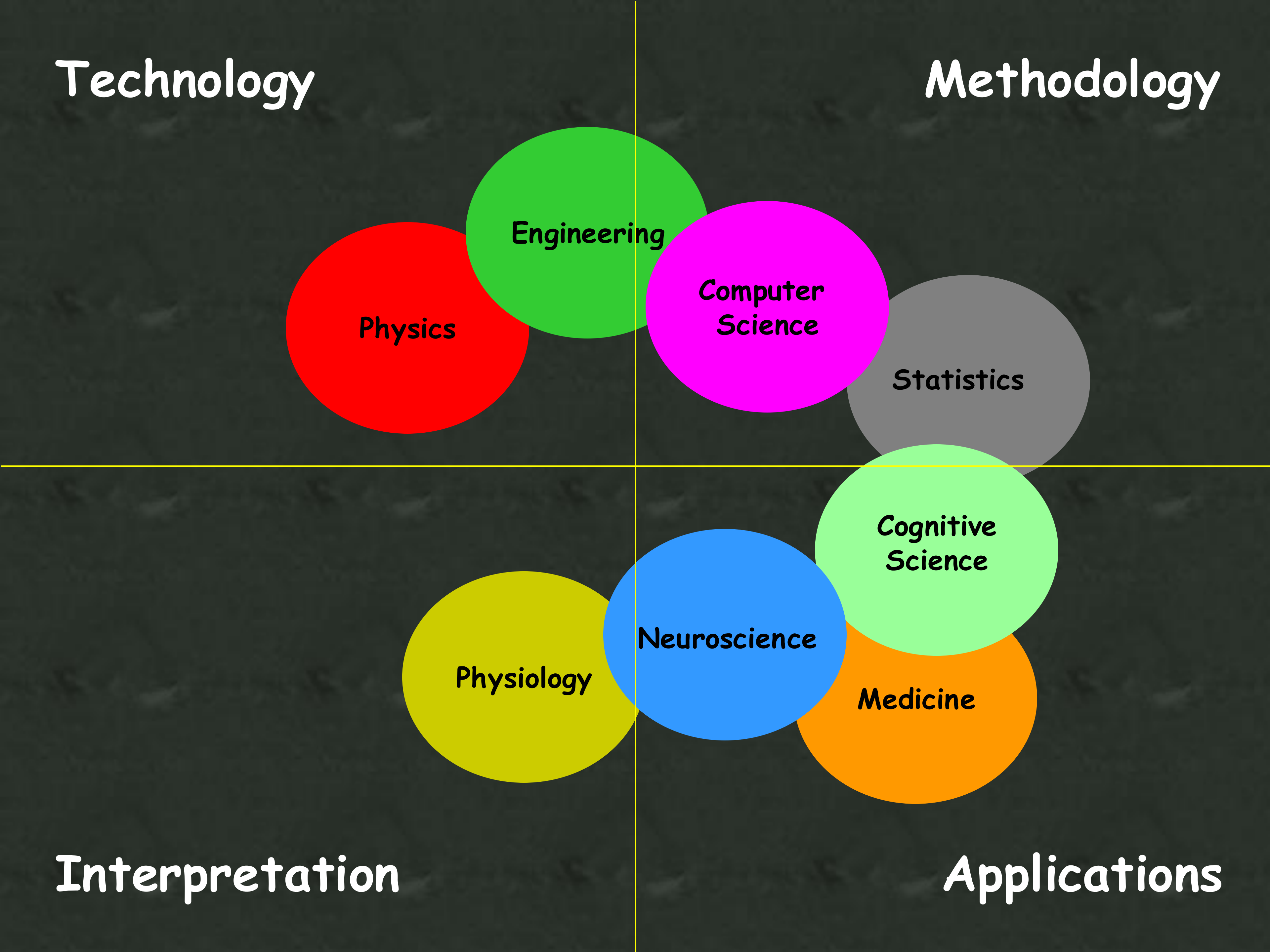
J. Illes, M. P. Kirschen, J. D. E. Gabrielli,
Nature Neuroscience, 6 (3)m p.205

Breakdown of fMRI papers by Journal





Percent Change in fMRI Publications of 2005 relative to Average (1992 - 2005) for Each Journal
NeuroImage
NeuroReport
Magnetic Resonance in Medicine
Human Brain Mapping
Journal of Cognitive Neuroscience
Journal of Neuroscience
Cerebral Cortex
Cognitive Brain Research
PNAS
Magnetic Resonance Imaging
Neuron
Brain
Neuropsychologia
Journal of Neurophysiology
Proceedings of SPIE-Optical Engineering
Neurology
Neuroscience Letters
Biological Psychiatry
Nature Neuroscience
Journal of Magnetic Resonance Imaging
European Journal of Neuroscience
Experimental Brain Research
American Journal of Psychiatry
Brain and Language
Science
Annals of Neurology
Psychiatry Research - Neuroimaging
JCBFM
NMR in Biomedicine
Brain and Cognition
Annals of the New York Academy of Sciences
IEEE Transactions on Medical Imaging
Epilepsia
Nature
-120
-80
-40
0
40
80
120
Percent Change (2005 relative to average from 1992 to 2005)


Technology
Methodology
Engineering
Physics
Computer Science
Statistics
Cognitive Science
Neuroscience
Physiology
Medicine
Interpretation
Applications

Technology

Coil arrays
Higher field strength
Higher resolution

Methodology

"Resting state"
Fluctuation assessment
Multi-modal integration
Pattern classification
Novel Functional Contrasts

Fluctuations
Dynamics
Cross - modal comparison

Interpretation

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation / therapy

Applications

Technology

Coil arrays
Higher field strength
Higher resolution

Methodology

"Resting state"
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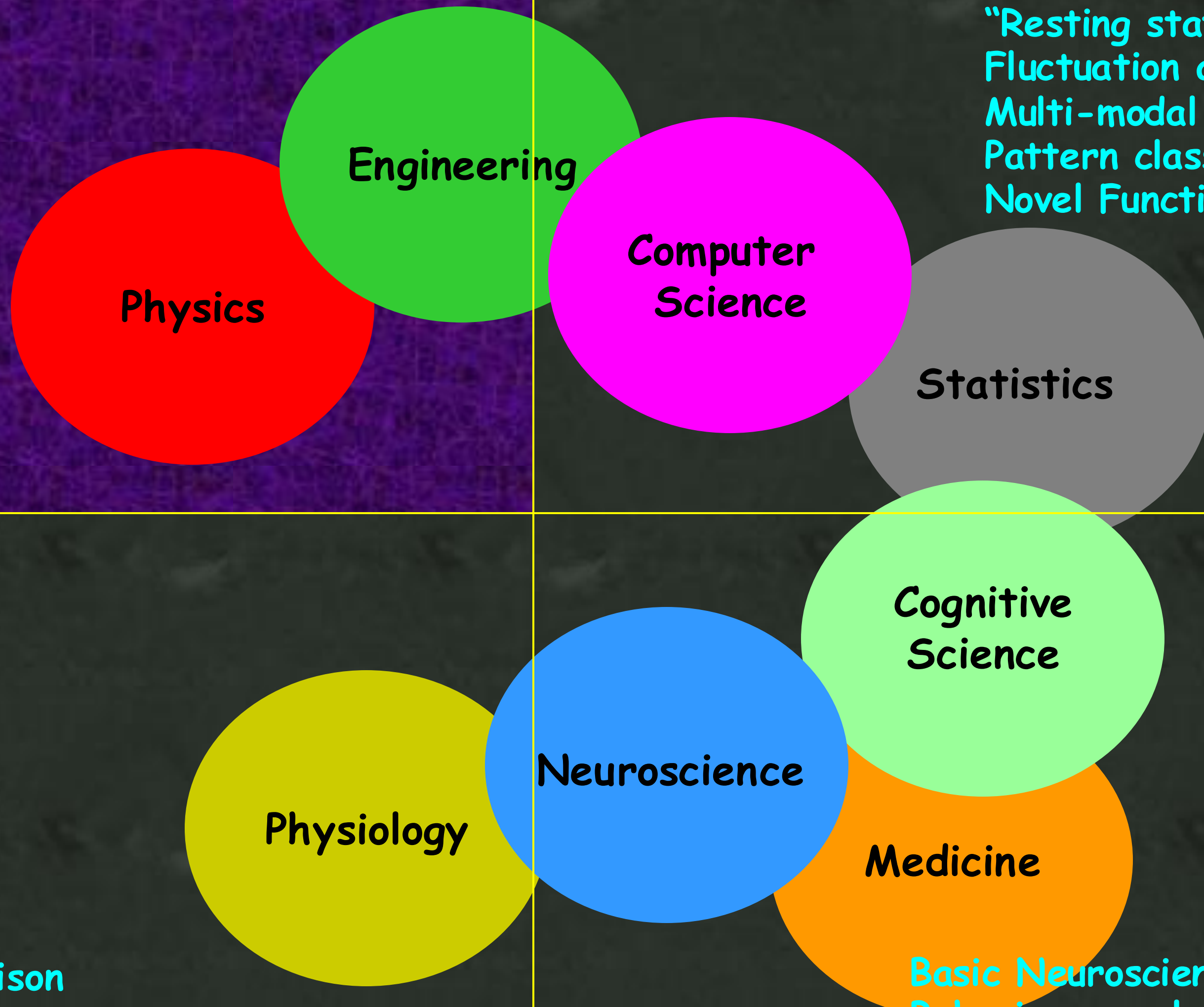
Novel Functional Contrasts



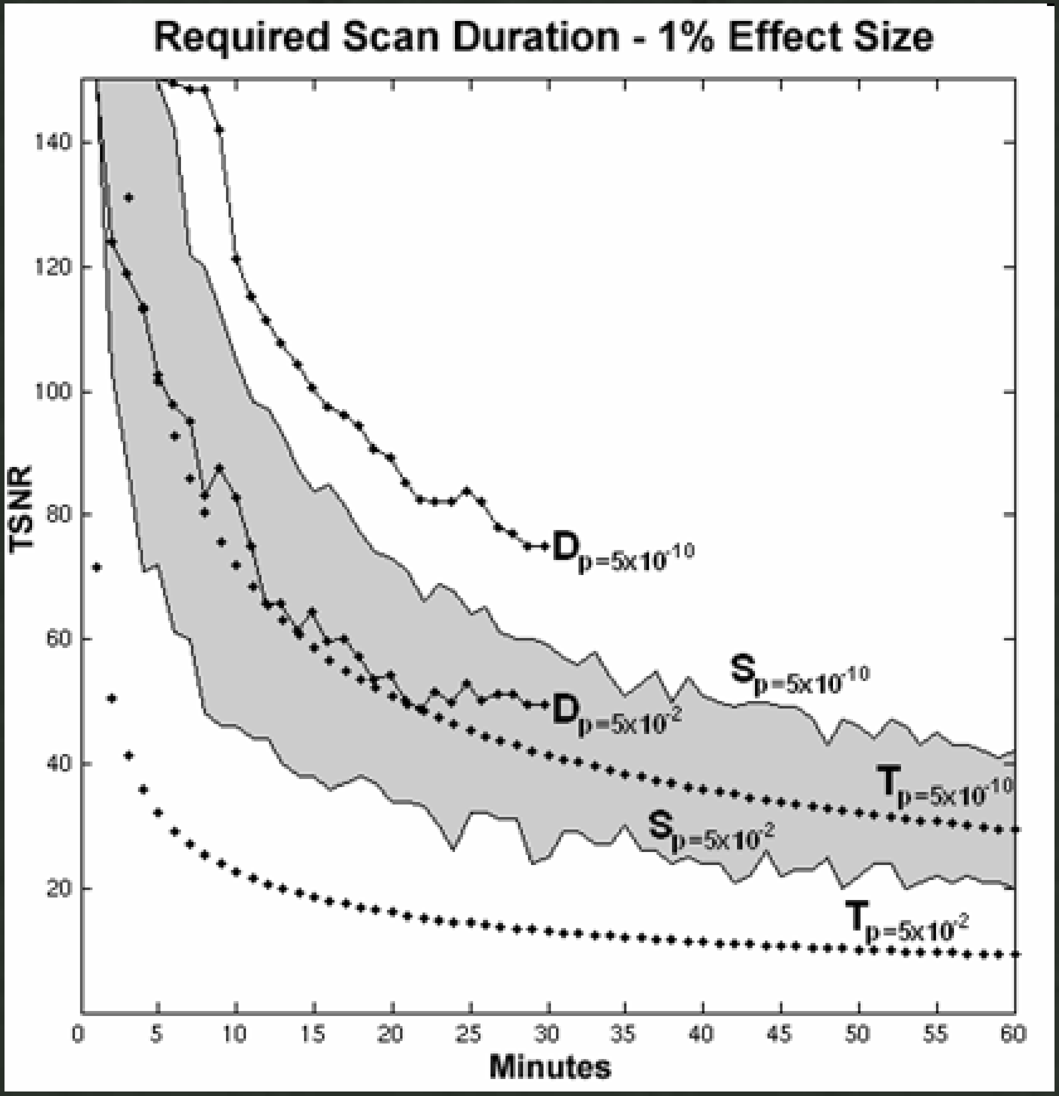
Fluctuations
Dynamics
Cross - modal comparison

Interpretation

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

Applications

Parallel Acquisition



Reasons for higher SNR

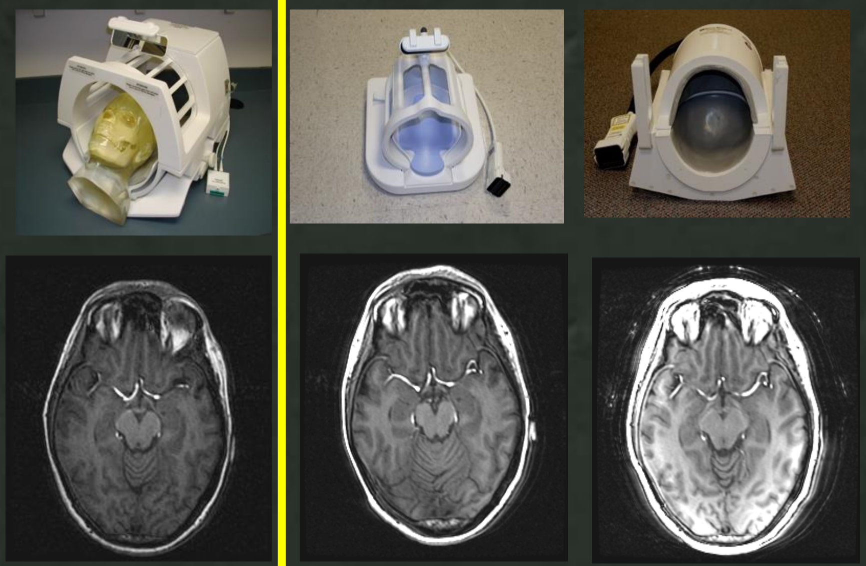
- Shorter scan duration
- Higher Resolution
- More subtle comparisons

Murphy et al.

