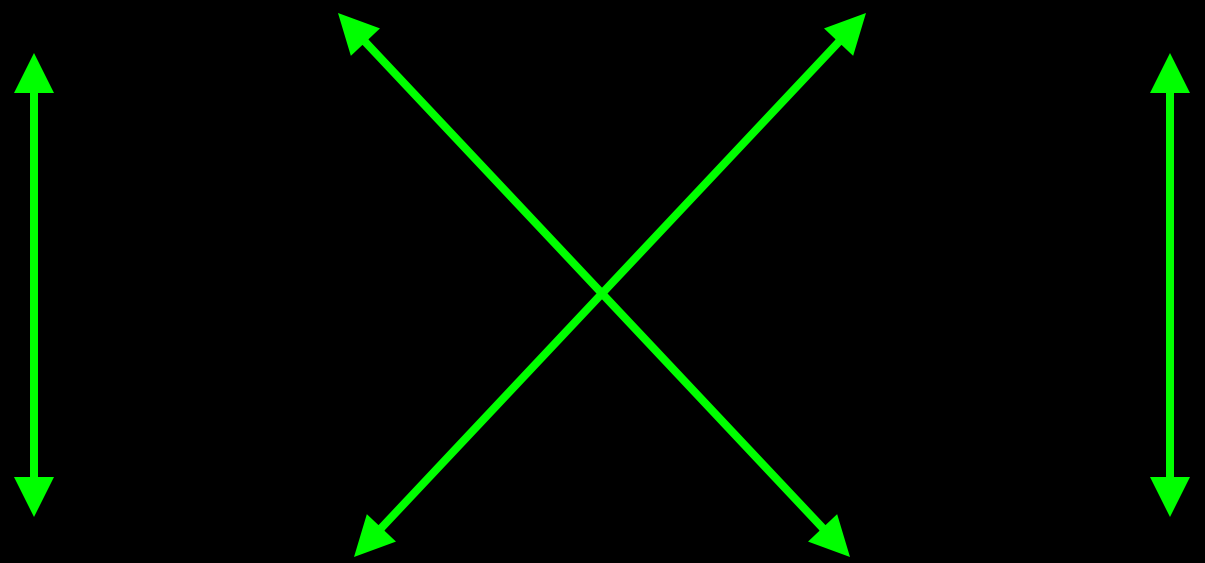
fMRI: Past, Present, and Future

Peter A. Bandettini, Ph.D

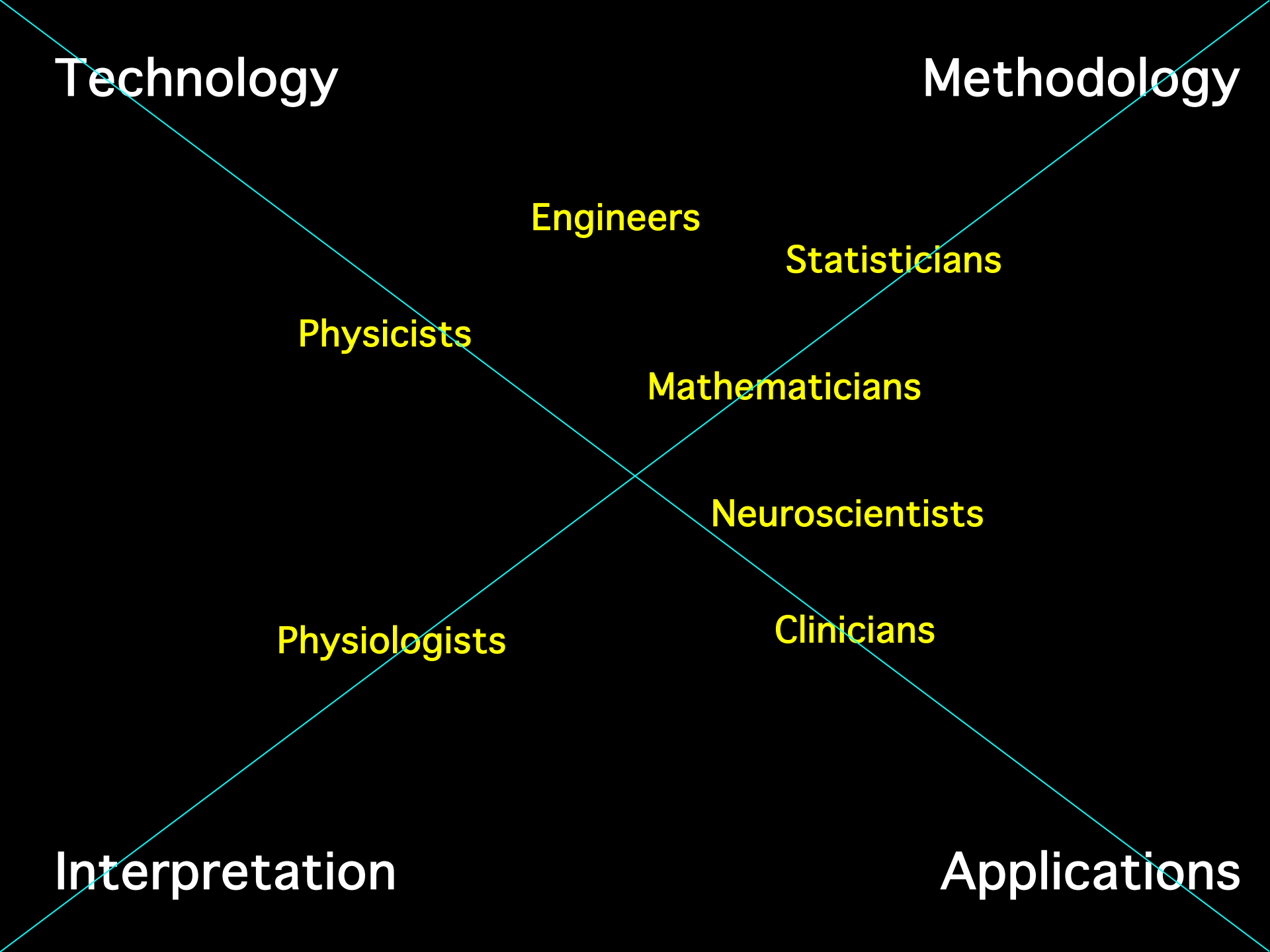
Unit on Functional Imaging Methods
&
3T Neuroimaging Core Facility

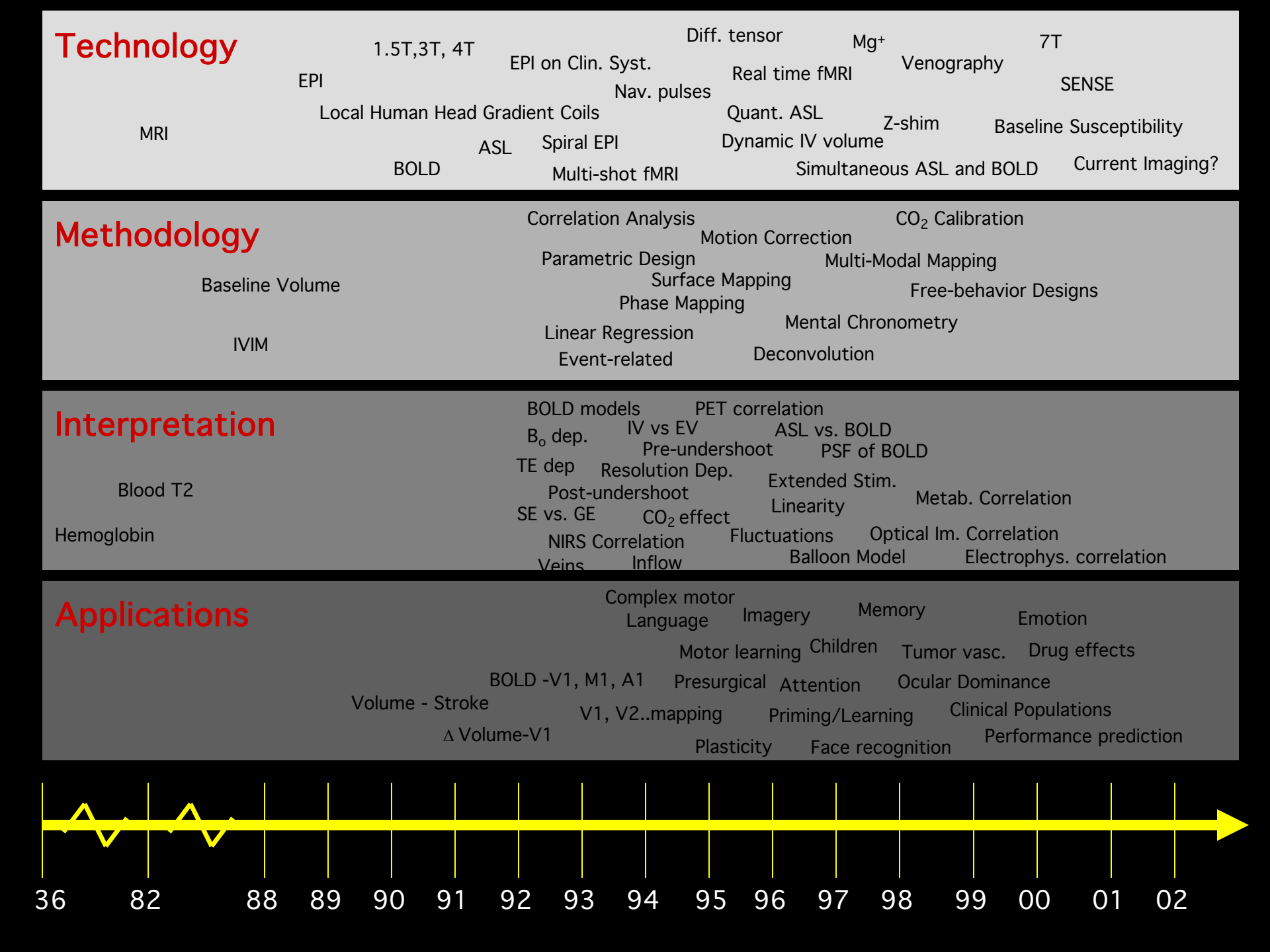
Laboratory of Brain and Cognition
National Institute of Mental Health

Technology ↔ Methodology



Interpretation ↔ Applications


Technology
Methodology
Engineers
Statisticians
Physicists
Mathematicians
Neuroscientists
Physiologists
Clinicians
Interpretation
Applications


Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
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ASL vs. BOLD
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PSF of BOLD
TE dep
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Volume - Stroke
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Performance prediction
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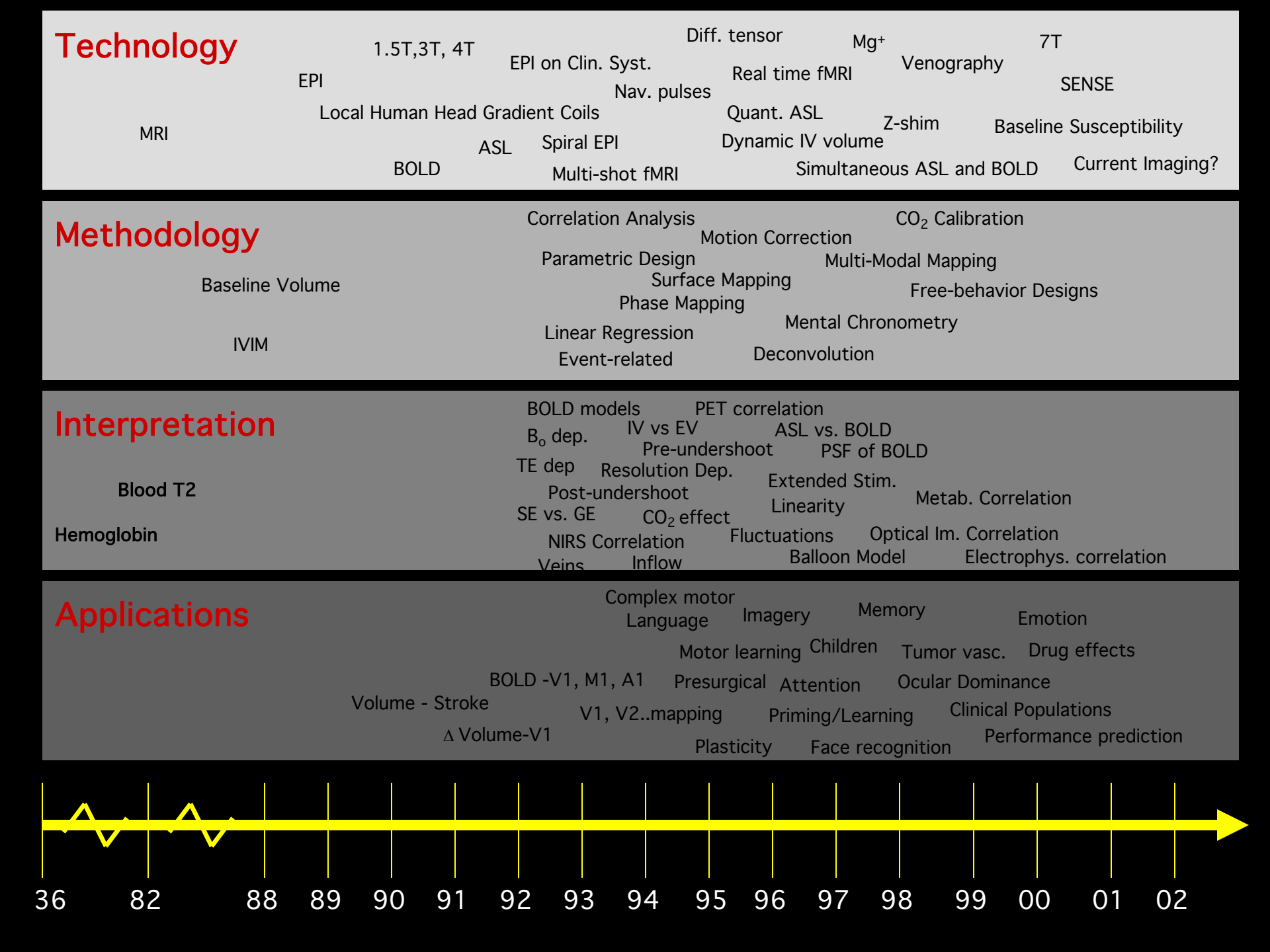
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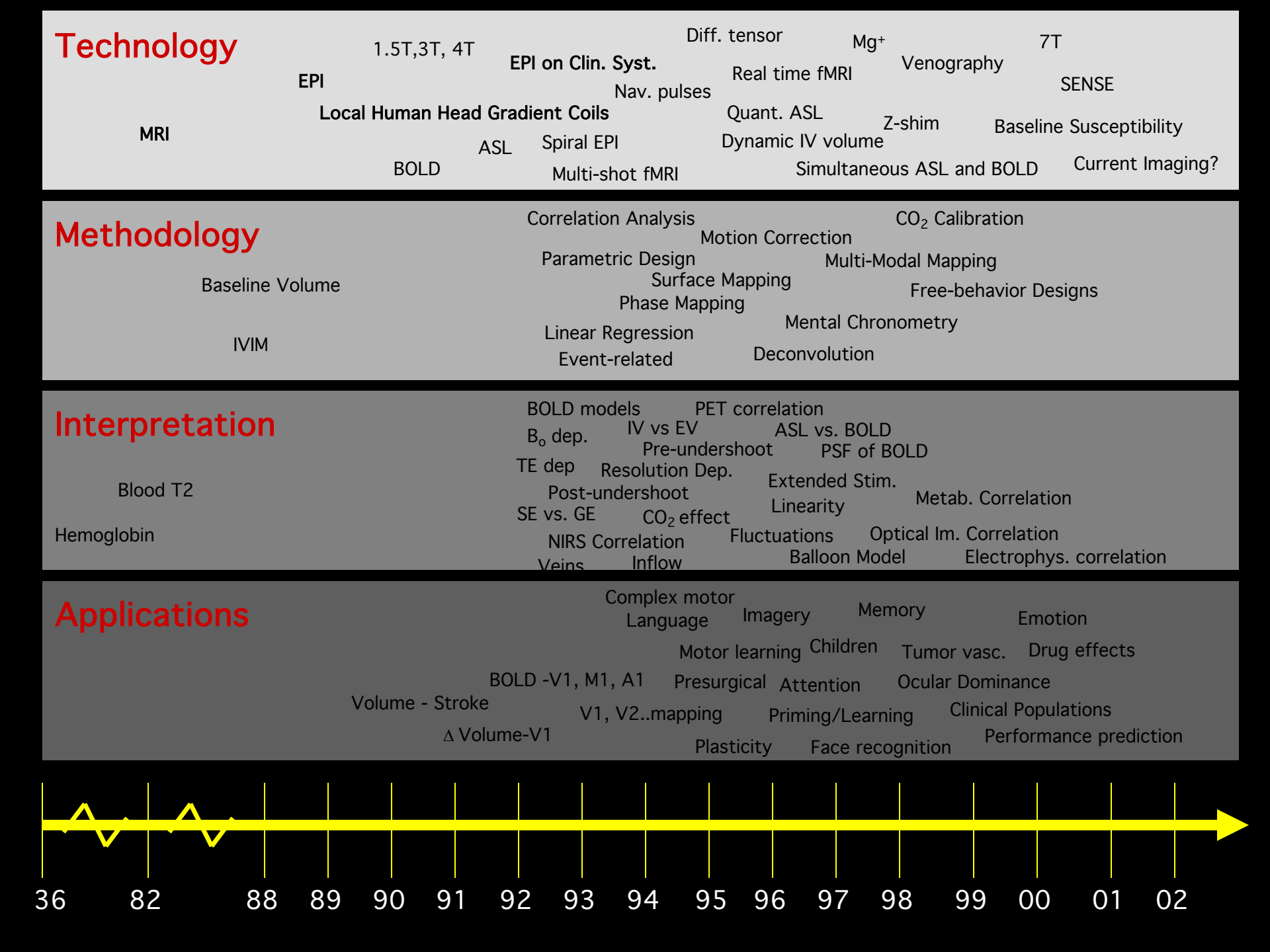
L. Pauling, C. D. Coryell, (1936) “The magnetic properties and structure of hemoglobin, oxyhemoglobin, and carbonmonoxyhemoglobin.” Proc.Natl. Acad. Sci. USA 22, 210-216.

Thulborn, K. R., J. C. Waterton, et al. (1982).“Oxygenation dependence of the transverse relaxation time of water protons in whole blood at high field.” Biochim. Biophys. Acta. 714: 265-270.

S. Ogawa, T. M. Lee, A. R. Kay, D. W. Tank, (1990) “Brain magnetic resonance imaging with contrast dependent on blood oxygenation.” Proc. Natl. Acad. Sci. USA 87, 9868-9872.

R. Turner, D. LeBihan, C. T. W. Moonen, D. Despres, J. Frank, (1991). Echo-planar time course MRI of cat brain oxygenation changes. Magn. Reson. Med. 27, 159-166.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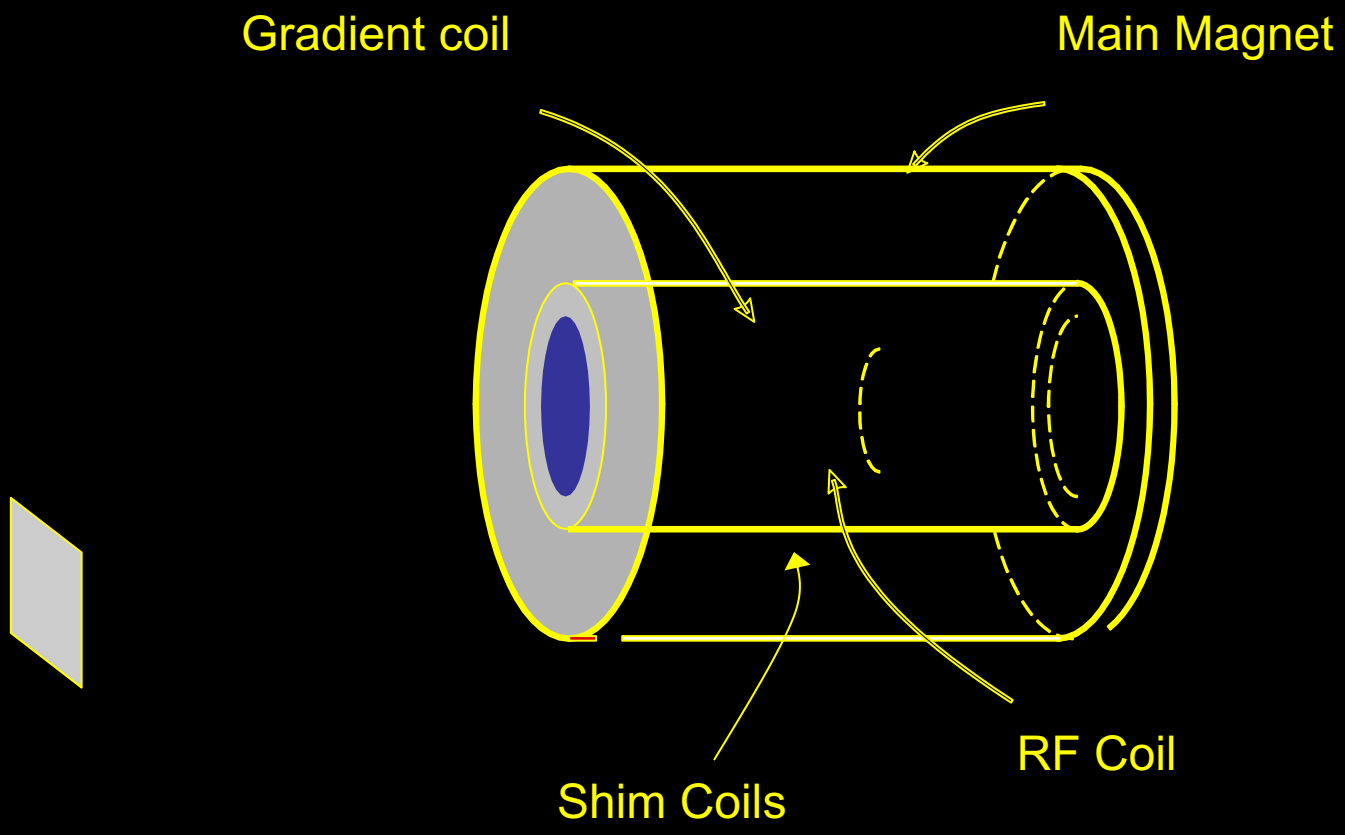
$$f_o = \gamma B_o$$

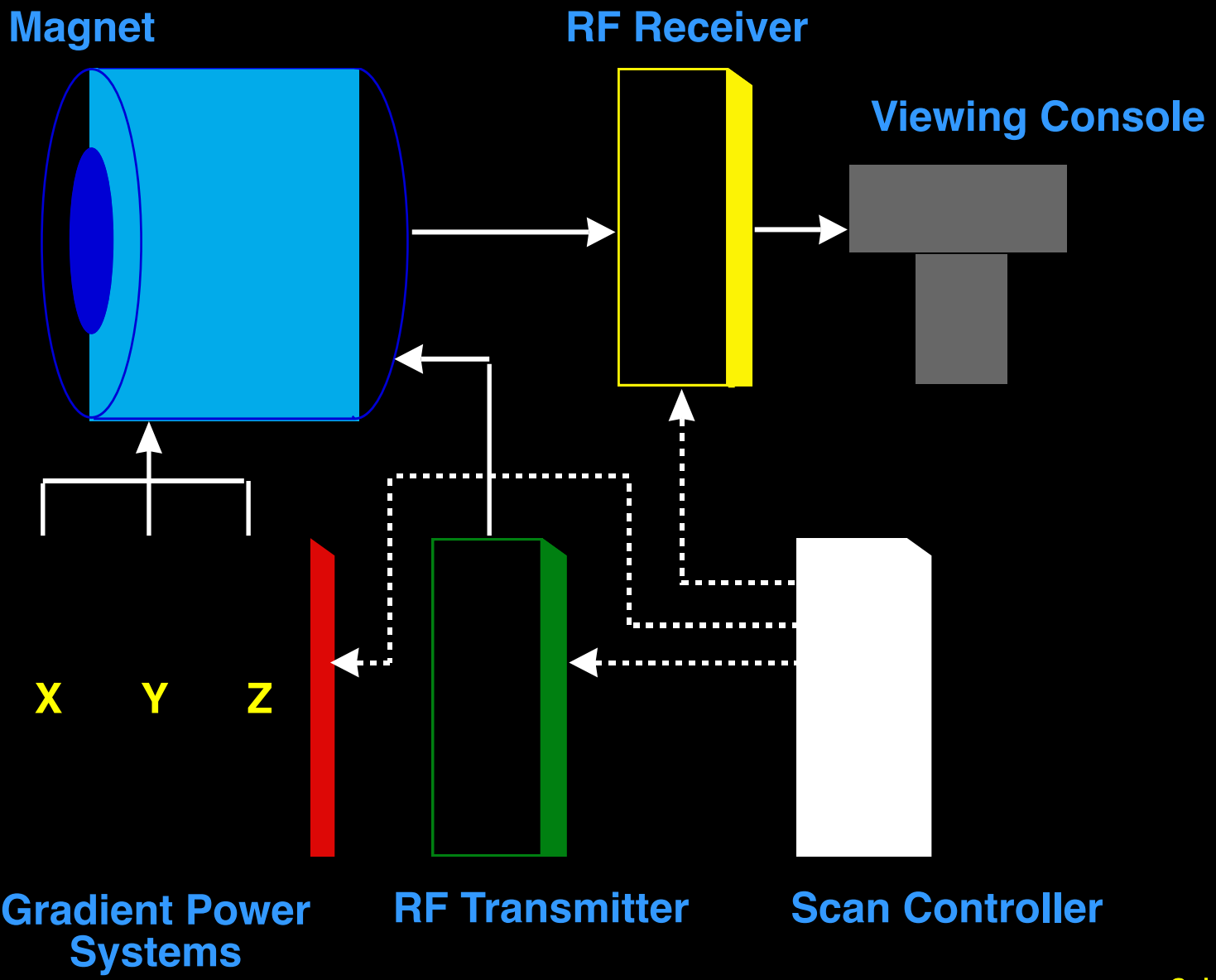
f_o = Larmor frequency

γ = gyromagnetic ratio (42.6 MHz/Tesla)

B_o = magnetic field strength (Tesla)

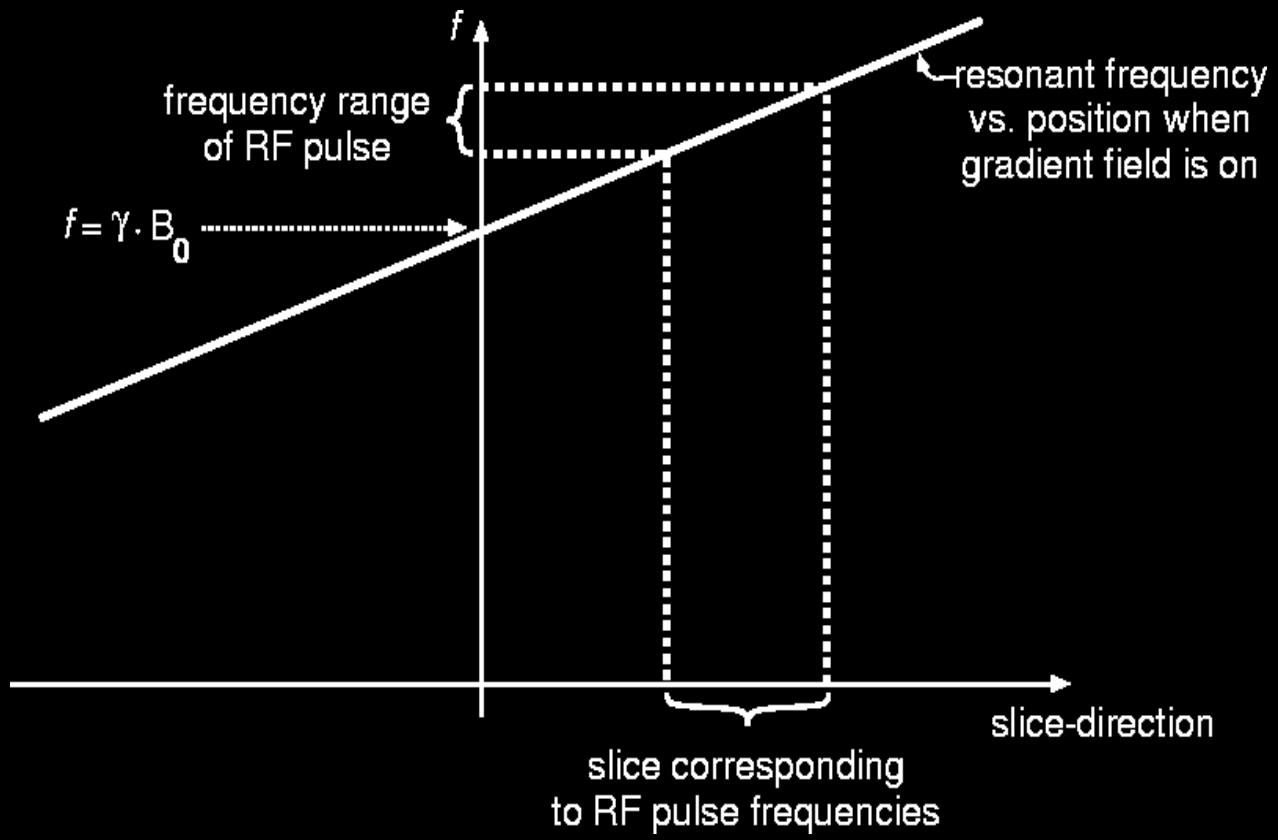

Gradient coil
Main Magnet
RF Coil
Shim Coils

Imaging System Components

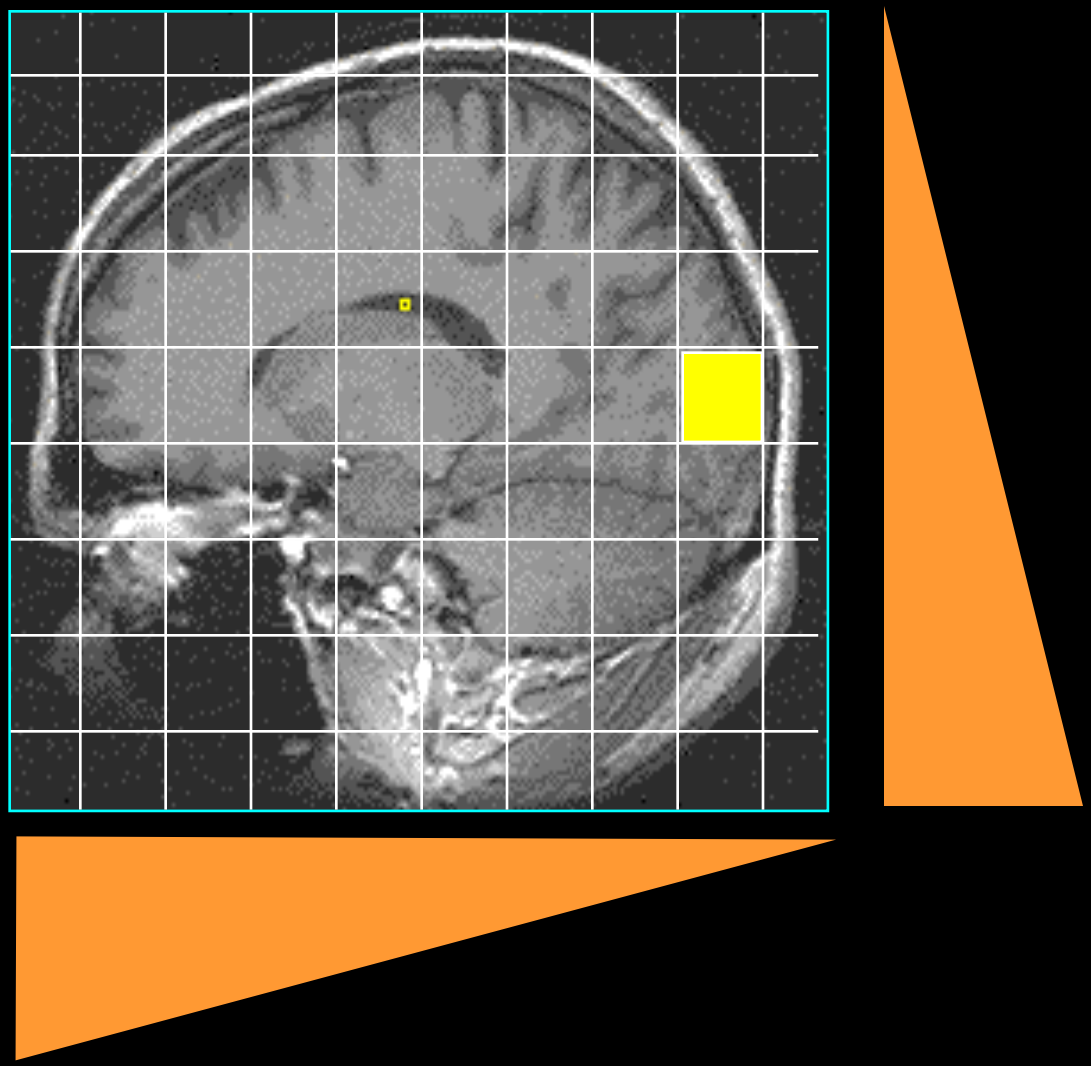


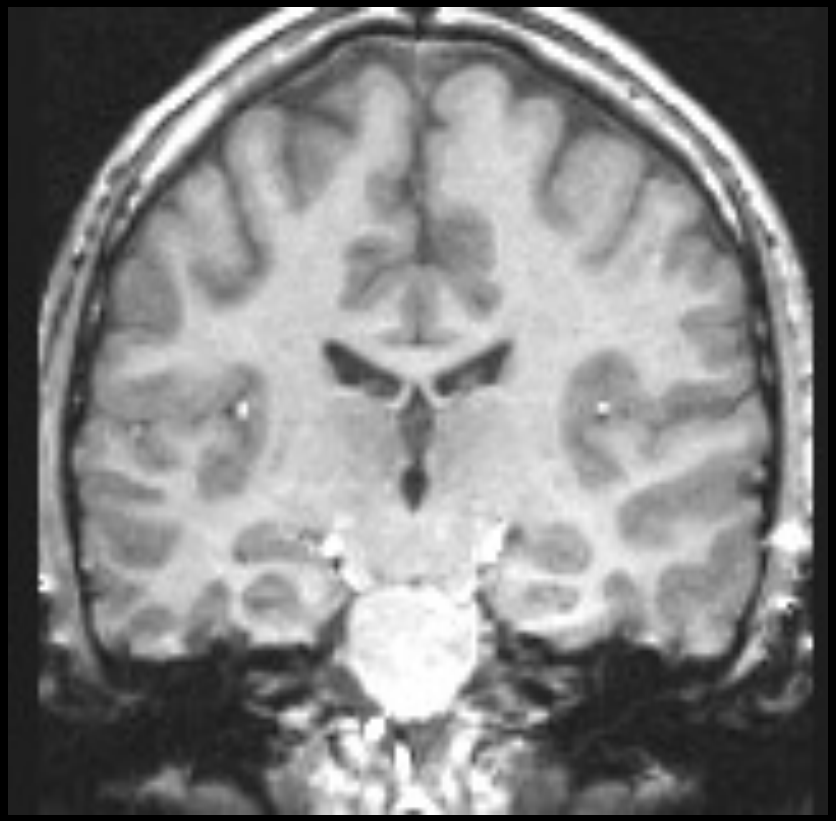
Cohen et al

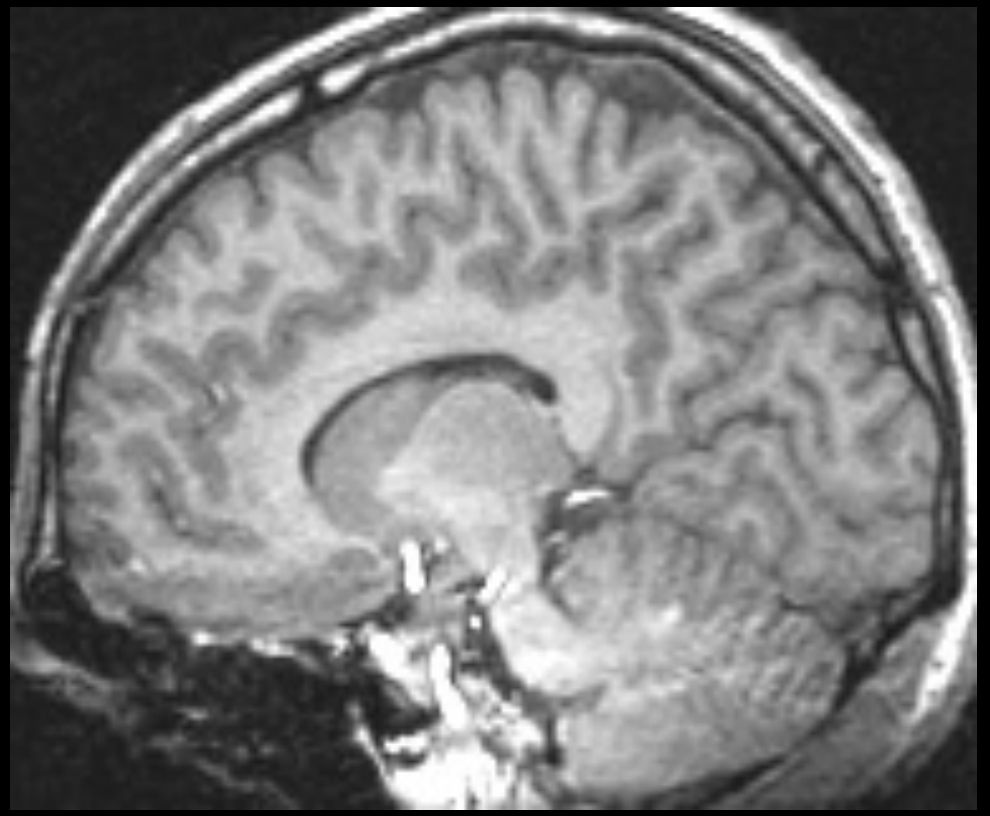
Slice Selection



In – Plane Spatial Localization



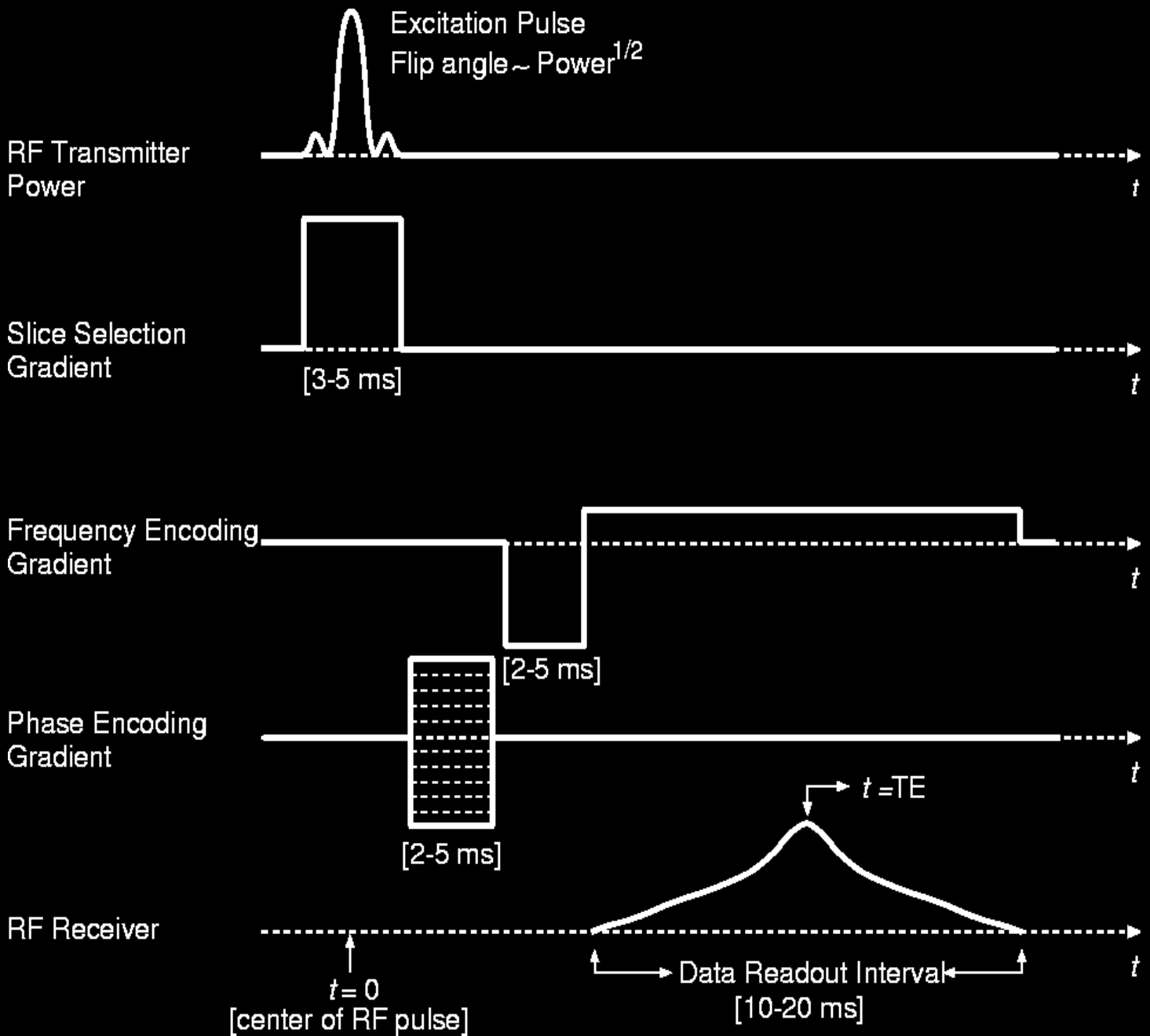




Souce of Anatomical Contrast: MRI Parameters

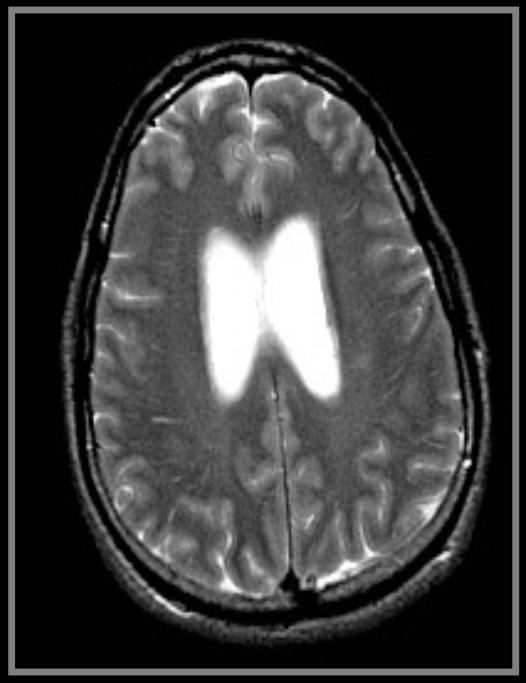
- Spin (Proton) Density
- T1 Relaxation Time
- T2, T2* Relaxation Times