Technology

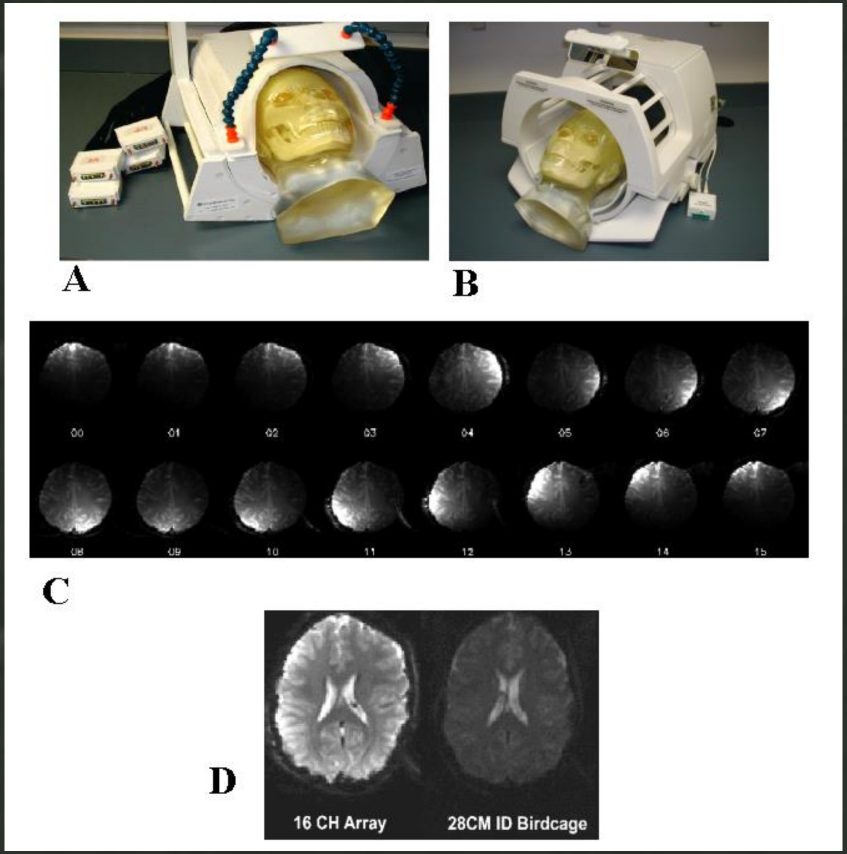
Parallel Acquisition

8 channel parallel receiver coil



GE birdcage | GE 8 channel coil | Nova 8 channel coil

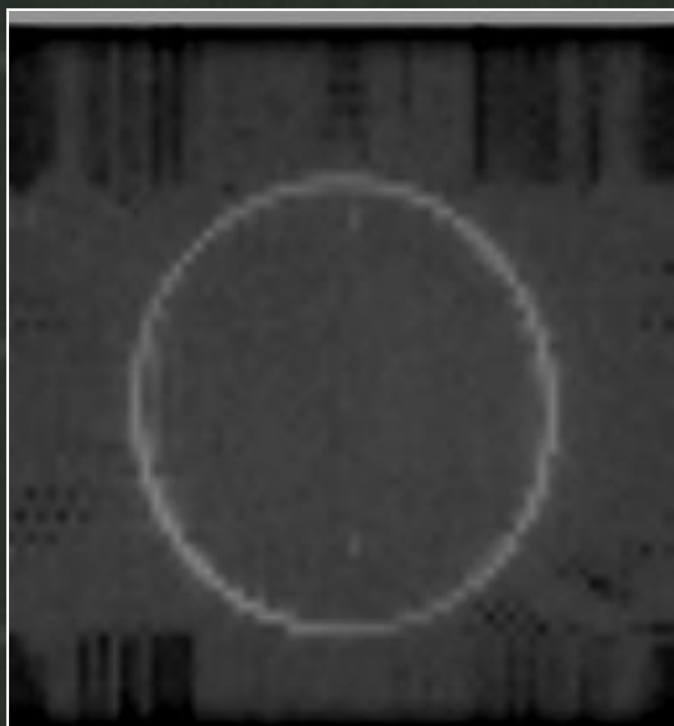
16 channel parallel receiver coil



J. Bodurka, et al, Magnetic Resonance in Medicine 51 (2004) 165-171.

Sensitivity and Noise

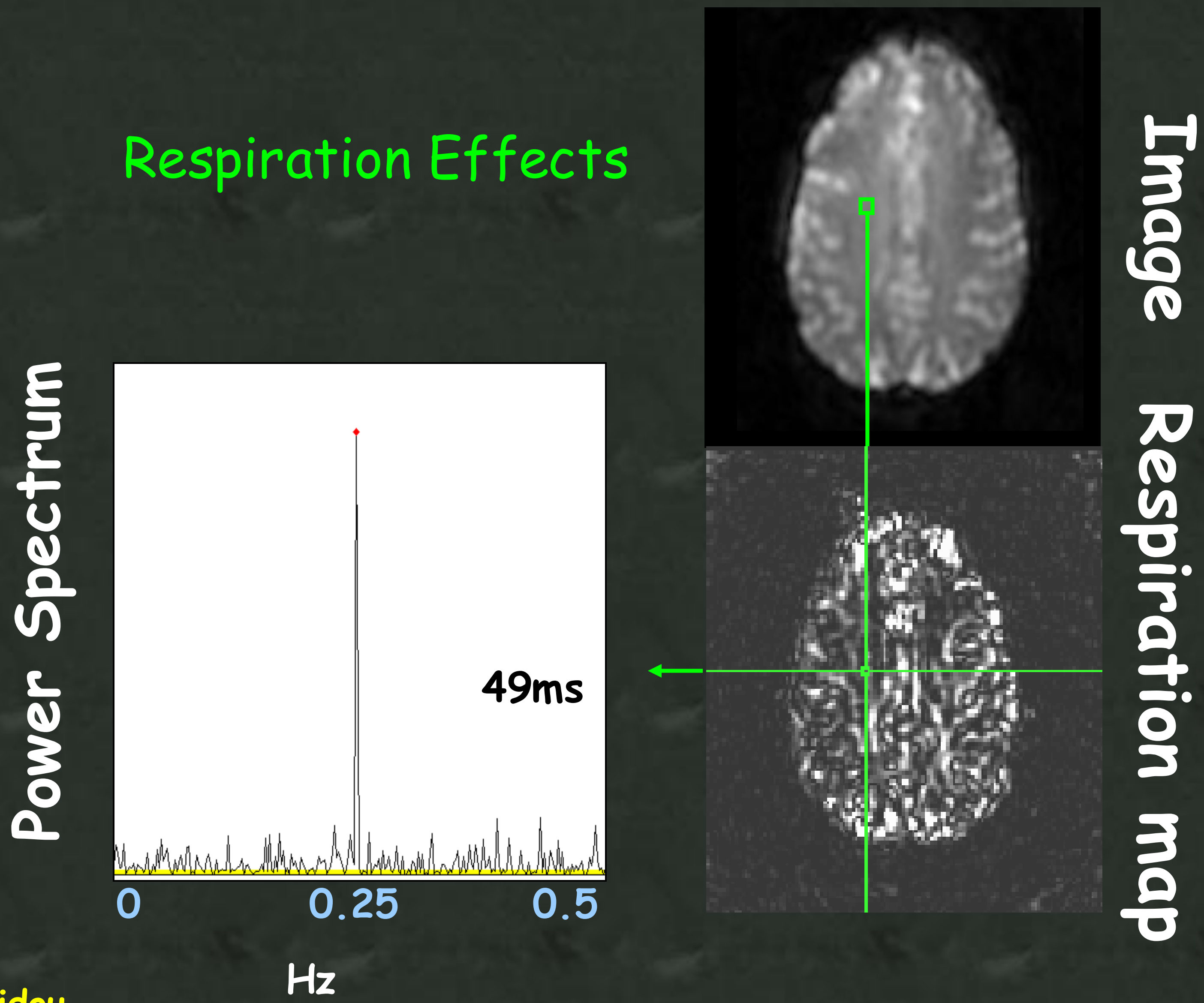
Phantom



Brain

Sensitivity and Noise

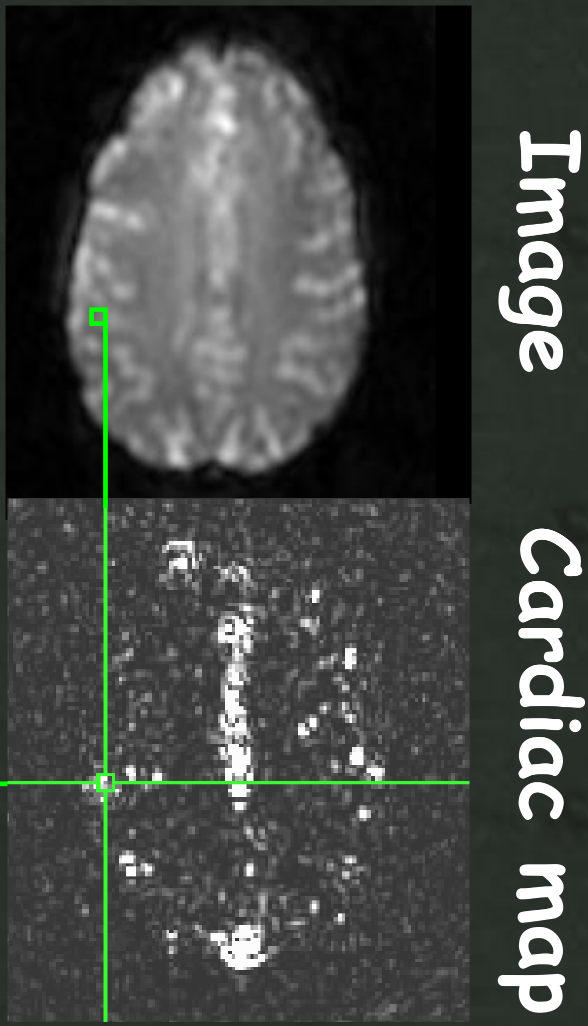
Respiration Effects

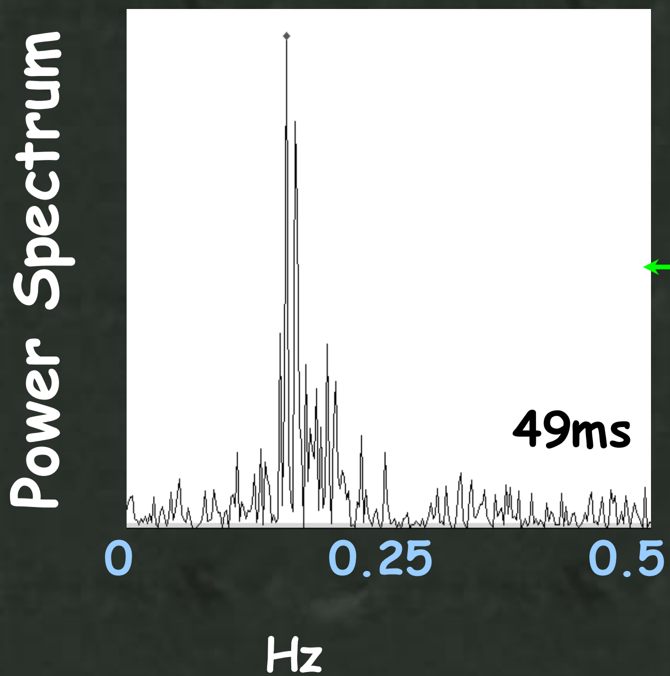


N. Petridou

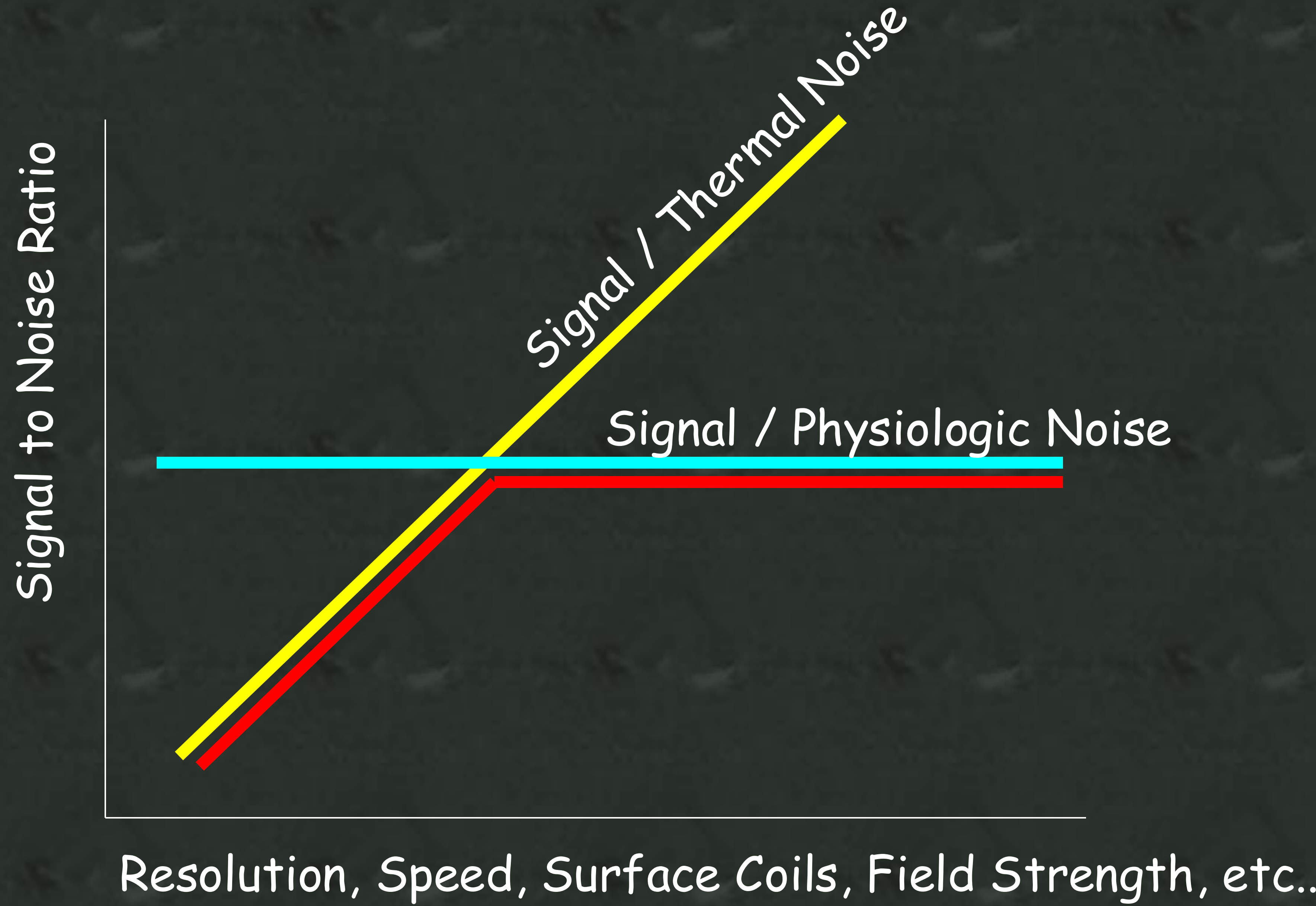
Sensitivity and Noise

Cardiac Effects



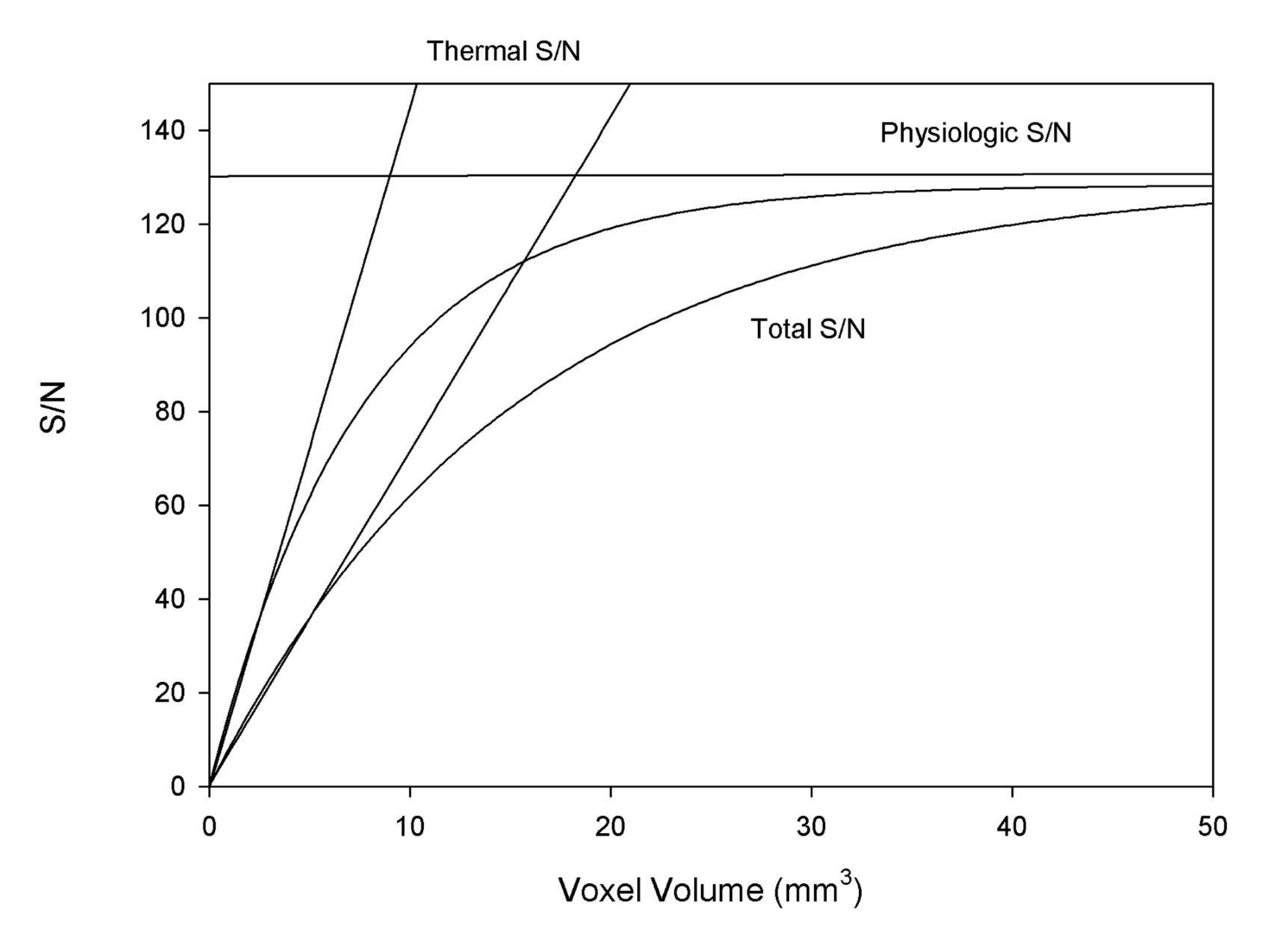


N. Petridou


Signal / Thermal Noise
Signal / Physiologic Noise
Signal to Noise Ratio
Resolution, Speed, Surface Coils, Field Strength, etc..

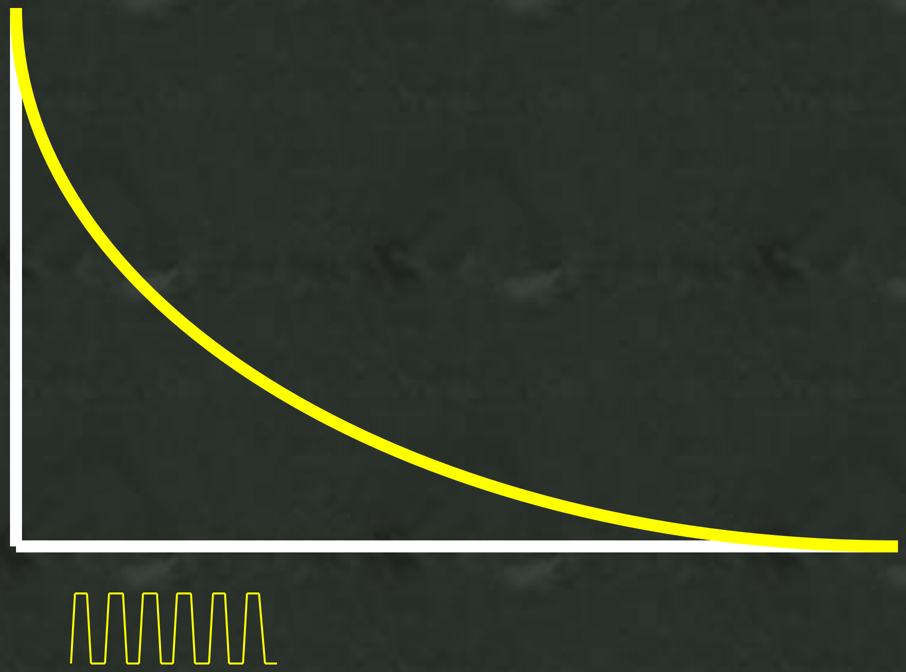
Simulated gains in TNSR with doubling sensitivity

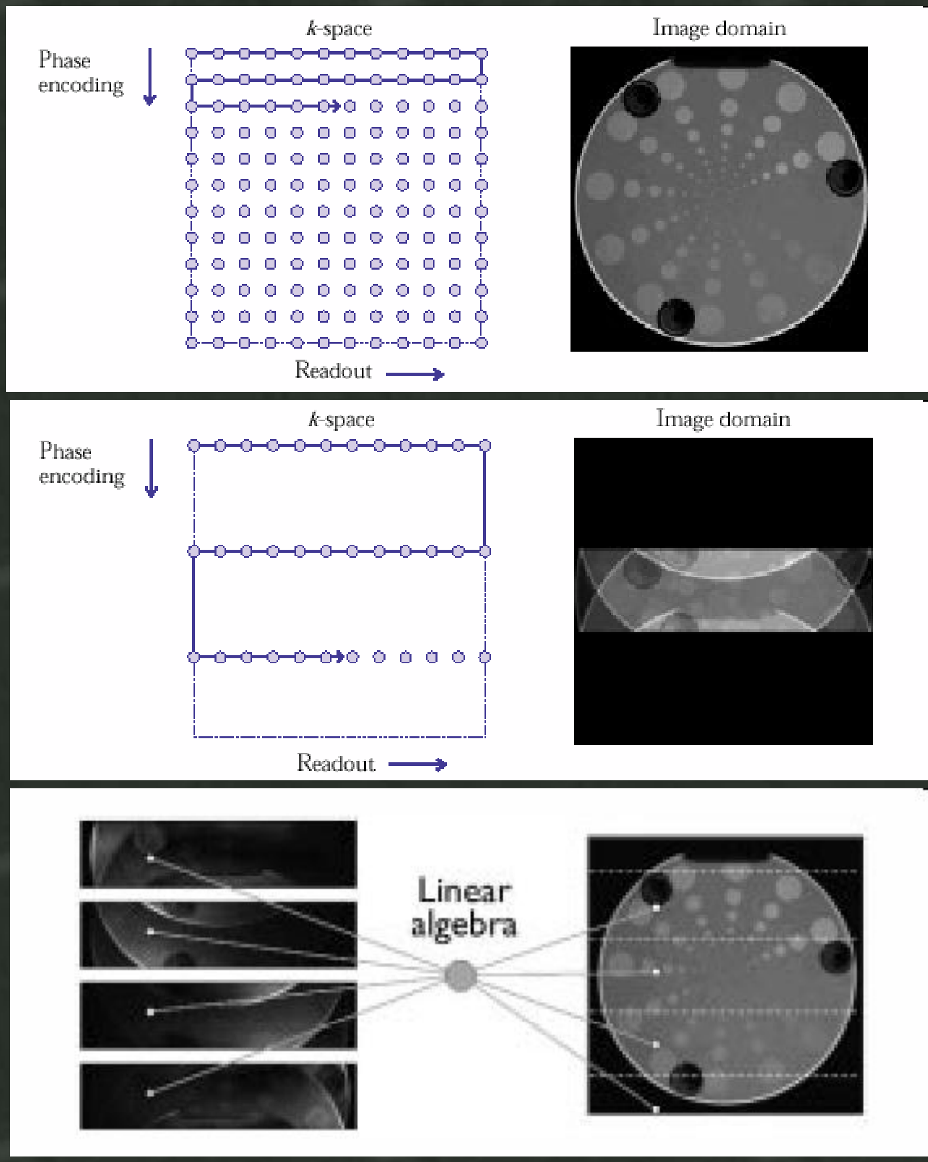
Temporal SNR



Technology

SENSE Imaging

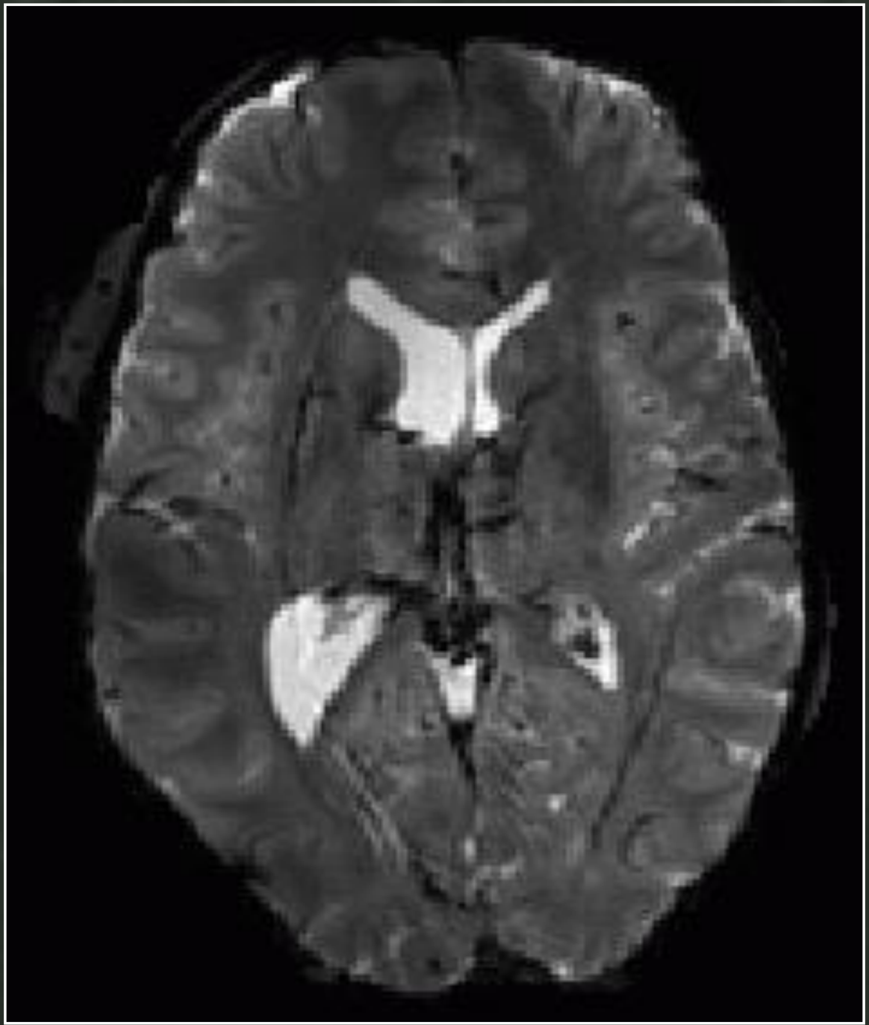




≈ 5 to 30 ms

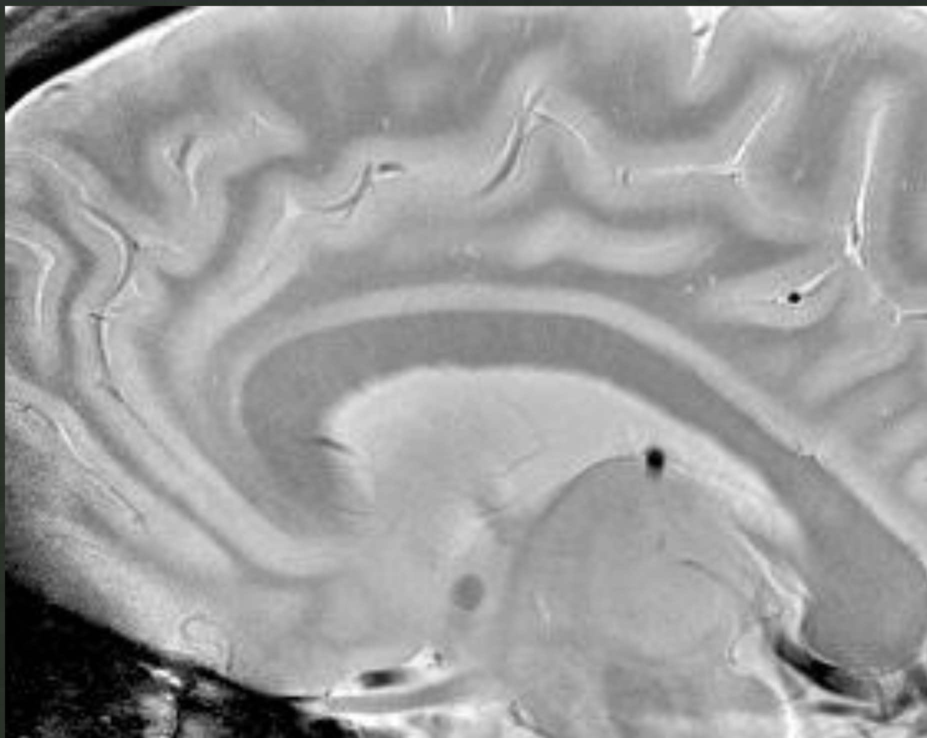
Pruessmann, et al.

SENSE Imaging

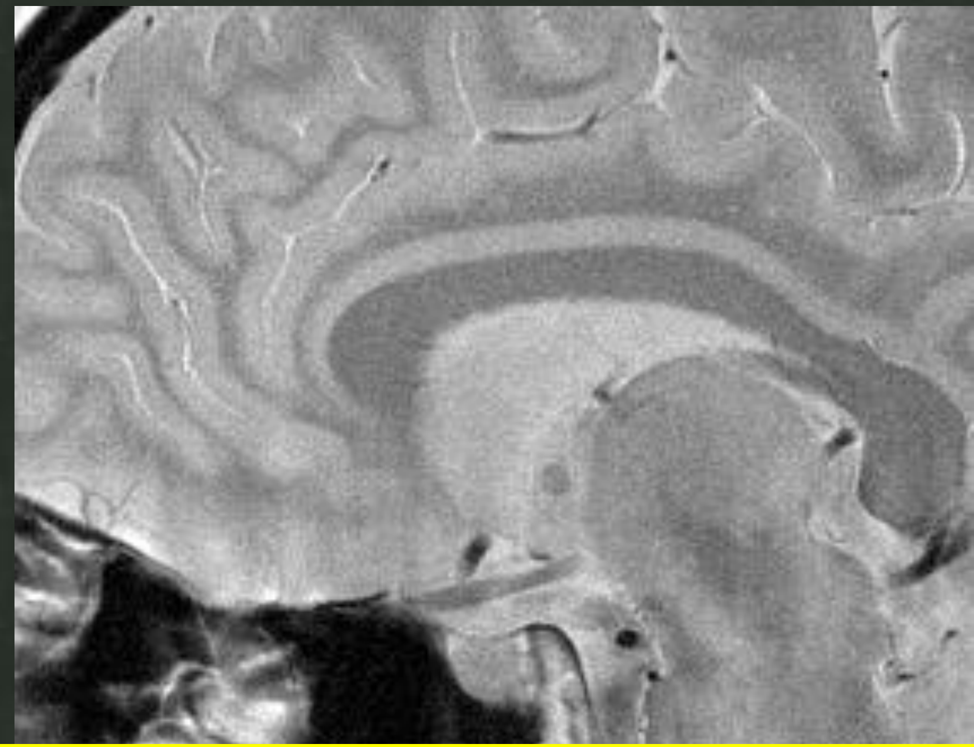


3T single-shot SENSE EPI using 16 channels: 1.25x1.25x2mm

7T head coil



3T head coil



TSE, 11 echoes, 7 min exam, 20cm FOV, 512x512 (0.4mm x 0.4mm), 3mm thick slices.

7T
white matter SNR =65
Gray matter SNR = 76

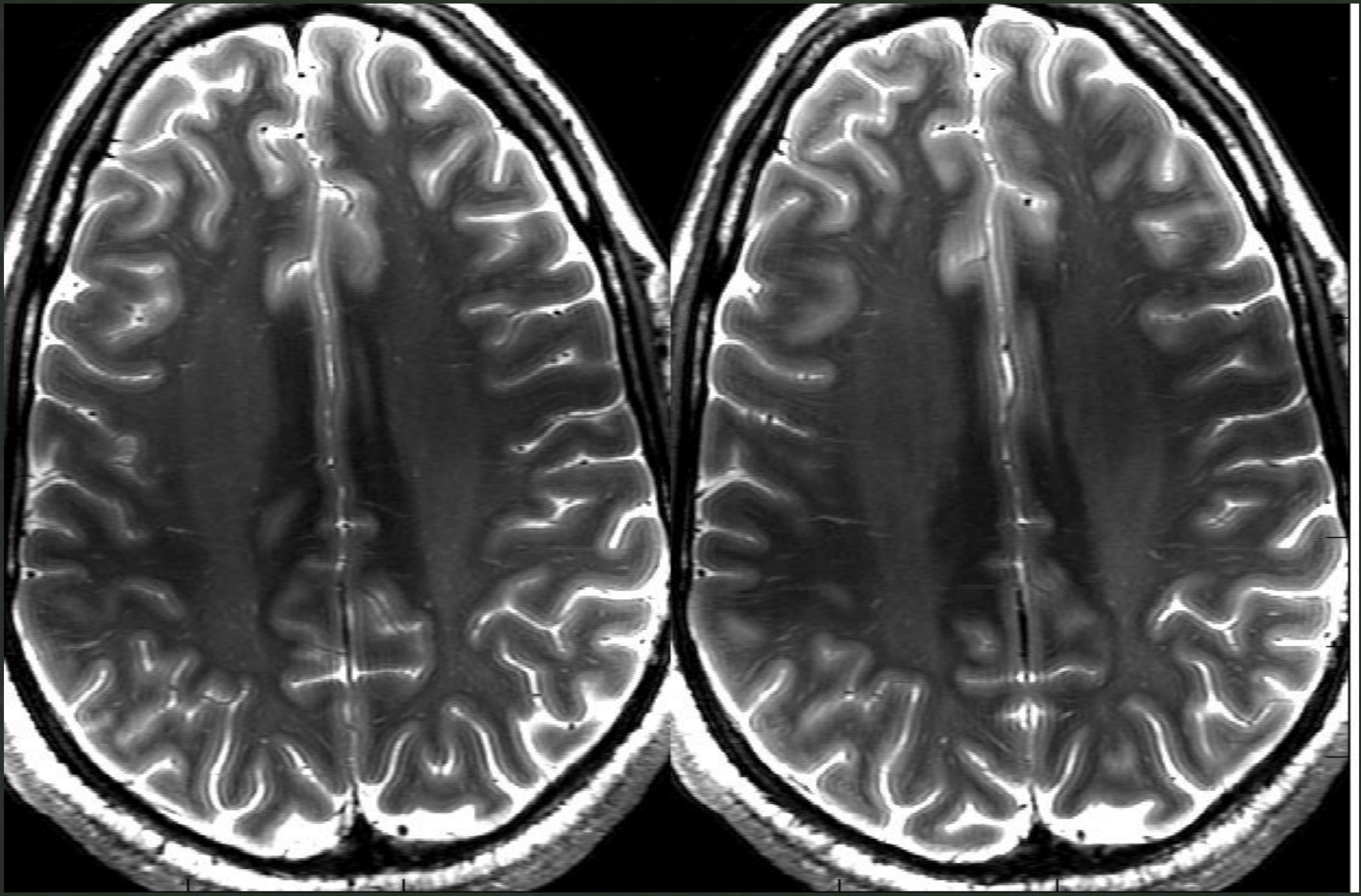
3T
white matter SNR =26
Gray matter SNR = 34