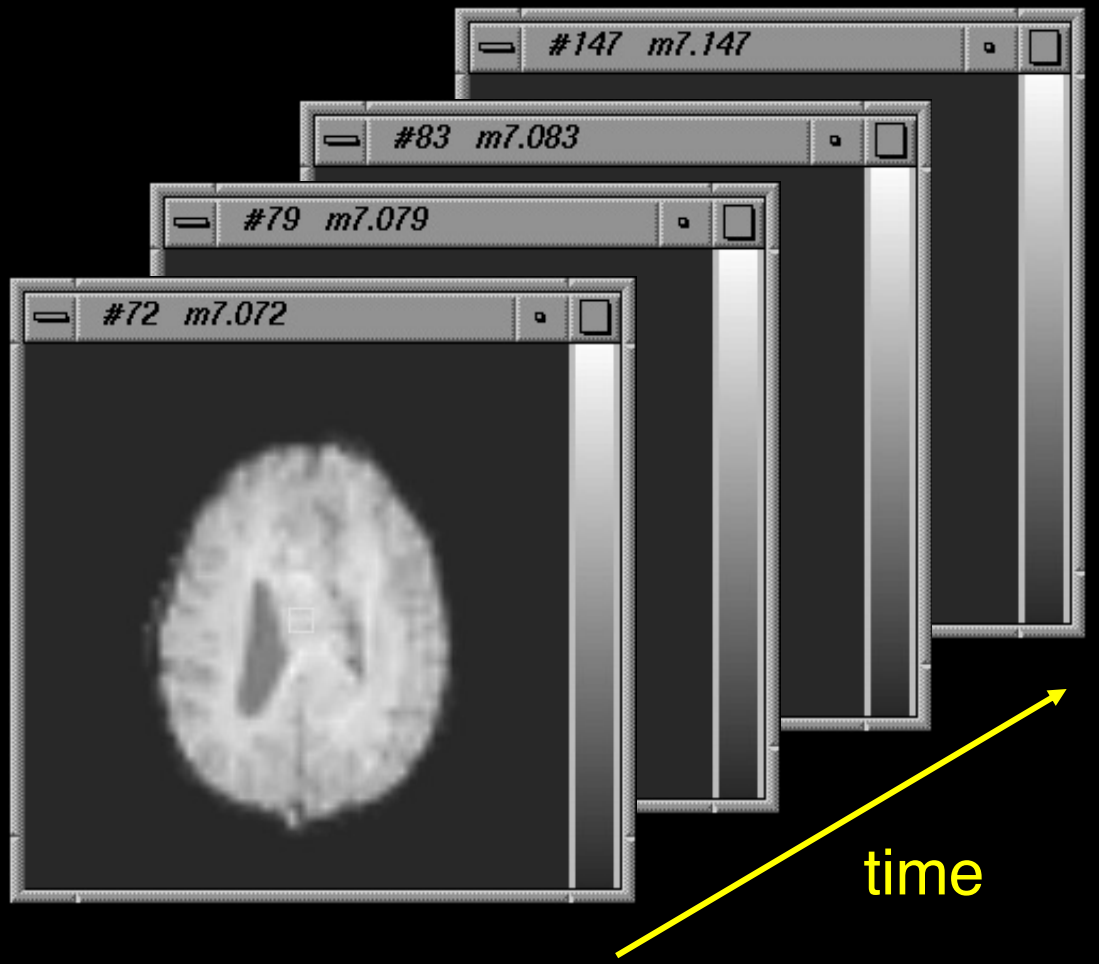
MRI Pulse Sequence for Gradient Echo Imaging



Illustrates sequence of events during scanning

As shown, this method (FLASH) takes 35 ms per RF shot, so would take 2.25 s for a 64×64 image

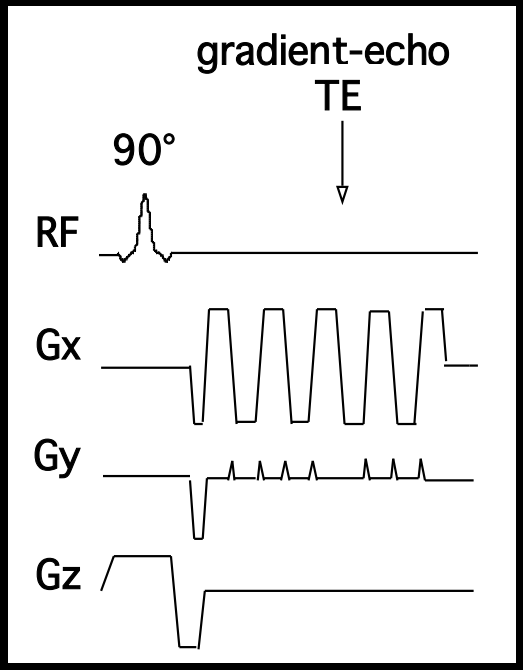


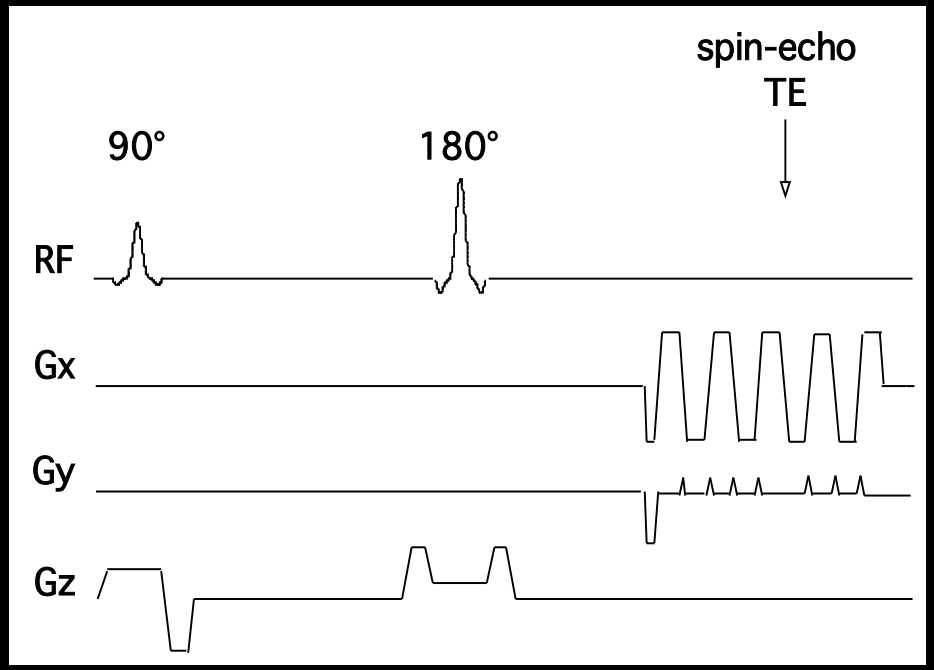


Anatomic

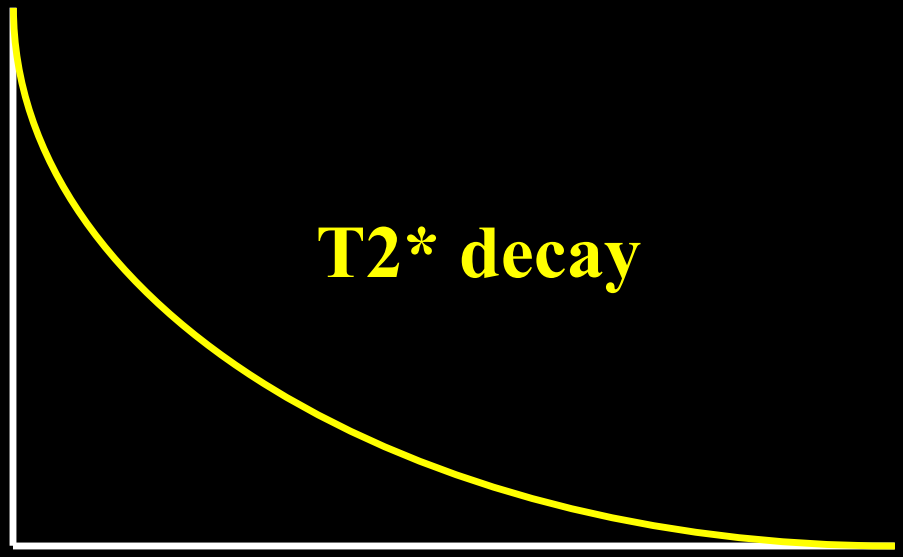
Functional

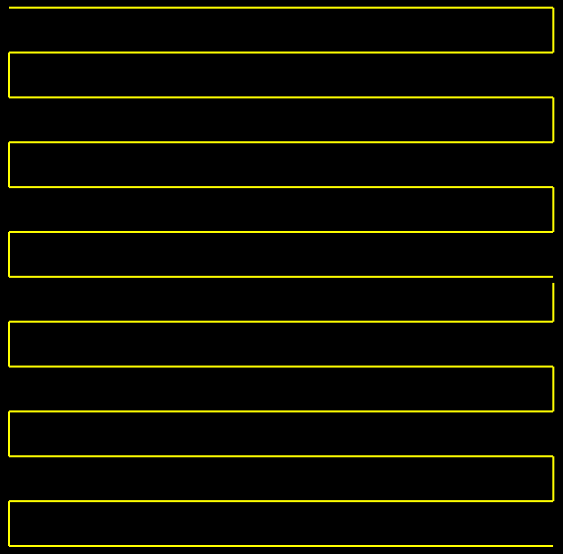
Echo-Planar Imaging





Single Shot Imaging





EPI Readout Window

≈ 20 to 40 ms

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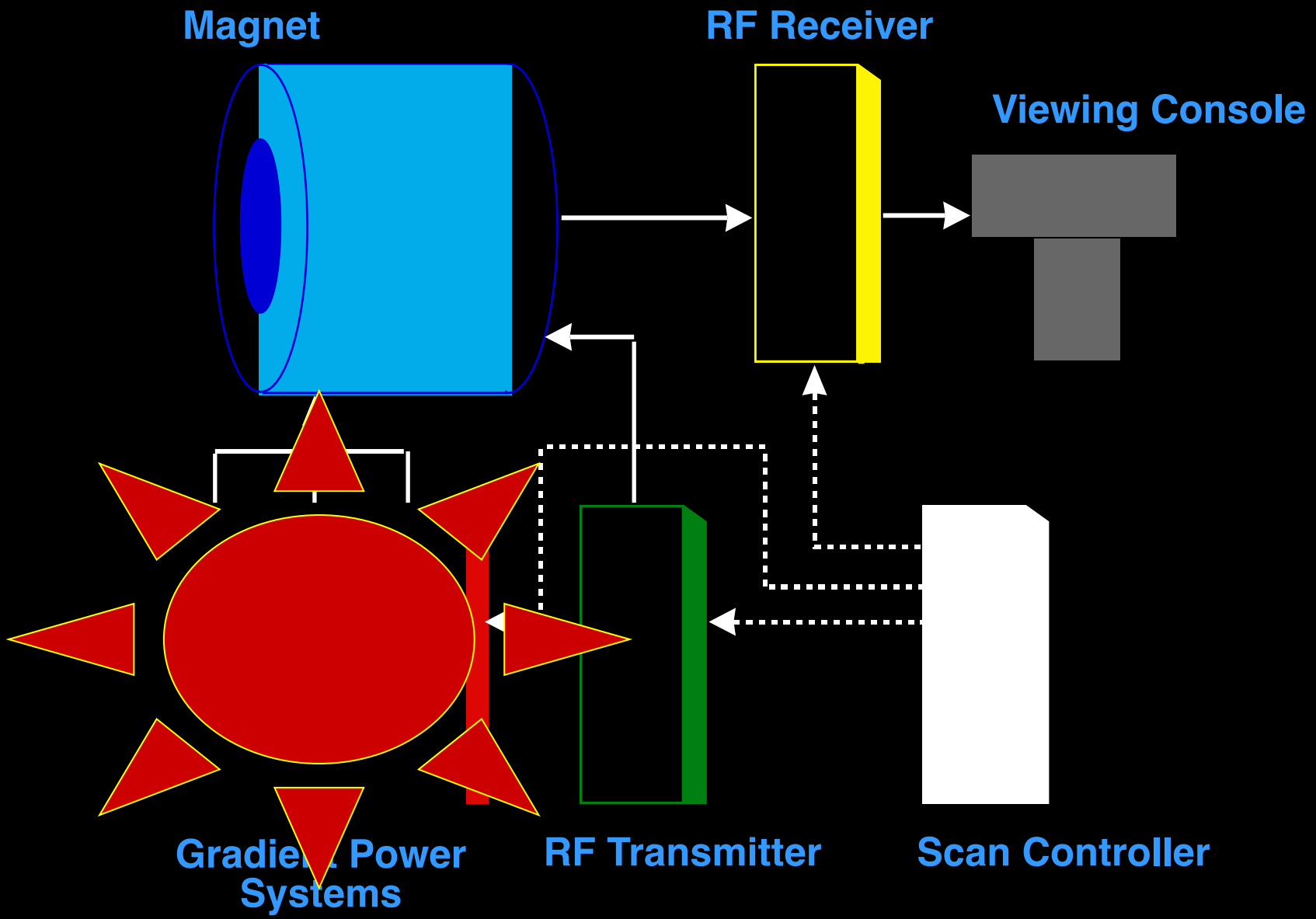

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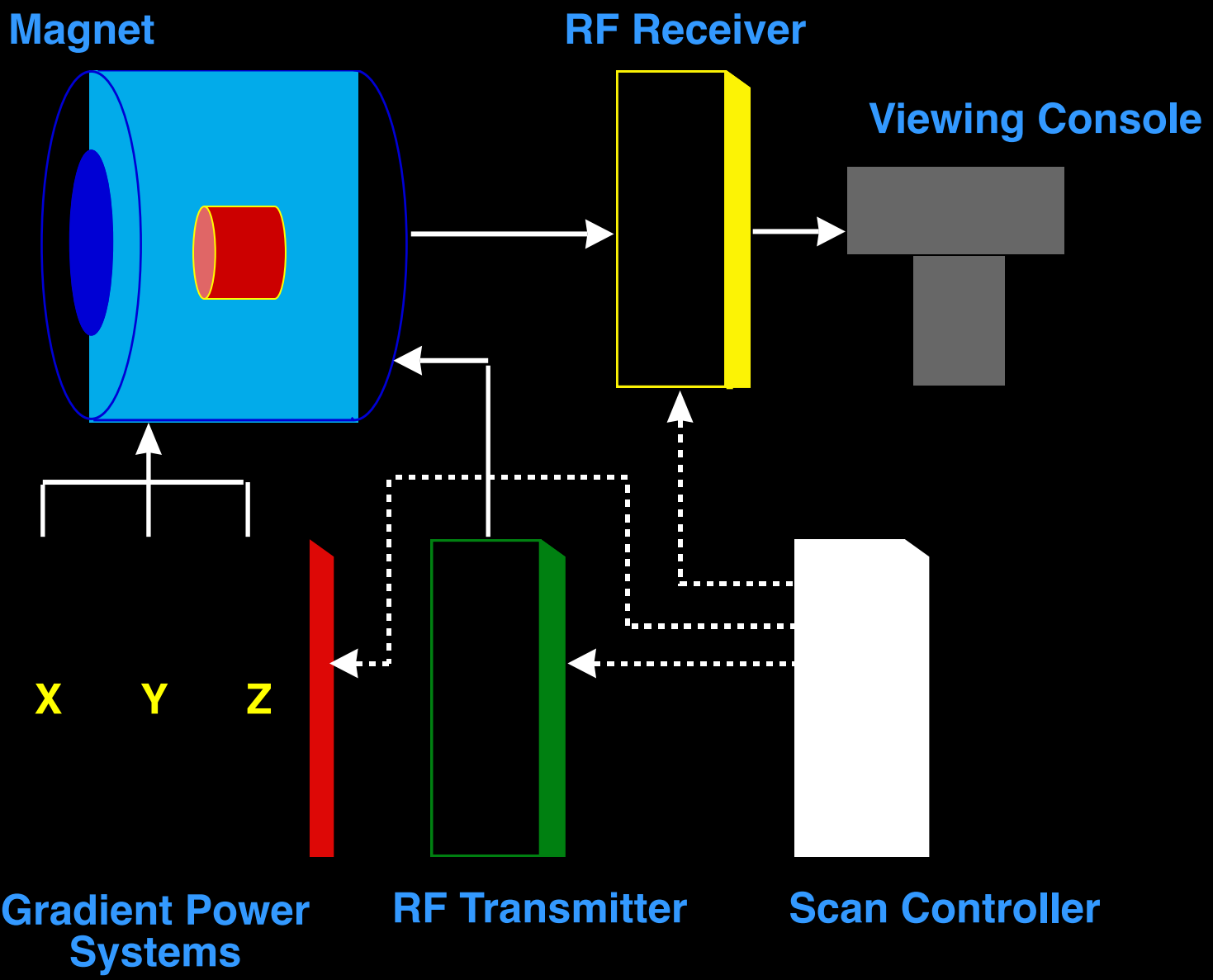
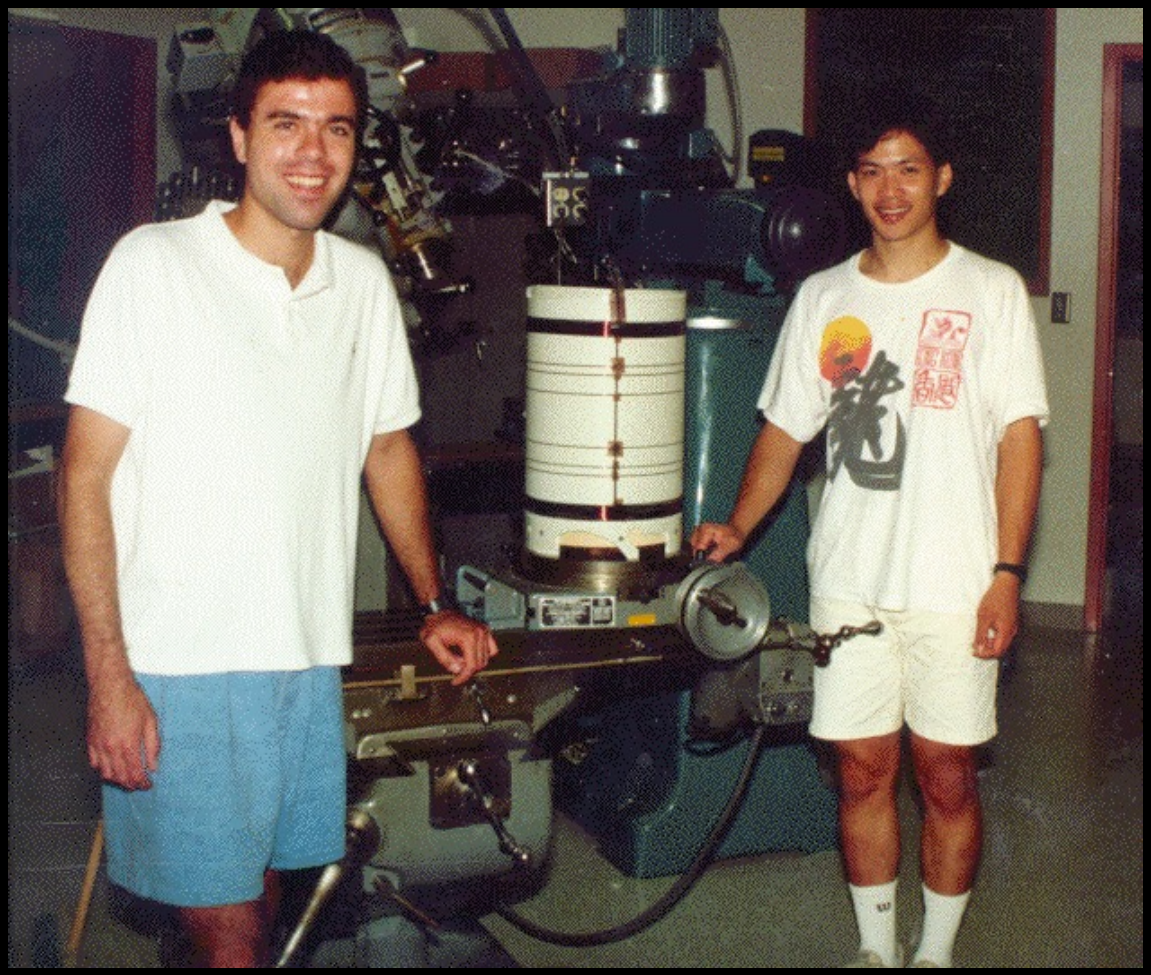


Local gradients solved the problem



August, 1991

1991-1992

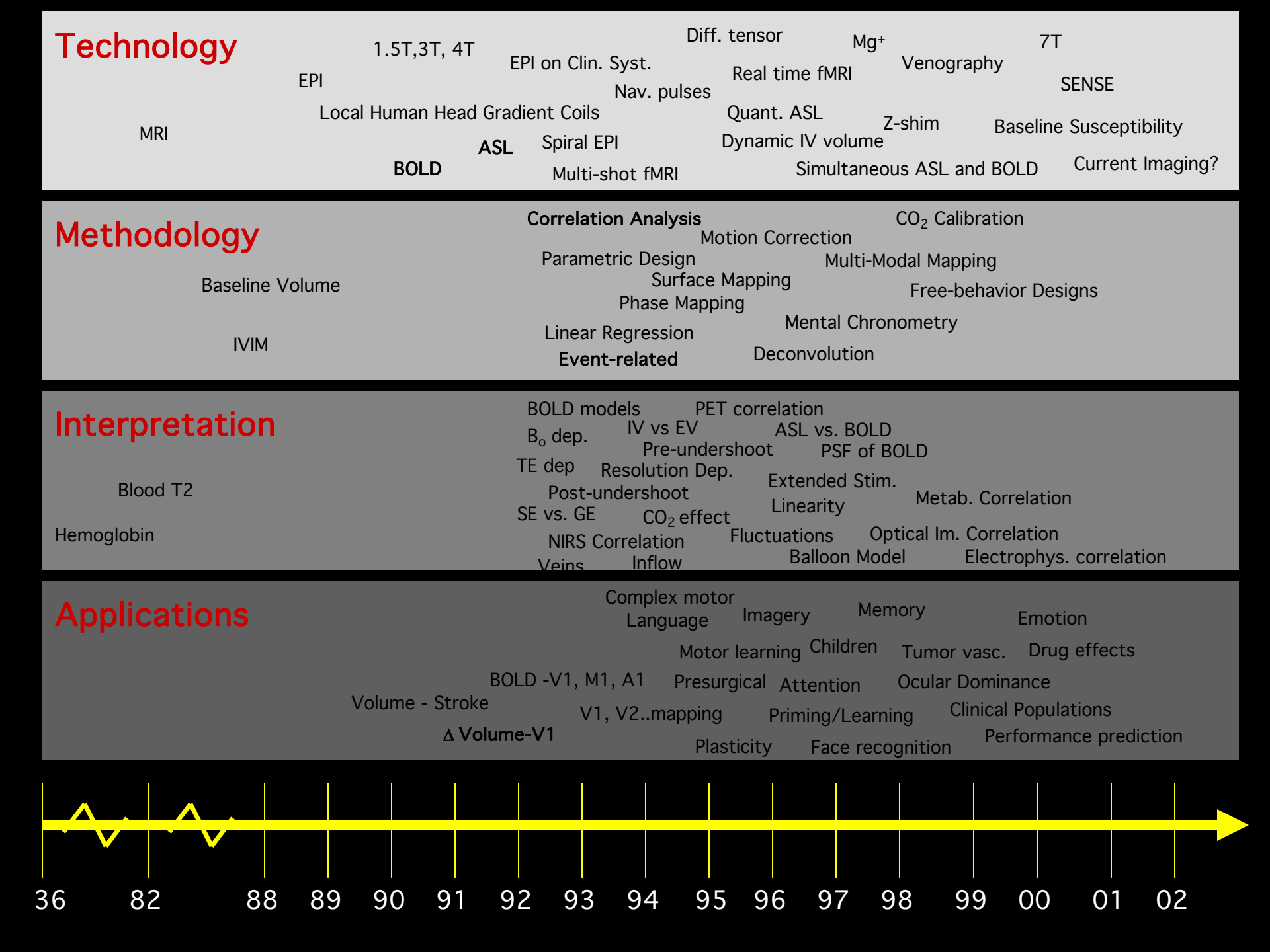
1992-1999

Functional MRI Methods

Blood Volume Imaging

BOLD Contrast

Arterial Spin Labeling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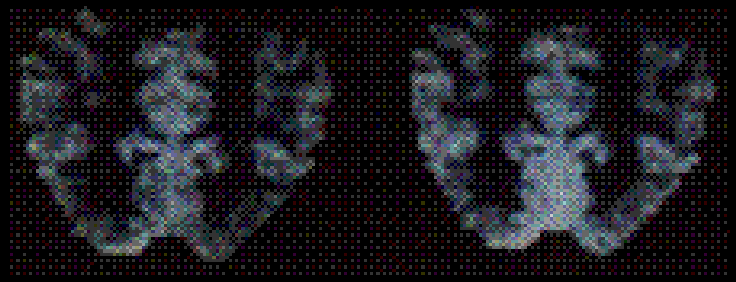
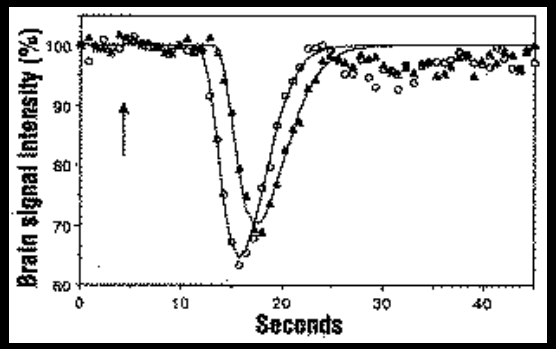
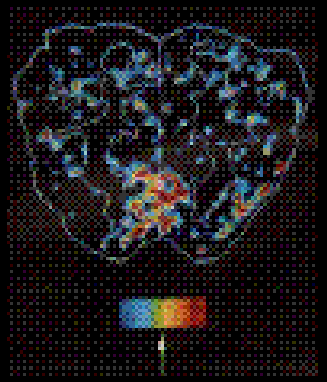
Blood Volume Imaging

Susceptibility Contrast agent bolus injection and time series collection of T2* or T2 - weighted images

Resting Active

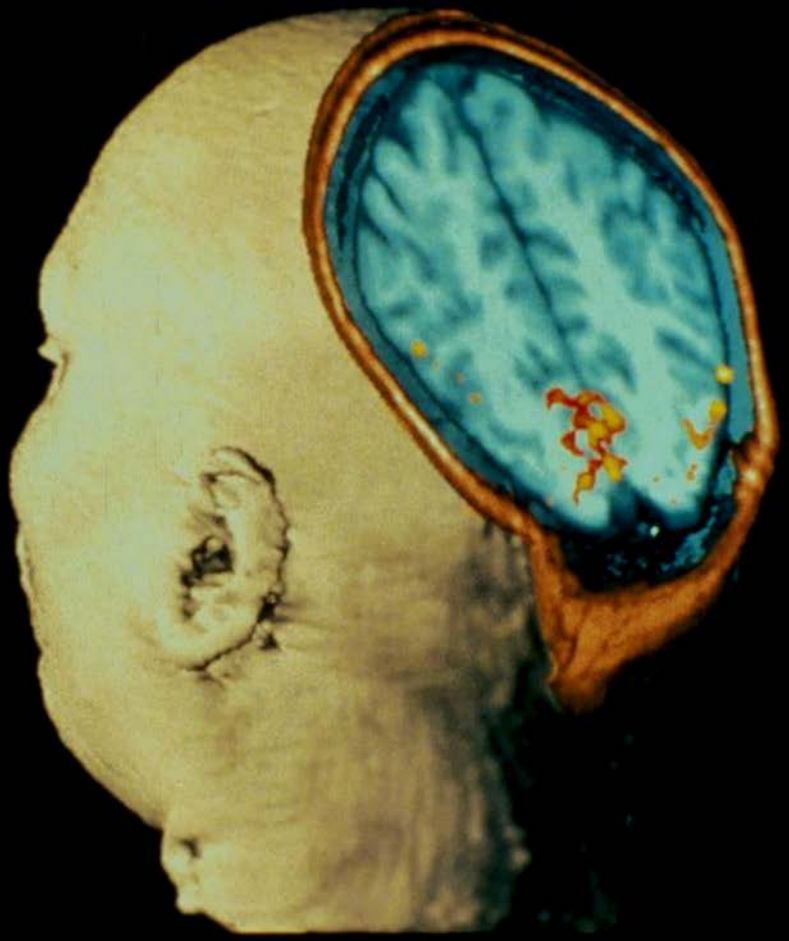






Blood Volume

Photic Stimulation

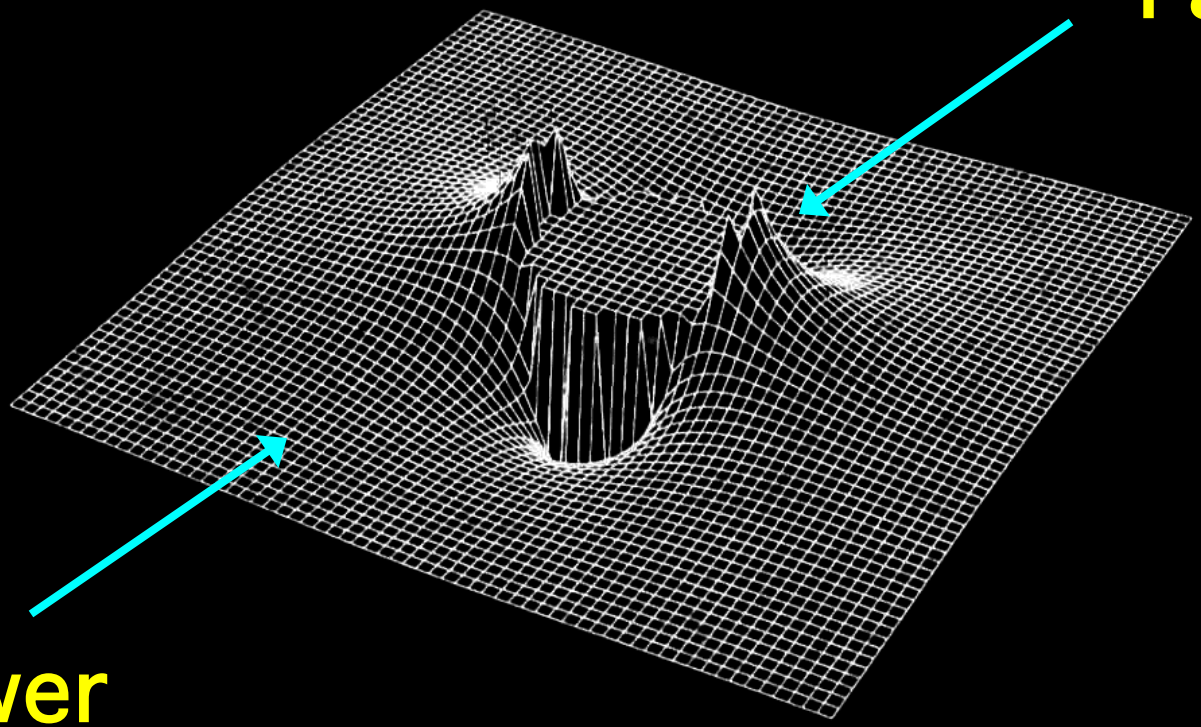


MRI Image showing activation of the Visual Cortex

From Belliveau, et al. Science Nov 1991

Susceptibility Contrast

Susceptibility-Induced Field Distortion in the Vicinity of a Microvessel $\perp$ to B_o.



Alternating Left and Right Finger Tapping

~ 1992

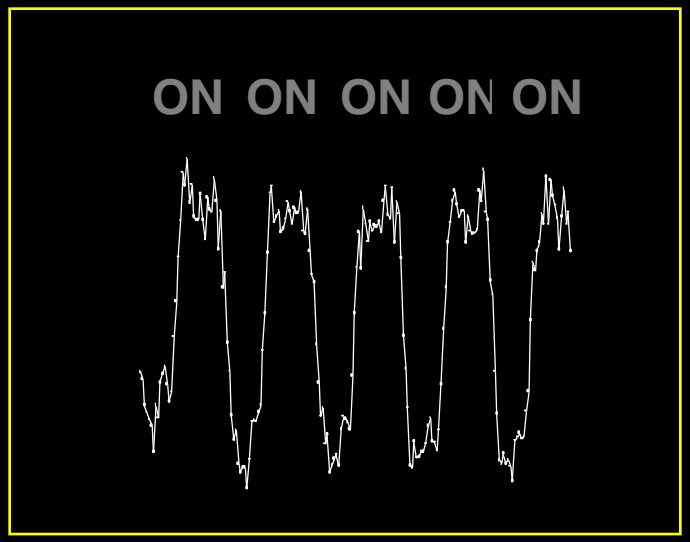
K. K. Kwong, et al, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.

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.

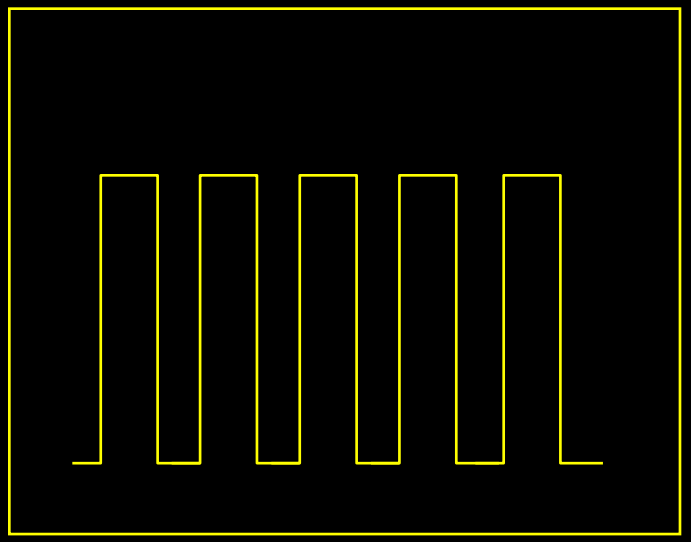
Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

Creating a Functional Image



Signal Time Course

X



Reference Function

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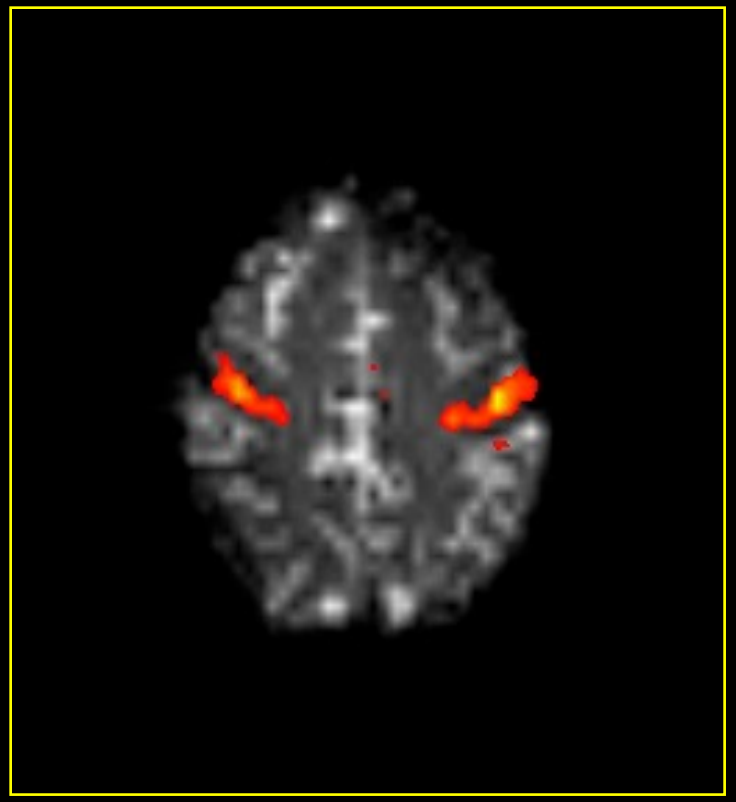
P. A. Bandettini, A. Jesmanowicz, E. C. Wong, J. S. Hyde, Processing strategies for time-course data sets in functional MRI of the human brain. *Magn. Reson. Med.* **30, 161-173 (1993).**

Cross Correlation Image



$$\frac{\text{Cross Correlation Image}}{\text{Anatomical Image}}$$

P. A. Bandettini, A. Jesmanowicz, E. C. Wong, J. S. Hyde, Processing strategies for time-course data sets in functional MRI of the human brain. *Magn. Reson. Med.* 30, 161-173 (1993).

Correlation analysis, Fourier analysis, t-test, f-test...
SPM, AFNI, brain voyager, FIASCO, FSL, free surfer...

Quality of results and importance of the findings depends on type of question asked, experimental method, and analysis method...