Courtesy Larry Wald

Technology

FSE **images** at 0.2x.2x1mm^3

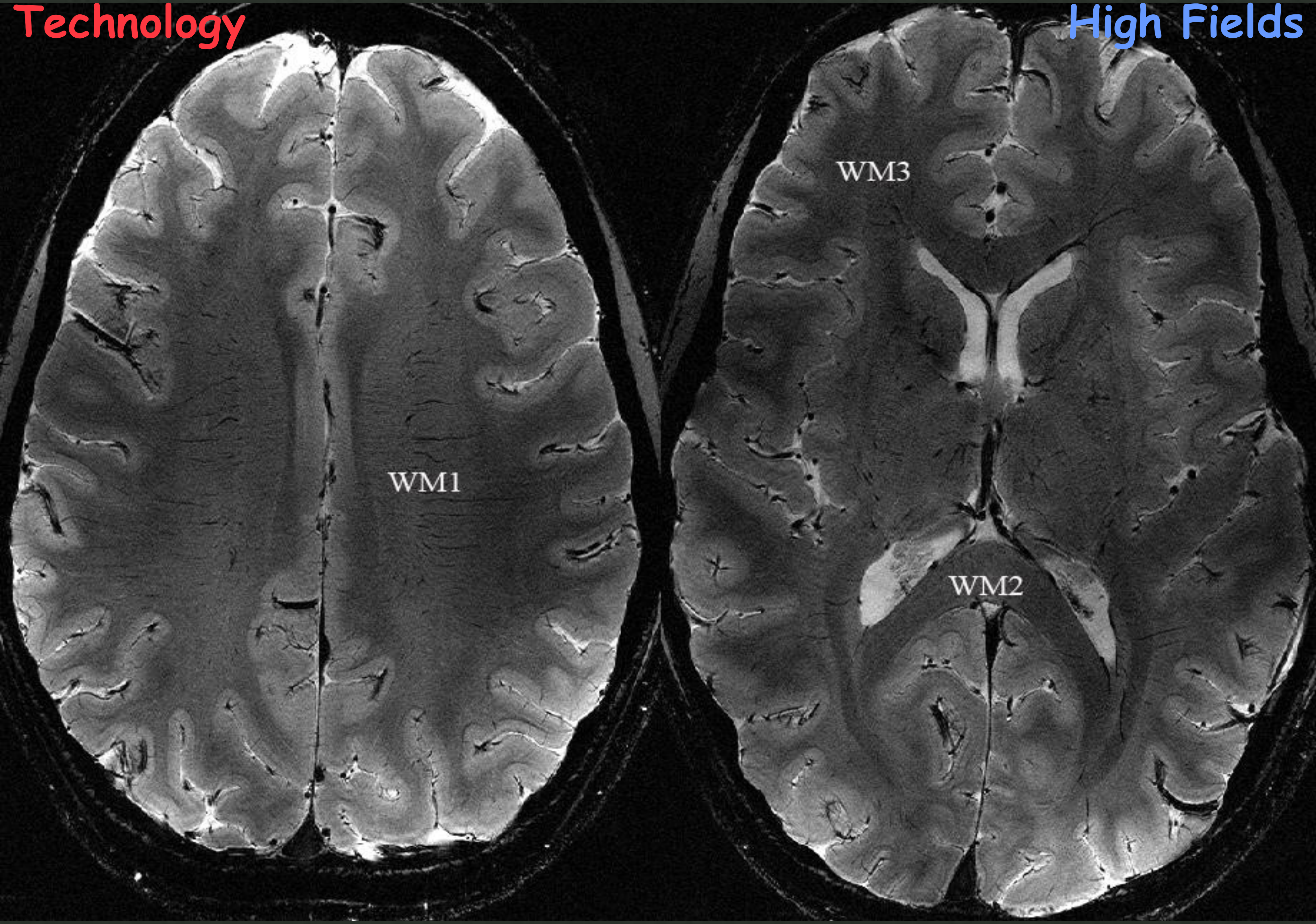
High Fields



Courtesy Tie-Qiang Li, NINDS

Technology

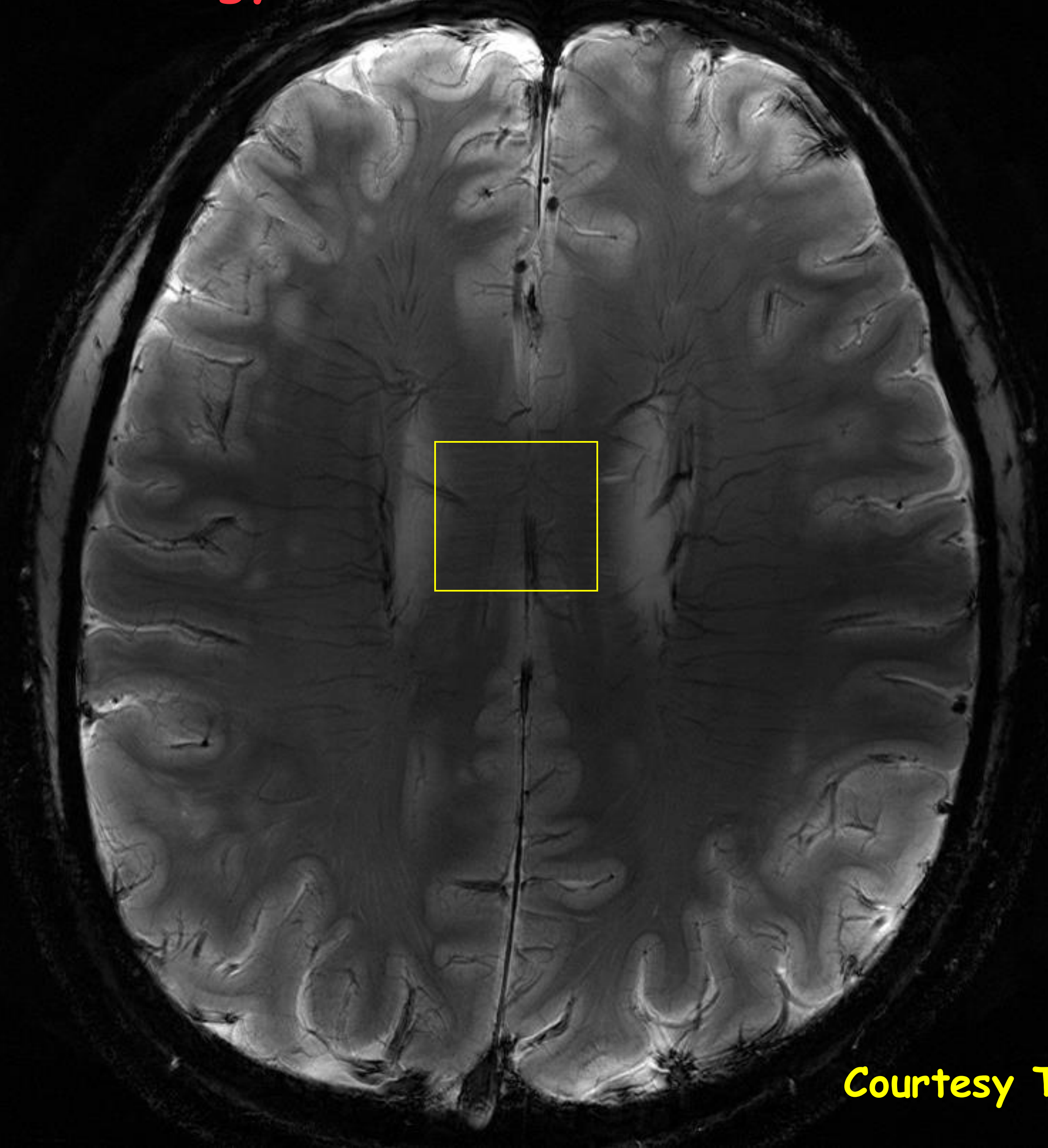
High Fields

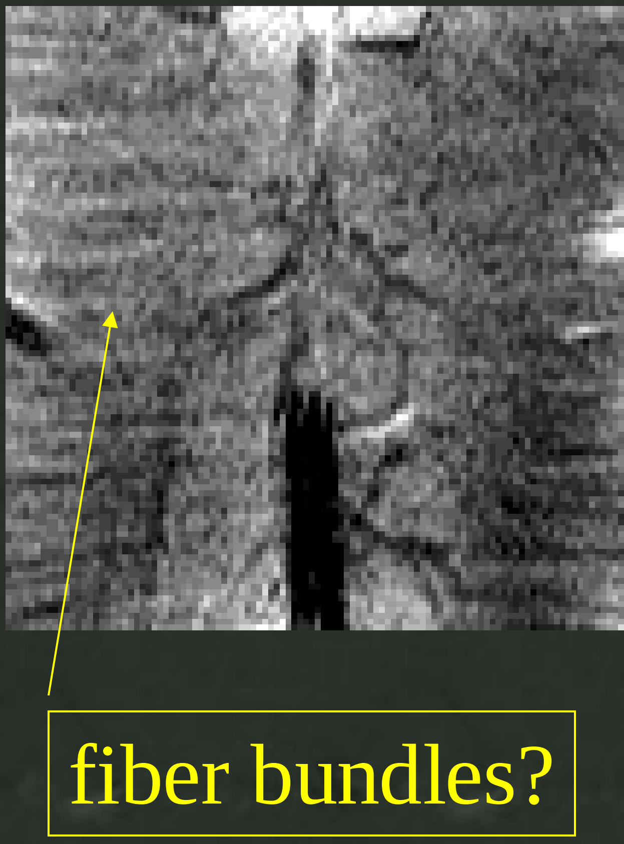


Courtesy Tie-Qiang Li, NINDS

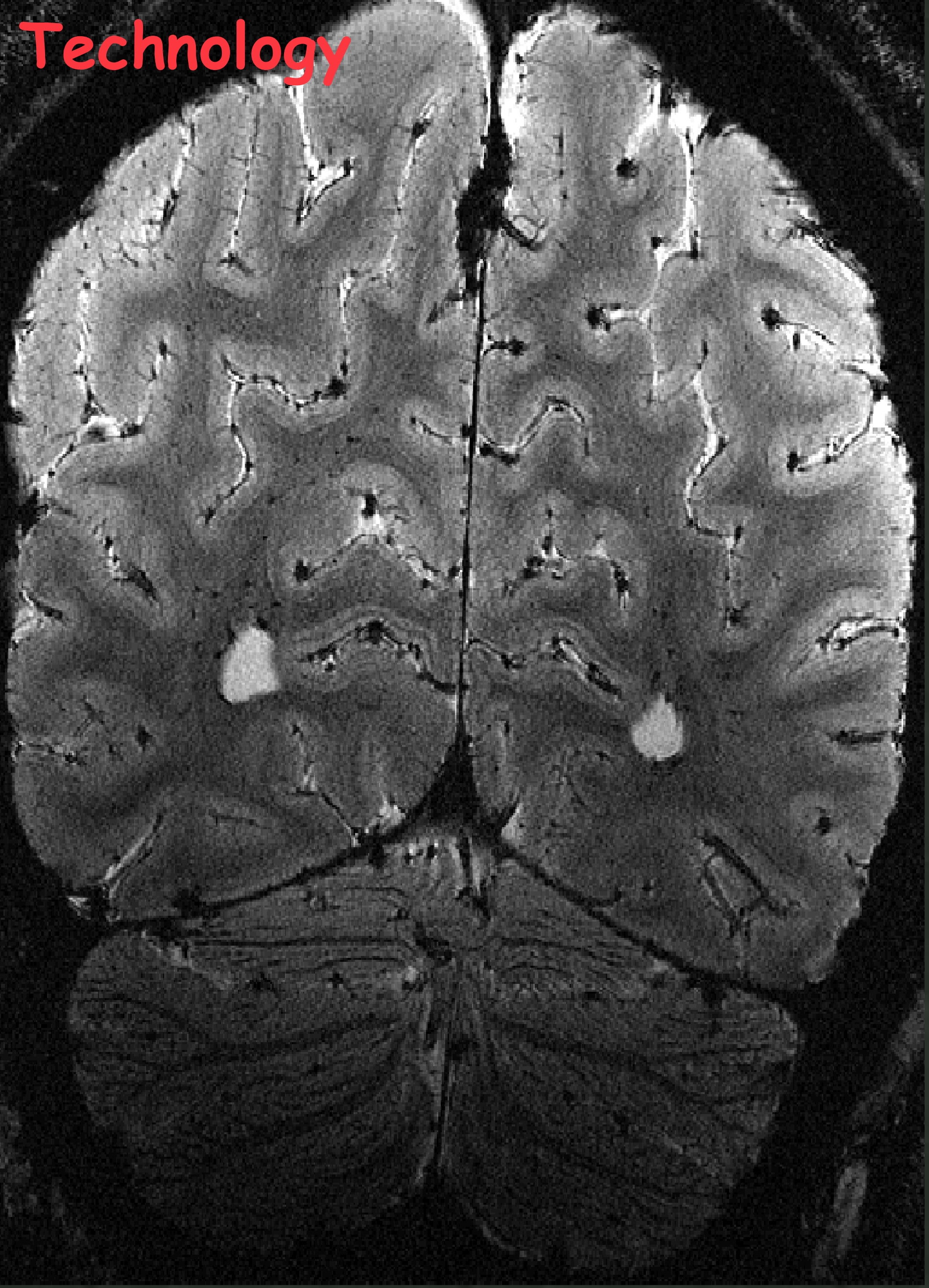
Technology

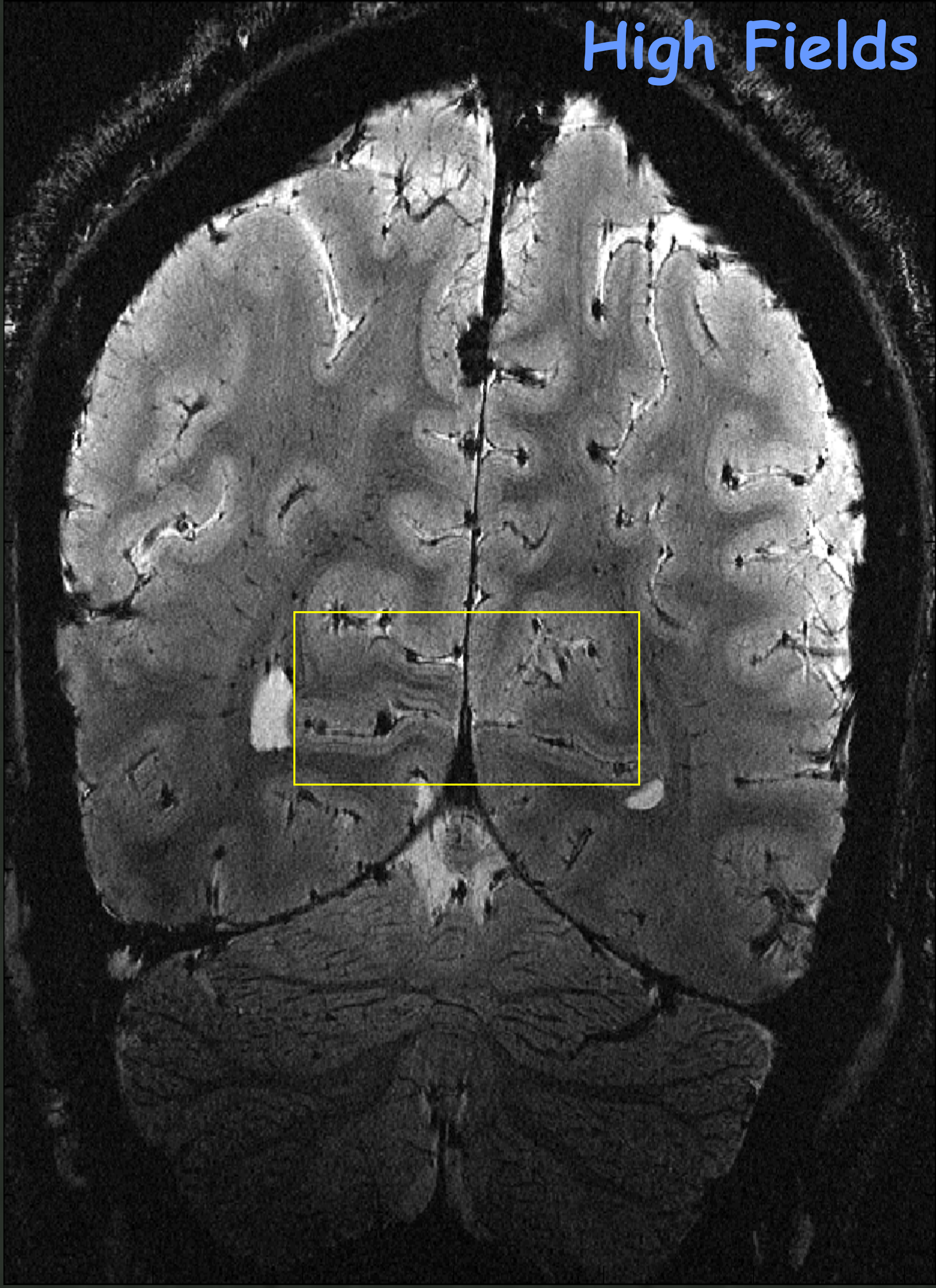
High Fields





Courtesy Tie-Qiang Li, NINDS





Courtesy Tie-Qiang Li, NINDS

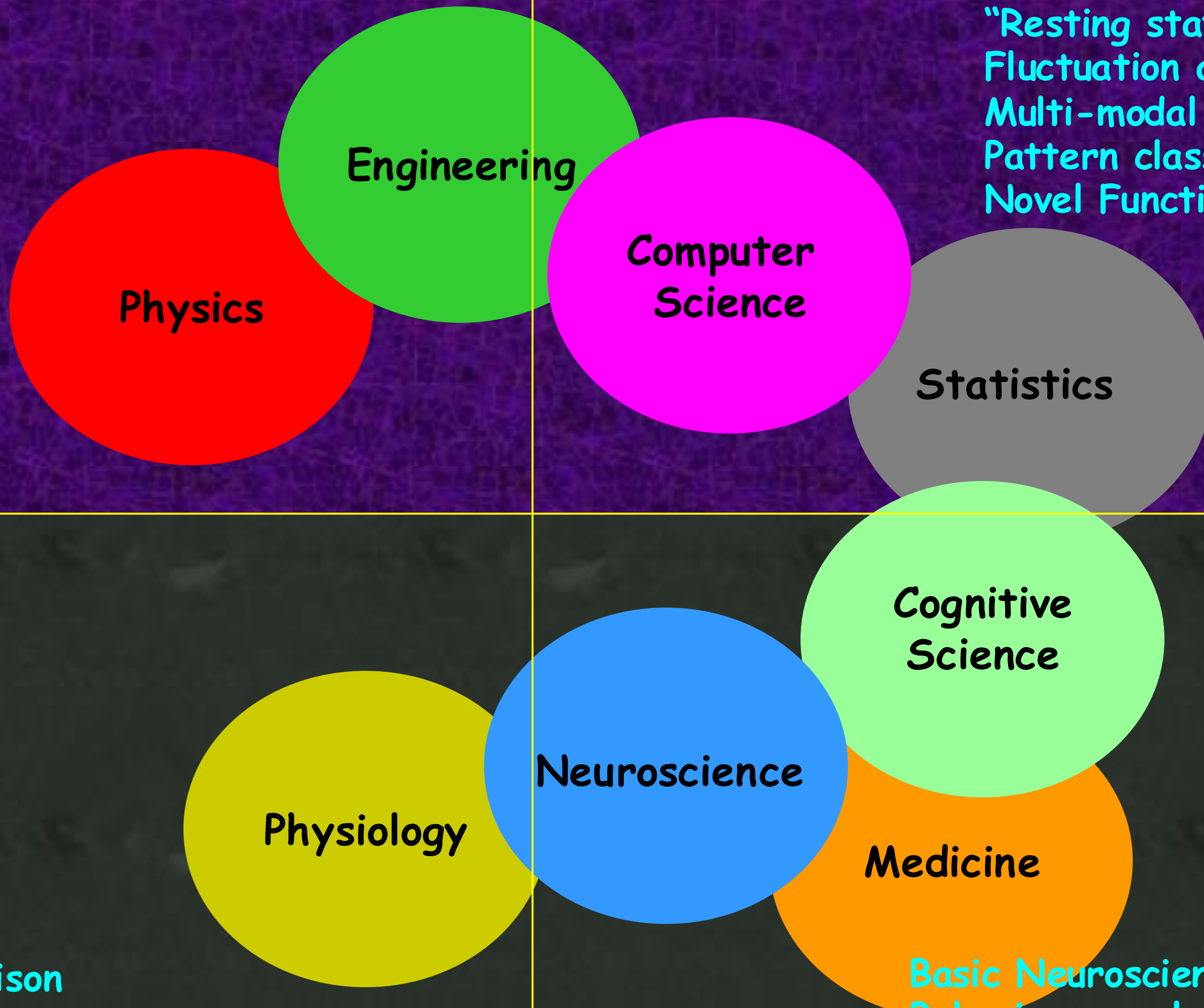
Layered structure in the visual cortex

Technology

Coil arrays
Higher field strength
Higher resolution

Methodology

"Resting state"
Fluctuation assessment
Multi-modal integration
Pattern classification
Novel Functional Contrasts



Fluctuations
Dynamics
Cross - modal comparison

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

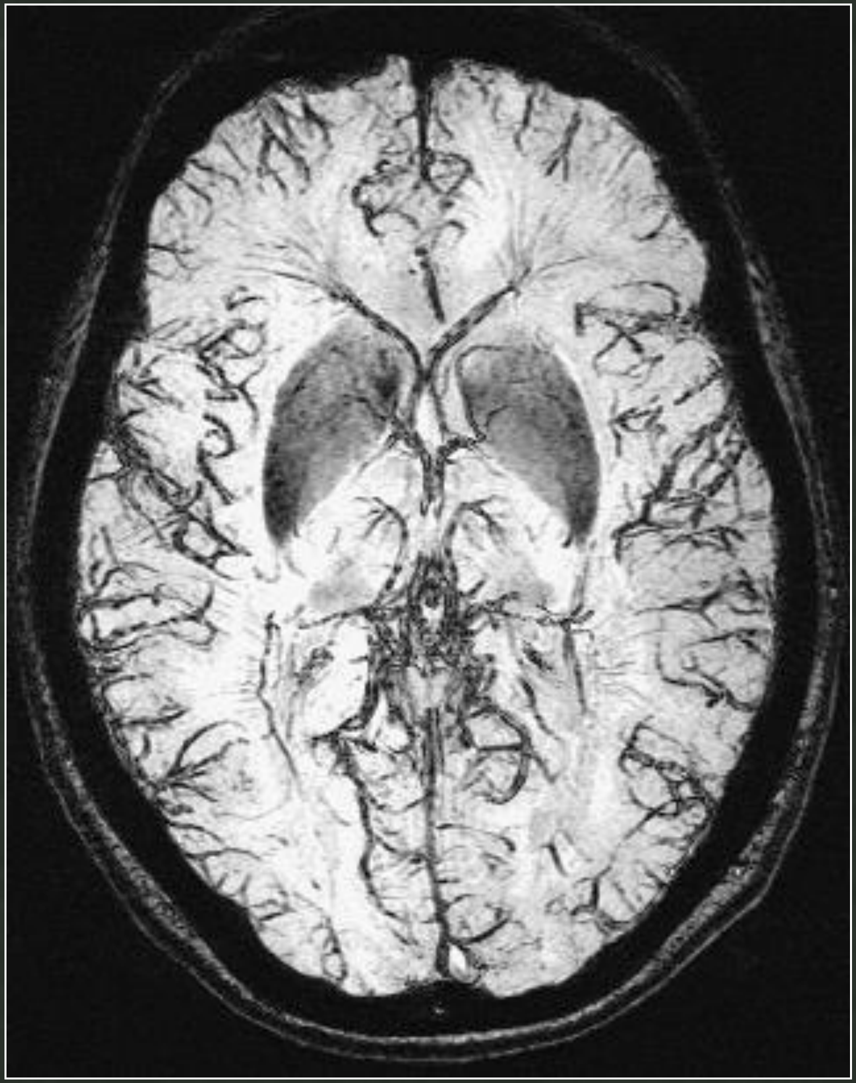
Interpretation

Applications

fMRI Contrast

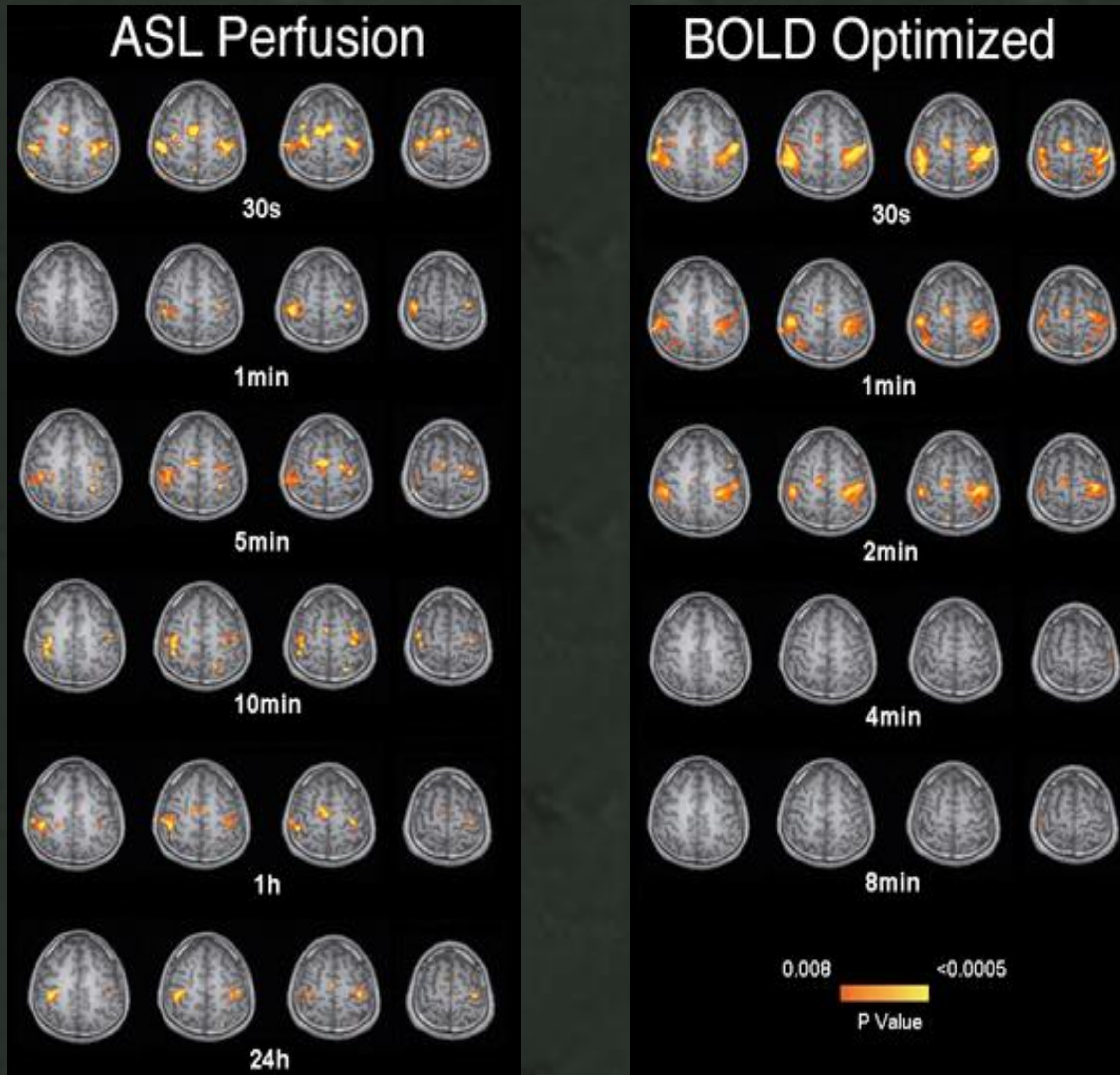
- Volume (gadolinium)
- BOLD
- Perfusion (ASL)
- $\Delta CMRO_2$
- ΔVolume (VASO)
- Neuronal Currents
- Diffusion coefficient
- Temperature