BOLD Contrast in the Detection of Neuronal Activity

Cerebral Tissue Activation

↓

Local Vasodilation

↓

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

↓

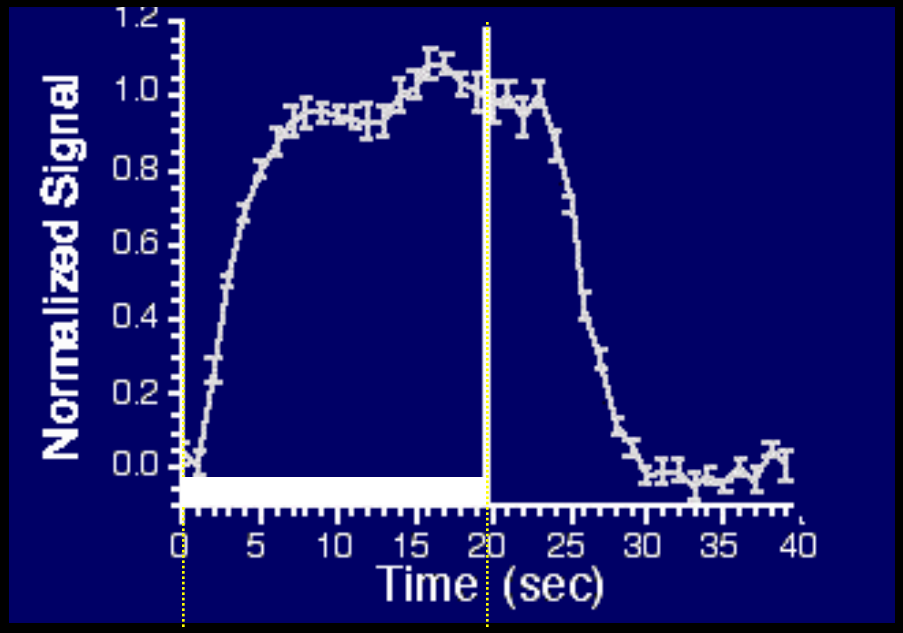
Decrease in susceptibility-related intravoxel dephasing → Increase in T2 and T2*

↓

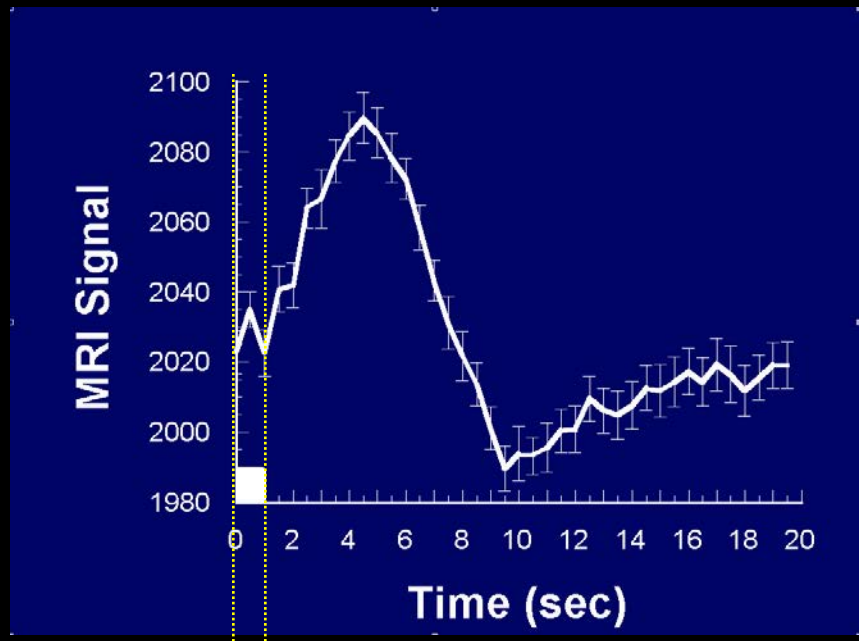
Local Signal Increase in T2 and T2* - weighted sequences

The BOLD Signal

Blood Oxygenation Level Dependent (BOLD) signal changes

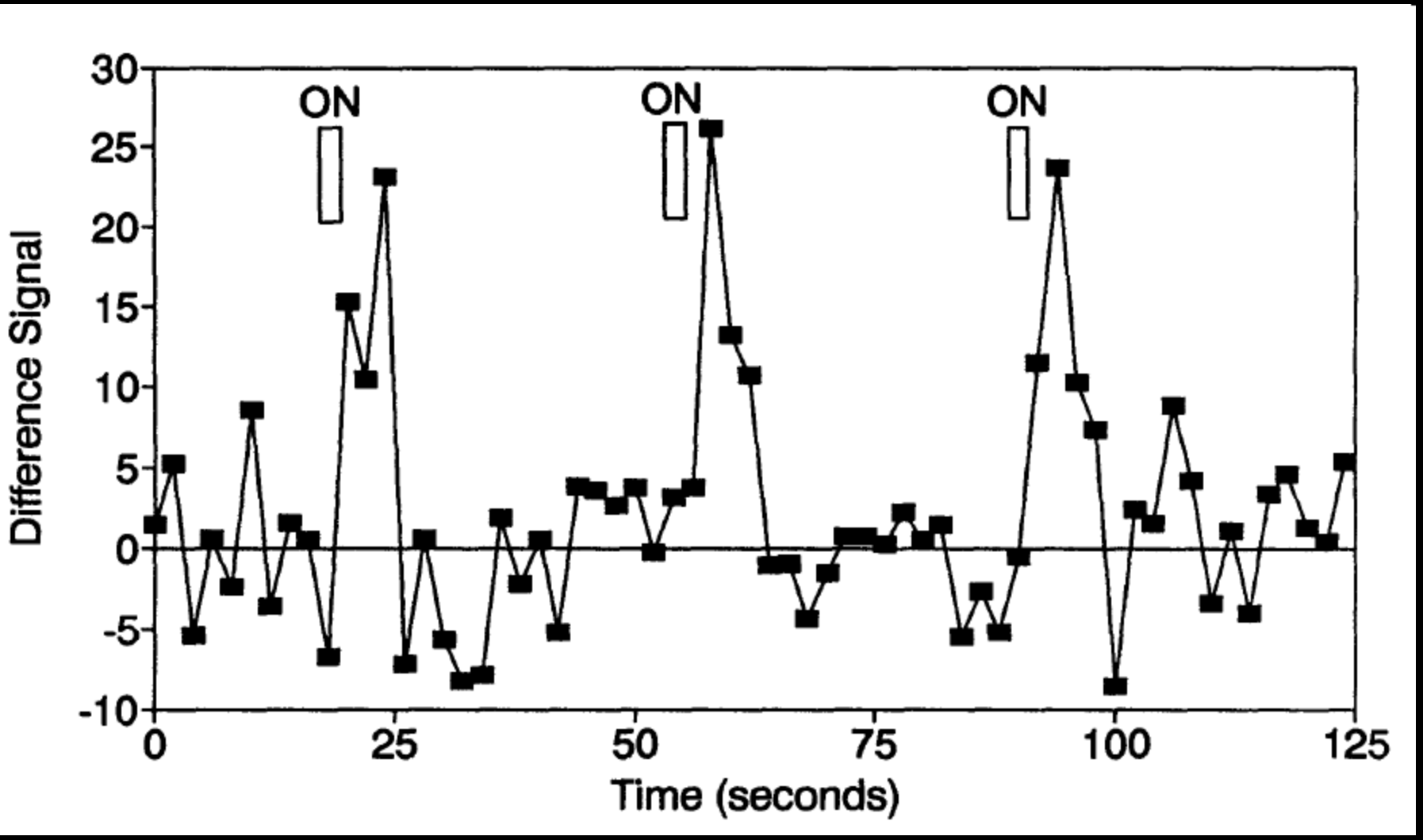


task



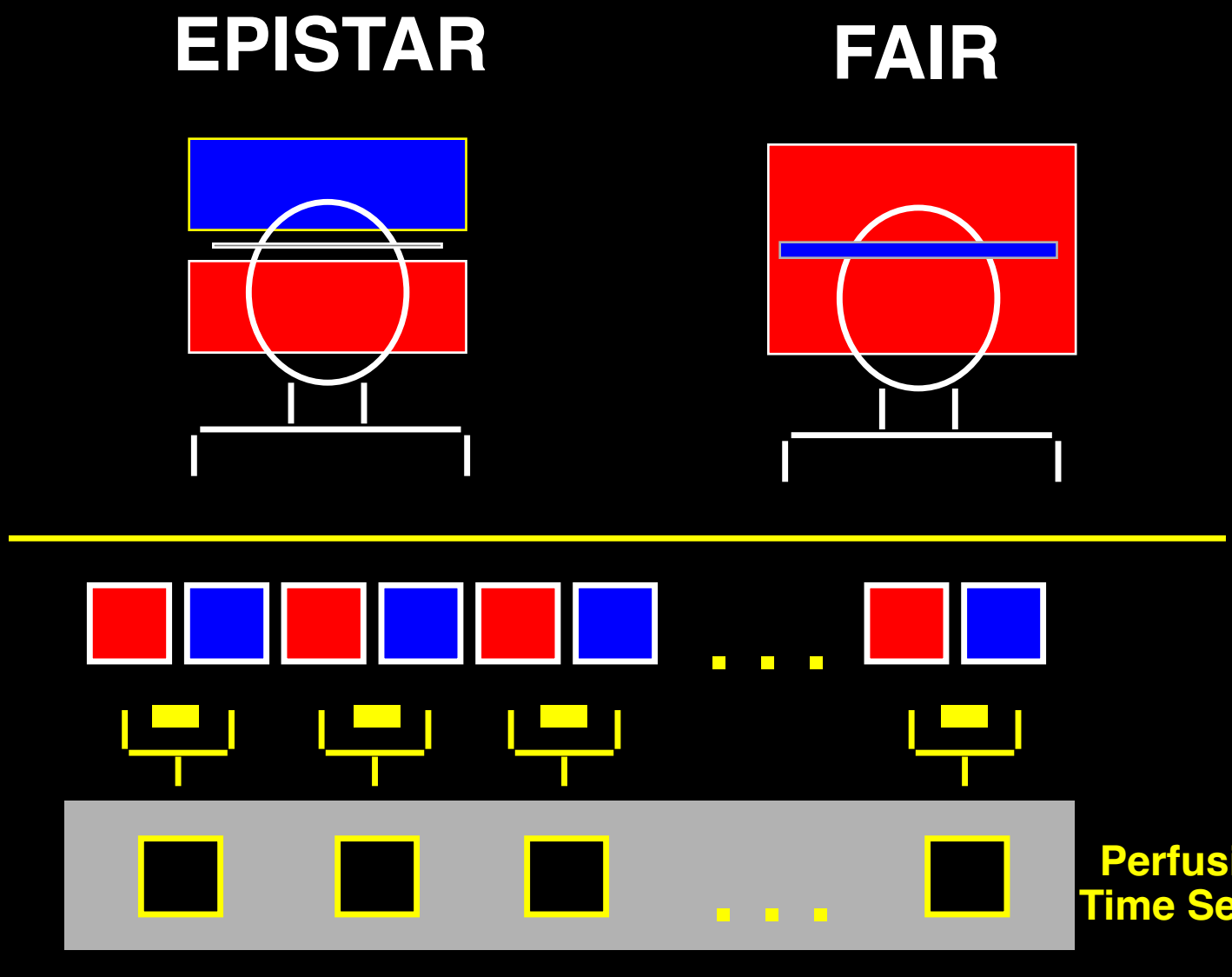
task

First Event-related fMRI Results



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.

Blood Perfusion



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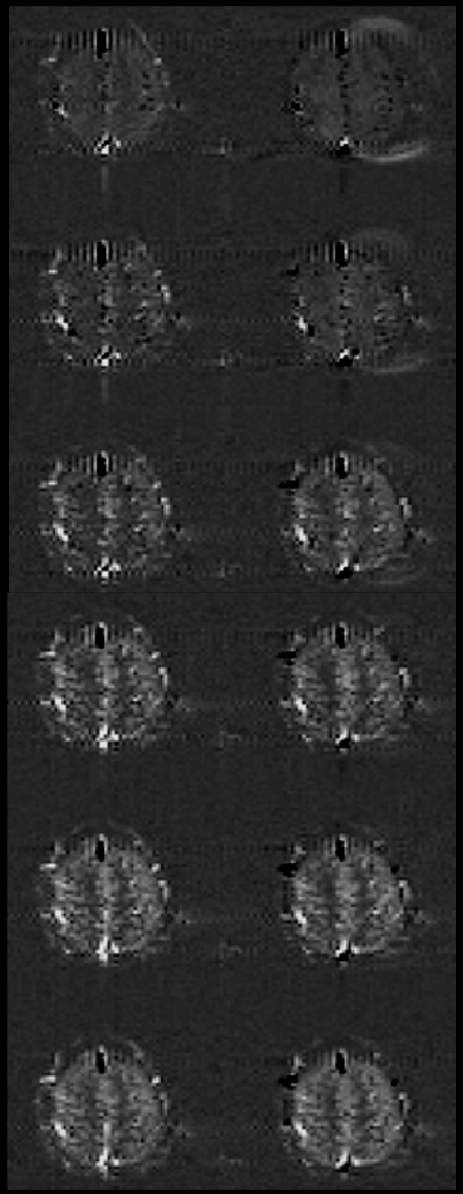
200		
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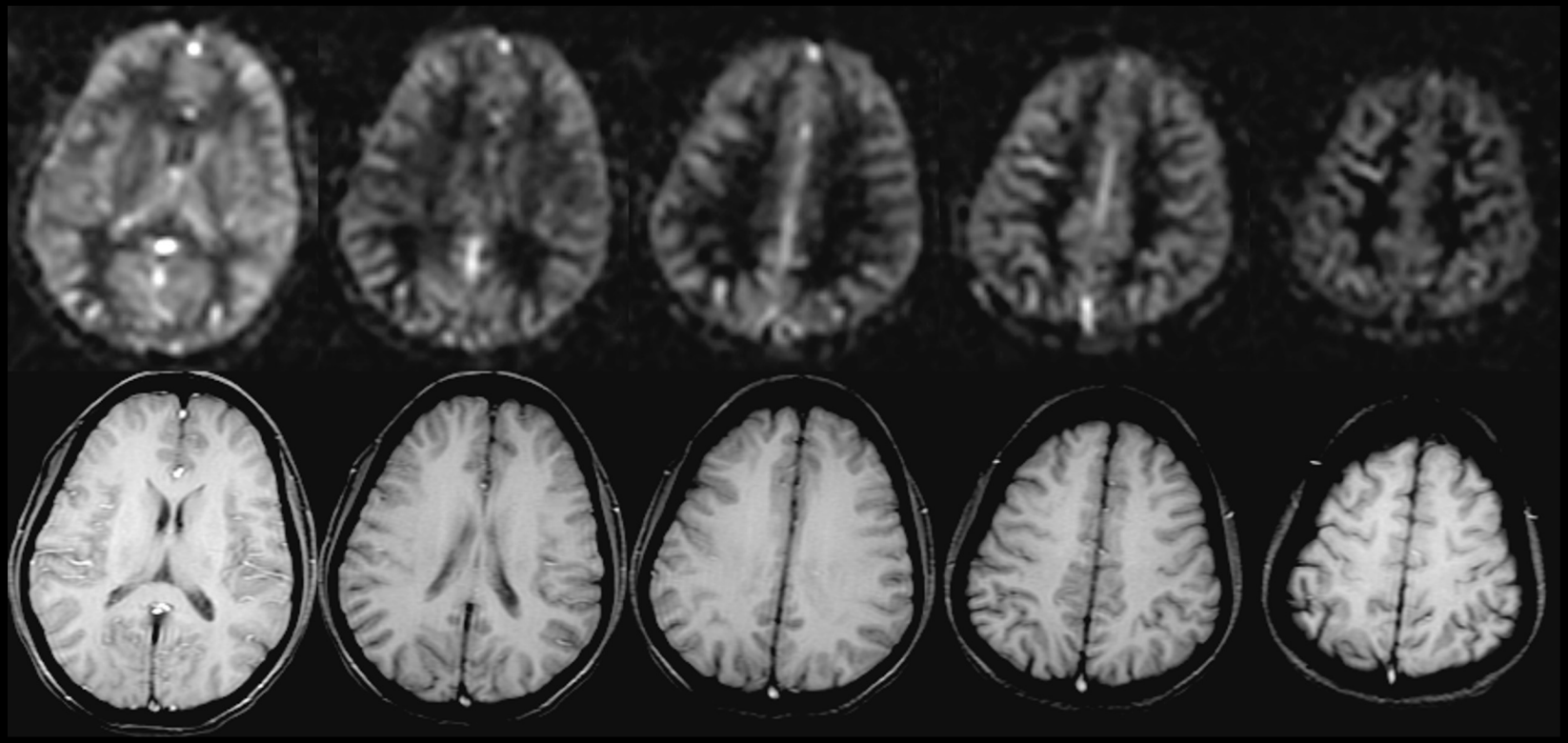


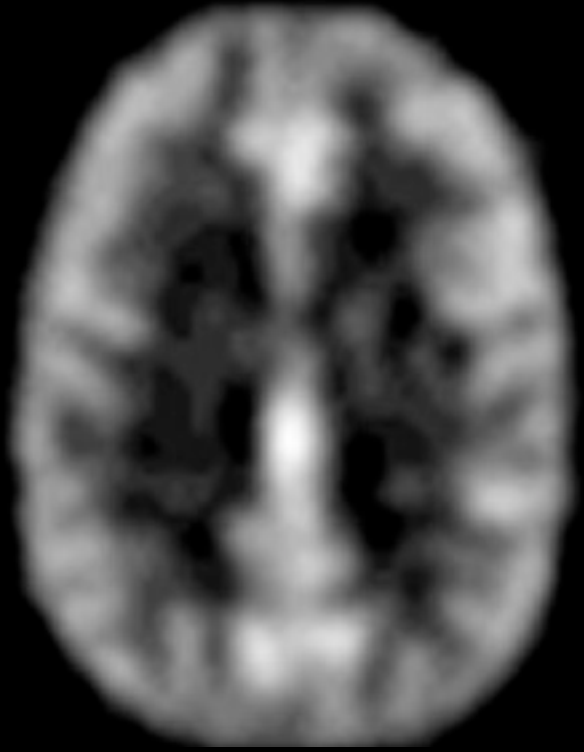
Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) “Magnetic resonance imaging of perfusion using spin-inversion of arterial water.” Proc. Natl. Acad. Sci. USA 89, 212-216.

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.

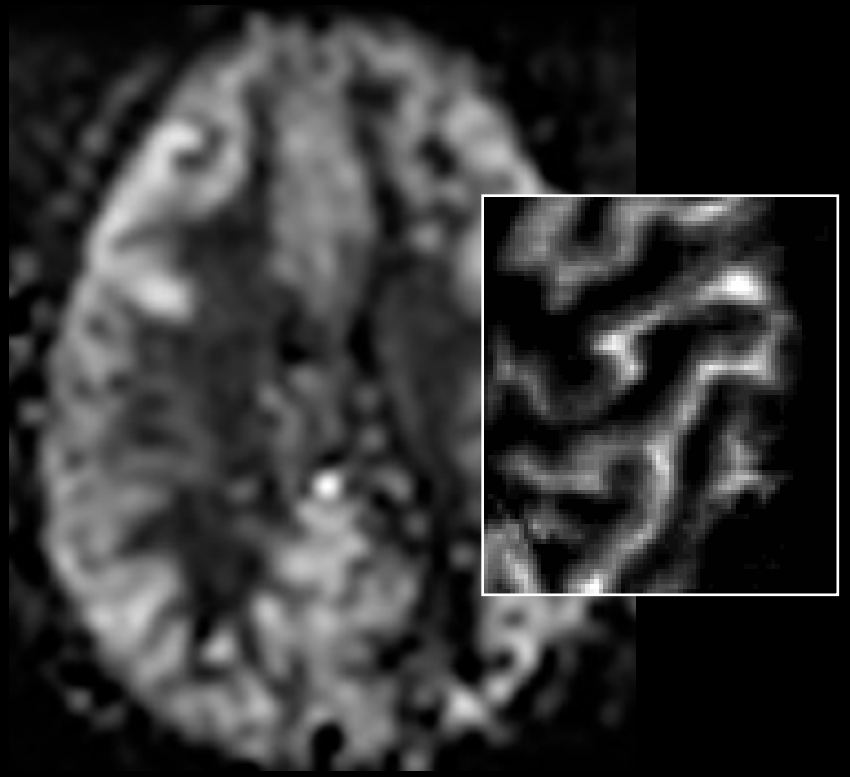
Kim, S.-G. (1995) “Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping.” Magn. Reson. Med. **34**, 293-301.

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

Comparison with Positron Emission Tomography



PET: $H_2{}^{15}O$



MRI: ASL

	+	-
Volume	• unique information • baseline information • multislice trivial	• invasive • low C / N for func.
BOLD	• highest C / N • easy to implement • multislice trivial • non invasive • highest temp. res.	• complicated signal • no baseline info.
Perfusion	• unique information • control over ves. size • baseline information • non invasive	• multislice non trivial • lower temp. res. • low C / N

Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

Refinements

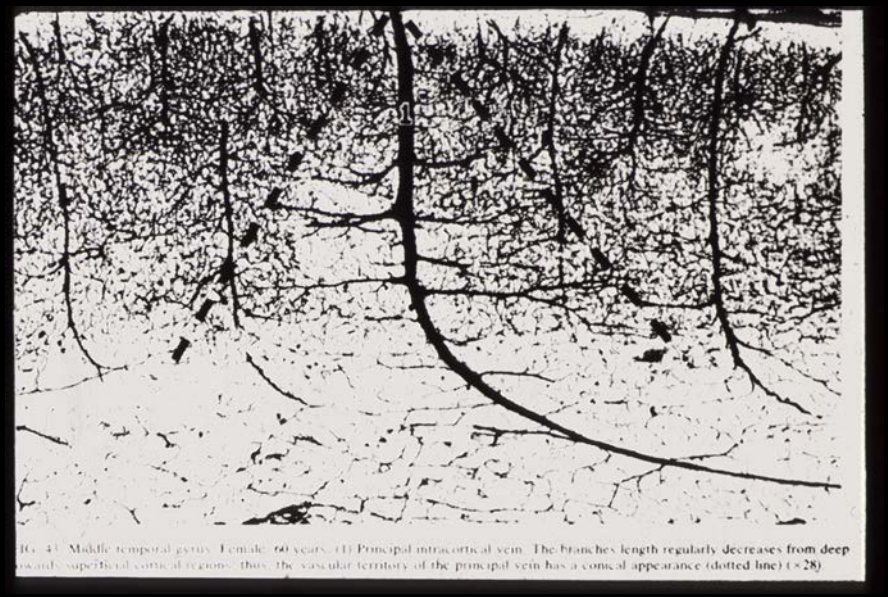
BOLD Contrast Interpretation

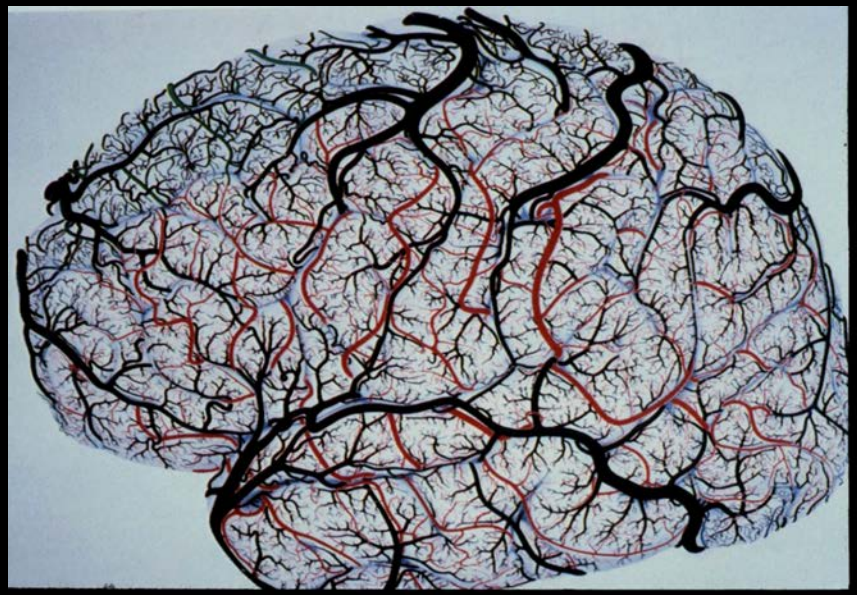
Dynamics, Paradigm Design and Processing

Applications

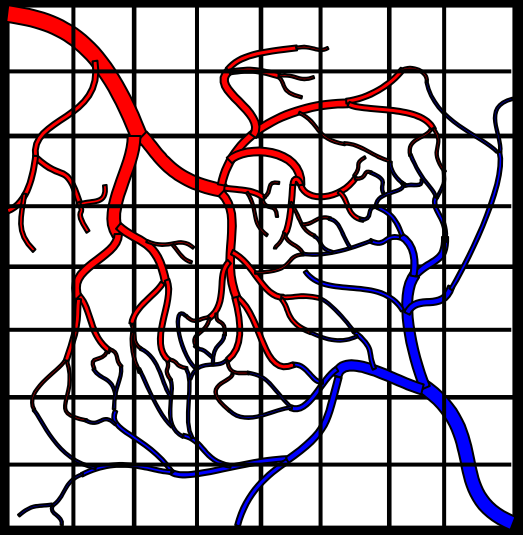
The Neuroscientists' Challenge:

...to make progressively more precise inferences using fMRI without making too many assumptions about non-neuronal physiologic factors.





Neuronal Activation



Measured Signal

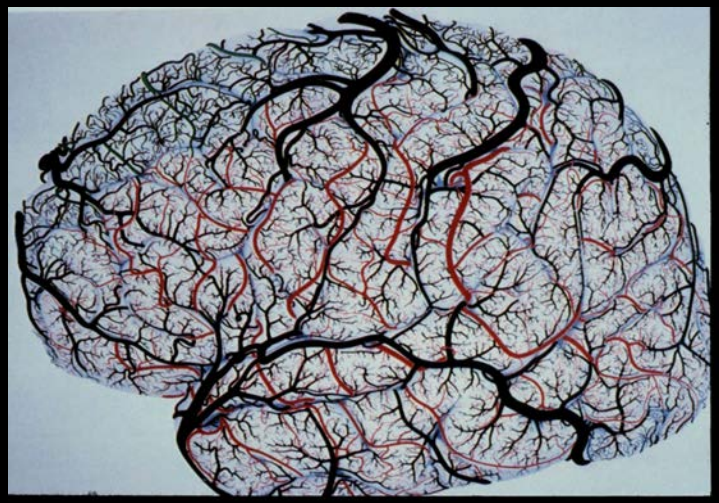
?

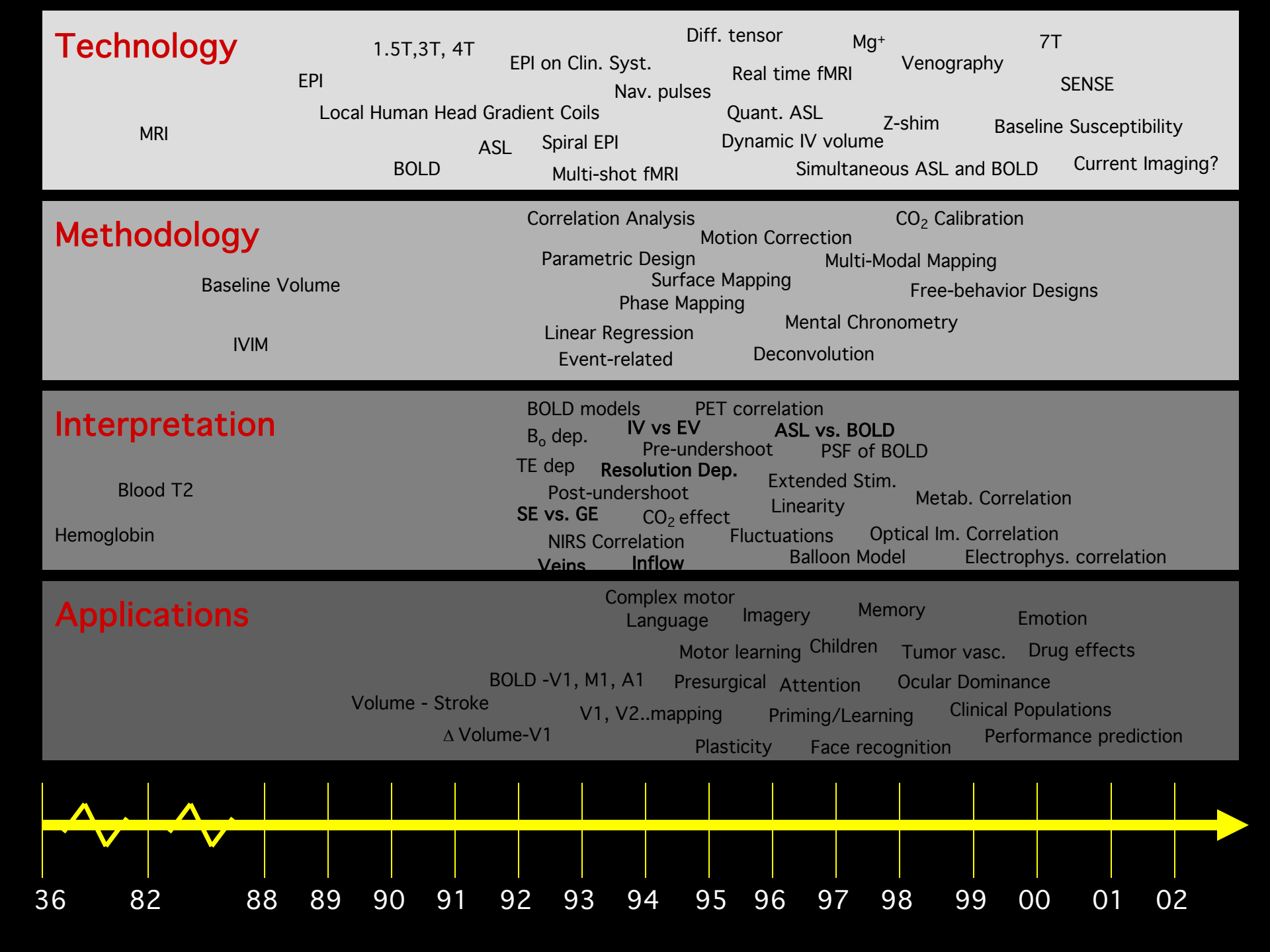
Hemodynamics

?

?

Noise




Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
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Z-shim
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MRI
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ASL
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Clinical Populations
Δ Volume-V1
Plasticity
Face recognition
Performance prediction
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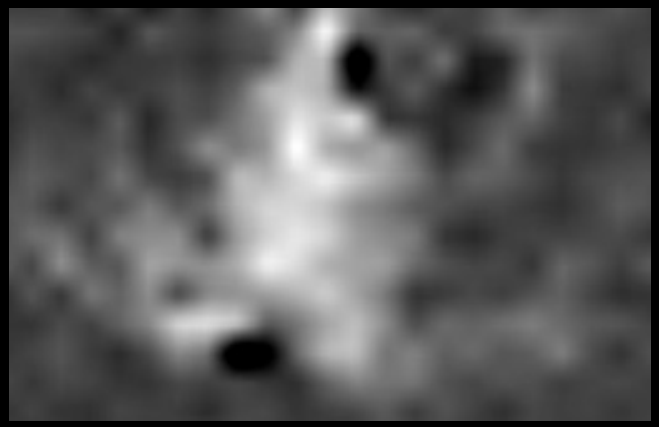
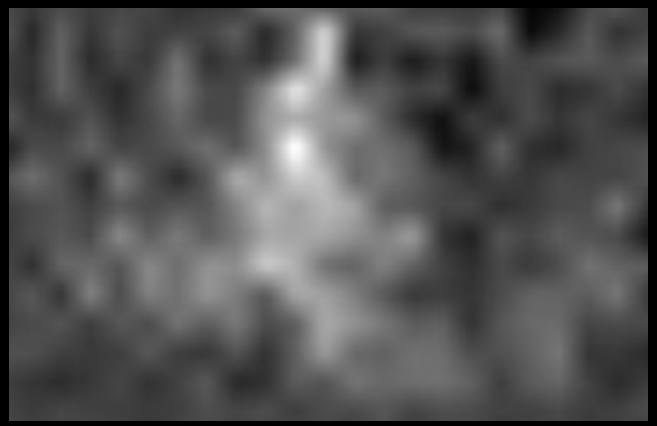
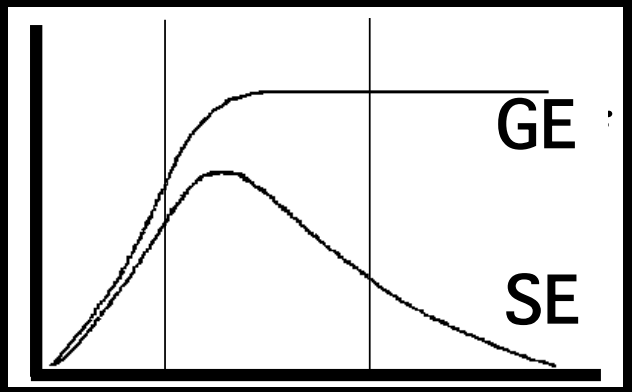




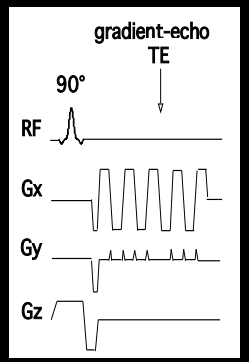
Contrast

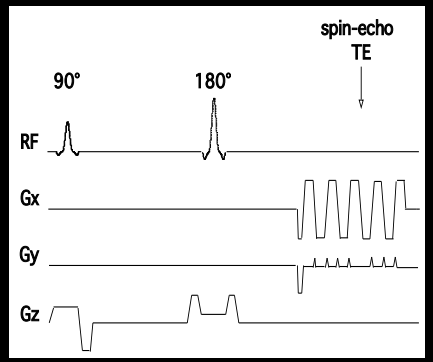


2.5 to 3 μm 3 to 15 μm 15 to ∞ μm

compartment size

Gradient - Echo





Spin - Echo

T1 - weighted

Flow weighted

T2* weighted

BOLD weighted

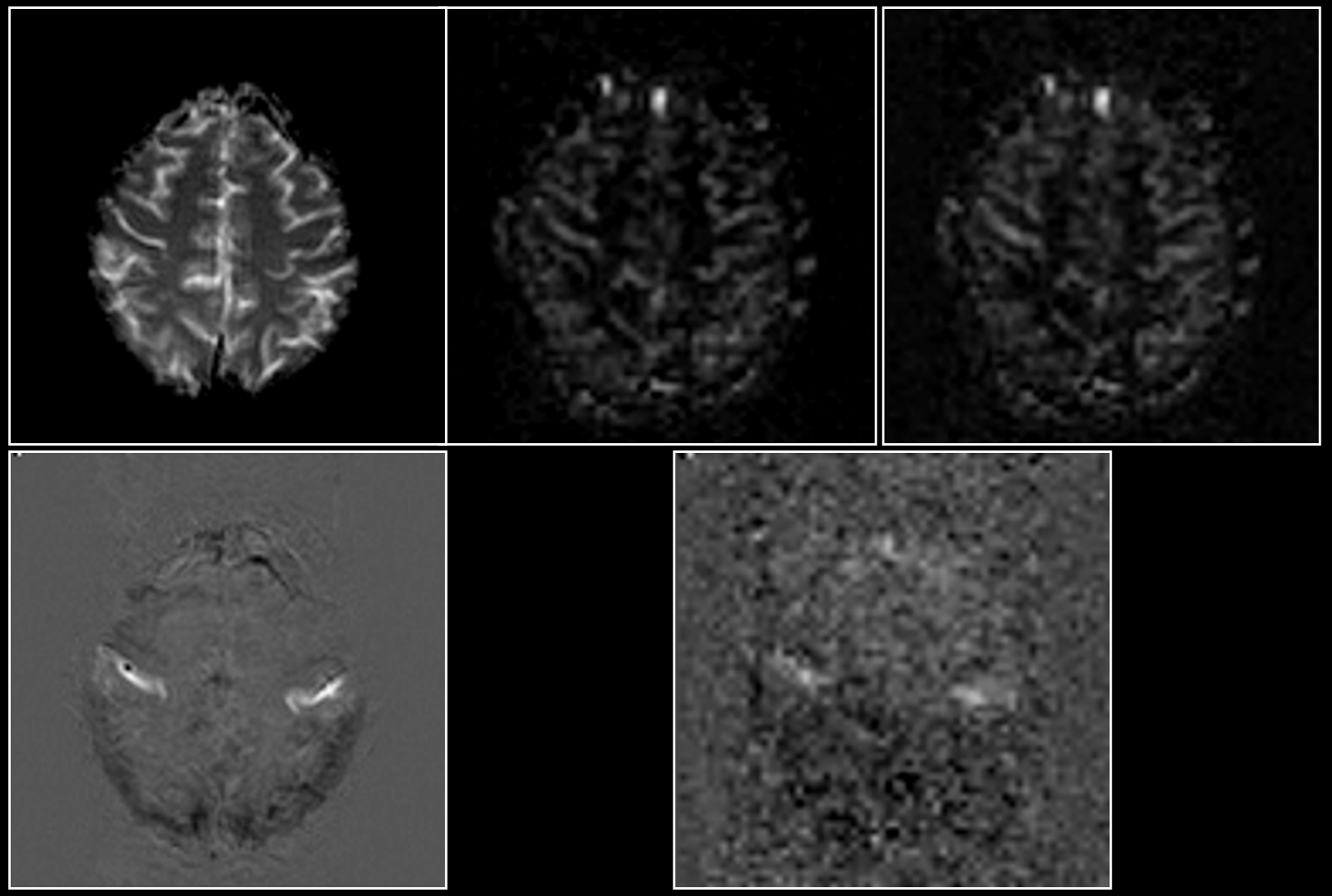
T1 and T2* weighted

Flow and BOLD weighted

P. A. Bandettini, E. C. Wong, Echo - planar magnetic resonance imaging of human brain activation, *in* "Echo Planar Imaging: Theory, Technique, and Application" (F. Schmitt, M. Stehling, R. Turner, Eds.), p.493-530, Springer - Verlag, Berlin, 1997

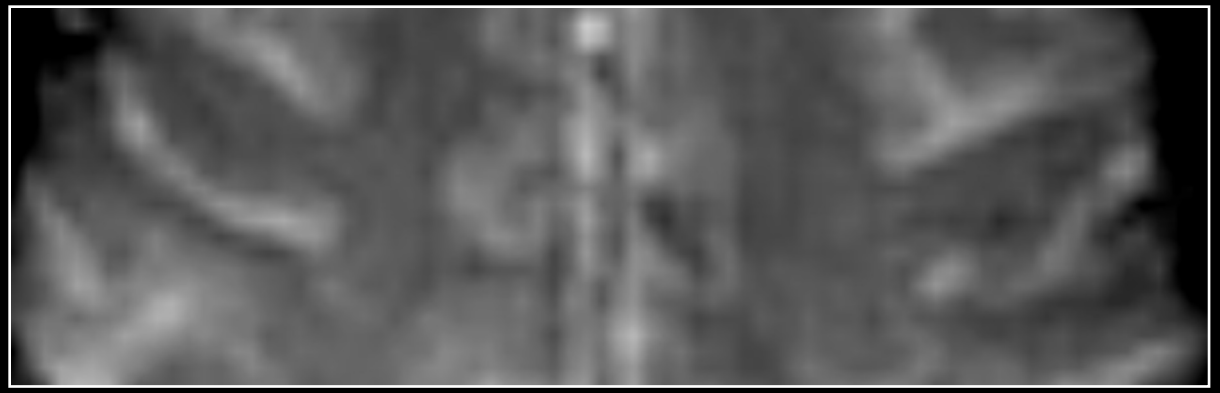
Perfusion

BOLD *Rest* *Activation*

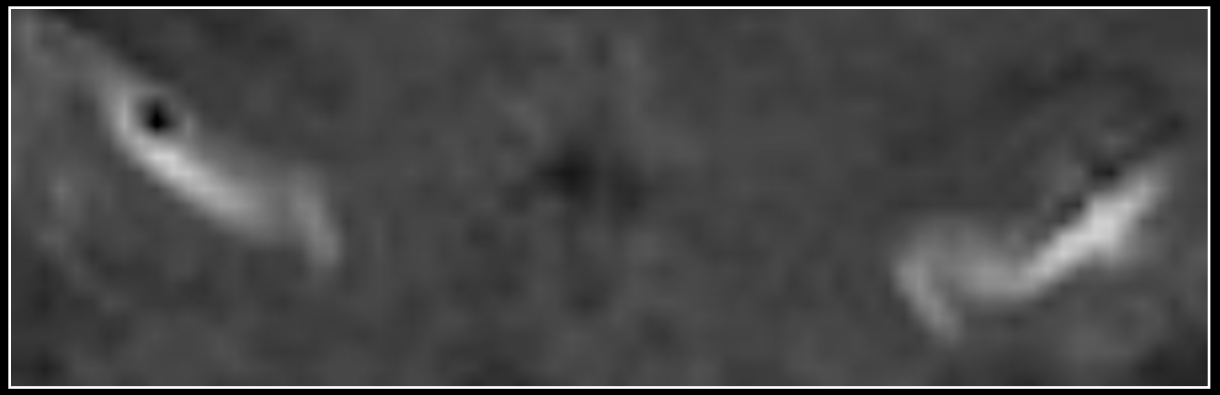


P. A. Bandettini, E. C. Wong, Magnetic resonance imaging of human brain function: principles, practicalities, and possibilities, *in* "Neurosurgery Clinics of North America: Functional Imaging" (M. Haglund, Ed.), p.345-371, W. B. Saunders Co., 1997.