BOLD effect to highlight veins: 3 Tesla



Bove-Bettis, et al (2004), SMRT

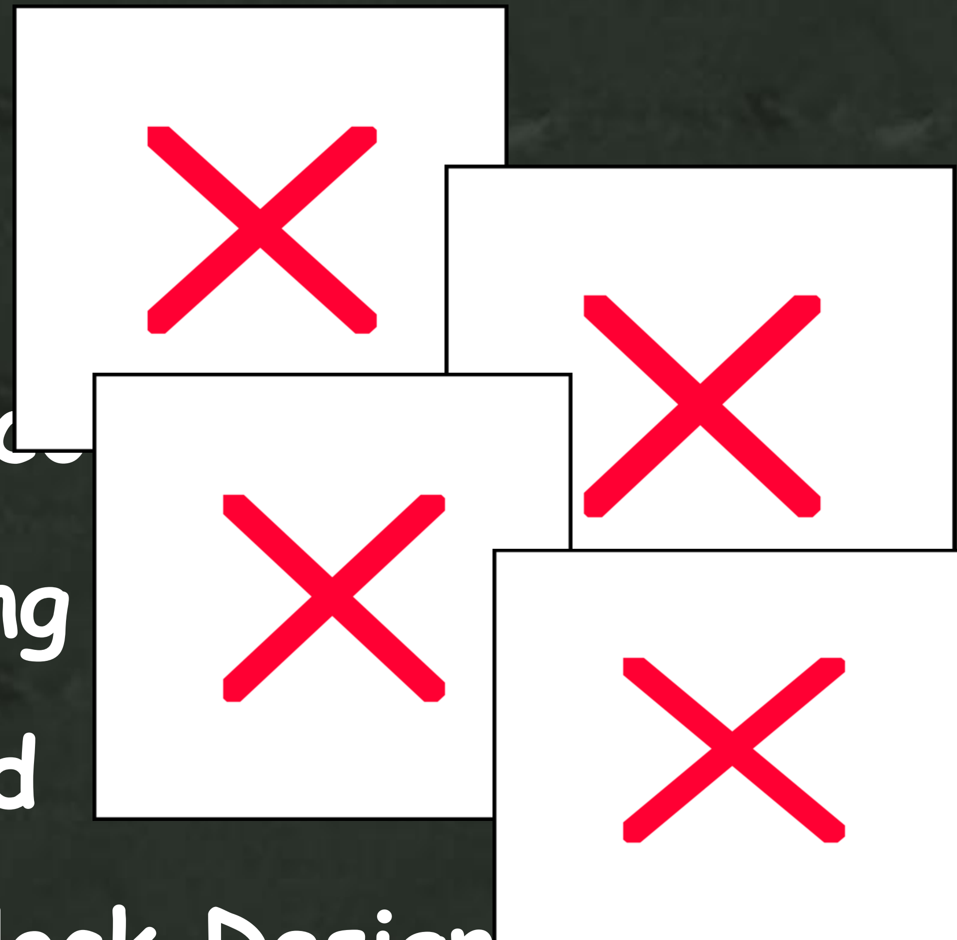
Perfusion vs. BOLD: Low Task Frequency

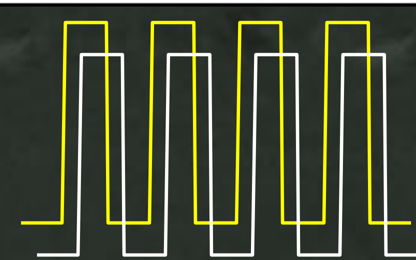


Wang et al., 2002

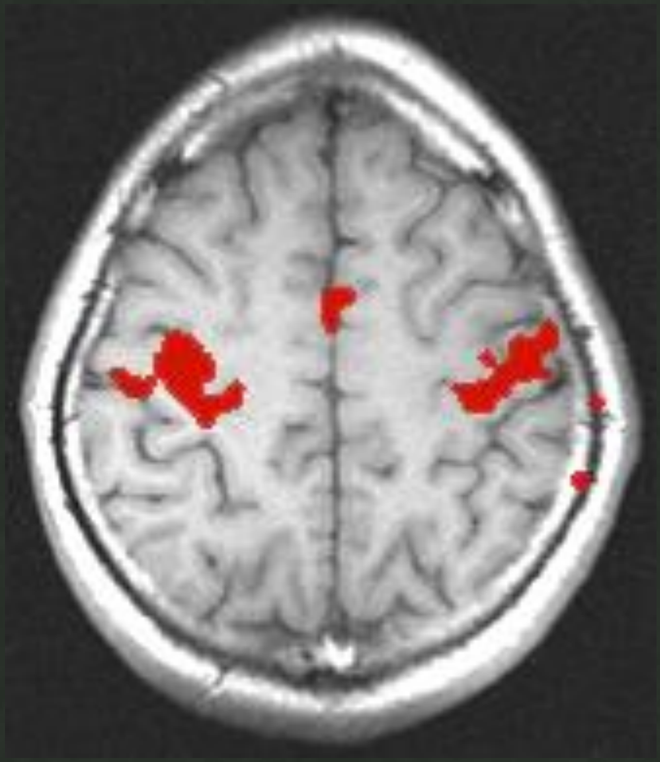
Methodology

1. Block Design
2. Frequency Enc
3. Phase Encoding
4. Event-Related
5. Orthogonal Block Design
6. Free Behavior Design.

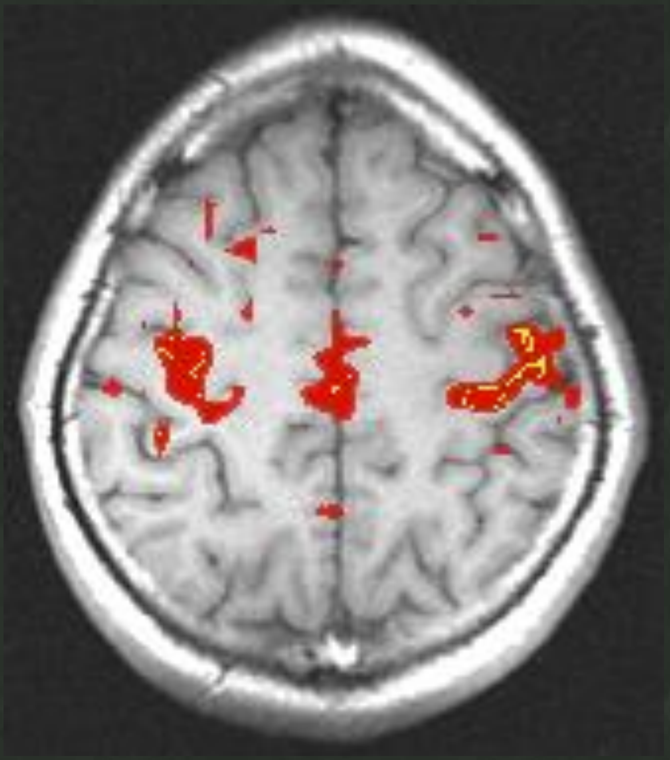




Resting State Correlations



Activation:
correlation with reference function



Rest:
seed voxel in motor cortex

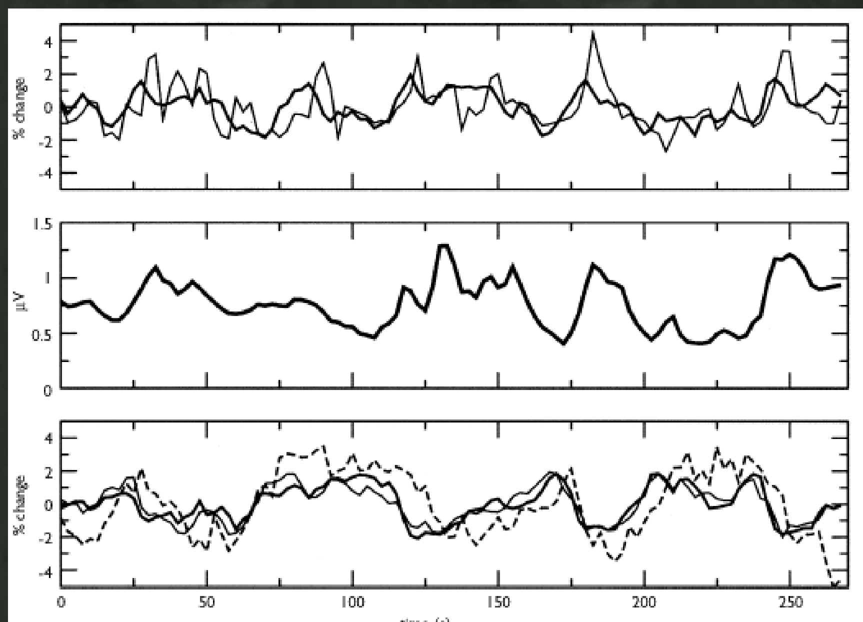
B. Biswal *et al.*, MRM, 34:537 (1995)

BOLD correlated with 10 Hz power during "Rest"

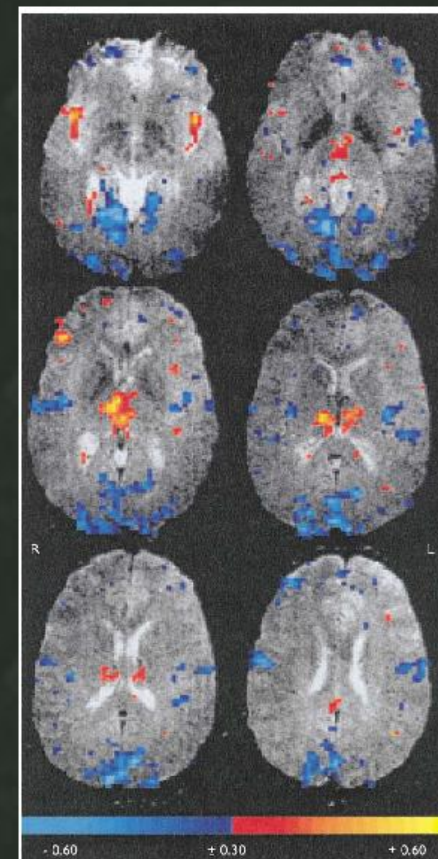
Positive

10 Hz power

Negative

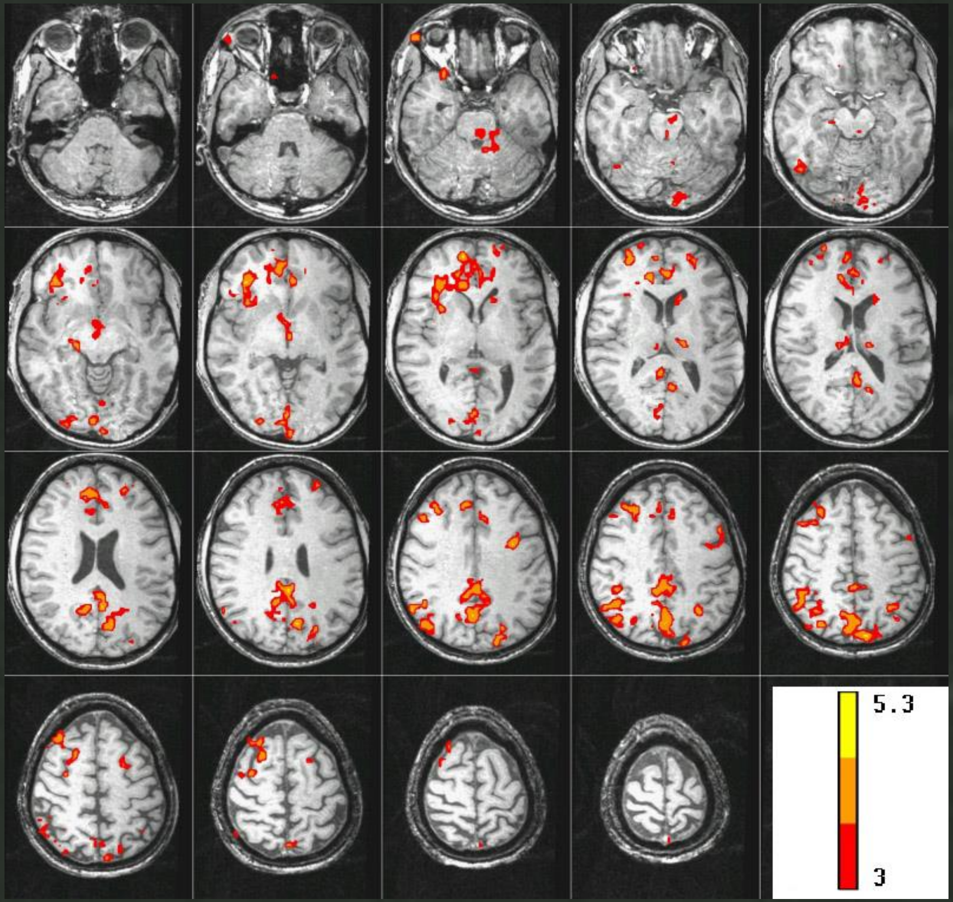


Goldman, et al (2002), Neuroreport



Methodology

BOLD correlated with SCR during "Rest"



J. C. Patterson II, L. G. Ungerleider, and P. A Bandettini, *NeuroImage* ***17****: 1787-1806, (2002).*

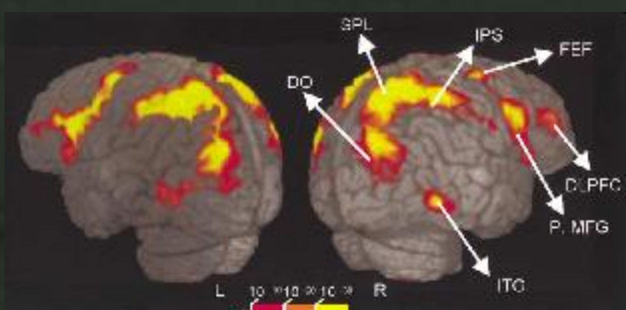
Mapping ⟷ "Reading"

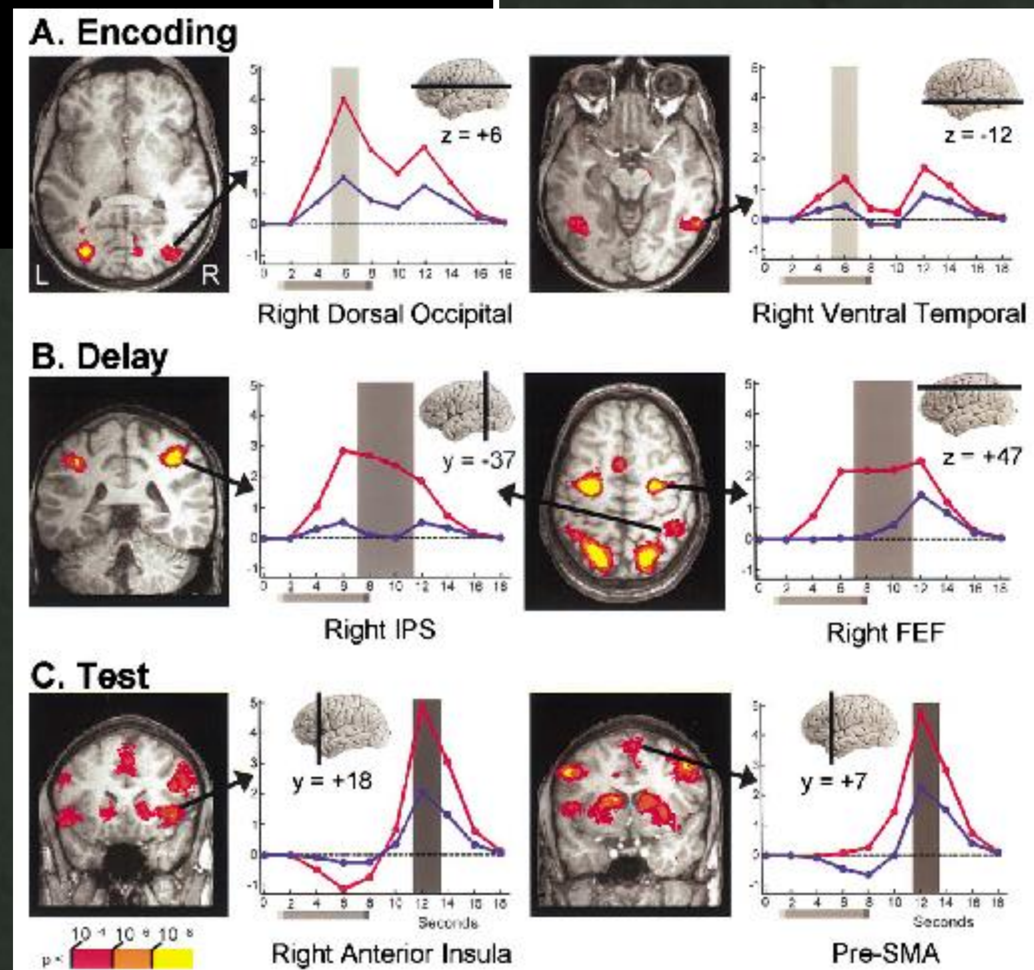
Pattern Classification

Neuron, Vol. 35, 975–987, August 29, 2002, Copyright ©2002 by Cell Press

Neural Correlates of Visual Working Memory: fMRI Amplitude Predicts Task Performance

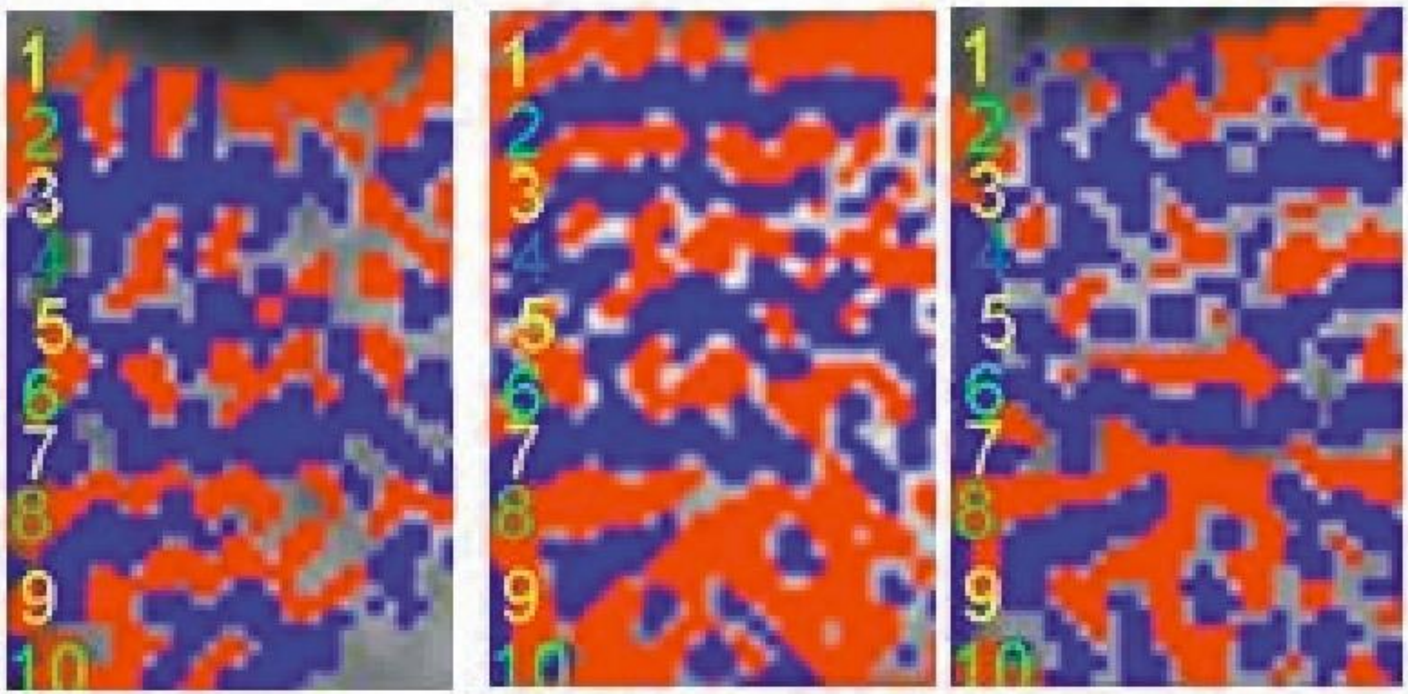
Luiz Pessoa,[1] Eva Gutierrez, Peter A. Bandettini, and Leslie G. Ungerleider
Laboratory of Brain and Cognition
National Institute of Mental Health
National Institutes of Health
Bethesda, Maryland 20892





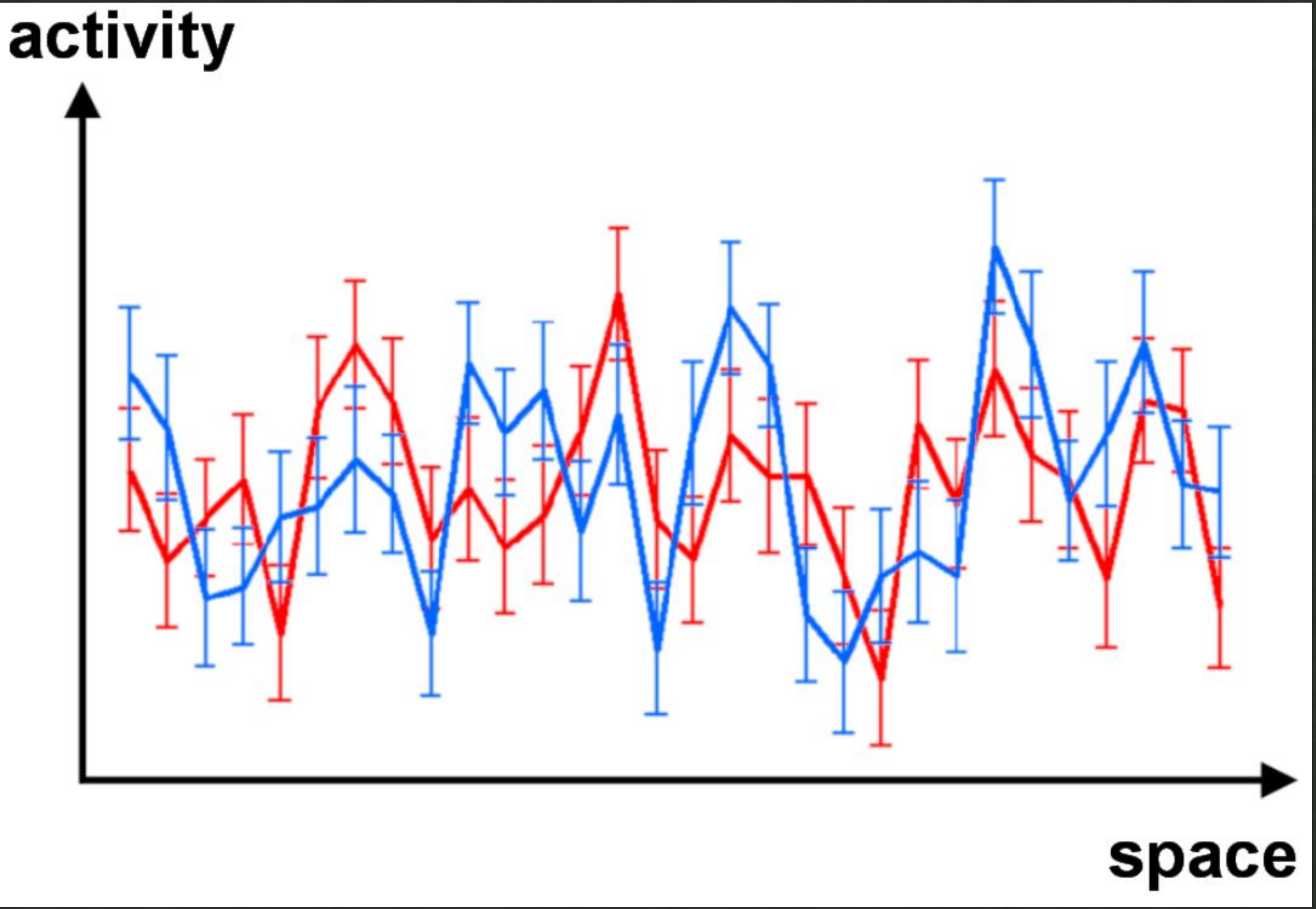
HSE-BOLD demonstration of ocular dominance columns

human, 7T, $0.5 \times 0.5 \times 3$ mm^3



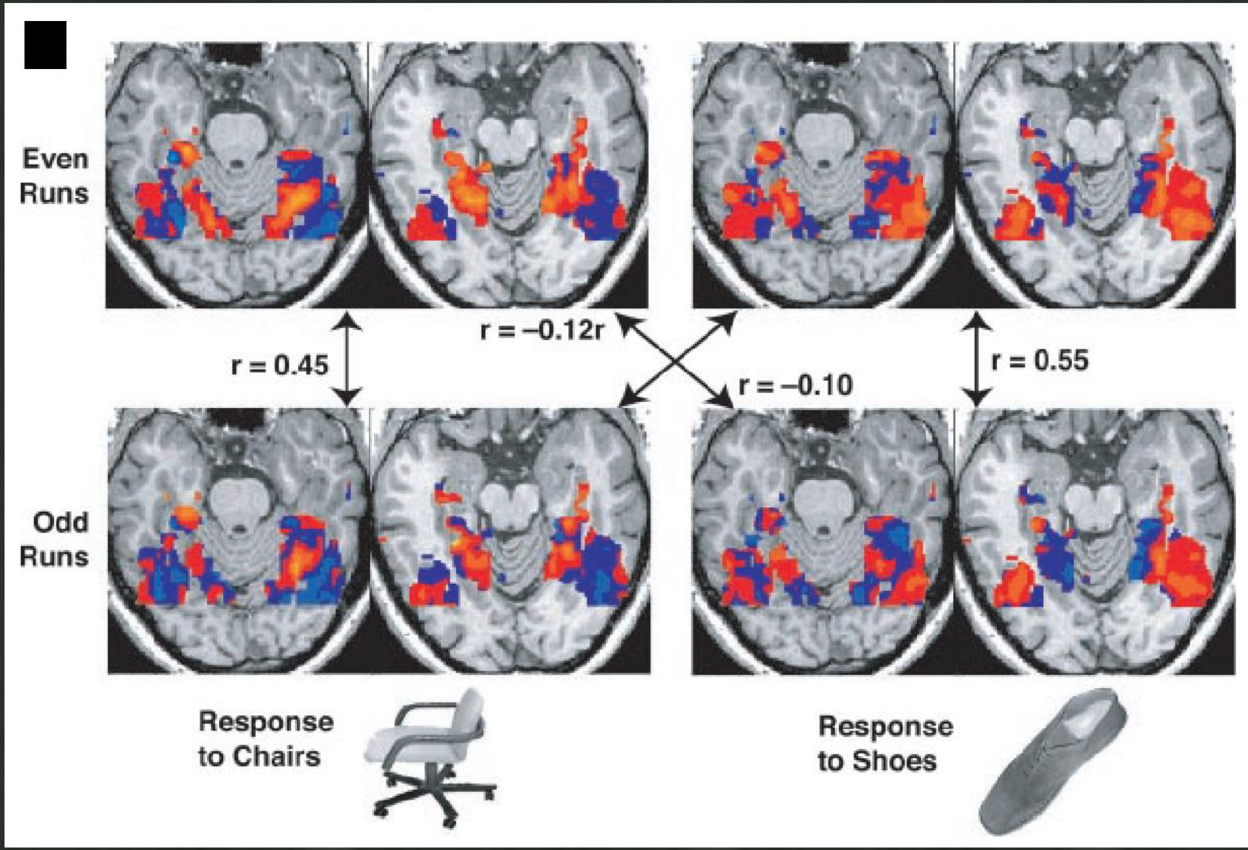
day 1 **day 2** **day 3**

Yacoub et al: differential maps contrasting stimulation of the left and right eye


activity
space

Ventral temporal category representations

- Object categories are associated with distributed representations in ventral temporal cortex
  - Present photos of common objects **blocked by category**.
  - Use fMRI to measure the pattern of high and low responses across large areas of ventral temporal cortex.
  - Observe **stable**, distributed "category representations"



Pattern-recognition analysis of fMRI activity

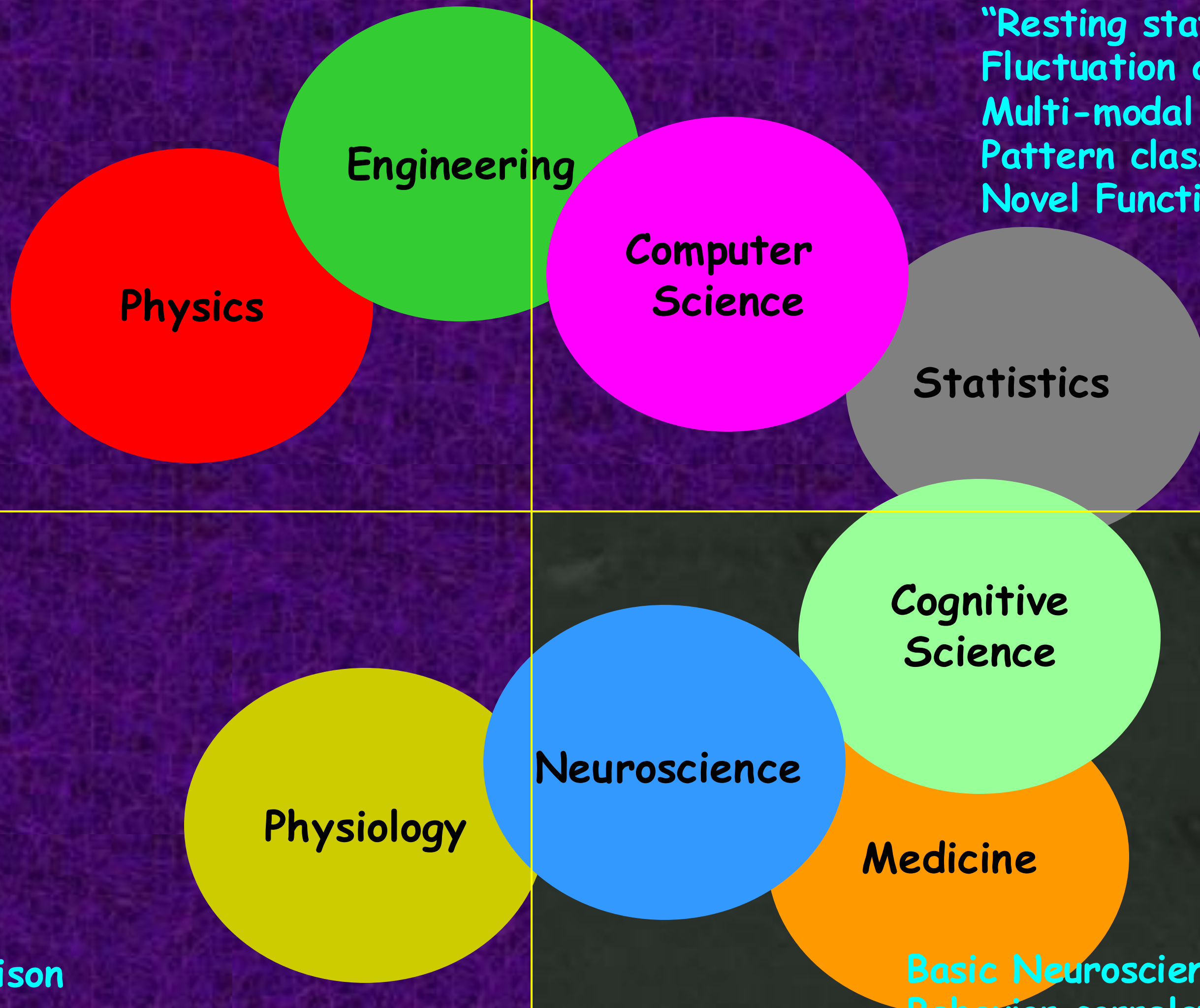
- Haxby et al. (2001)
- Cox & Savoy (2003)
- Carlson et al. (2003)
- Kamitani & Tong (2005)
- Haynes & Rees (2005)

Technology

Coil arrays
Higher field strength
Higher resolution

Methodology

"Resting state"
Fluctuation assessment
Multi-modal integration
Pattern classification
Novel Functional Contrasts



Fluctuations
Dynamics
Cross - modal comparison

Interpretation

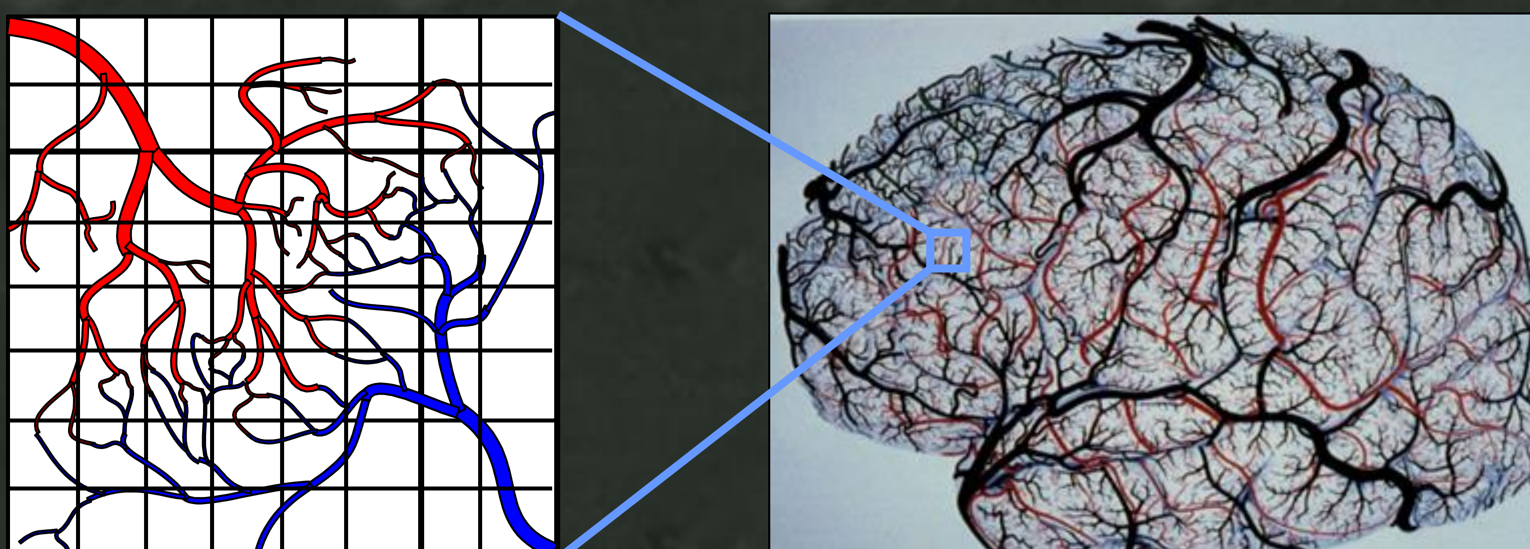
Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

Applications

Neuronal Activation ? Measured Signal

? Hemodynamics ?

? Noise



Altered neurovascular coupling: Pathology, drugs

Pathologic state / Drug	Reference
Carotid occlusion	Röther et al. 2002
Transient global ischemia	Schmitz et al. 1998
Penumbra of cerebral ischemia	Mies et al. 1993, Wolf et al. 1997
Subarachnoid hemorrhage	Dreier et al. 2000
Trauma	Richards et al. 2001
Epilepsy	Fink et al. 1996, Brühl et al. 1998, von Pannwitz et al. 2002
Alzheimer´s disease	Hock et al. 1996, Niwa et al. 2000
Theophylline	Ko et al. 1990, Dirnagl et al. 1994
Scopolamine	Tsukada et al. 1998

Courtesy of Arno Villringer

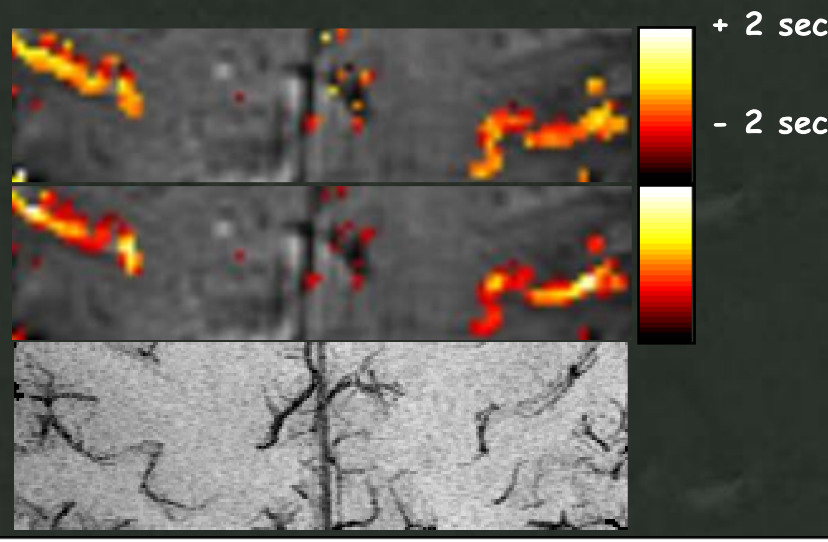
The HRF: Spatial and Temporal Resolution

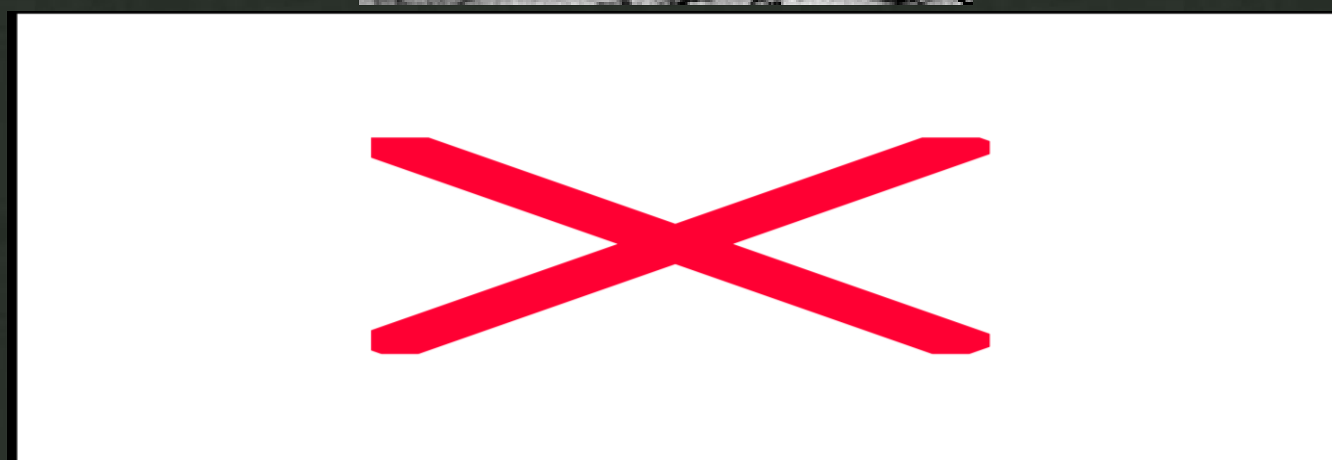
Latency Variation...