Anatomy



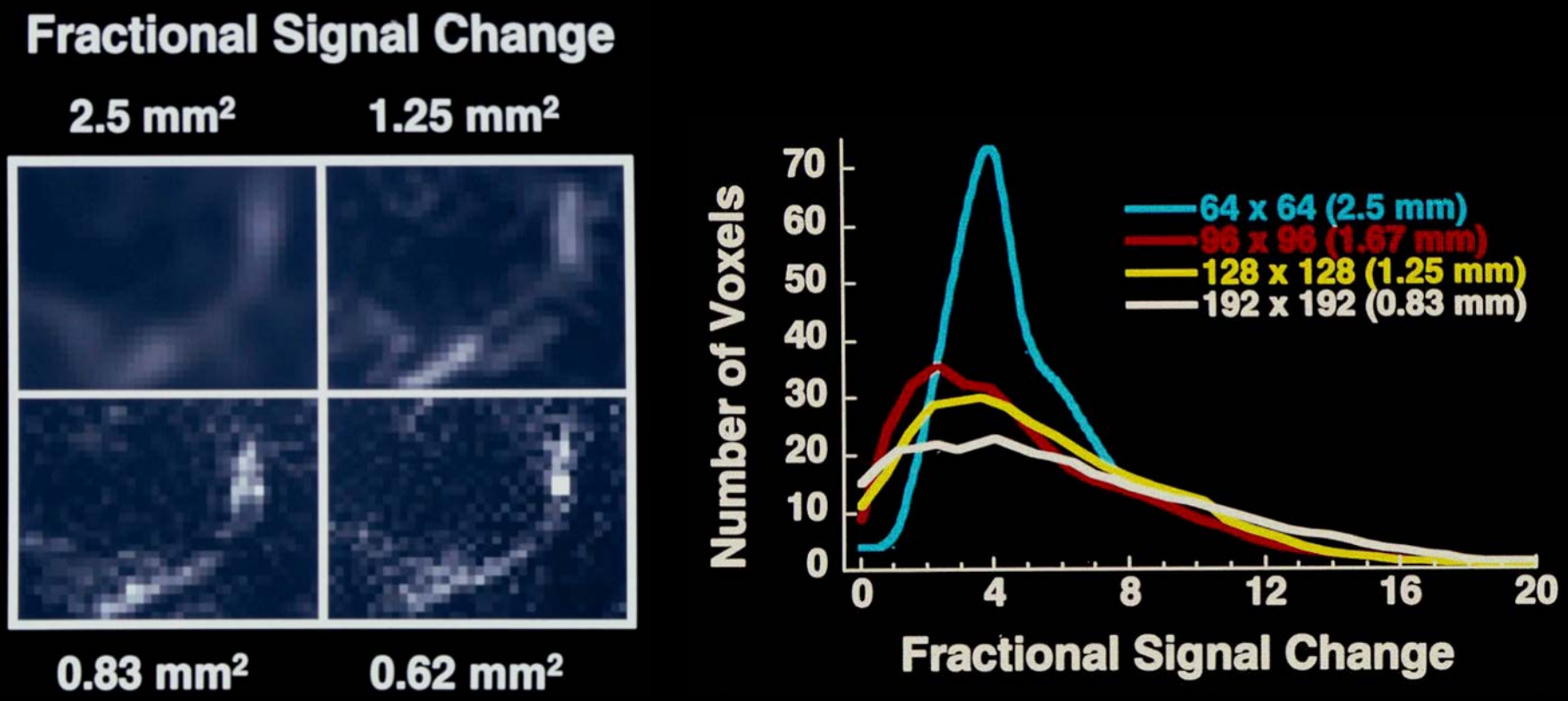
BOLD



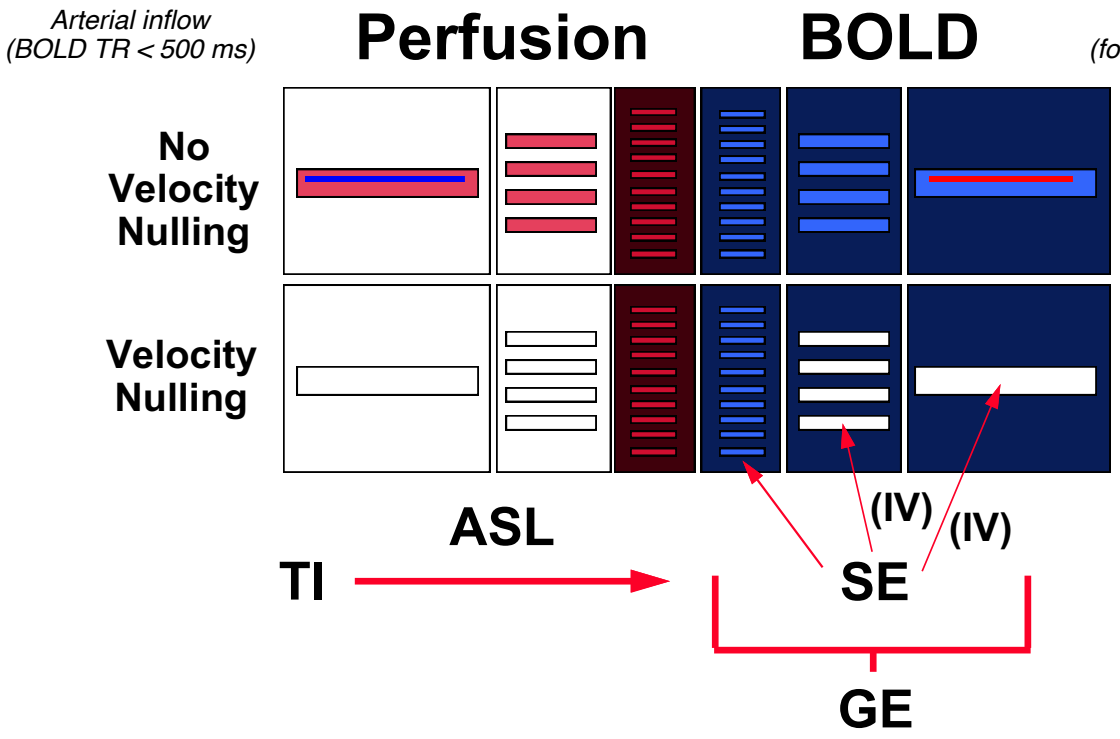
Perfusion

P. A. Bandettini, E. C. Wong, Magnetic resonance imaging of human brain function: principles, practicalities, and possibilities, *in* "Neurosurgery Clinics of North America: Functional Imaging" (M. Haglund, Ed.), p.345-371, W. B. Saunders Co., 1997.

Partial k-space imaging

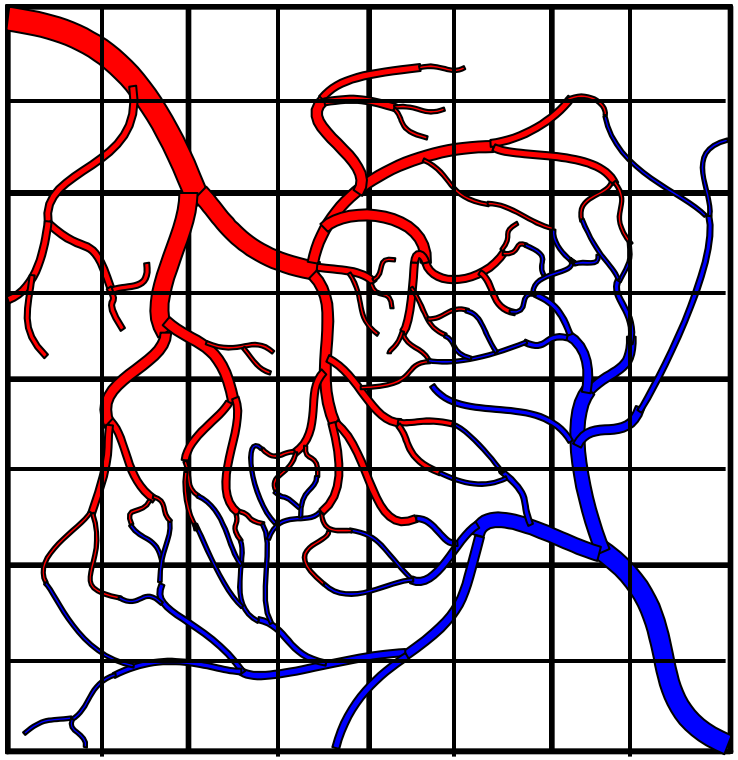


Jesmanowicz, P. A. Bandettini, J. S. Hyde, (1998) "Single shot half k-space high resolution EPI for fMRI at 3T." *Magn. Reson. Med.* 40, 754-762.



Pulse Sequence Sensitivity

Spatial Heterogeneity

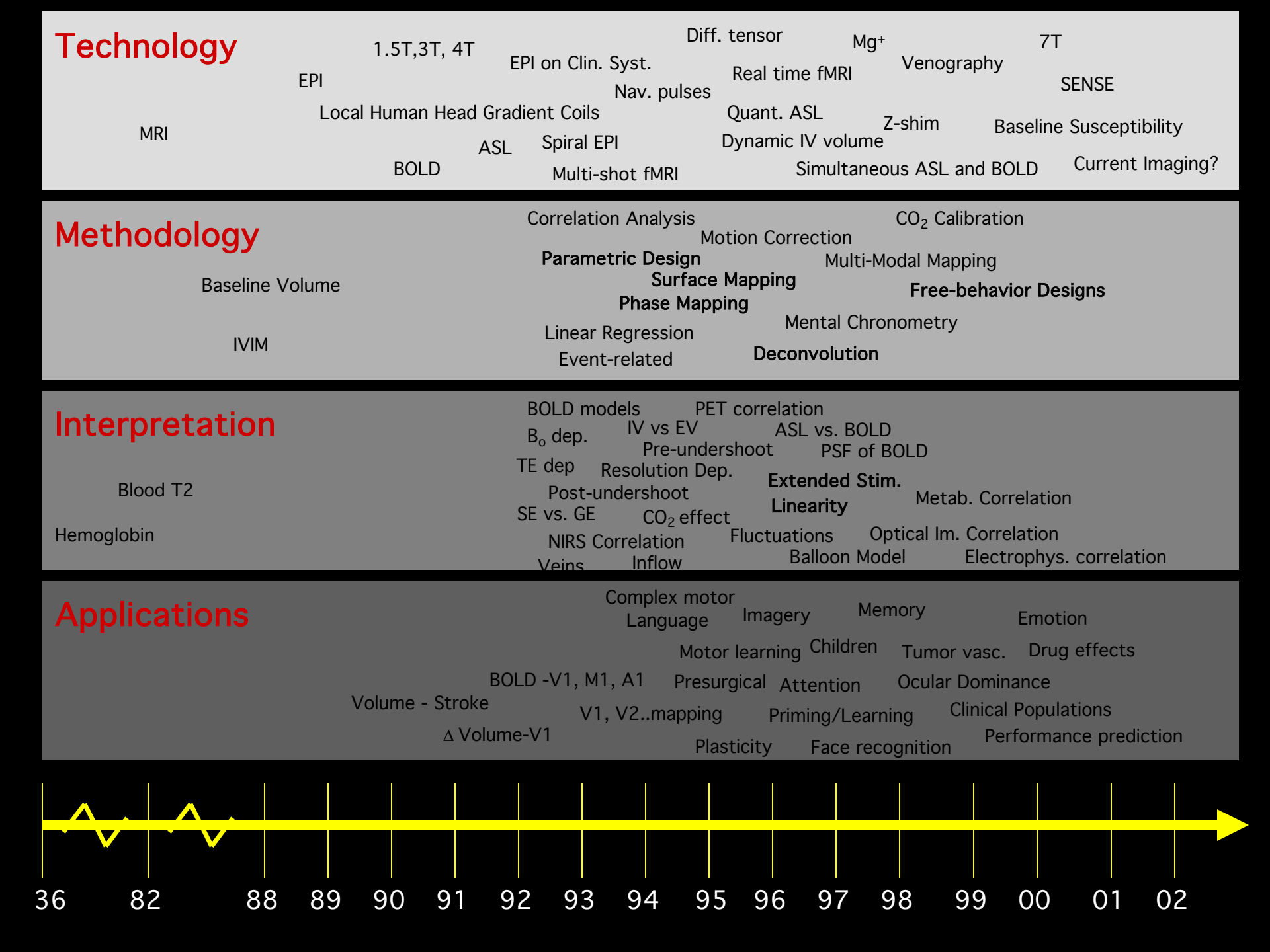


Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications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Δ Volume-V1
Plasticity
Face recognition
Performance prediction
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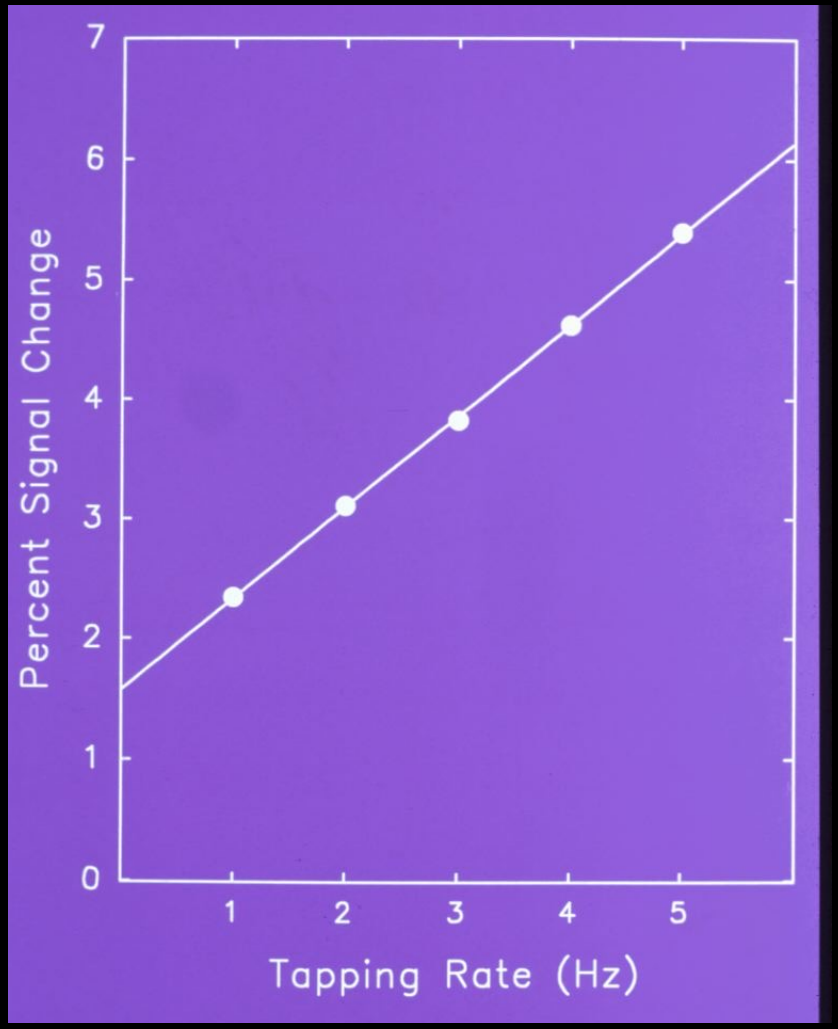
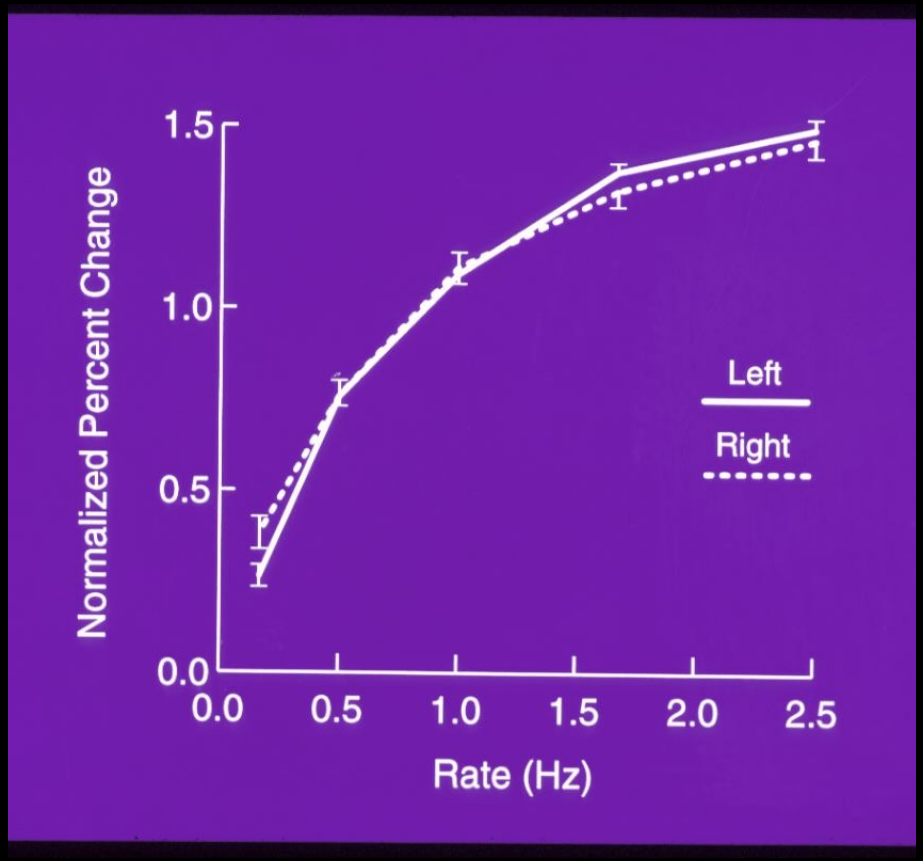
Motor Cortex

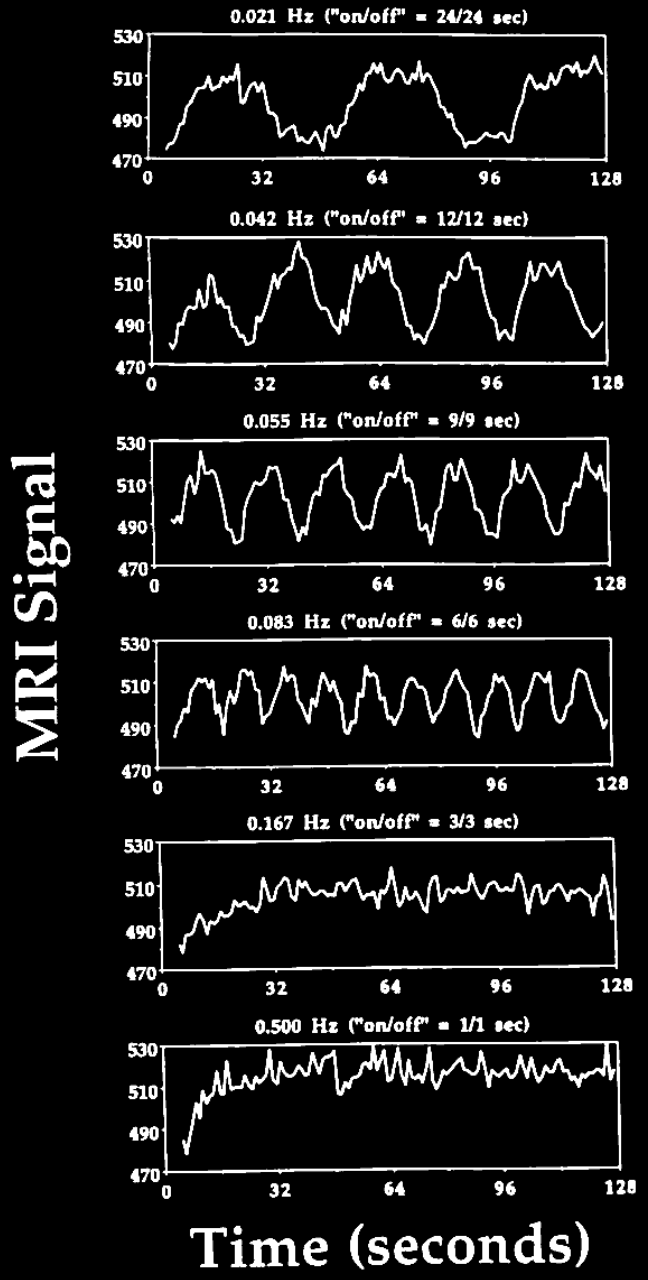


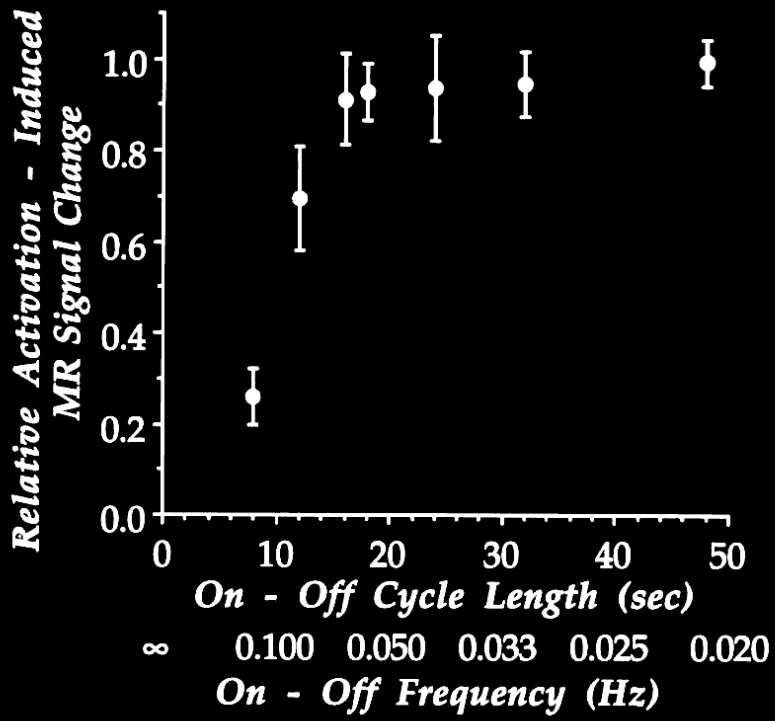
S. M. Rao et al, (1996) "Relationship between finger movement rate and functional magnetic resonance signal change in human primary motor cortex." *J. Cereb. Blood Flow and Met.* 16, 1250-1254.

Auditory Cortex



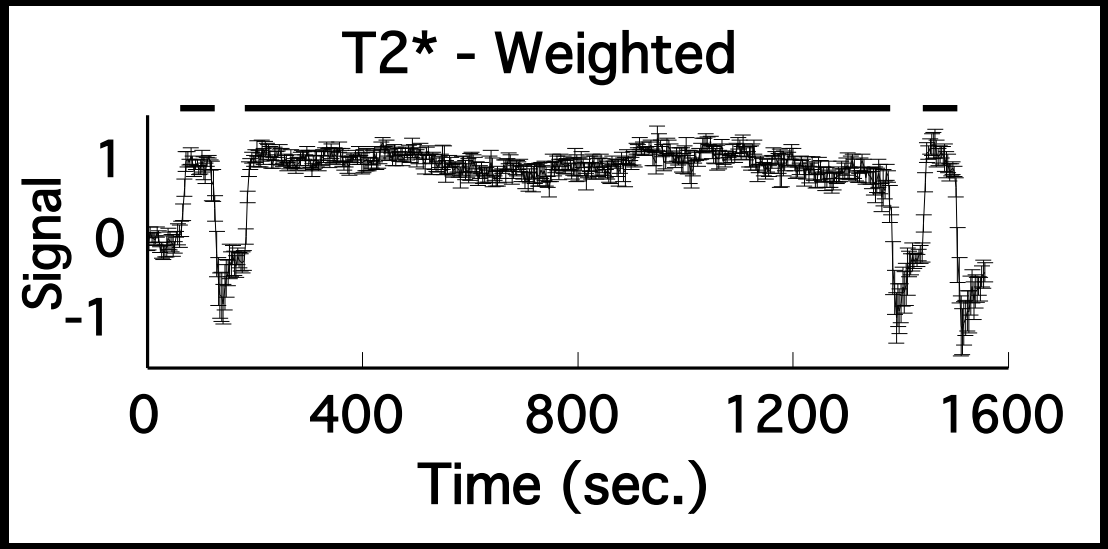
J. R. Binder, et al, (1994). "Effects of stimulus rate on signal response during functional magnetic resonance imaging of auditory cortex." *Cogn. Brain Res.* 2, 31-38



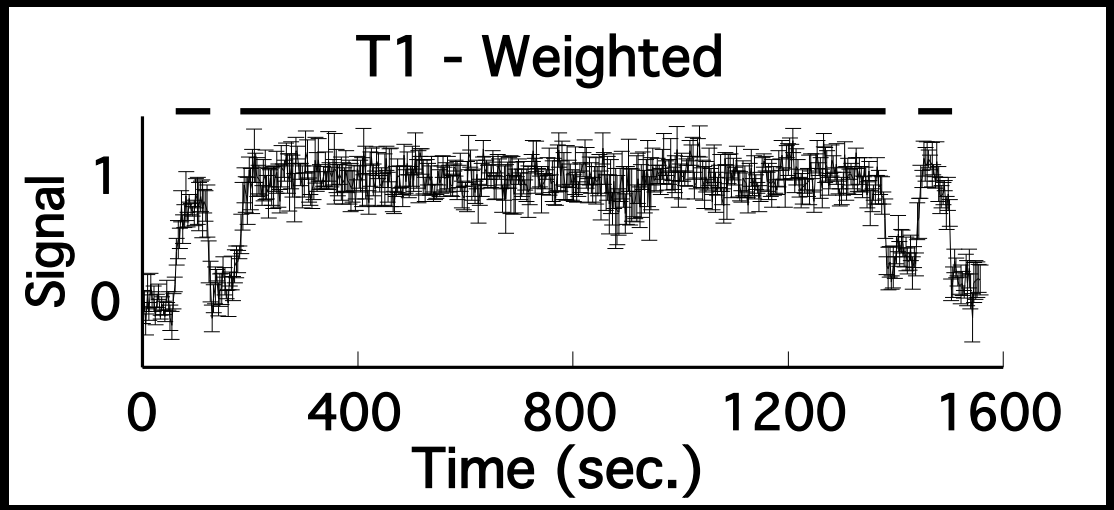


P. A. Bandettini, Functional MRI temporal resolution *in* "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

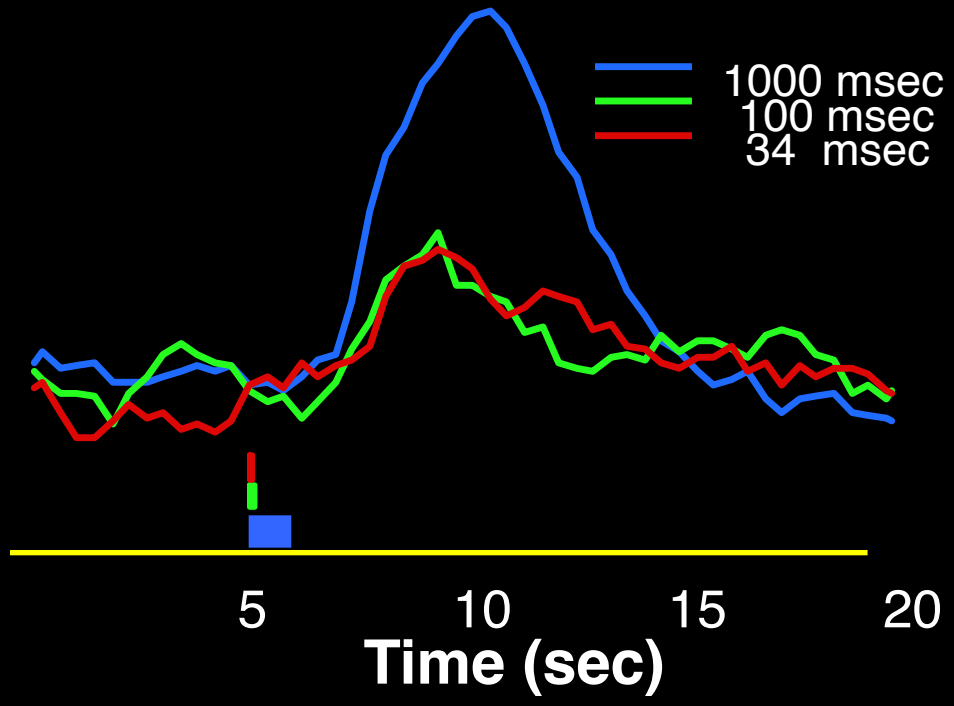
BOLD



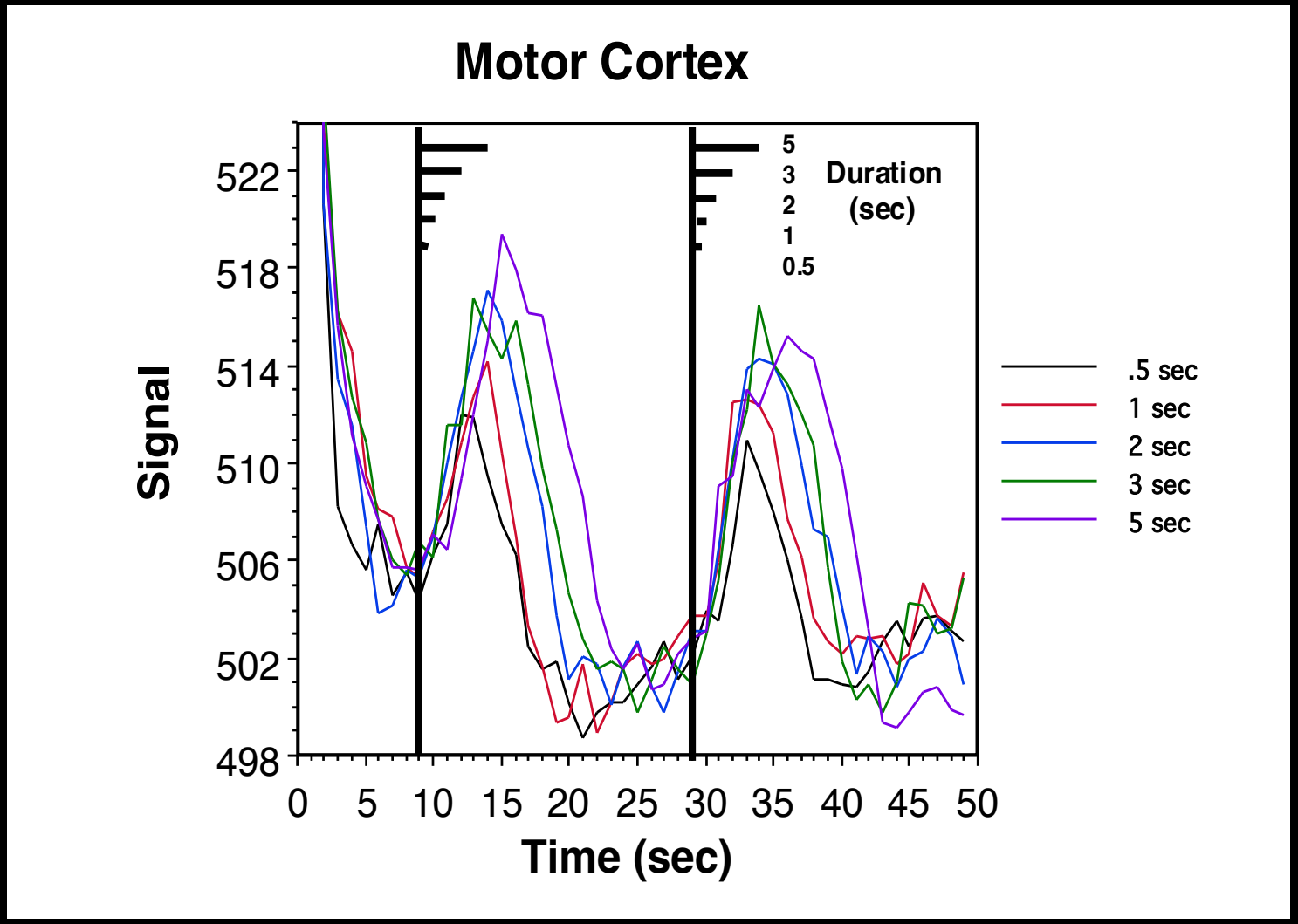
Flow



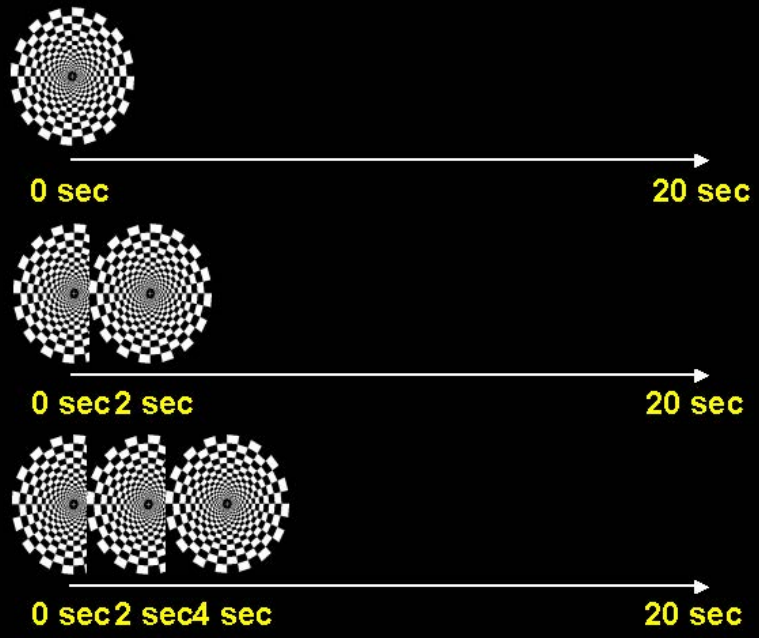
P. A. Bandettini, K. K. Kwong, T. L. Davis, R. B. H. Tootell, E. C. Wong, P. T. Fox, J. W. Belliveau, R. M. Weisskoff, B. R. Rosen, (1997). "Characterization of cerebral blood oxygenation and flow changes during prolonged brain activation." *Human Brain Mapping* 5, 93-109.



R. L. Savoy, et al., Pushing the temporal resolution of fMRI: studies of very brief visual stimuli, onset variability and asynchrony, and stimulus-correlated changes in noise [oral], 3'rd Proc. Soc. Magn. Reson., Nice, p. 450. (1995).



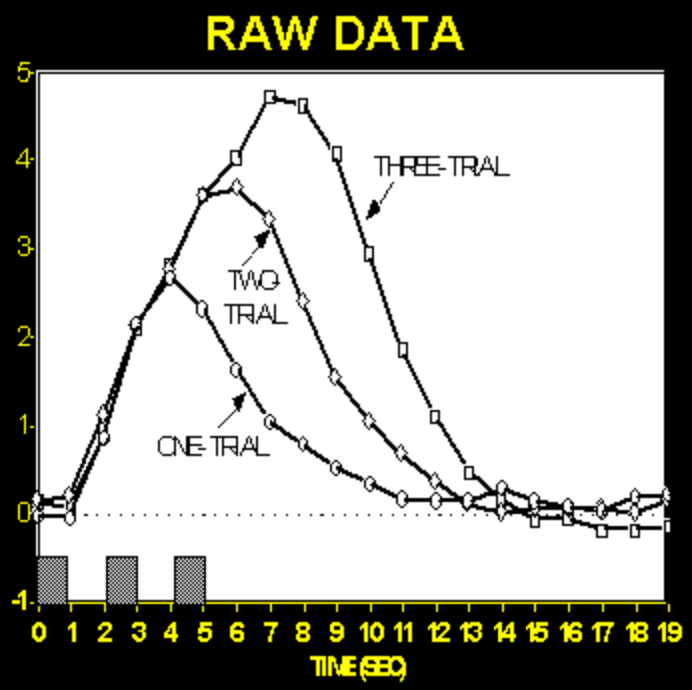
Bandettini, et al., The functional dynamics of blood oxygenation level contrast in the motor cortex, 12'th Proc. Soc. Magn. Reson. Med., New York, p. 1382. (1993).

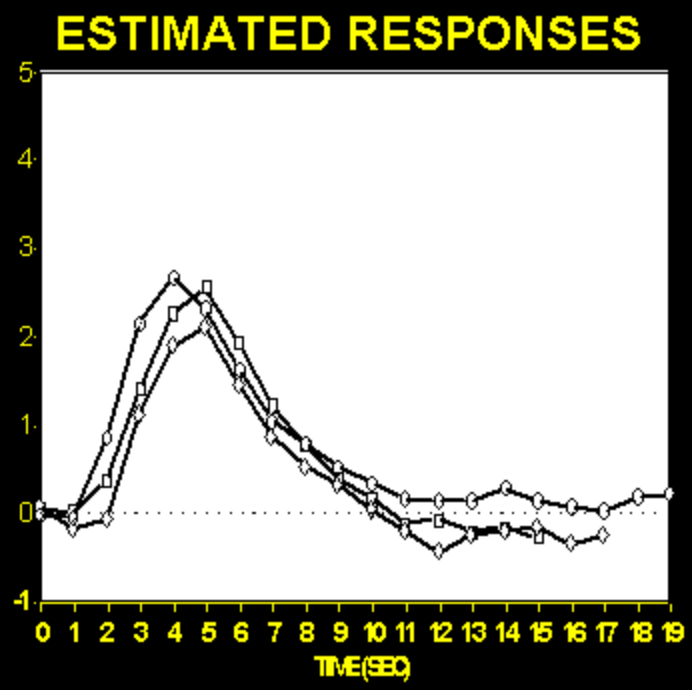


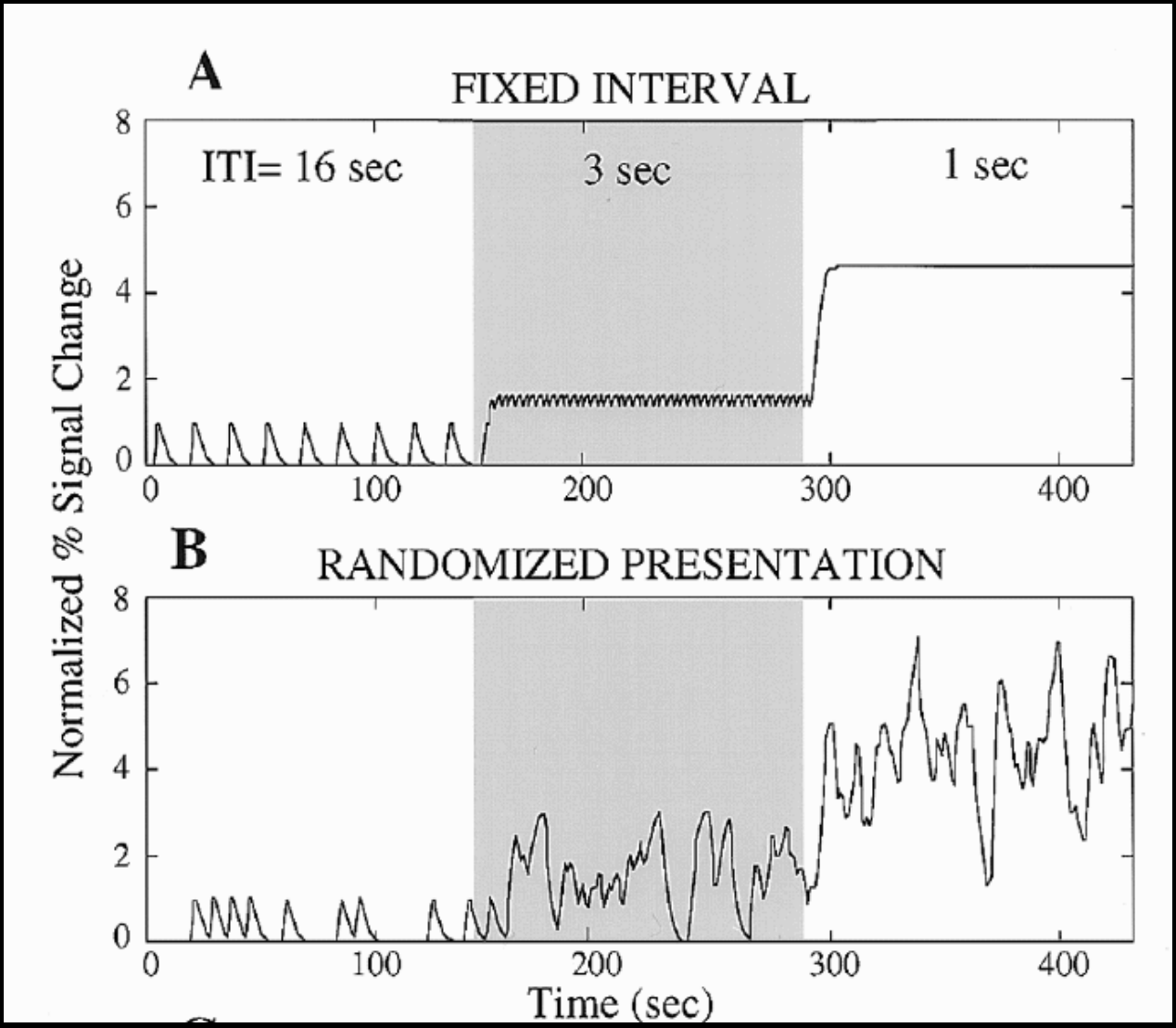
Human Brain Mapping 5:329–340(1997)

Selective Averaging of Rapidly Presented Individual Trials Using fMRI

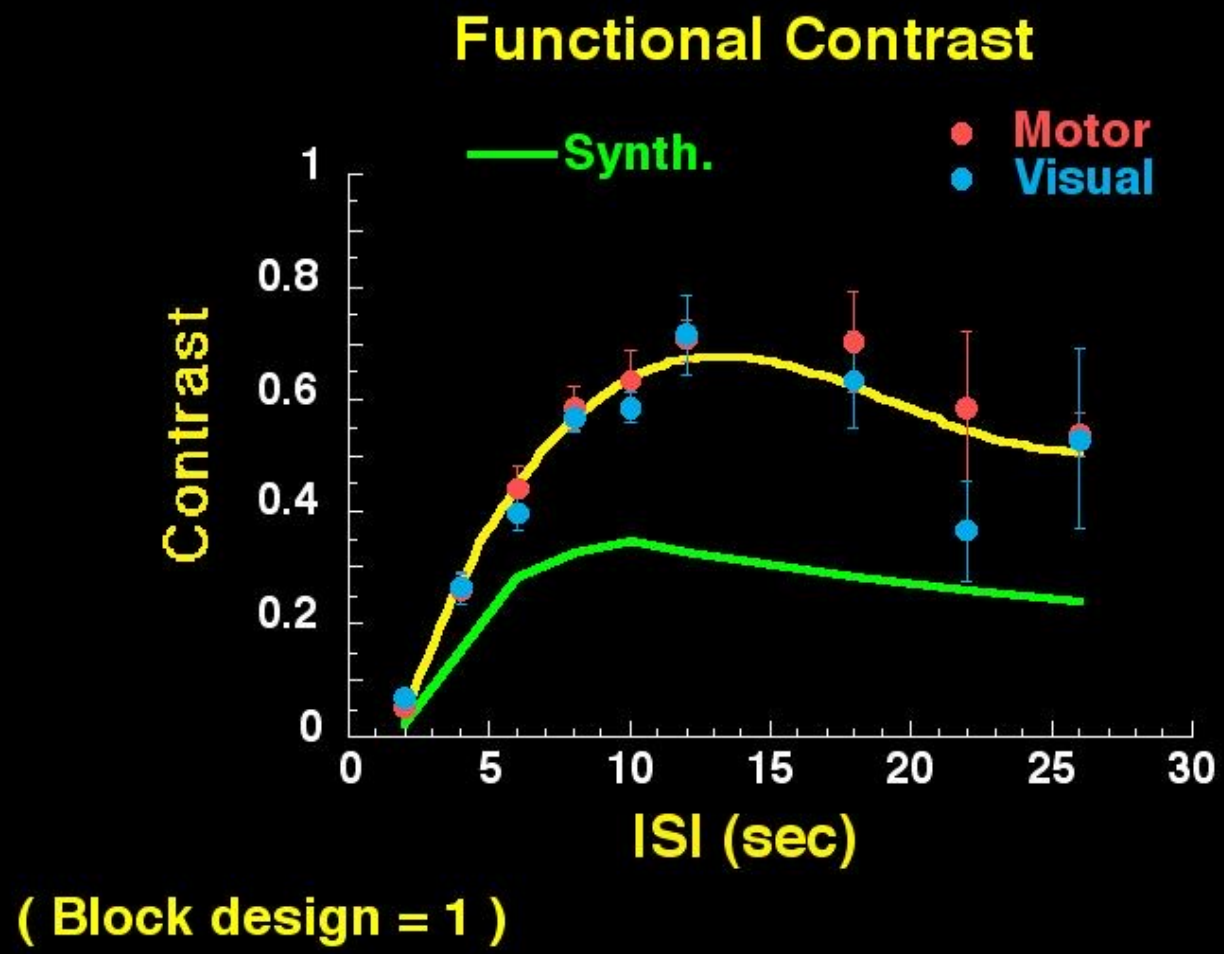
Anders M. Dale* and Randy L. Buckner





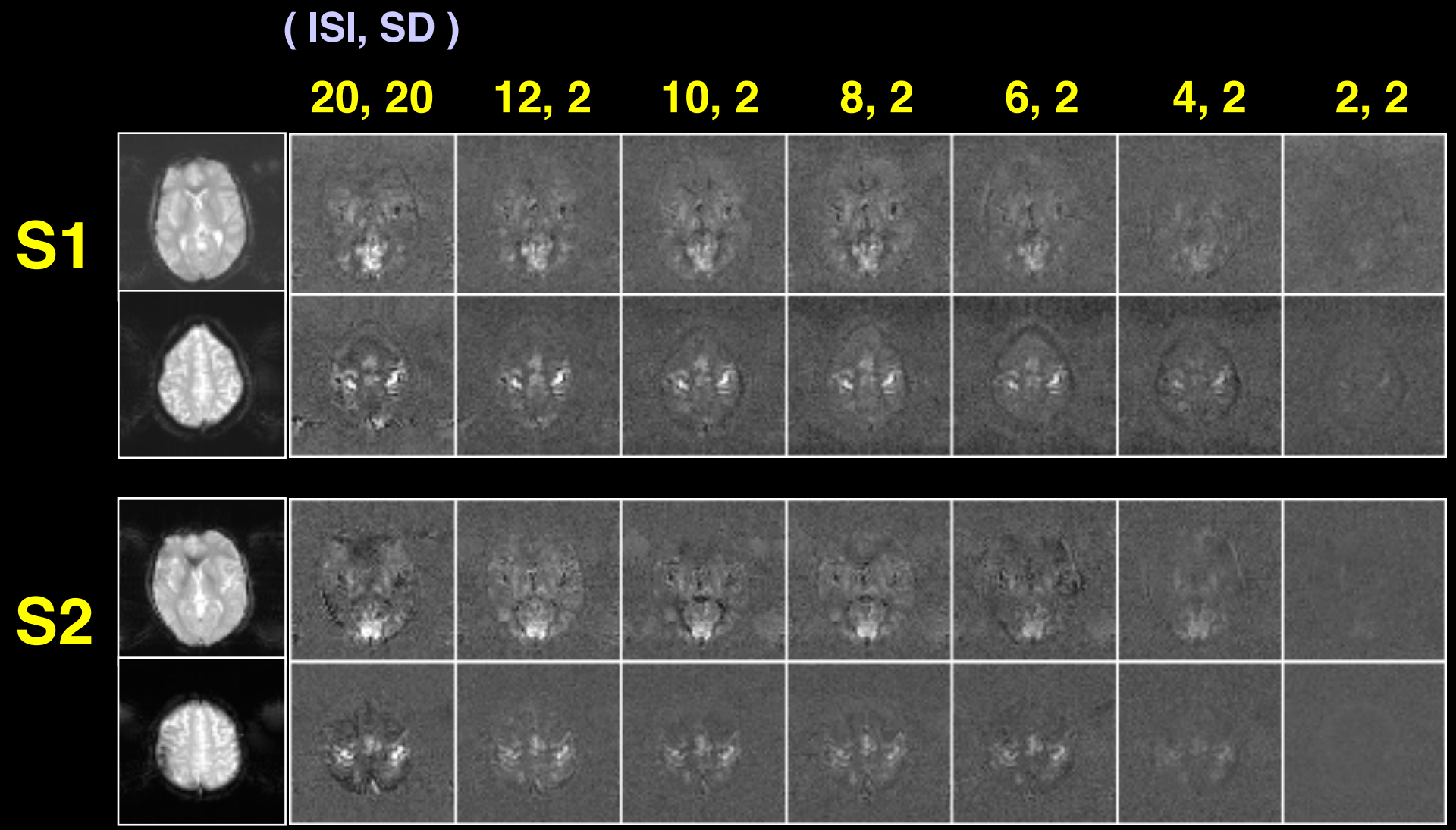


M.A. Burock et al. *NeuroReport*, 9, 3735-9 (1998)



P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* 43: 540-548 (2000).

Contrast to Noise Images

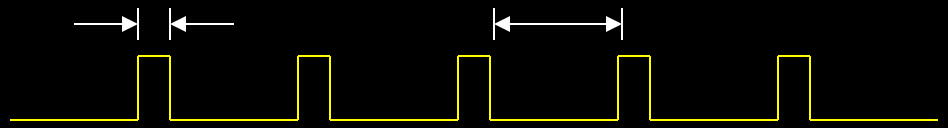


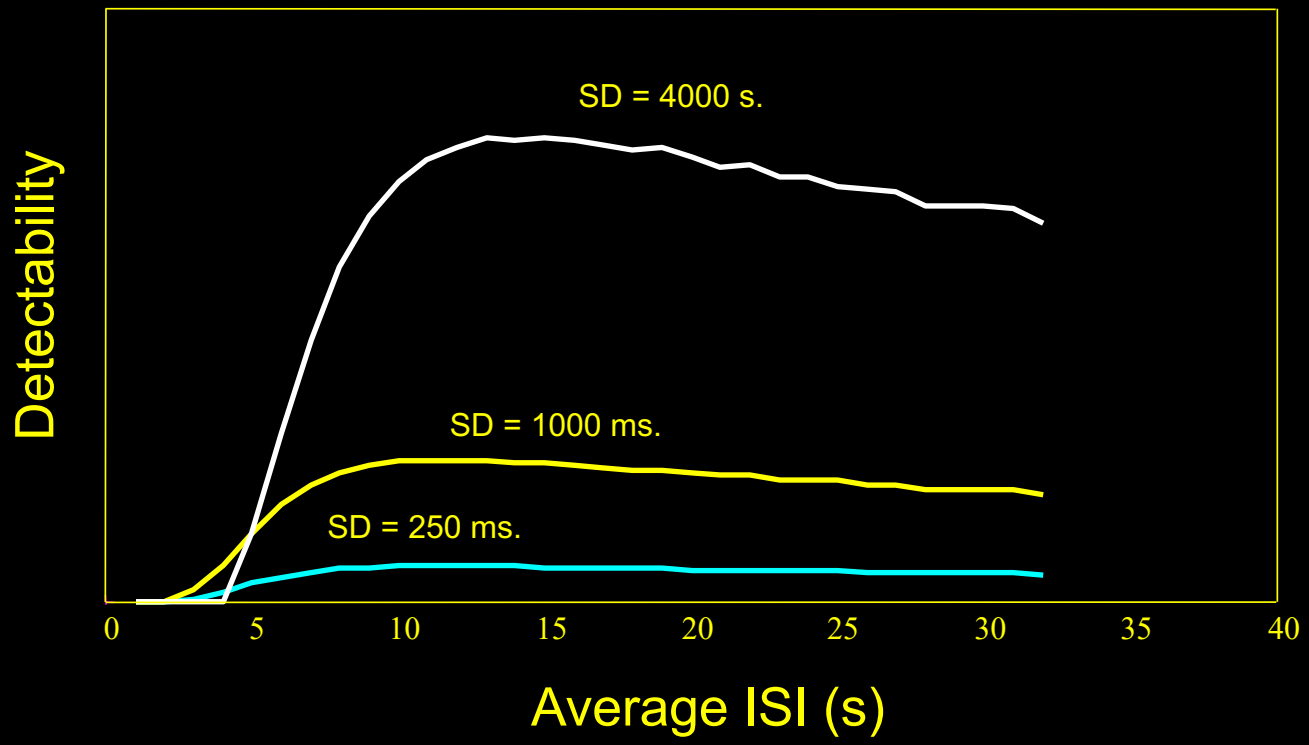
P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* 43: 540-548 (2000).

Detectability – constant ISI

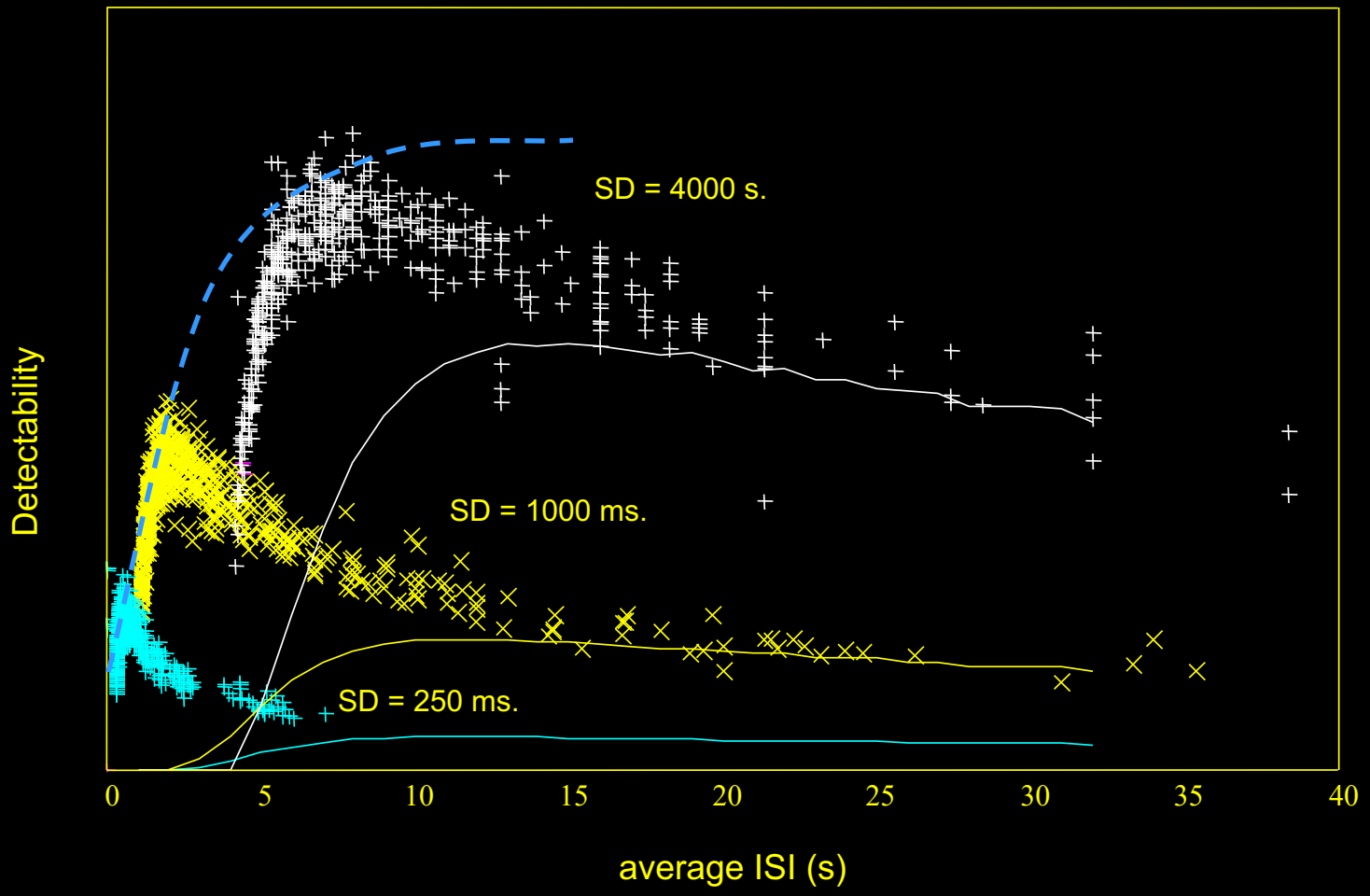
SD – stimulus duration

ISI – inter-stimulus interval



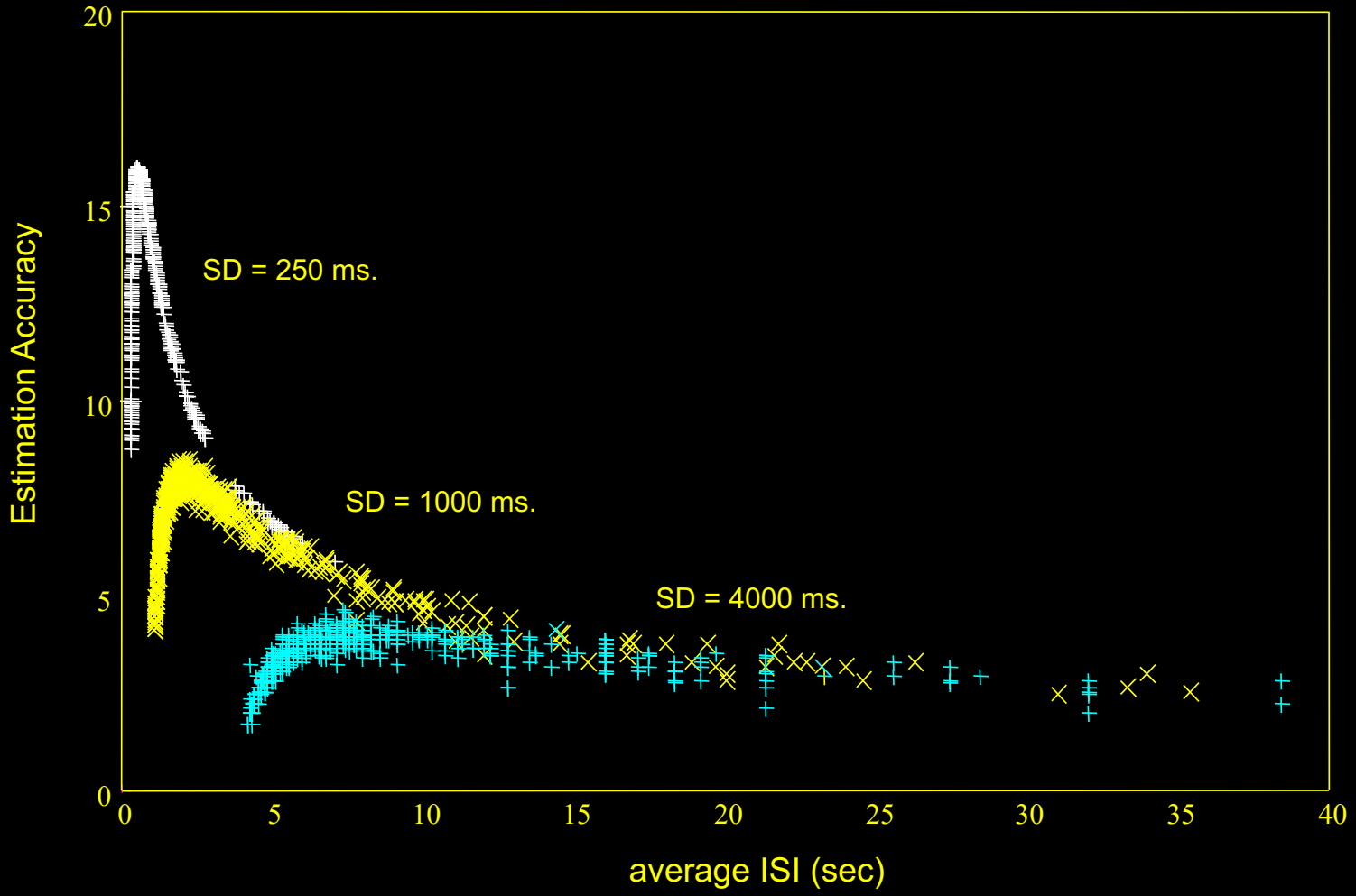


Detectability vs. Average ISI



R. M. Birn, R. W. Cox, P. A. Bandettini, Detection versus estimation in Event-Related fMRI: choosing the optimal stimulus timing. *NeuroImage* 15: 262-264, (2002).

Estimation accuracy vs. average ISI



R. M. Birn, R. W. Cox, P. A. Bandettini, Detection versus estimation in Event-Related fMRI: choosing the optimal stimulus timing. *NeuroImage* 15: 262-264, (2002).

Neuronal Activation Input Strategies

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

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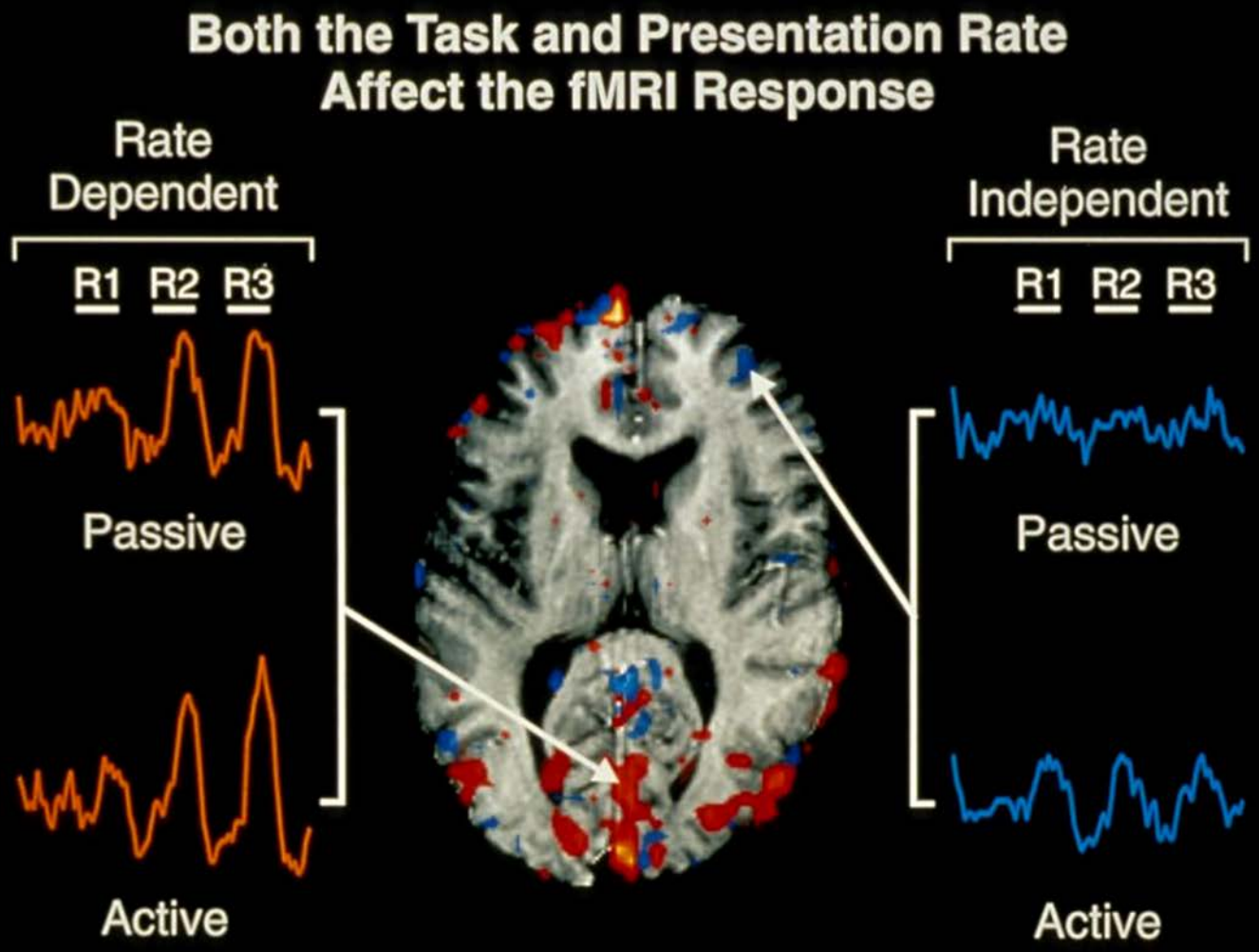

E. A. DeYoe, P. A. Bandettini, J. Nietz, D. Miller, P. Winas, Methods for functional magnetic resonance imaging (FMRI). *J. Neuroscience Methods* 54, 171-187 (1994).

Neuronal Activation Input Strategies

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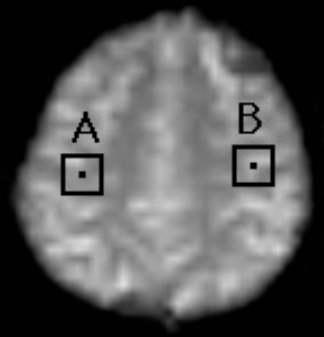
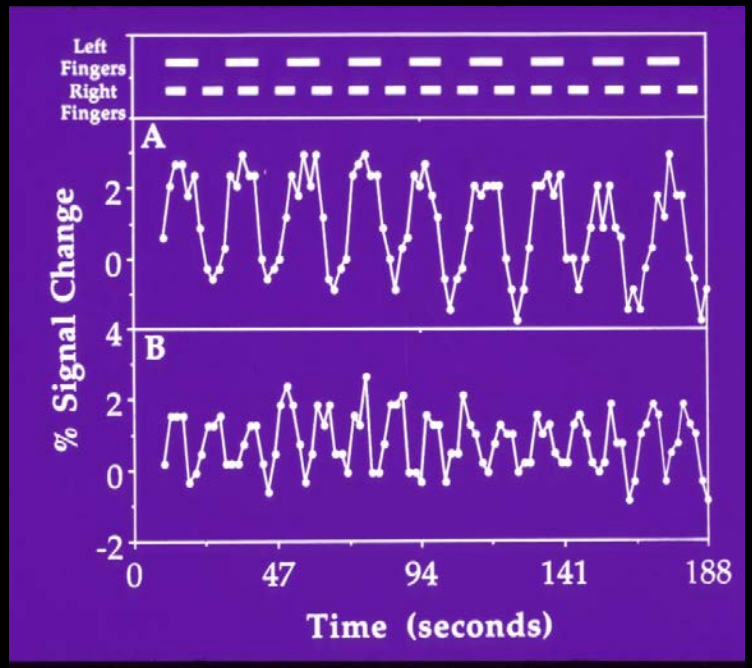
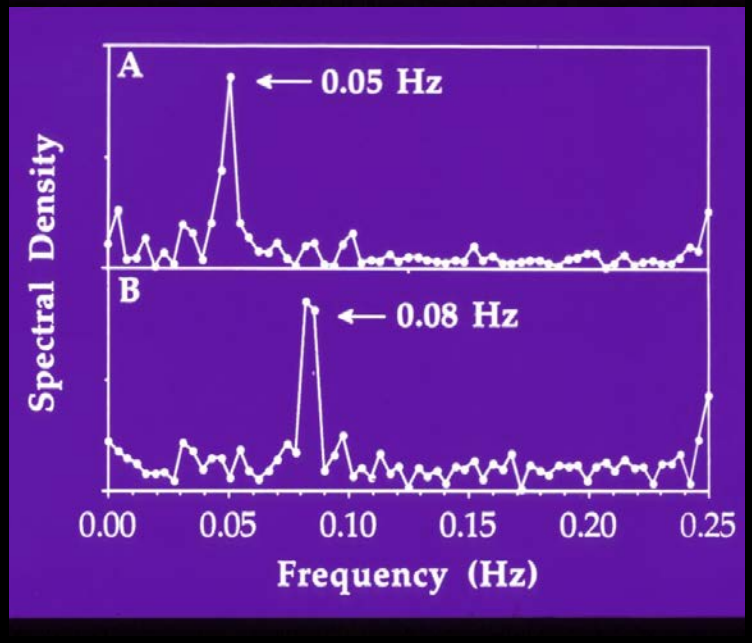
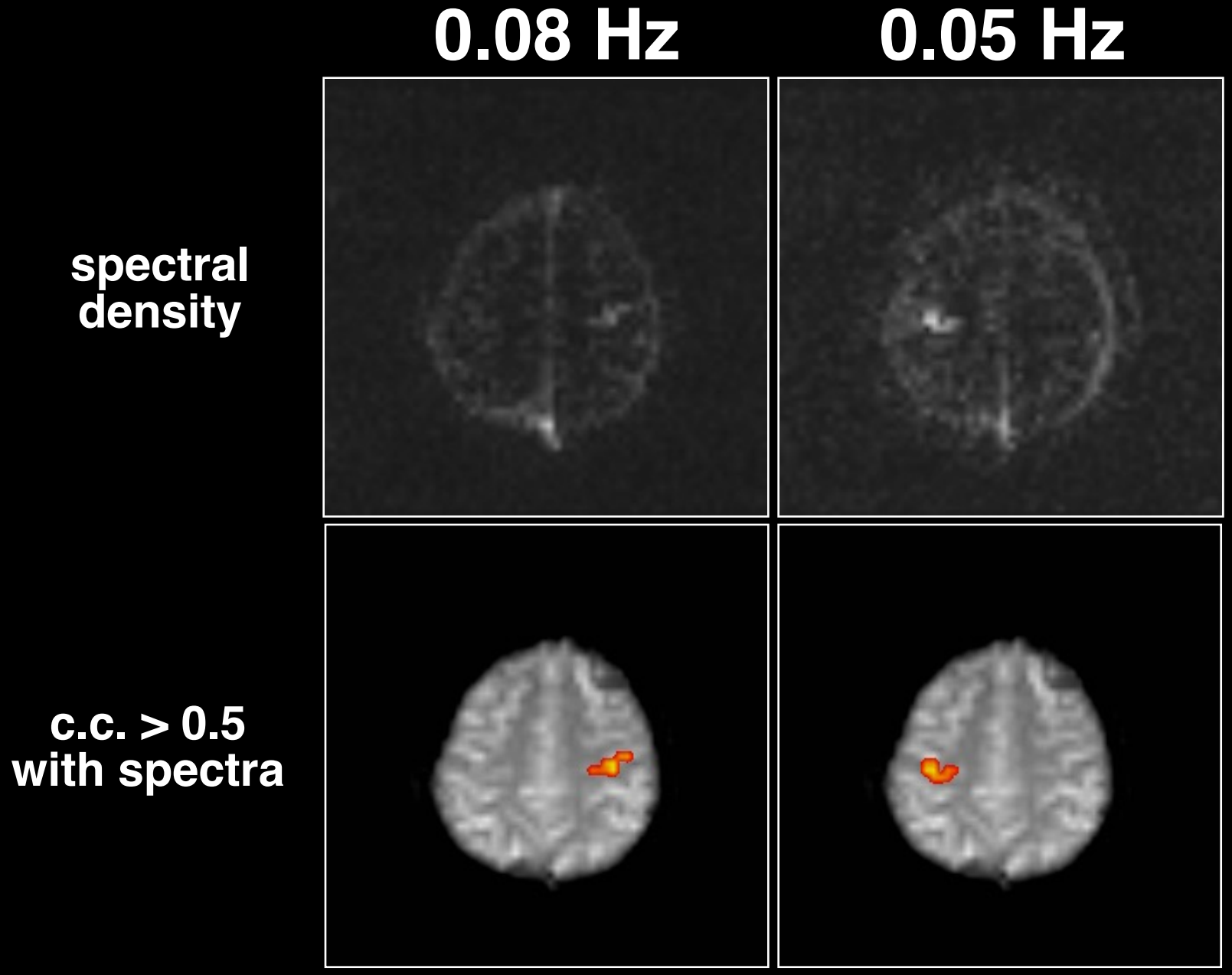






P. A. Bandettini, A. Jesmanowicz, E. C. Wong, J. S. Hyde, Processing strategies for time-course data sets in functional MRI of the human brain. *Magn. Reson. Med.* 30, 161-173 (1993).



P. A. Bandettini, A. Jesmanowicz, E. C. Wong, J. S. Hyde, Processing strategies for time-course data sets in functional MRI of the human brain. *Magn. Reson. Med.* 30, 161-173 (1993).

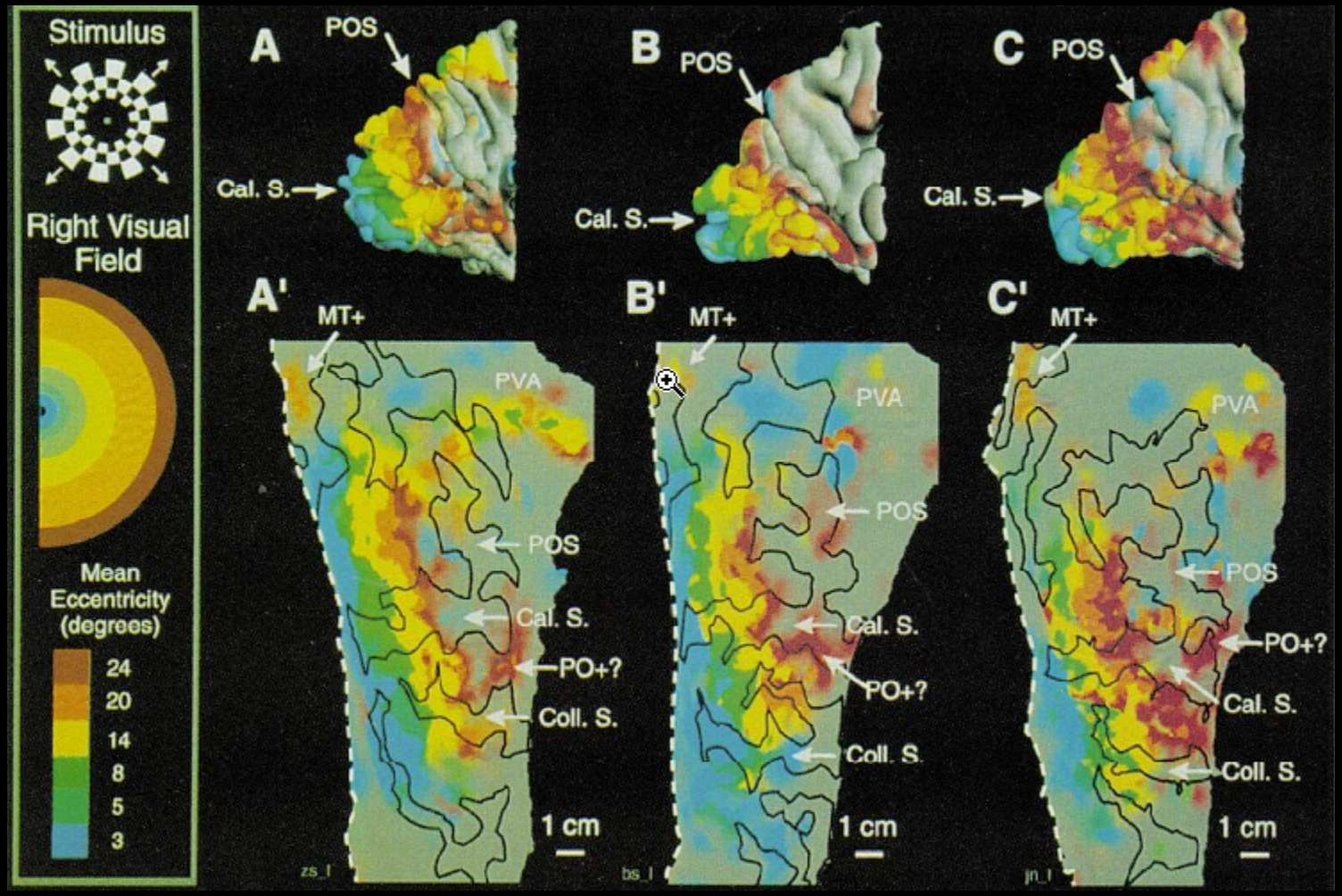
Neuronal Activation Input Strategies

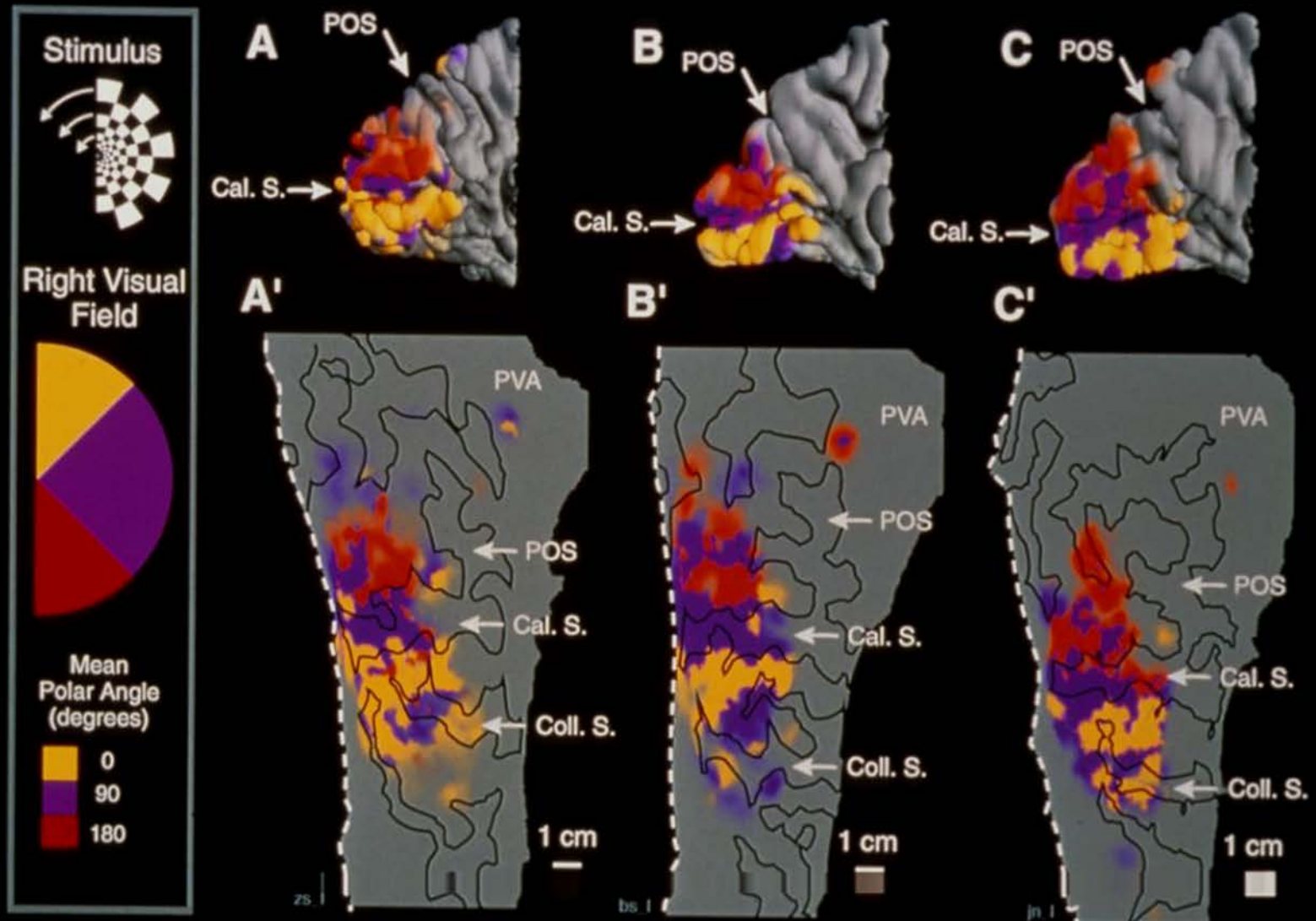
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. **Phase Encoding**
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 2382–2386, March 1996
Neurobiology