Latency

Magnitude

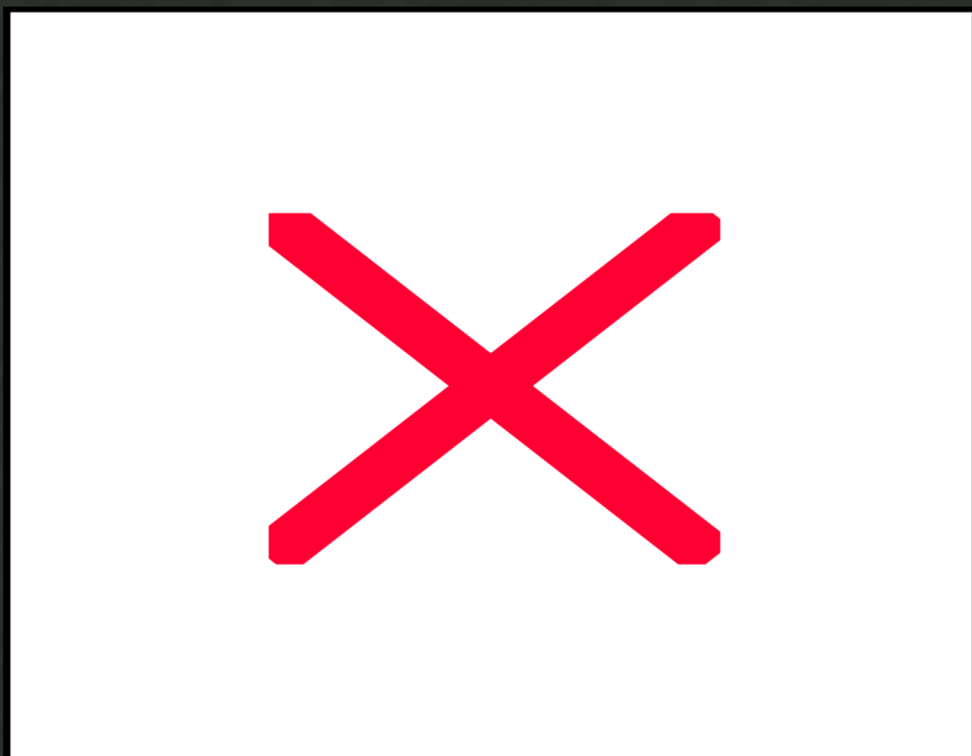
Venogram





P. A. Bandettini, (1999) "Functional MRI" 205-220.

The HRF: Spatial and Temporal Resolution



Word vs. Non-word

0°, 60°, 120° Rotation

Bellgowan, et al (2003), PNAS 100, 15820-15283

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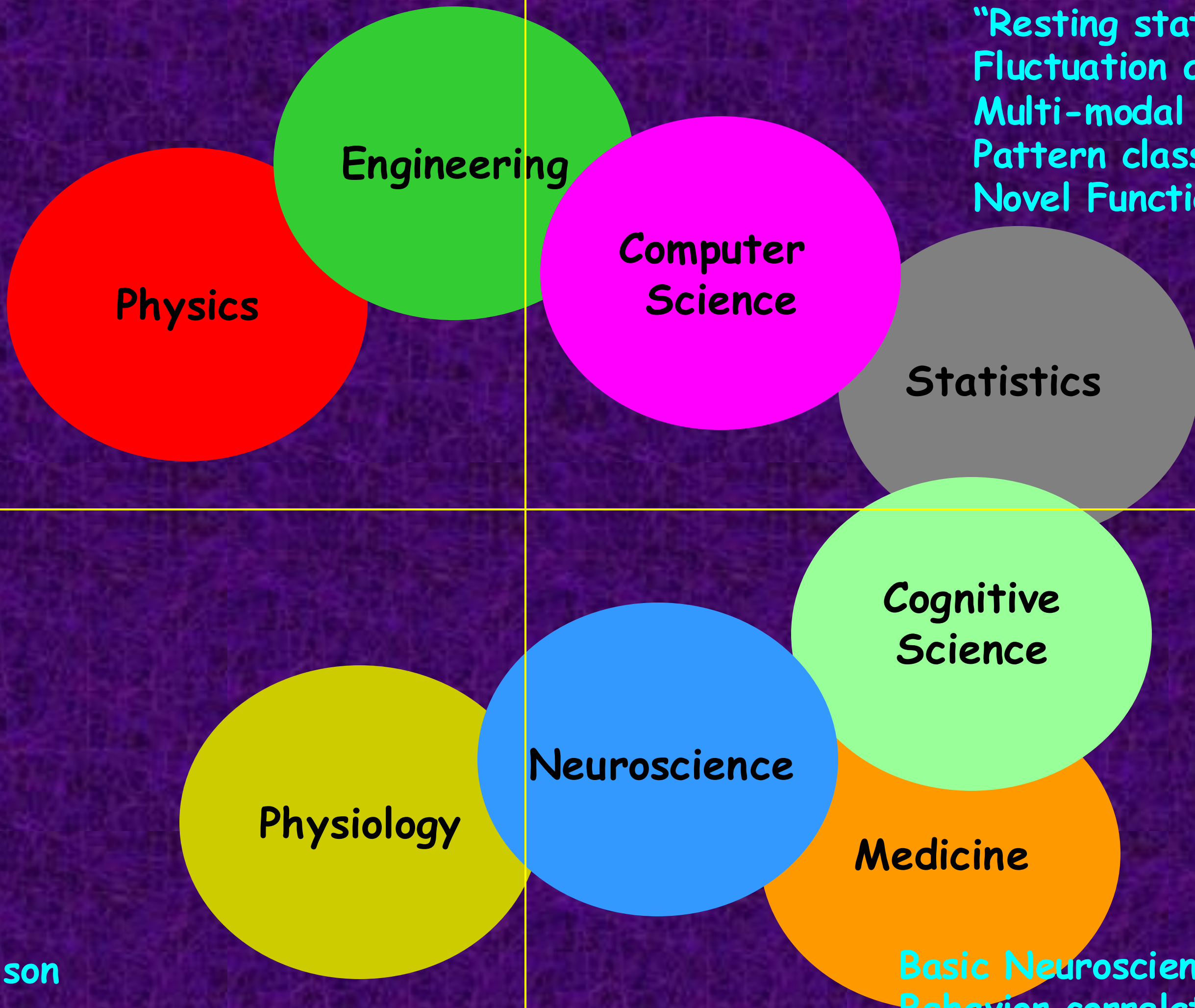

Fluctuations
Dynamics
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Applications

Current Uses of fMRI

Understanding normal brain organization and changes

-networks involved with specific tasks (low to high level processing)
-changes over time (seconds to years)
-correlates of behavior (response accuracy, performance changes…)

Clinical research

-correlates of specifically activated networks to clinical populations
-presurgical mapping
-epileptic foci mapping
-drug effects

Potential uses of fMRI

***Complementary* use for clinical diagnosis**

-utilization of clinical research results

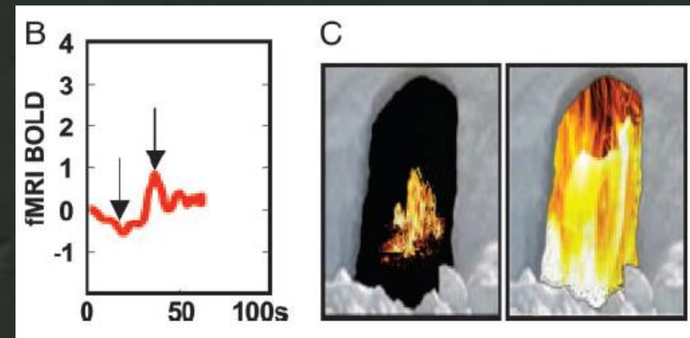
Clinical treatment and assessment

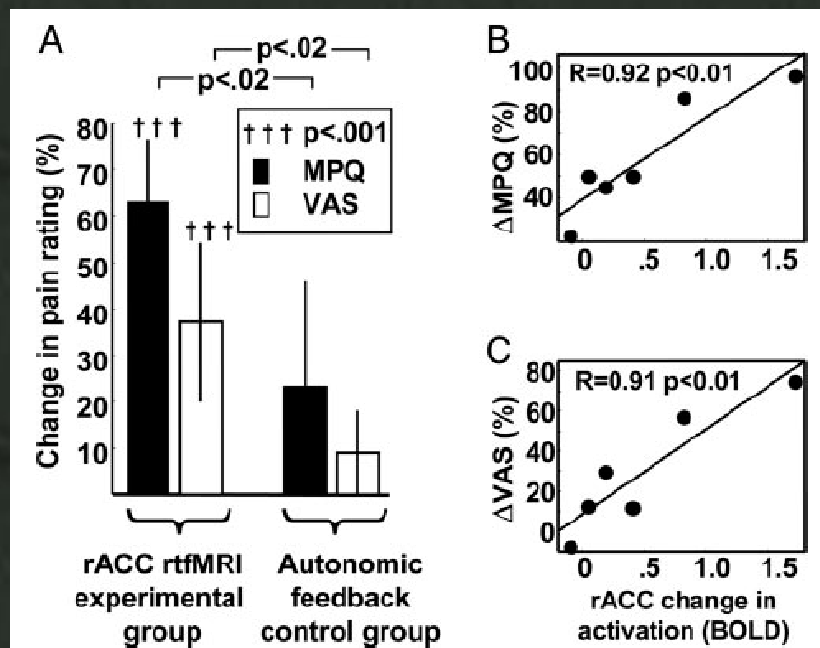
-drug, therapy, rehabilitation, biofeedback

Non clinical uses

-complementary use with behavioral results
-lie detection
-prediction of behavior tendencies (many contexts)
-brain/computer interface

Real time fMRI feedback to reduce chronic pain



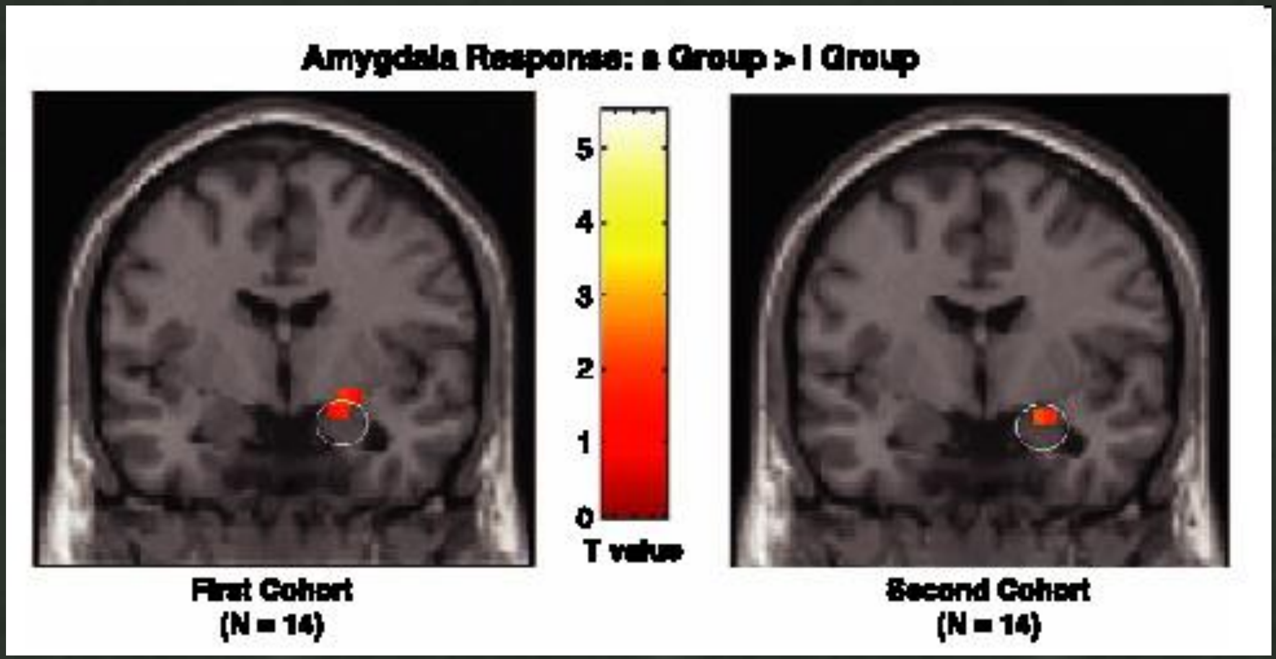


Control over brain activation and pain learned by using real-time functional MRI, R. C. deCharms, et al. PNAS, 102; 18626-18631 (2005)

Comparison of two groups of *normal* individuals with differences in the Serotonin Transporter Gene

Serotonin Transporter Genetic Variation and the Response of the Human Amygdala

Ahmad R. Hariri,[1] Venkata S. Mattay,[1] Alessandro Tessitore,[1] Bhaskar Kolachana,[1] Francesco Fera,[1] David Goldman,[2] Michael F. Egan,[1] Daniel R. Weinberger[1*]



SCIENCE VOL 297 19 JULY 2002

Applications

Human Brain Mapping 15:157–164(2002)
DOI 10.1002/hbm.10020

Lie Detection by Functional Magnetic Resonance Imaging

Tatia M.C. Lee,[1*] Ho-Ling Liu,[2] Li-Hai Tan,[3] Chetwyn C.H. Chan,[4] Srikanth Mahankali,[5] Ching-Mei Feng,[5] Jinwen Hou,[5] Peter T. Fox,[5] and Jia-Hong Gao[5]

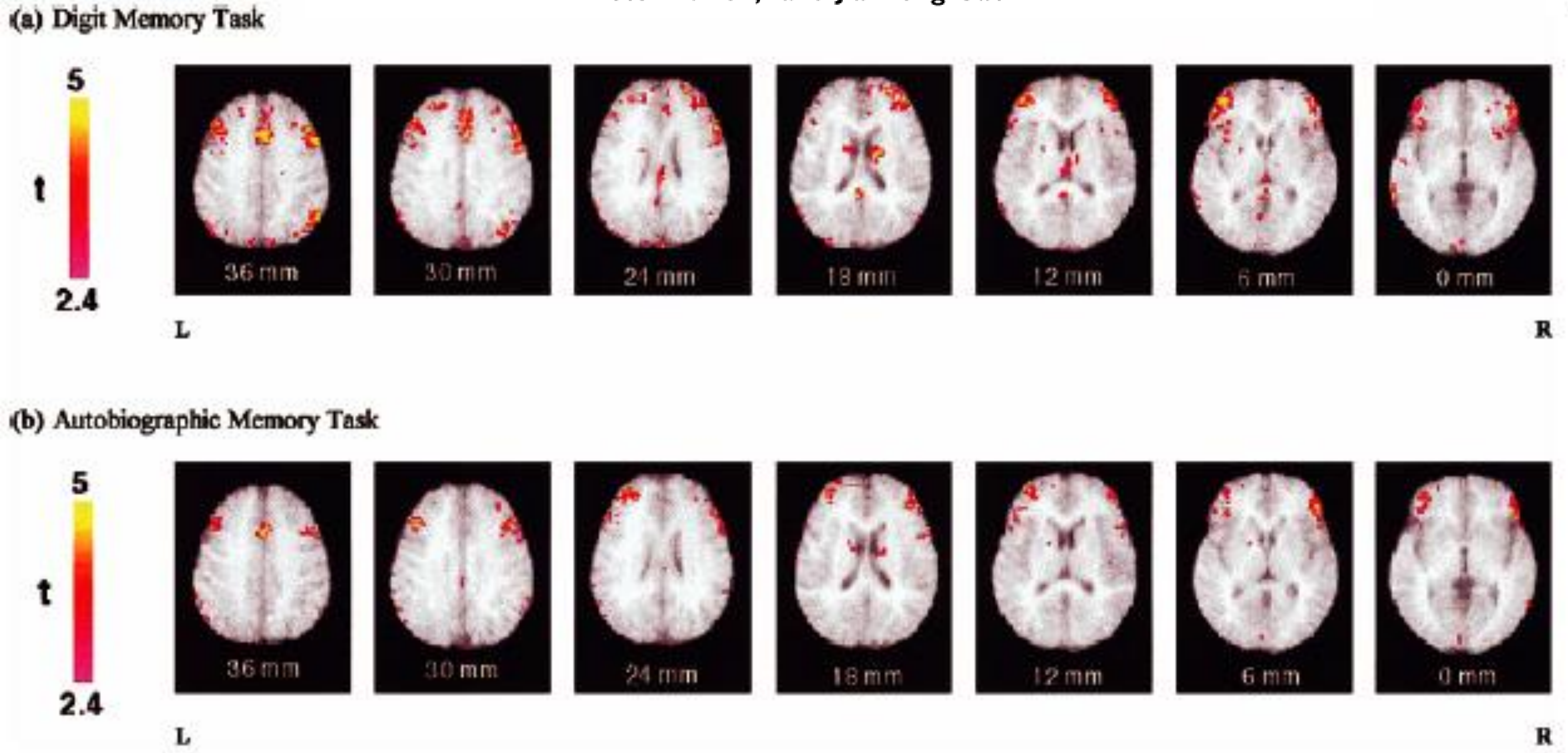


Figure 1.
Functional maps. Normalized activation brain maps averaged across five subjects demonstrating the statistically significant activations ($P < 0.01$) in the faking memory impairment condition with the activation for making accurate recall removed when performing on forced choice testing using (**a**) Digit Memory and (**b**) Autobiographic Memory tasks. Planes are axial sections, labeled with the height (mm) relative to the bicommissural line. L, left hemisphere; R, right hemisphere.

Section on Functional Imaging Methods

Rasmus Birn
David Knight
Anthony Boemio
Nikolaus Kriegeskorte
Kevin Murphy
Monica Smith
Douglass Ruff
Joey Dunsmoor
Scott Phelps
Jon West

Functional MRI Facility

Kay Kuhns
Sean Marrett
Wen-Ming Luh
Jerzy Bodurka
Adam Thomas
James Hoskie

Karen Bove-Bettis
Ellen Condon
Sahra Omar
Alda Ottley
Paula Rowser
Janet Ebron