Mapping striate and extrastriate visual areas in human cerebral cortex

EDGAR A. DEYOE*, GEORGE J. CARMAN†, PETER BANDETTINI‡, SETH GLICKMAN*, JON WIESER*, ROBERT COX§, DAVID MILLER¶, AND JAY NEITZ*




Stimulus
Right Visual Field
Mean Polar Angle (degrees)
0
90
180
A
POS
Cal. S.
B
POS
Cal. S.
C
POS
Cal. S.
A'
PVA
POS
Cal. S.
Coll. S.
1 cm
zs
B'
PVA
POS
Cal. S.
Coll. S.
1 cm
bs
C'
PVA
POS
Cal. S.
Coll. S.
1 cm
jn

Neuronal Activation Input Strategies

1. Block Design
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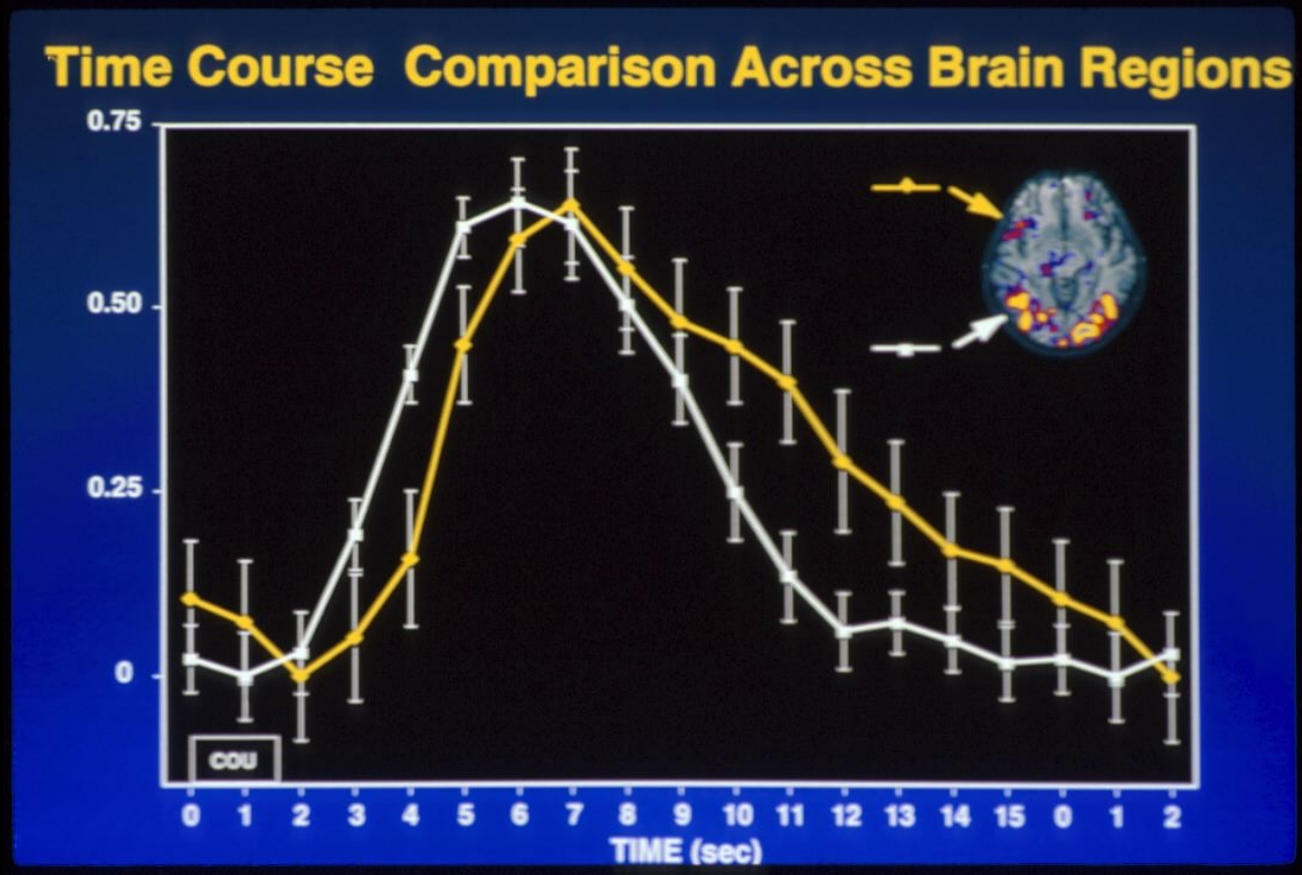
Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 14878–14883, December 1996
Neurobiology

Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging

(neuroimaging/single trial/language/prefrontal)

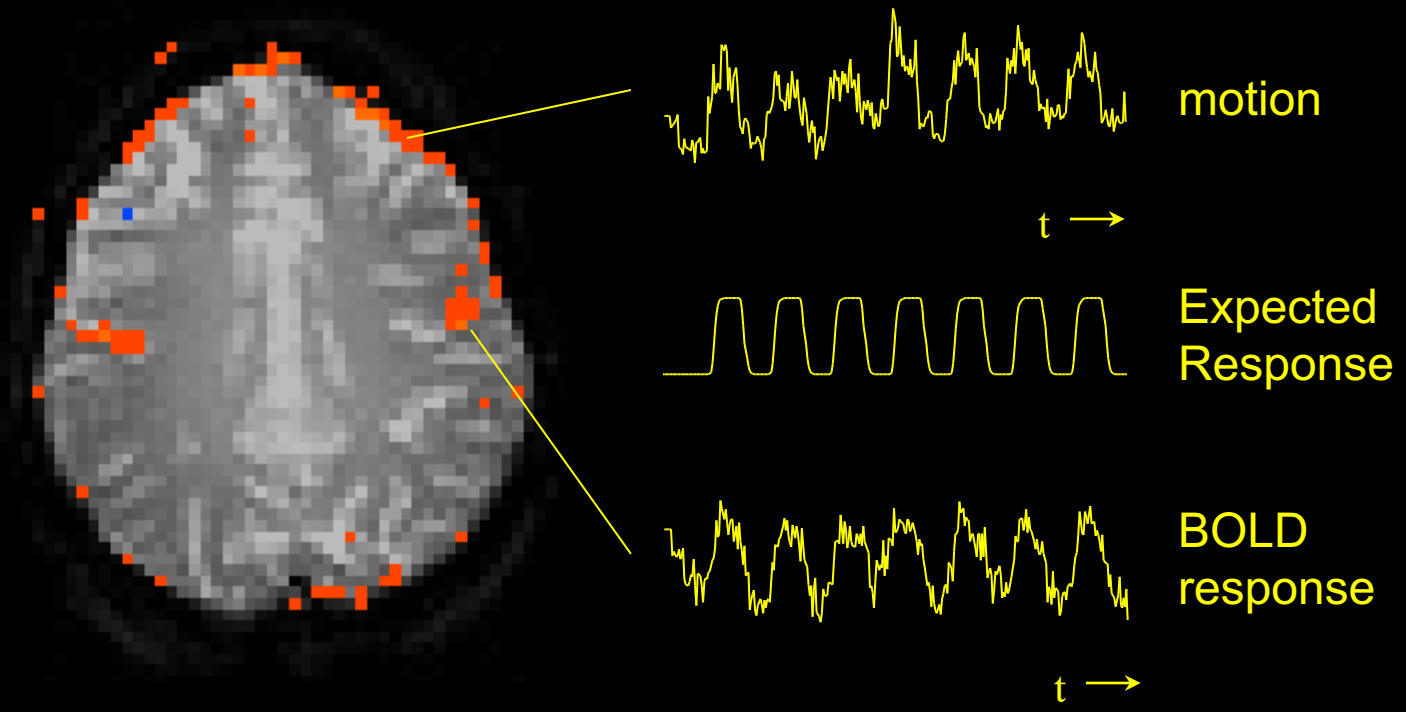
RANDY L. BUCKNER[†‡§¶], PETER A. BANDETTINI[†‡], KATHLEEN M. O'CRAVEN[†‖], ROBERT L. SAVOY[†‖], STEVEN E. PETERSEN[*††], MARCUS E. RAICHLE[§*†††], AND BRUCE R. ROSEN[†‡]



Event Related Advantages

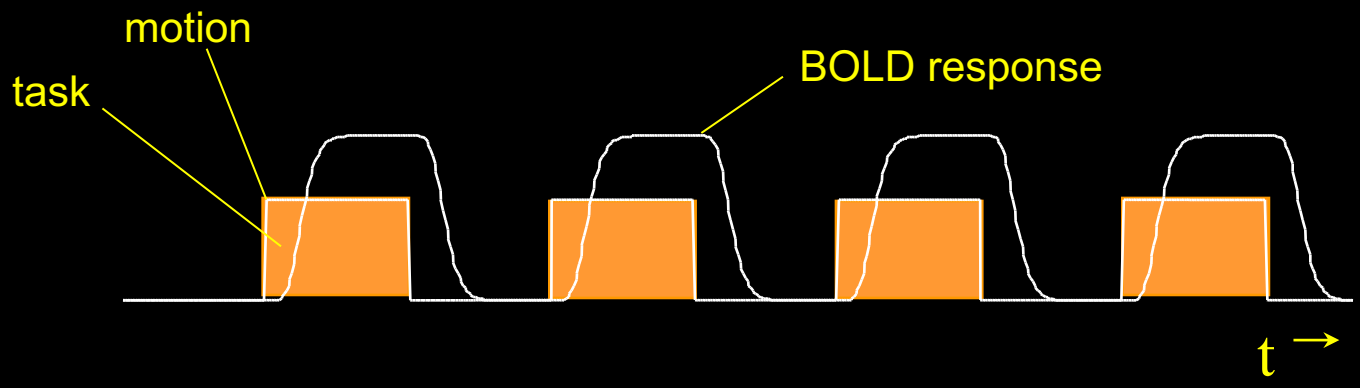
- Task Randomization
- Post acquisition, Performance-based, data binning
- Natural presentation
- Reduction of habituation effects
- Overt responses
- Reduction of scanner noise effects
- More precise estimation of hemodynamic respons

Speaking - Blocked Trial

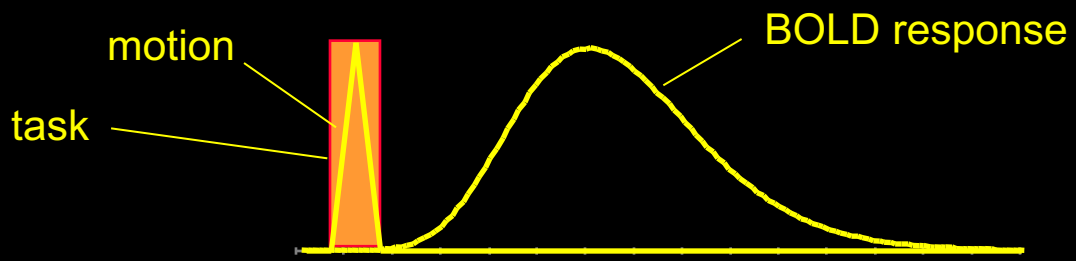


fMRI during tasks that involve brief motion

Blocked Design

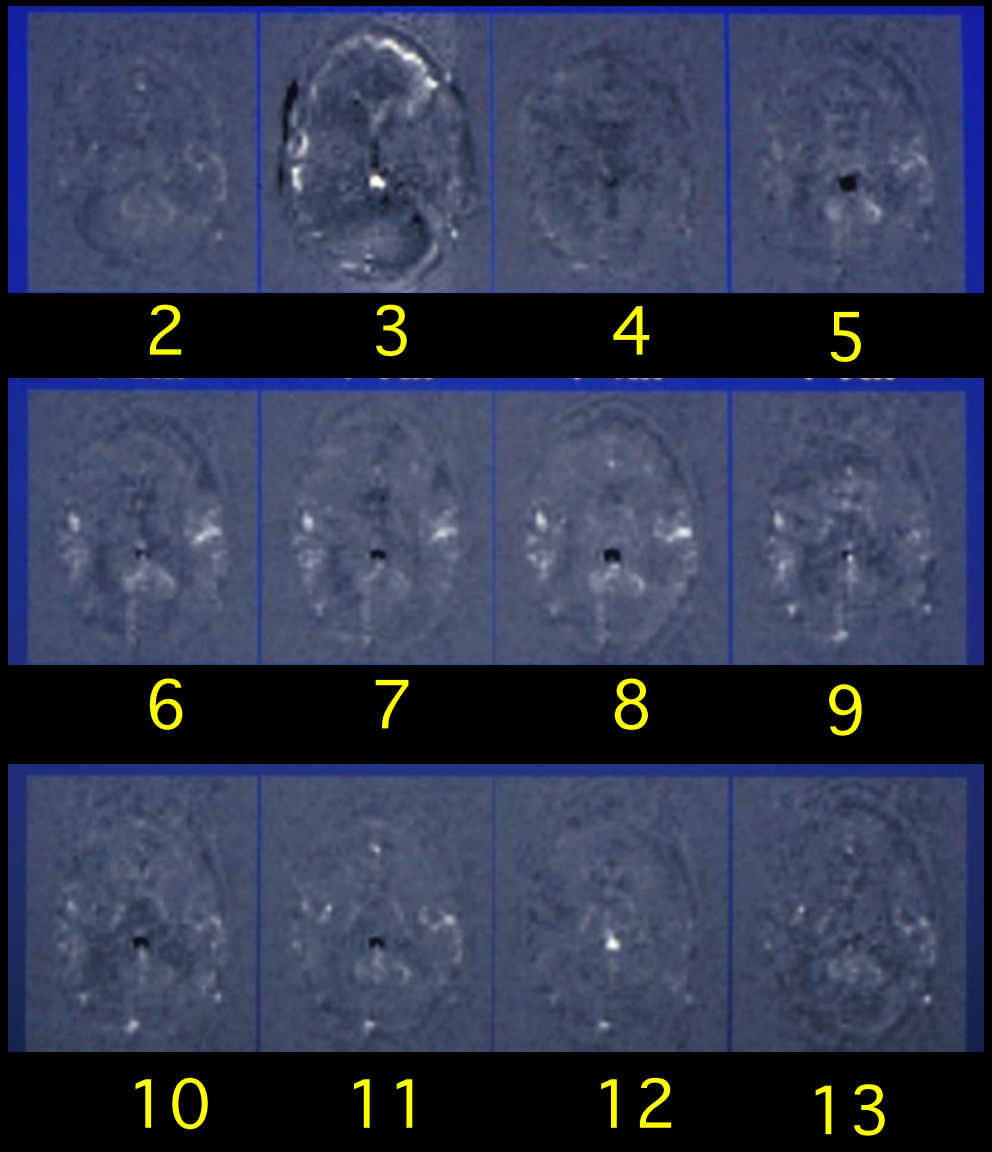


Event-Related Design



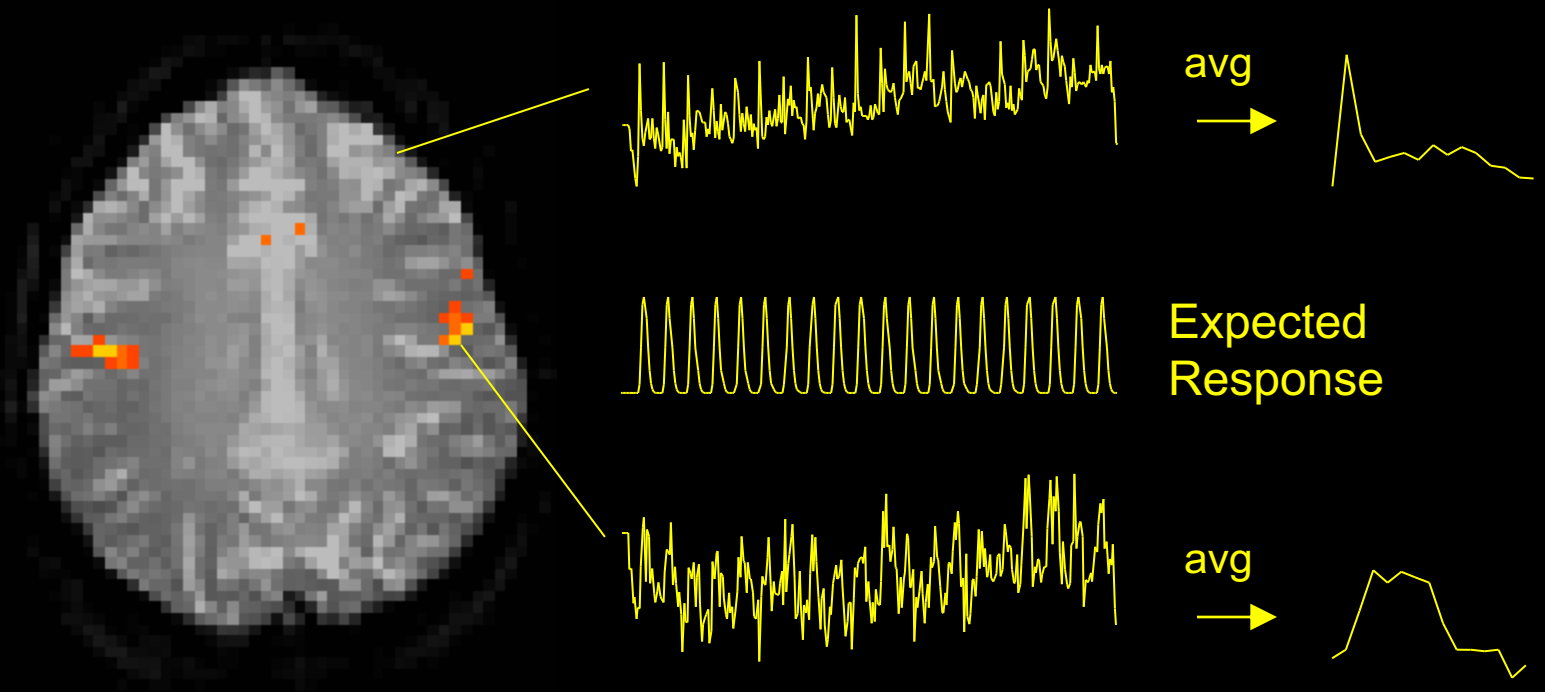
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Overt Word Production



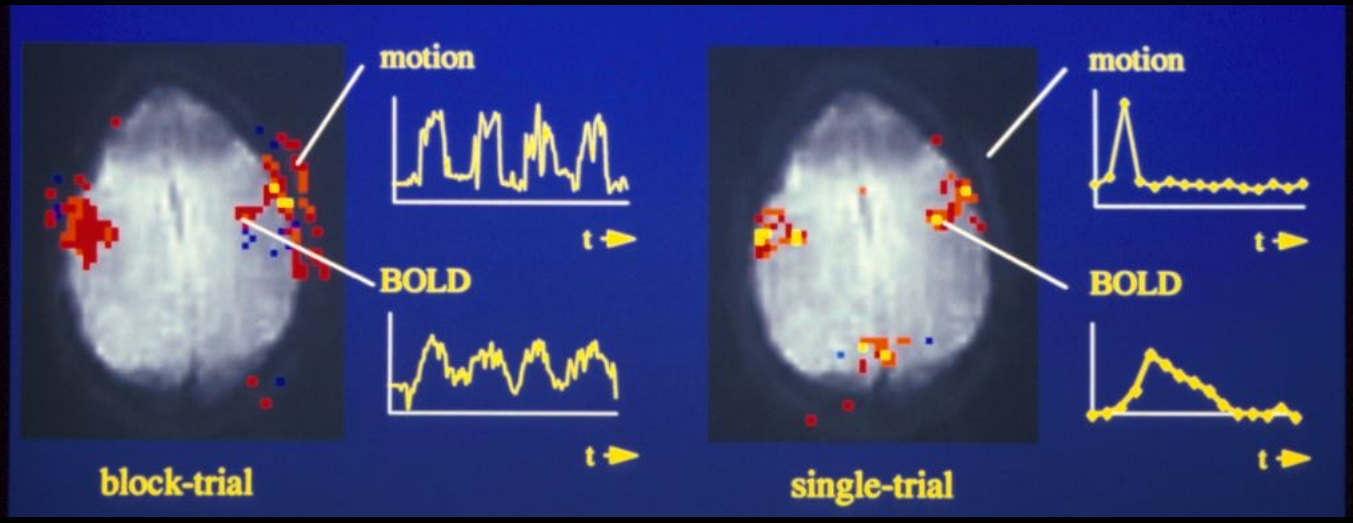
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Speaking - ER-fMRI

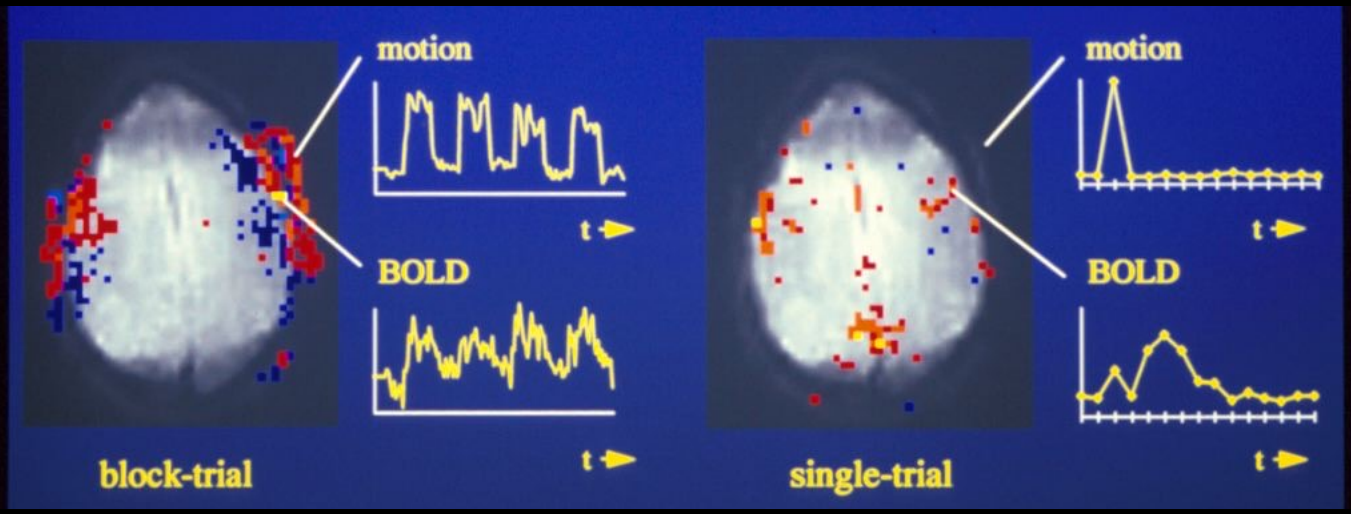


R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Tongue Movement



Jaw Clenching



Neuronal Activation Input Strategies

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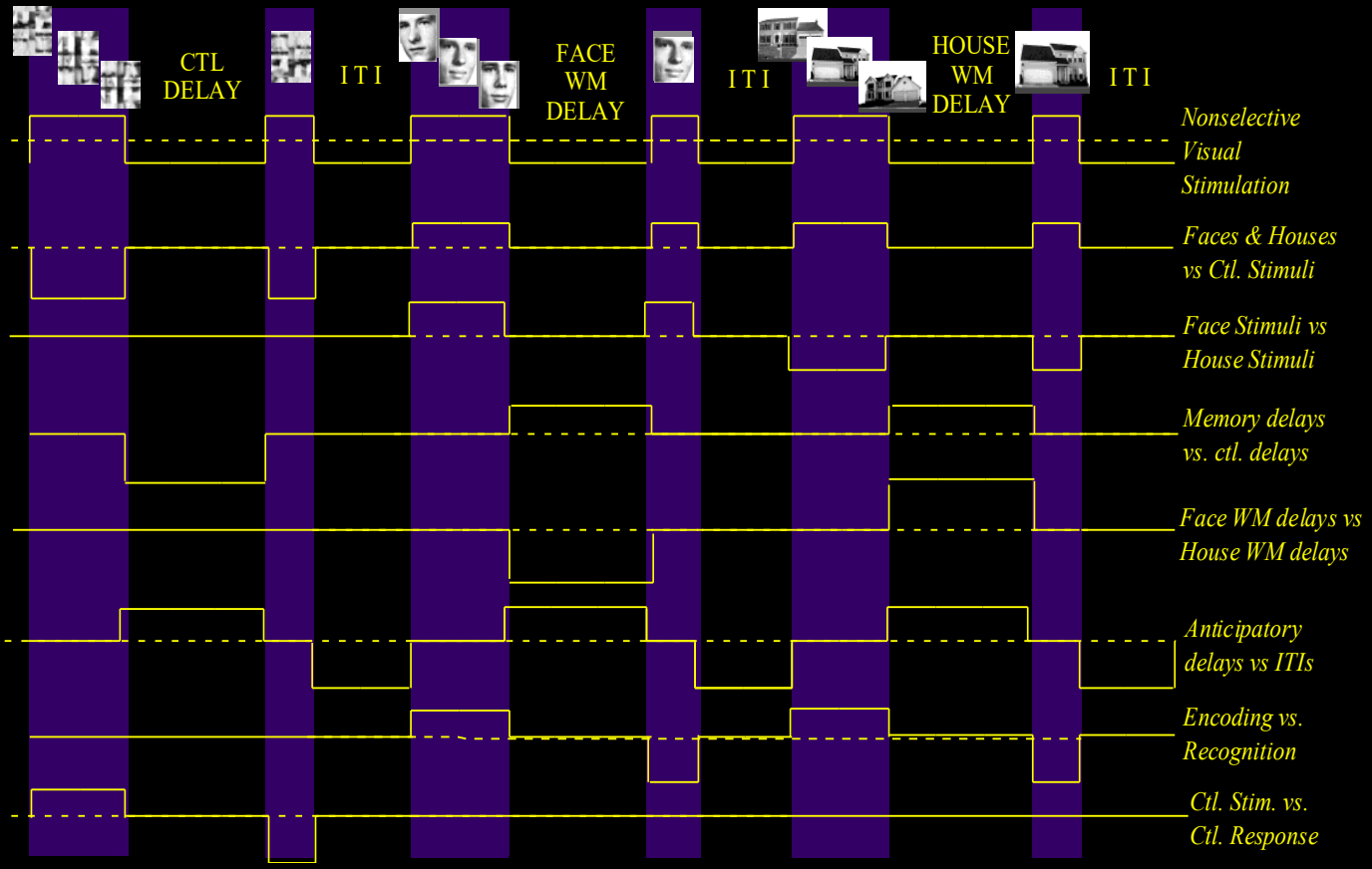
4. Phase Encoding
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

Example of a Set of Orthogonal Contrasts for Multiple Regression



Courtney, S. M., L. G. Ungerleider, et al. (1997). "Transient and sustained activity in a distributed neural system for human working memory." Nature 386(6625): 608-11.

Neuronal Activation Input Strategies

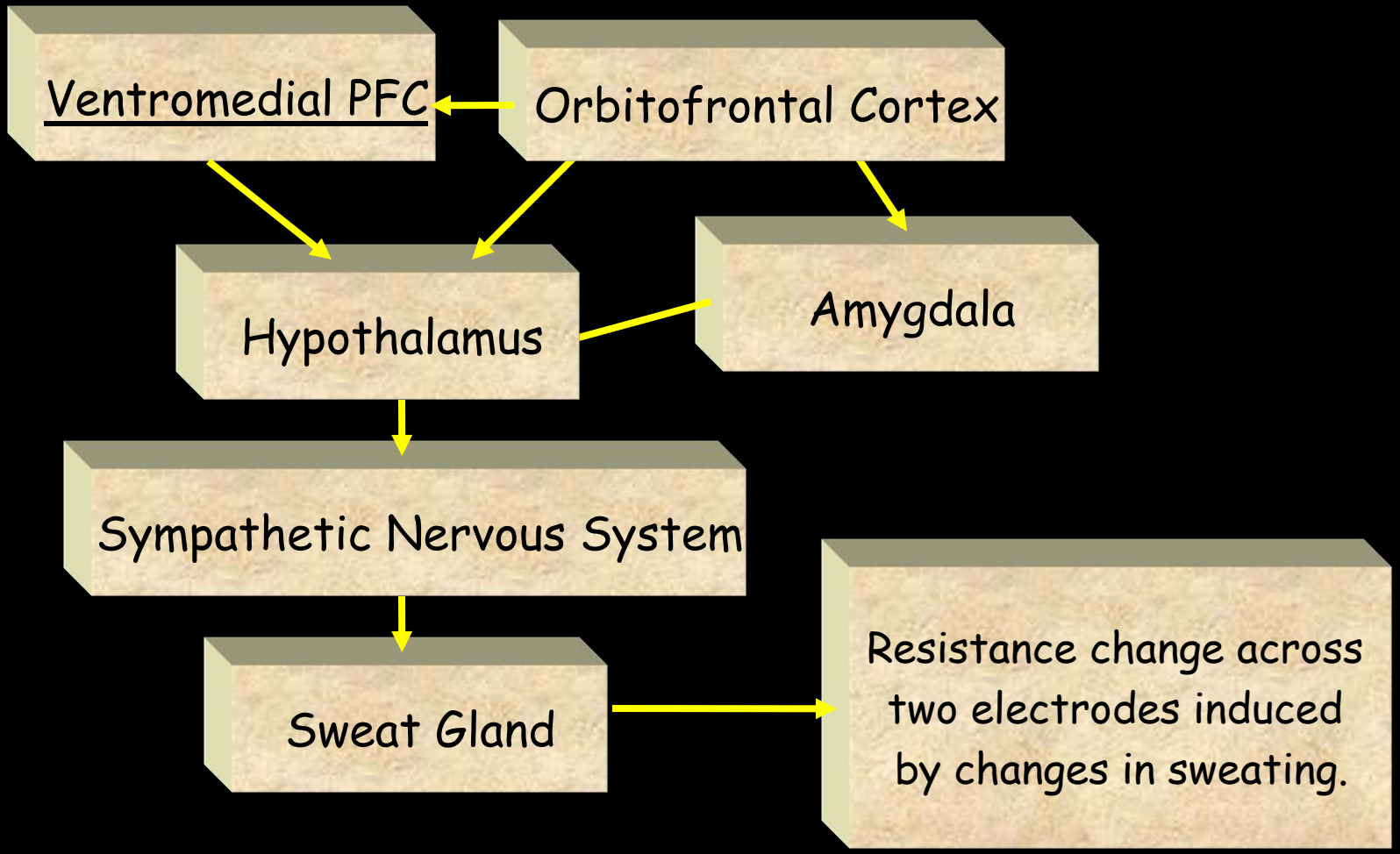
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. Phase Encoding
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

Free Behavior Design

Use a continuous measure as a reference function:

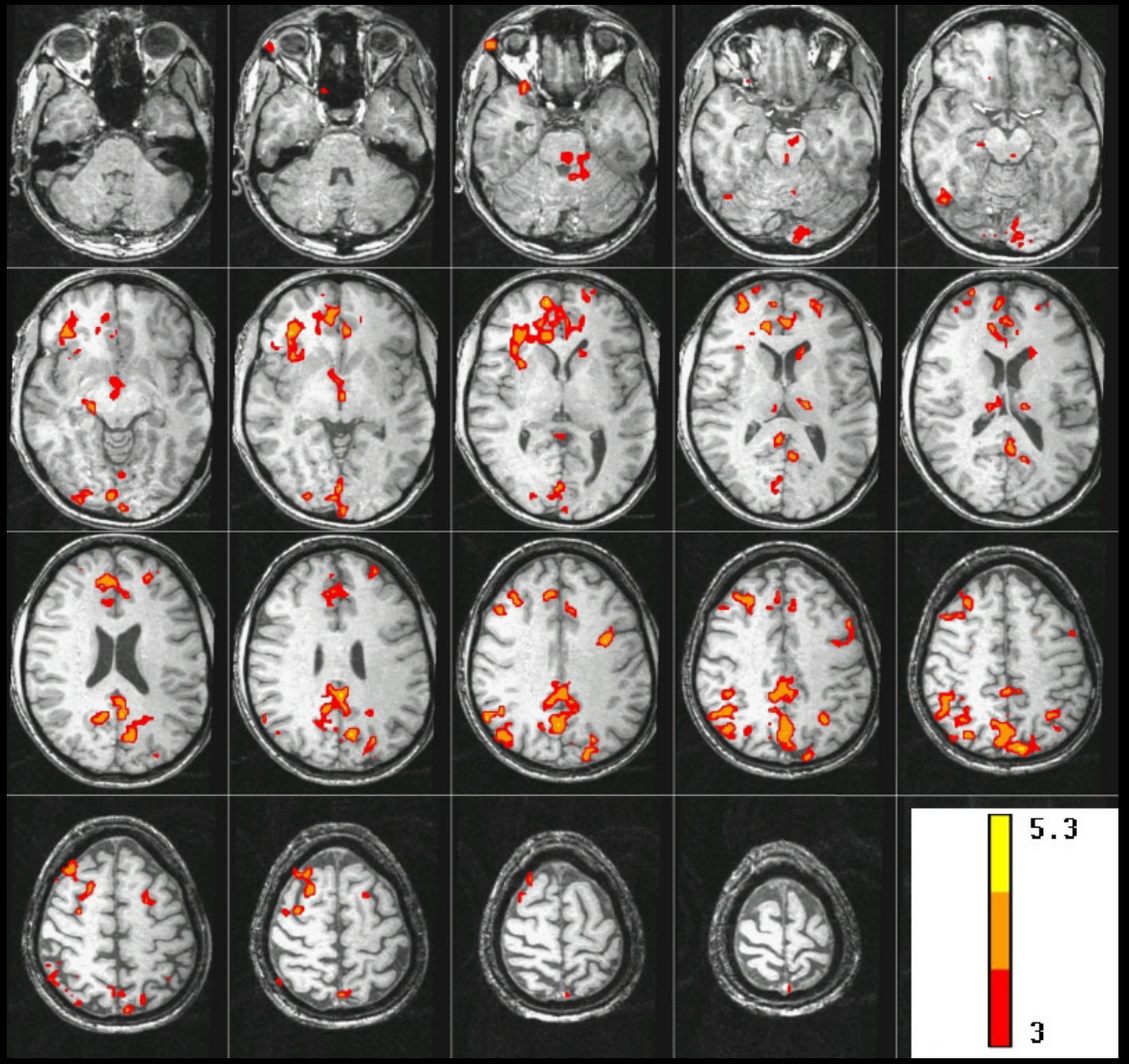
- Task performance
- Skin Conductance
- Heart, respiration rate..
- Eye position
- EEG

The Skin Conductance Response (SCR)



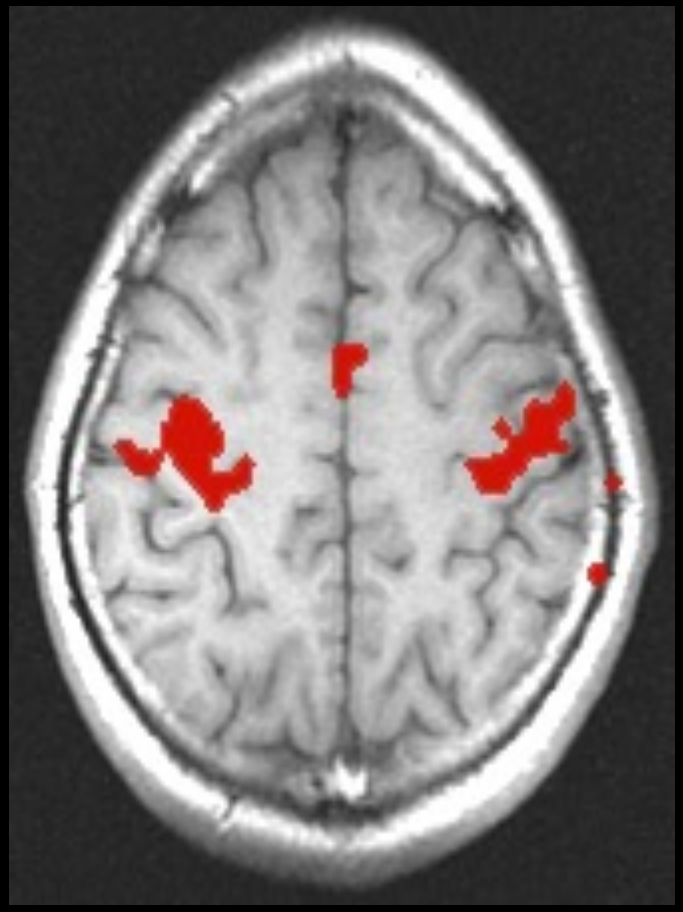
Patterson et al. (submitted)

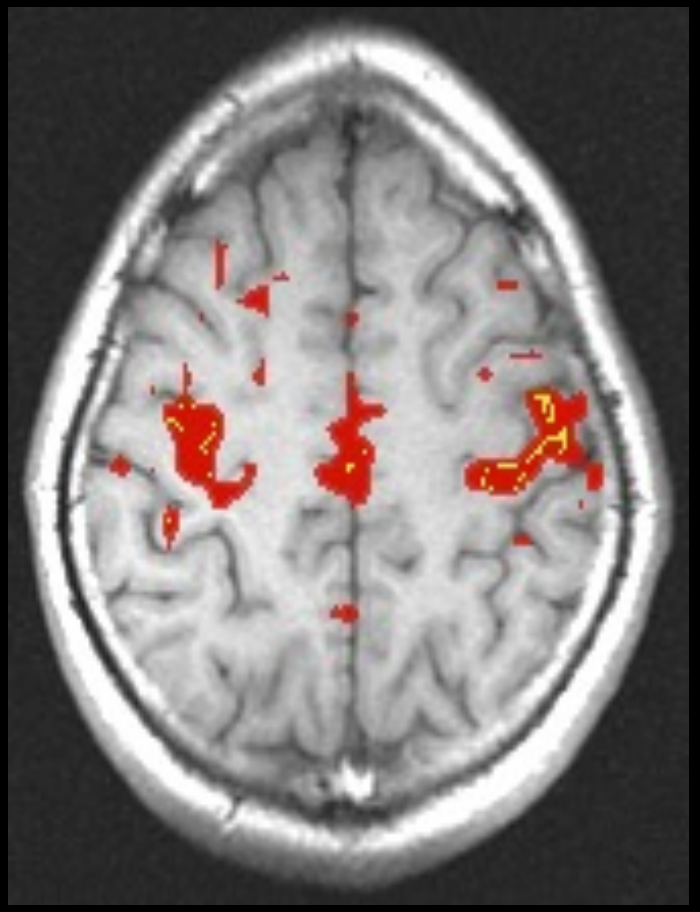
Brain activity correlated with SCR during "Rest"



Patterson et al. (submitted)

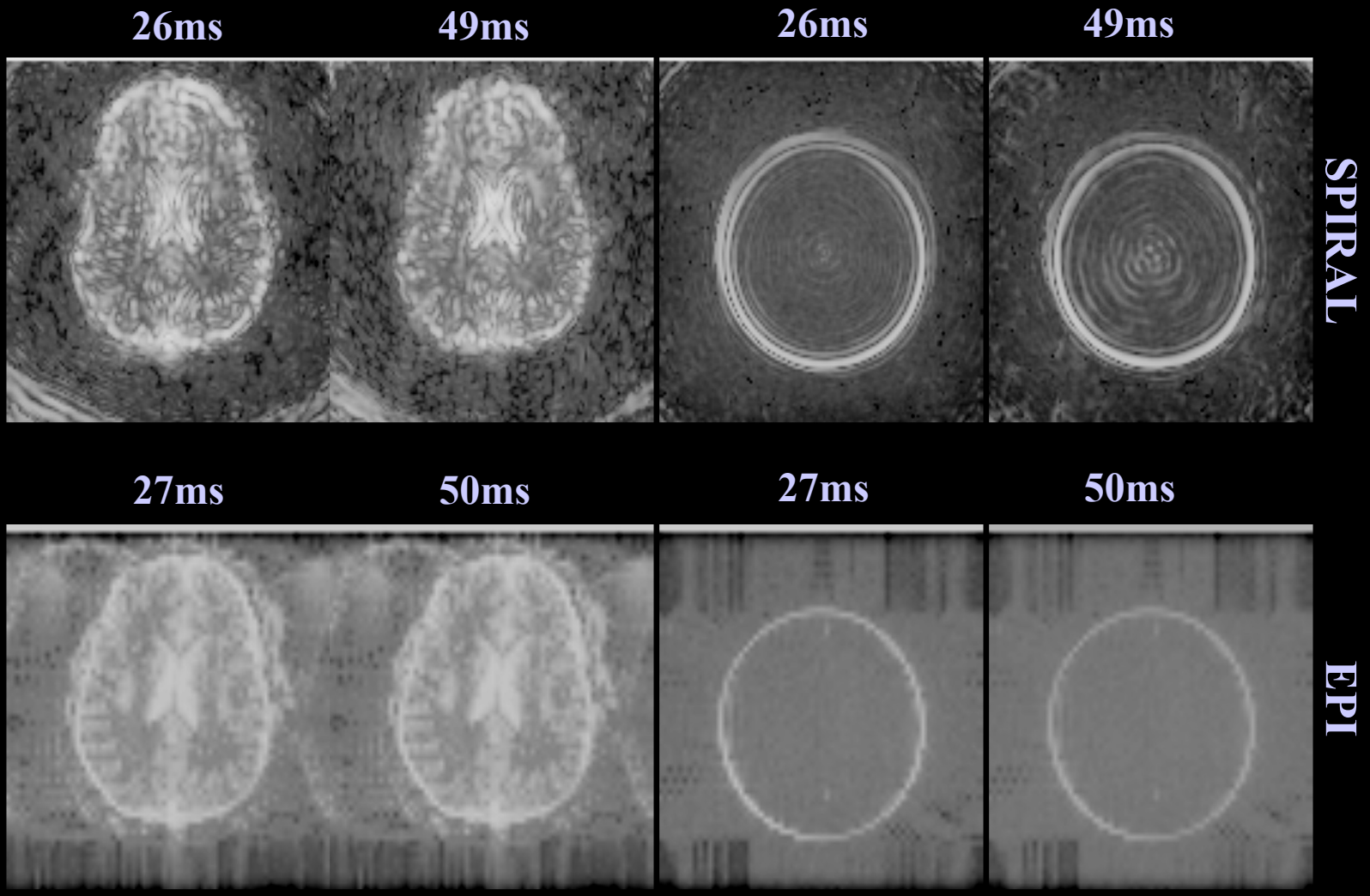
Resting Hemodynamic Autocorrelations



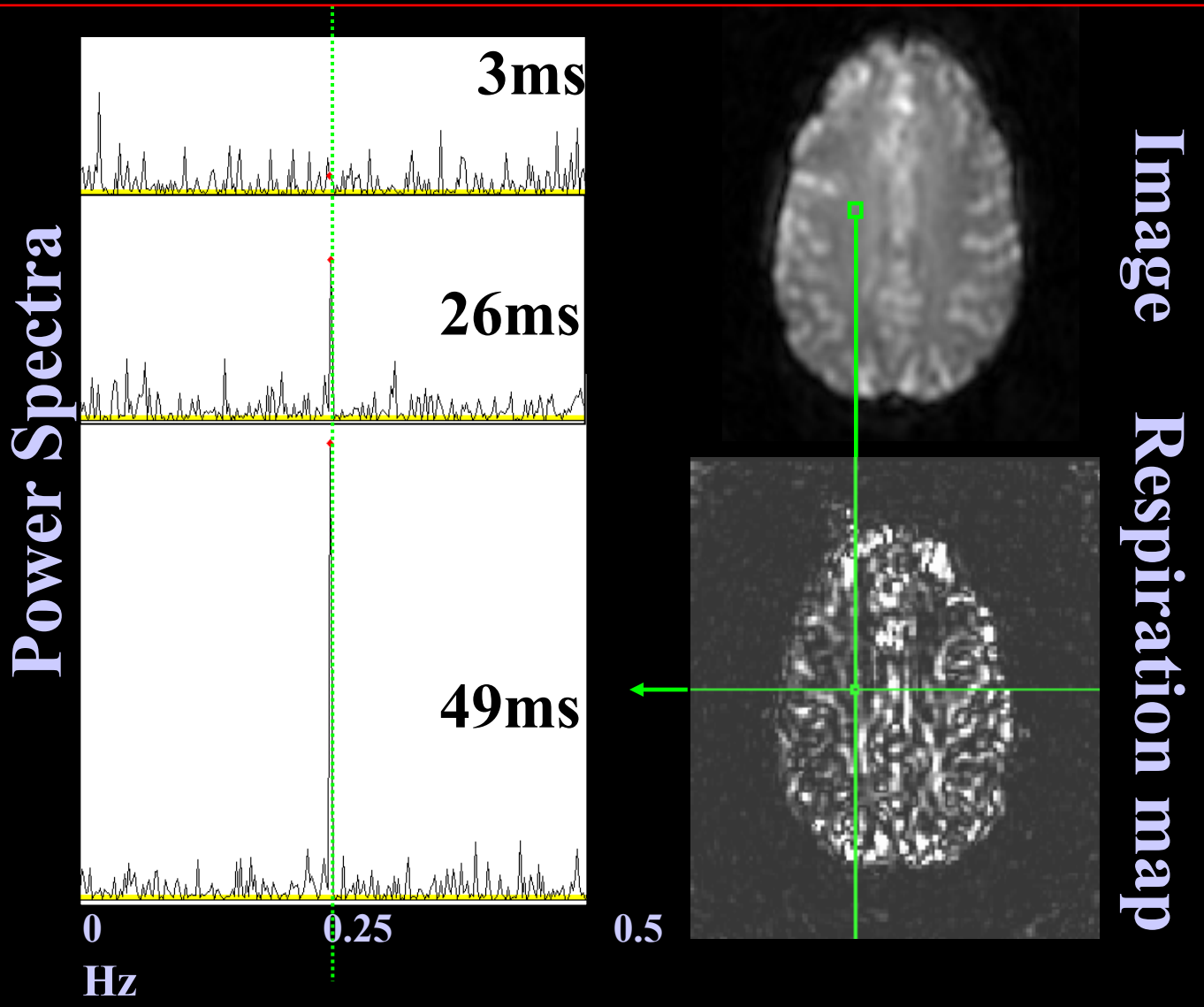


B. Biswal *et al*., MRM, 34:537 (1995)

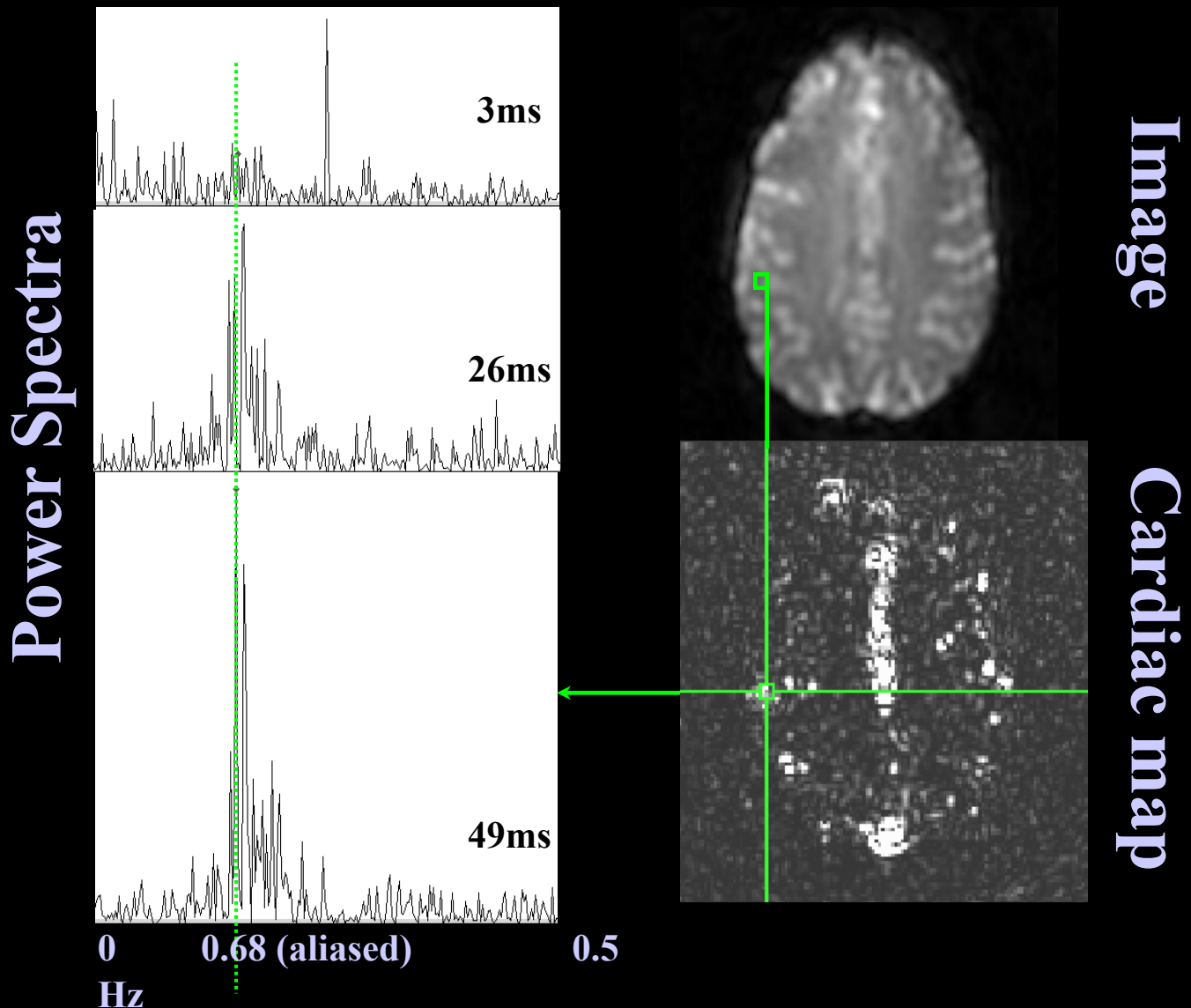
Temporal vs. Spatial SNR- 3T



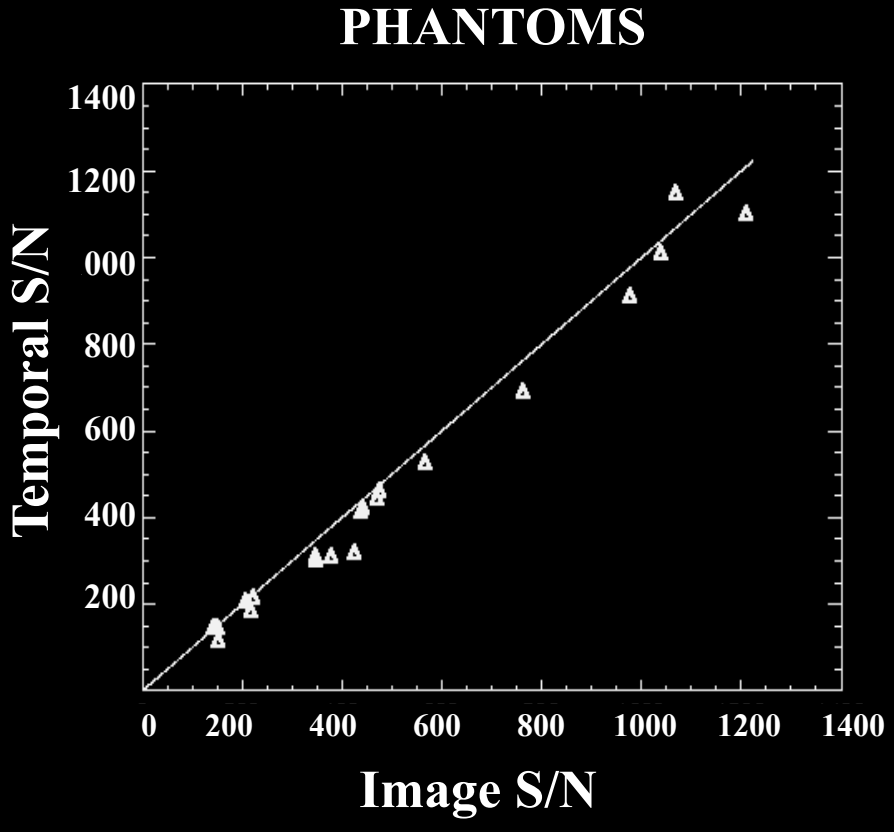
0.25 Hz Breathing at 3T

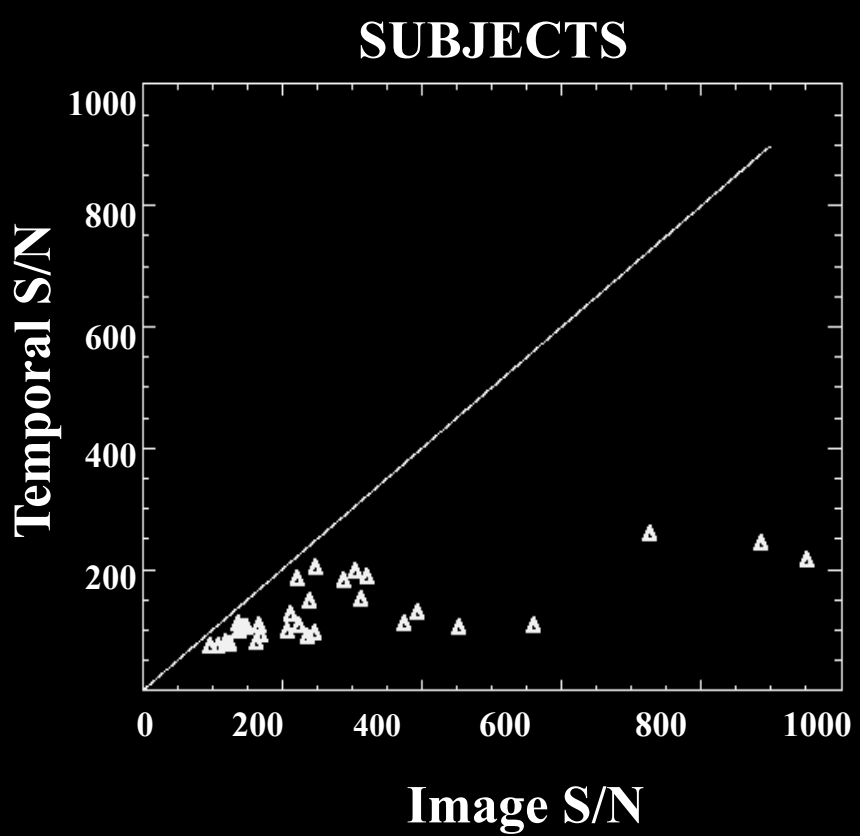


0.68 Hz Cardiac rate at 3T



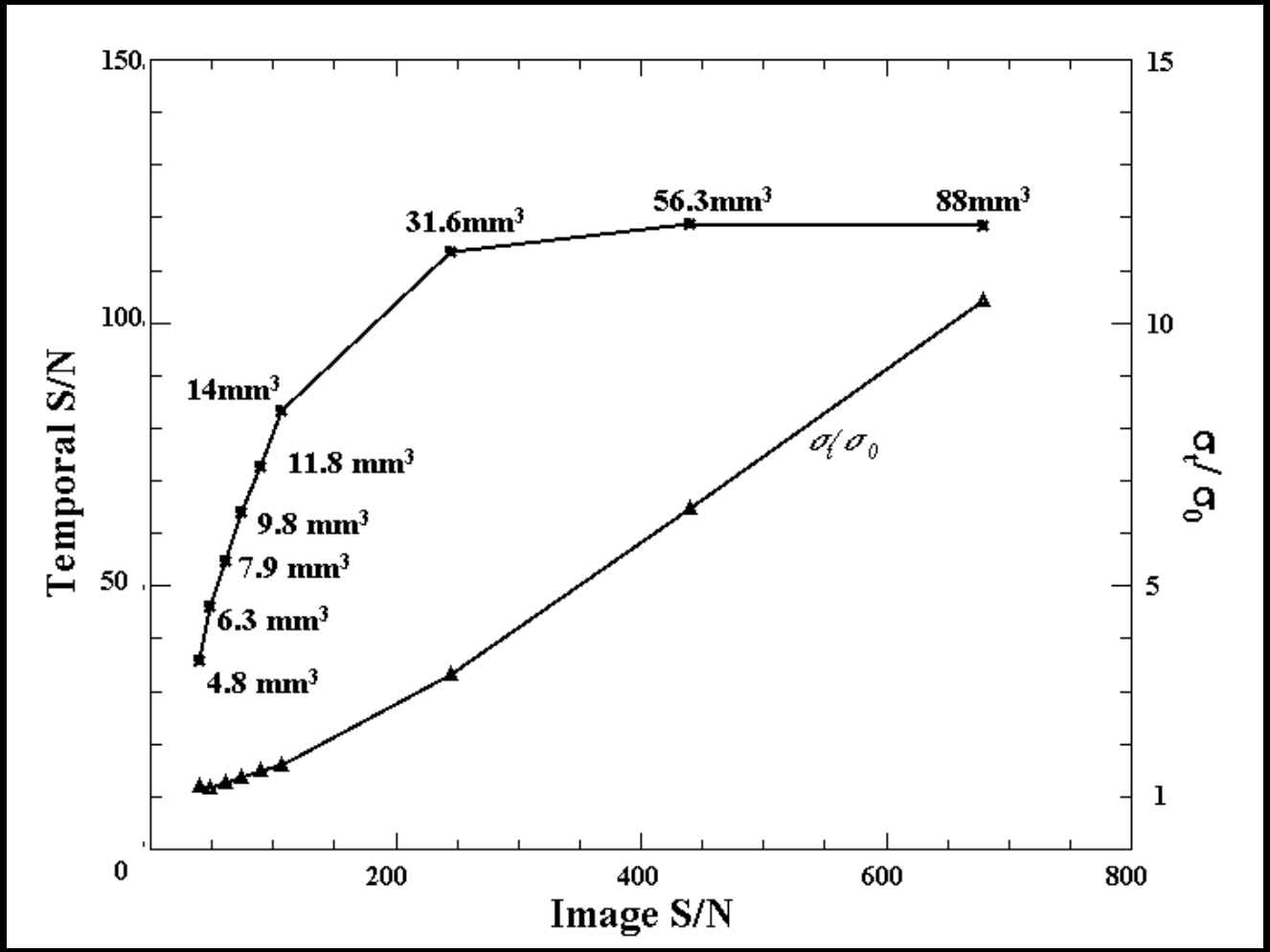
Temporal S/N vs. Image S/N





N. Petridou

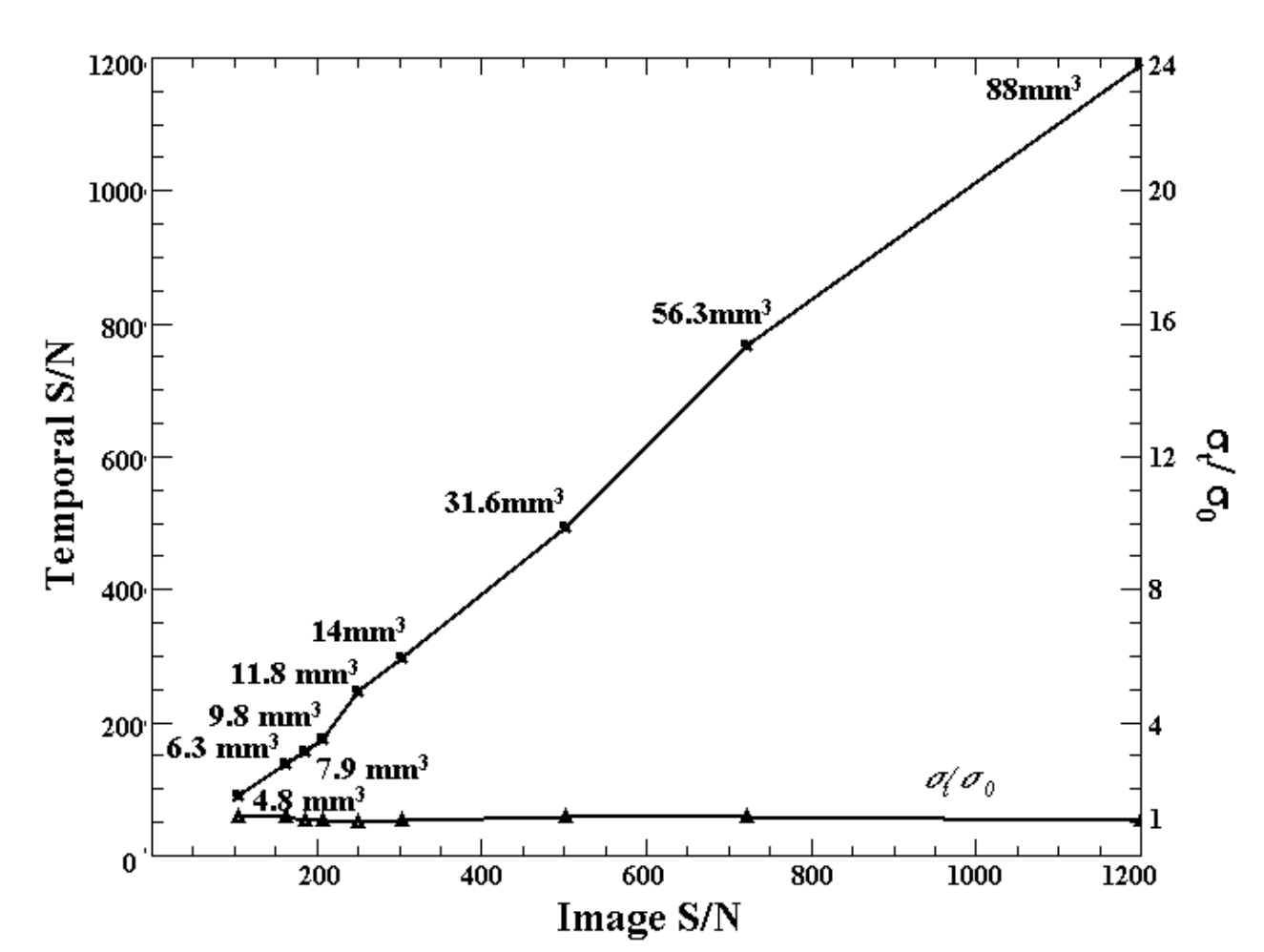
Temporal vs. Image S/N
Optimal Resolution Study



Human data

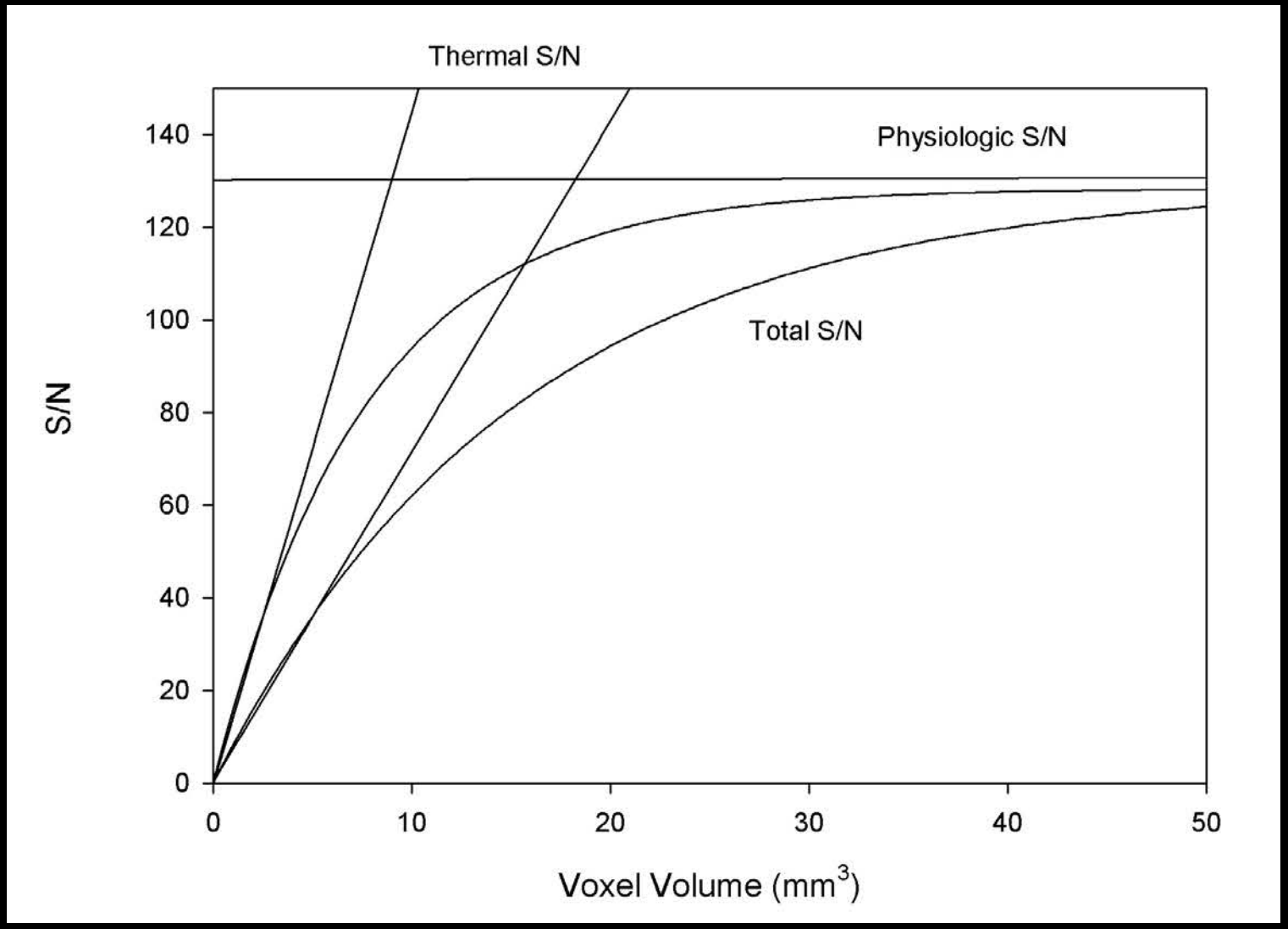
Petridou et al

Temporal vs. Image S/N
Optimal Resolution Study

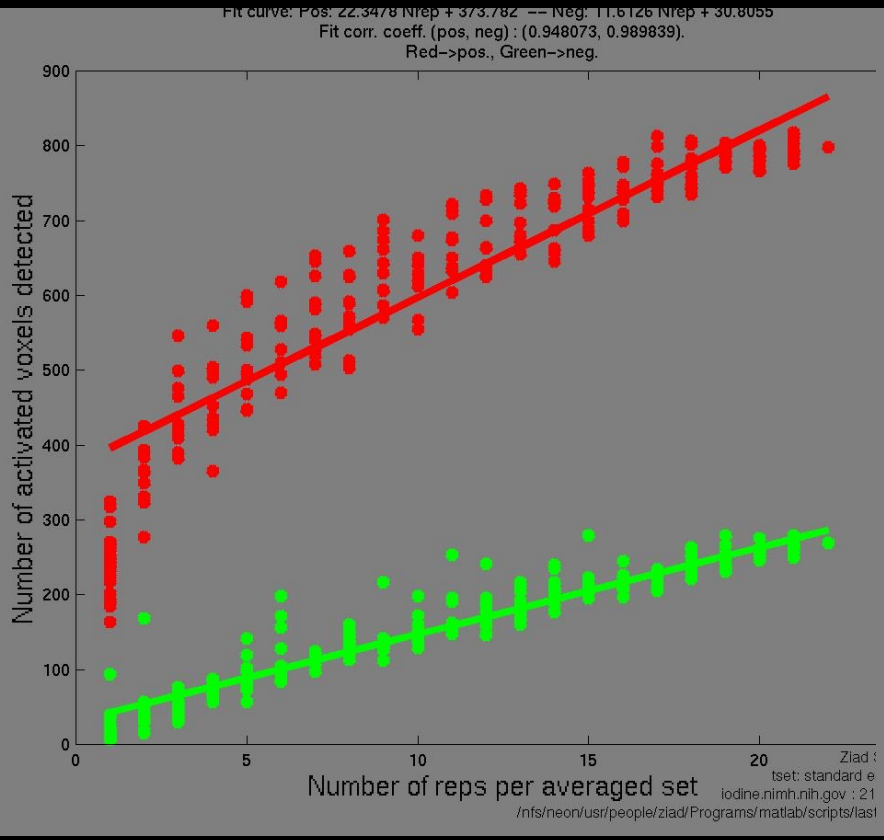


Phantom data

Petridou et al

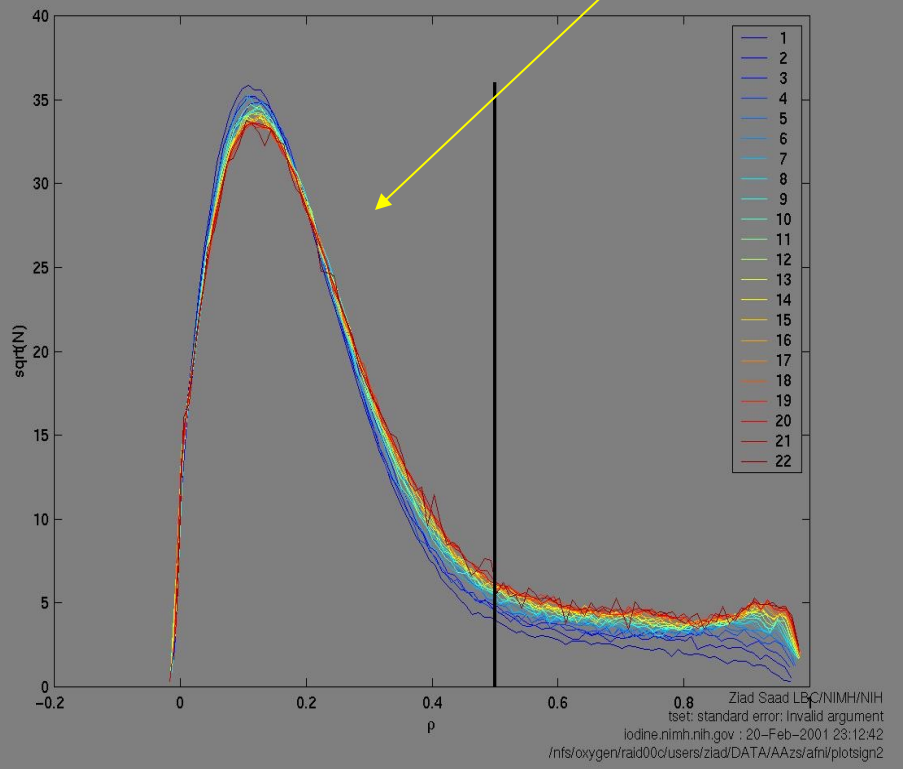

Thermal S/N
Physiologic S/N
Total S/N
S/N
0
20
40
60
80
100
120
140
0
10
20
30
40
50
Voxel Volume (mm3)

Continuously Growing Activation Area

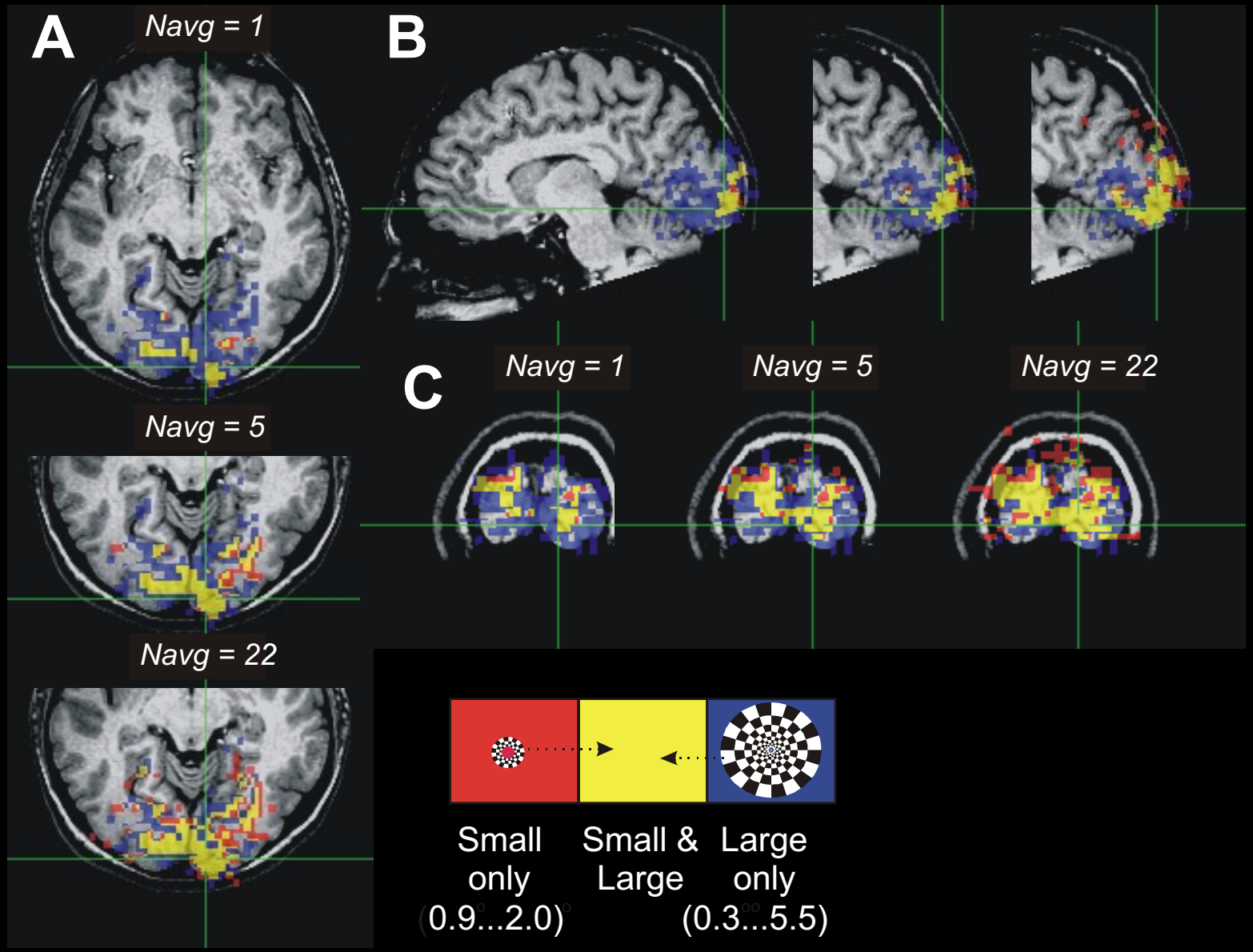


CC Histogram

Inflection Point



Ziad Saad, et al (Submitted)


A
Navg = 1
Navg = 5
Navg = 22
B
C
Navg = 1
Navg = 5
Navg = 22
Small only (0.9...2.0)
Small & Large
Large only (0.3...5.5)

Motion

Recognize?
- Edge effects
- Shorter signal change latencies
- Unusually high signal changes
- External measuring devices

Correct?
- Image registration algorithms
- Orthogonalize to motion-related function *(cardiac, respiration, movement)*
- Navigator echo for k-space alignment *(for multishot techniques)*
- Re-do scan

Bypass?
- Paradigm timing strategies..
- Gating (with T1-correction)

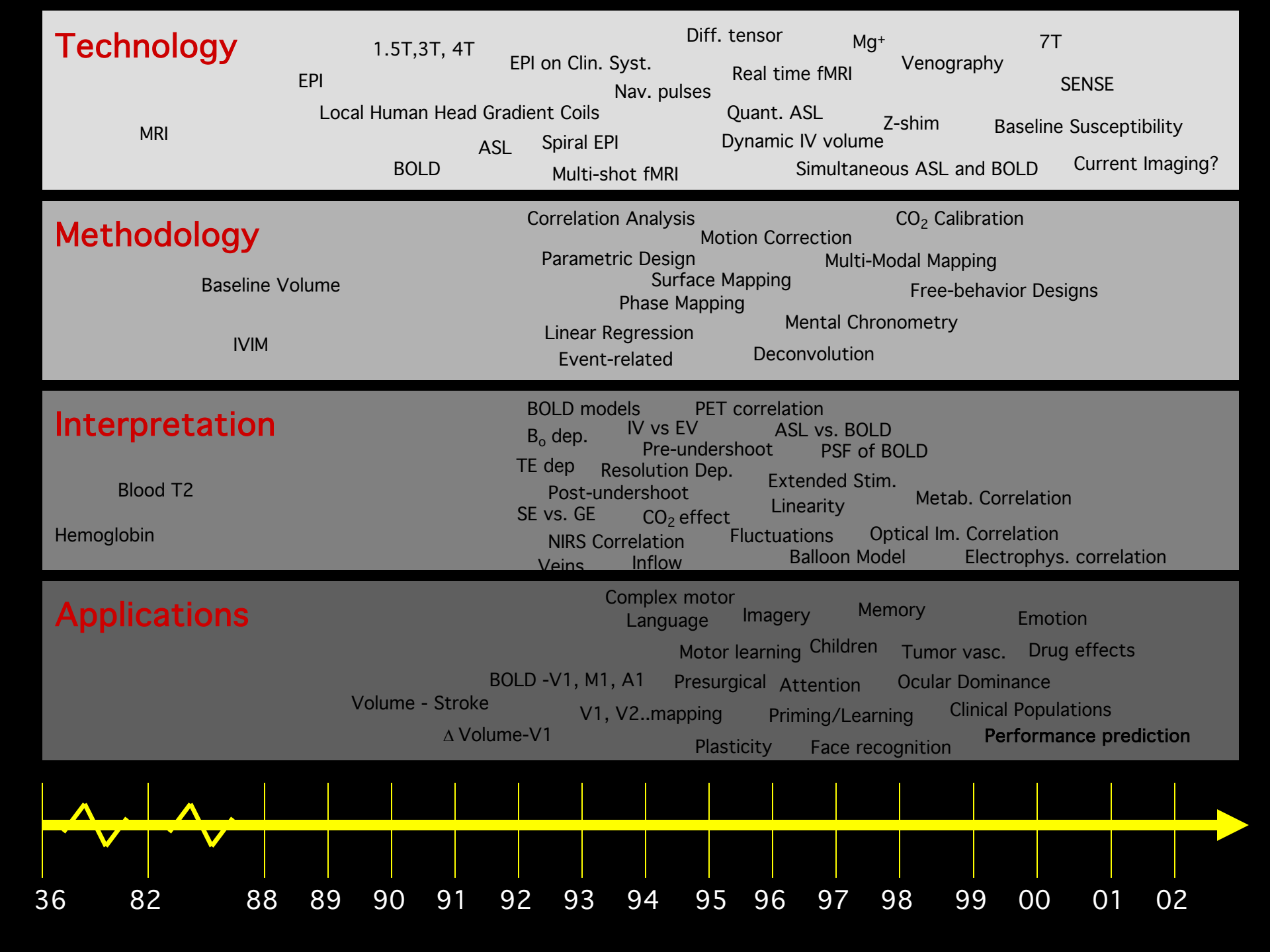
Suppress?
- Flatten image contrast
- Physical restraint
- Averaging, smoothing

Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

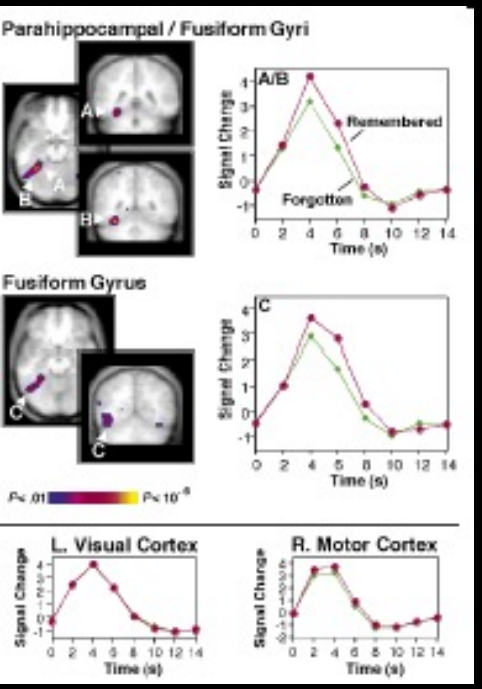

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
ASL
Spiral EPI
Dynamic IV volume
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation Analysis
CO2 Calibration
Motion Correction
Parametric Design
Multi-Modal Mapping
Baseline Volume
Surface Mapping
Free-behavior Designs
Phase Mapping
Mental Chronometry
Linear Regression
IVIM
Deconvolution
Event-related
Interpretation
BOLD models
PET correlation
IV vs EV
B0 dep.
ASL vs. BOLD
Pre-undershoot
PSF of BOLD
TE dep
Resolution Dep.
Extended Stim.
Blood T2
Post-undershoot
Linearity
Metab. Correlation
SE vs. GE
CO2 effect
Hemoglobin
Fluctuations
Optical Im. Correlation
NIRS Correlation
Balloon Model
Electrophys. correlation
Veins
Inflow
Applications
Complex motor
Language
Imagery
Memory
Emotion
Motor learning
Children
Tumor vasc.
Drug effects
BOLD -V1, M1, A1
Presurgical
Attention
Ocular Dominance
Volume - Stroke
V1, V2..mapping
Priming/Learning
Clinical Populations
Δ Volume-V1
Plasticity
Face recognition
Performance prediction
36
82
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02

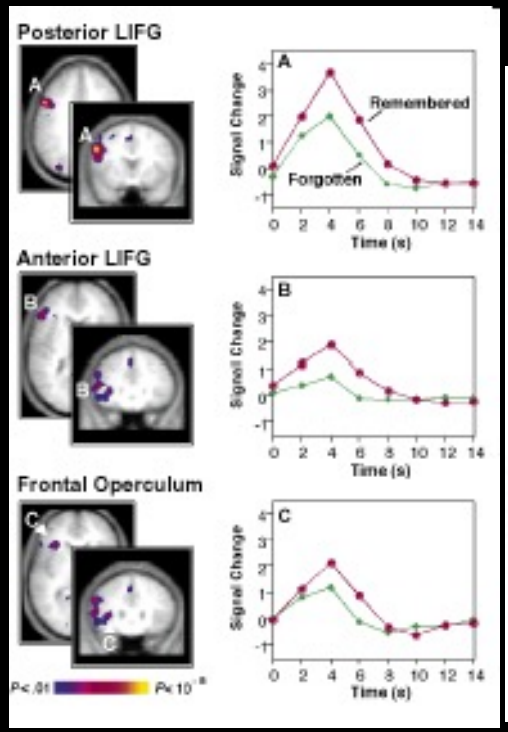
Building Memories: Remembering and Forgetting of Verbal Experiences as Predicted by Brain Activity

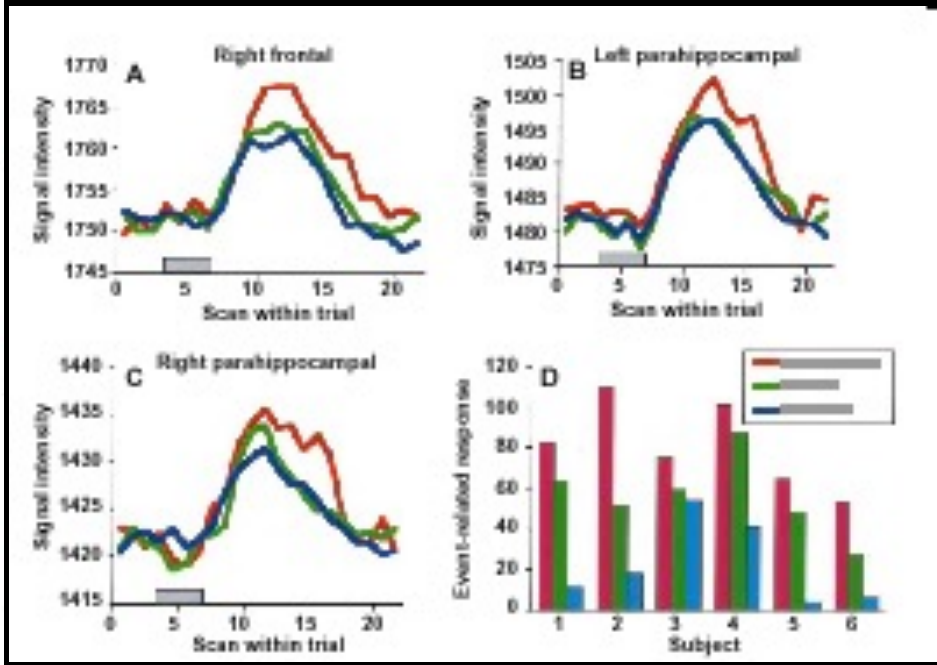
Anthony D. Wagner,* Daniel L. Schacter, Michael Rotte,† Wilma Koutstaal, Anat Maril, Anders M. Dale, Bruce R. Rosen, Randy L. Buckner

Making Memories: Brain Activity that Predicts How Well Visual Experience Will Be Remembered

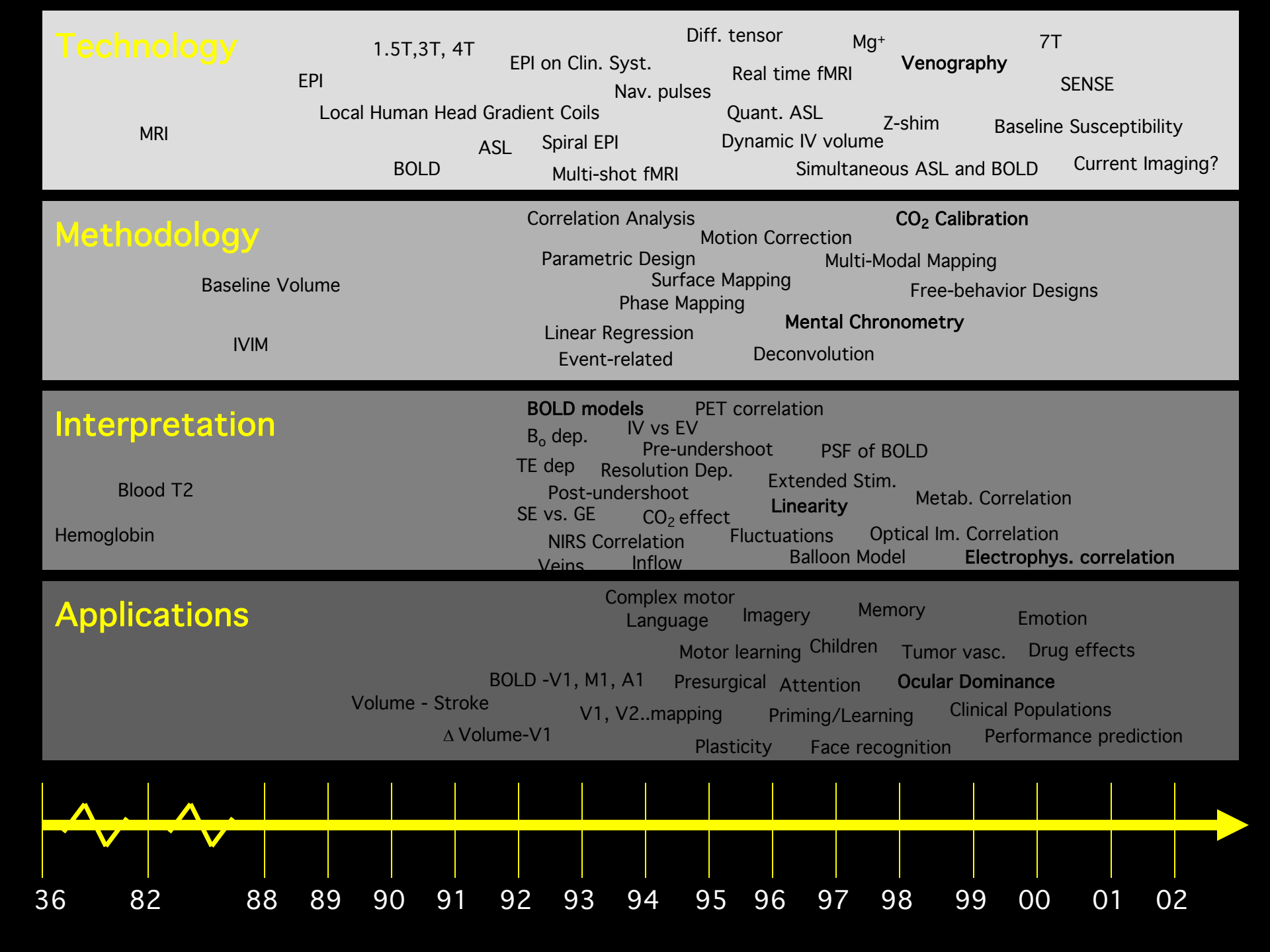
James B. Brewer,* Zuo Zhao, John E. Desmond, Gary H. Glover, John D. E. Gabrieli







Science, Vol 281, August 1998


Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
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Baseline Susceptibility
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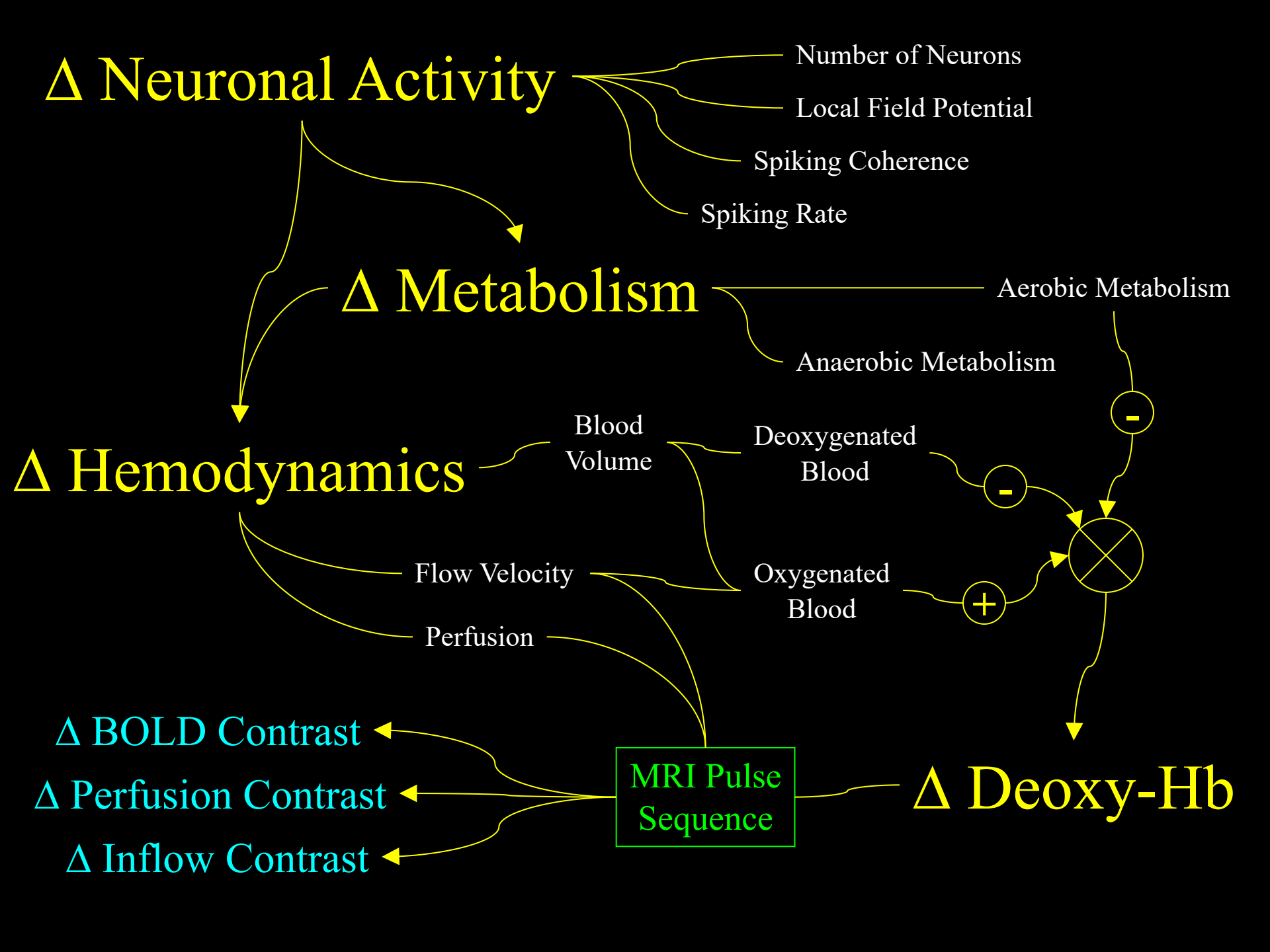
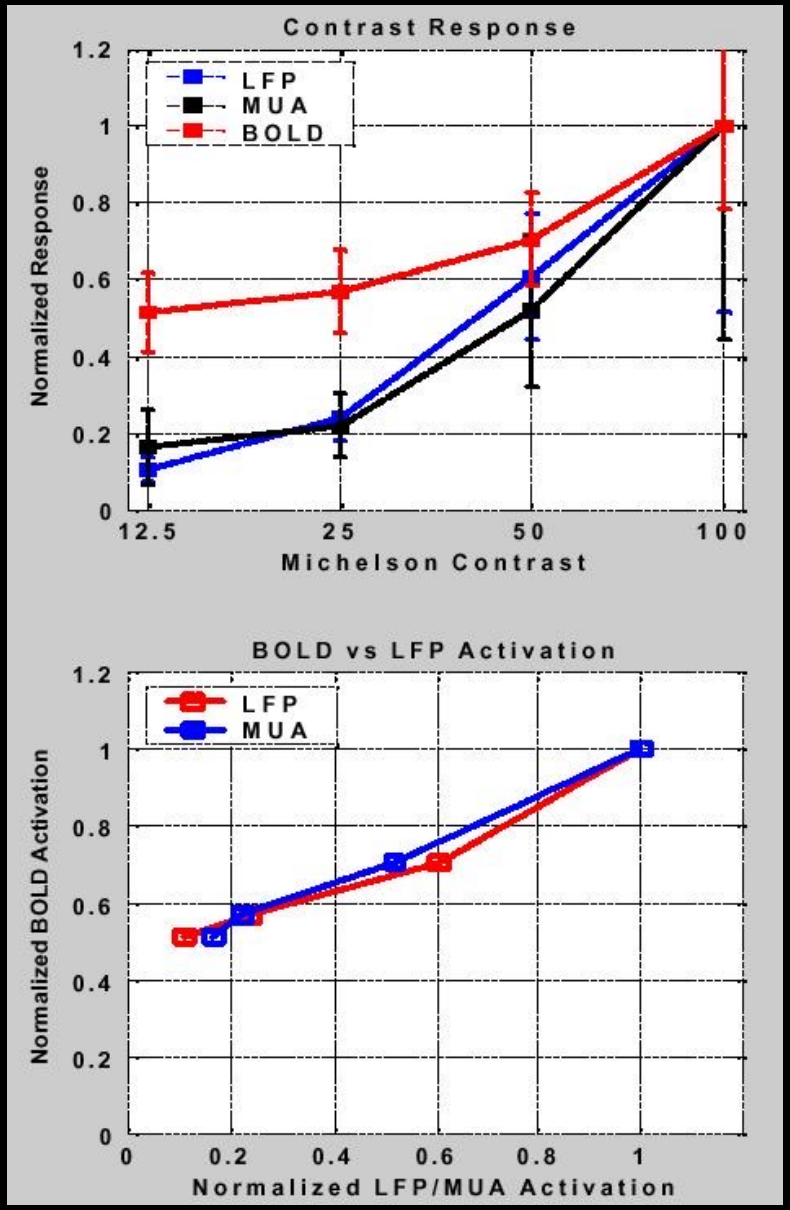
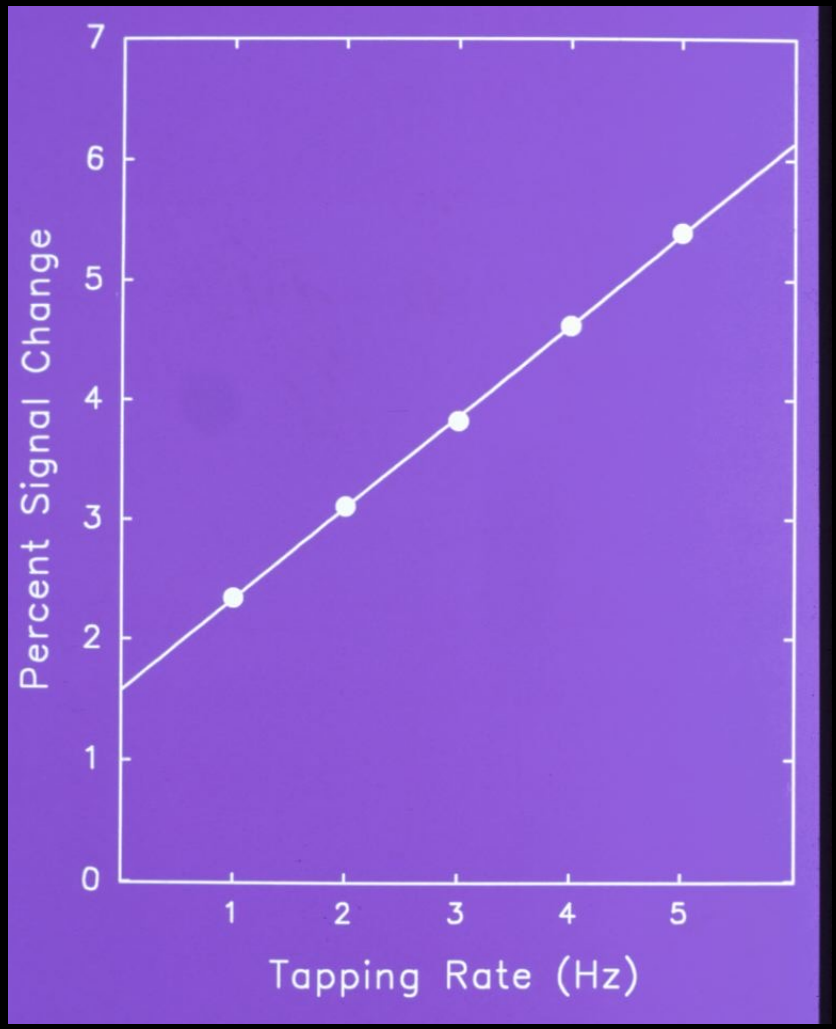
PSF of BOLD
TE dep
Resolution Dep.
Extended Stim.
Blood T2
Post-undershoot
Linearity
Metab. Correlation
SE vs. GE
CO2 effect
Hemoglobin
Fluctuations
Optical Im. Correlation
NIRS Correlation
Balloon Model
Electrophys. correlation
Veins
Inflow
Applications
Complex motor
Language
Imagery
Memory
Emotion
Motor learning
Children
Tumor vasc.
Drug effects
BOLD -V1, M1, A1
Presurgical
Attention
Ocular Dominance
Volume - Stroke
V1, V2..mapping
Priming/Learning
Clinical Populations
Δ Volume-V1
Plasticity
Face recognition
Performance prediction
36
82
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02


Δ Neuronal Activity
Number of Neurons
Local Field Potential
Spiking Coherence
Spiking Rate
Δ Metabolism
Aerobic Metabolism
Anaerobic Metabolism
Δ Hemodynamics
Blood Volume
Deoxygenated Blood
Flow Velocity
Oxygenated Blood
Perfusion
-
-
+
Δ BOLD Contrast
Δ Perfusion Contrast
Δ Inflow Contrast
MRI Pulse Sequence
Δ Deoxy-Hb



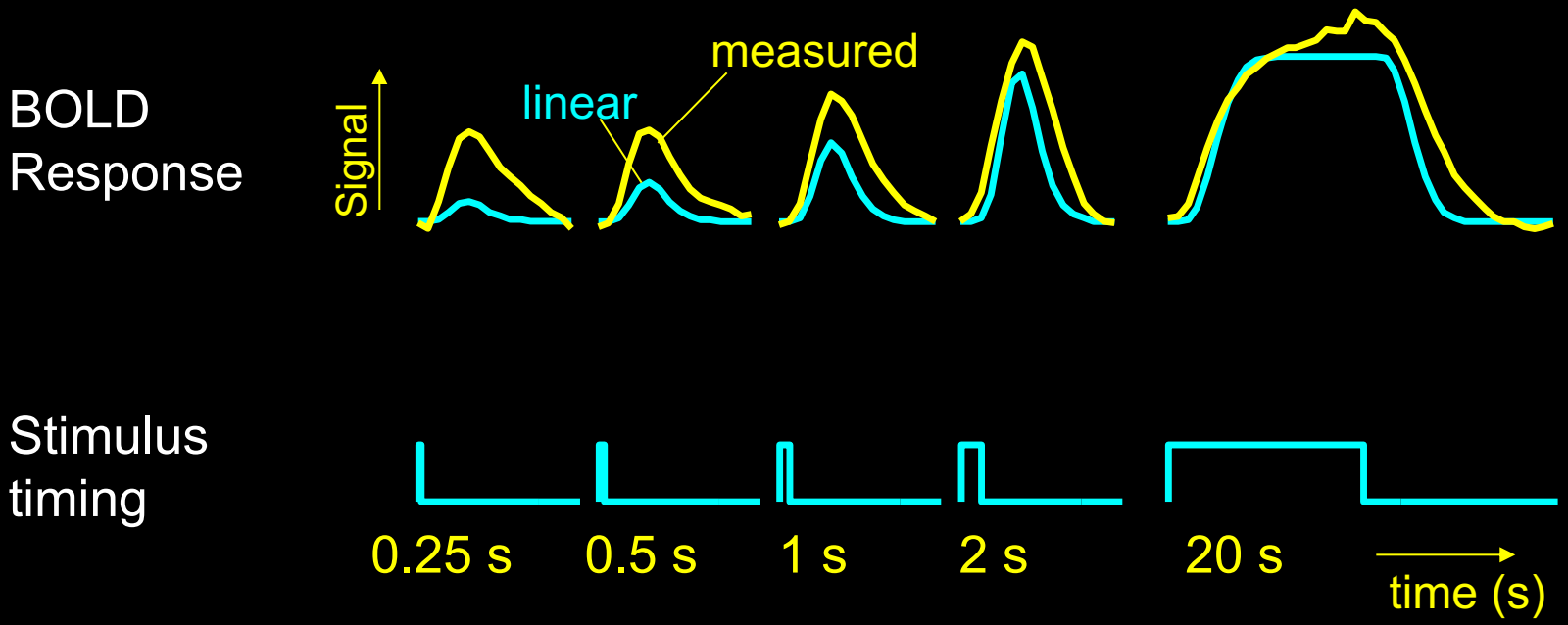
Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157



S. M. Rao et al, (1996) "Relationship between finger movement rate and functional magnetic resonance signal change in human primary motor cortex." *J. Cereb. Blood Flow and Met.* 16, 1250-1254.

Dynamic Nonlinearity Assessment

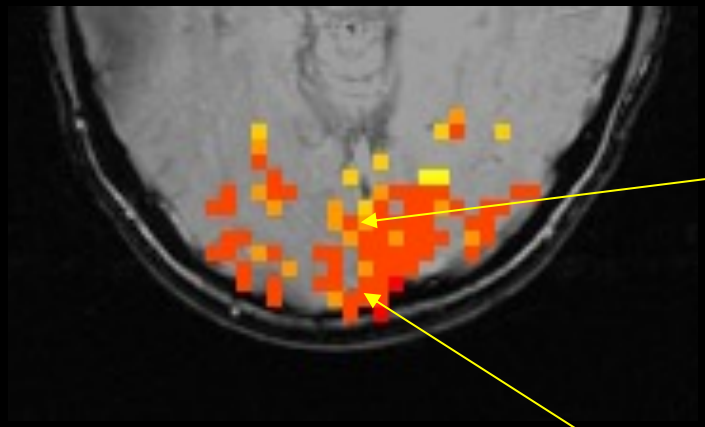
Different stimulus "ON" periods

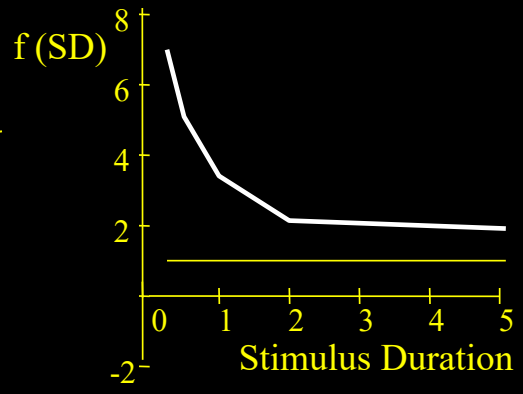


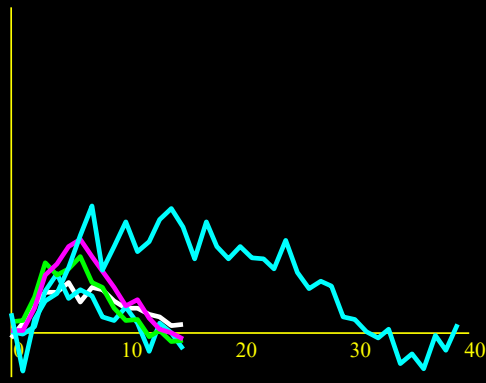
Brief stimuli produce larger responses than expected

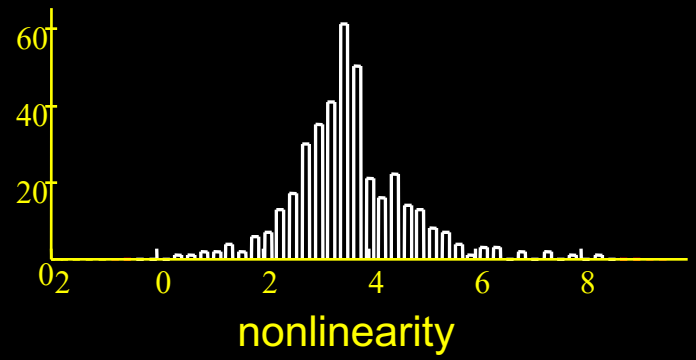
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

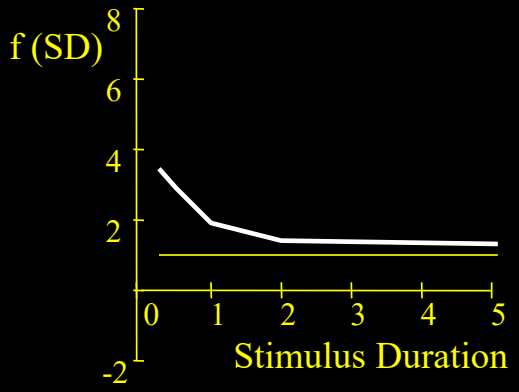
Spatial Heterogeneity of BOLD Nonlinearity

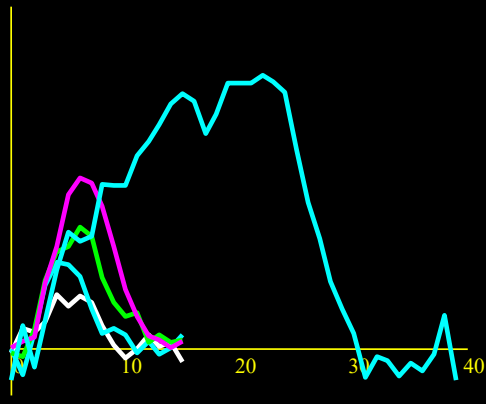












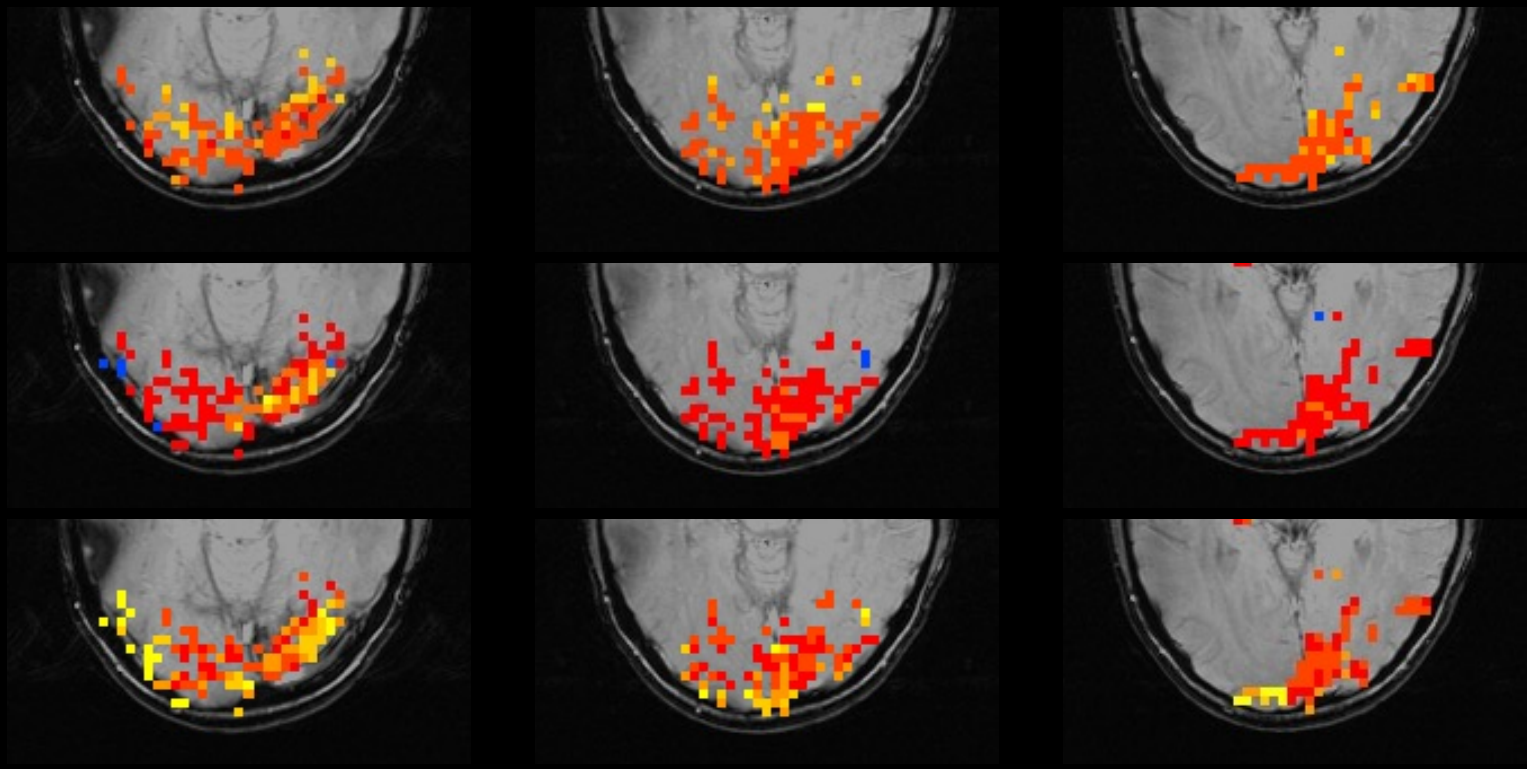
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

Results – visual task

Nonlinearity

Magnitude

Latency



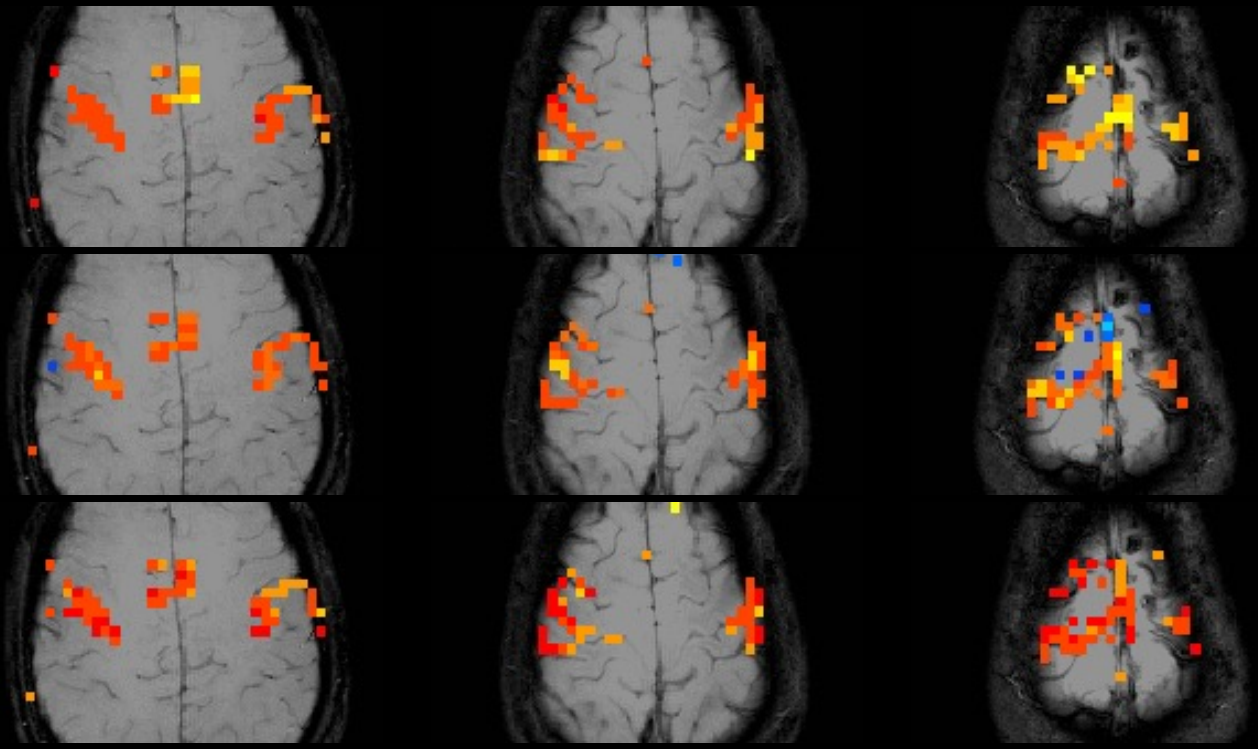
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

Results – motor task

Nonlinearity

Magnitude

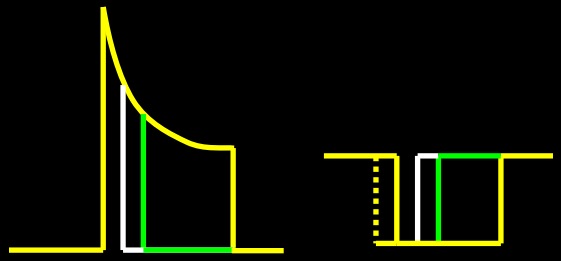
Latency



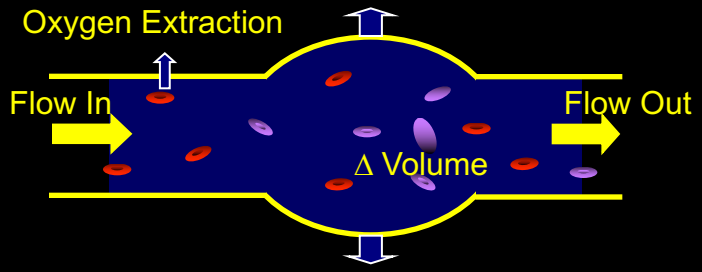
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

Sources of this Nonlinearity

- Neuronal

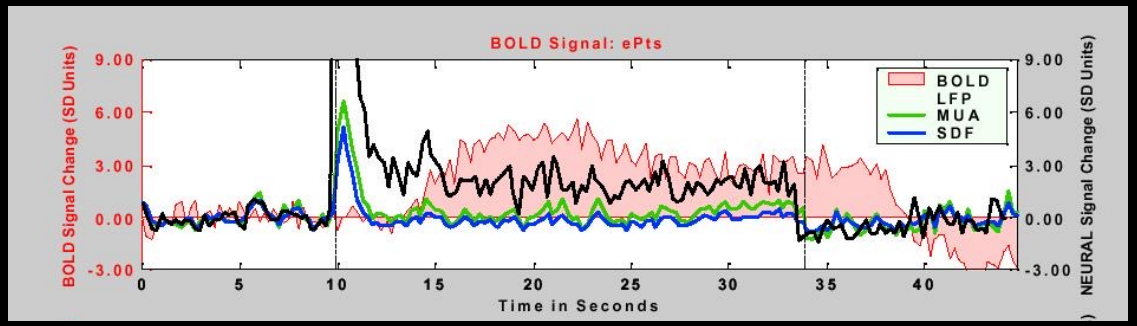


- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics

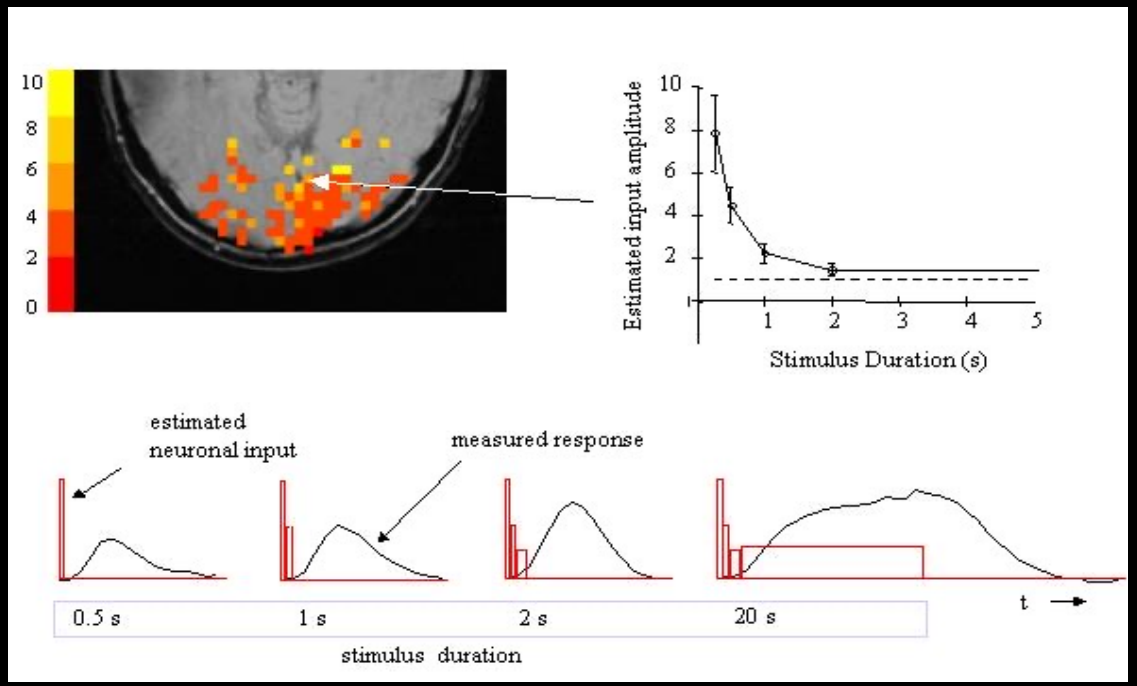


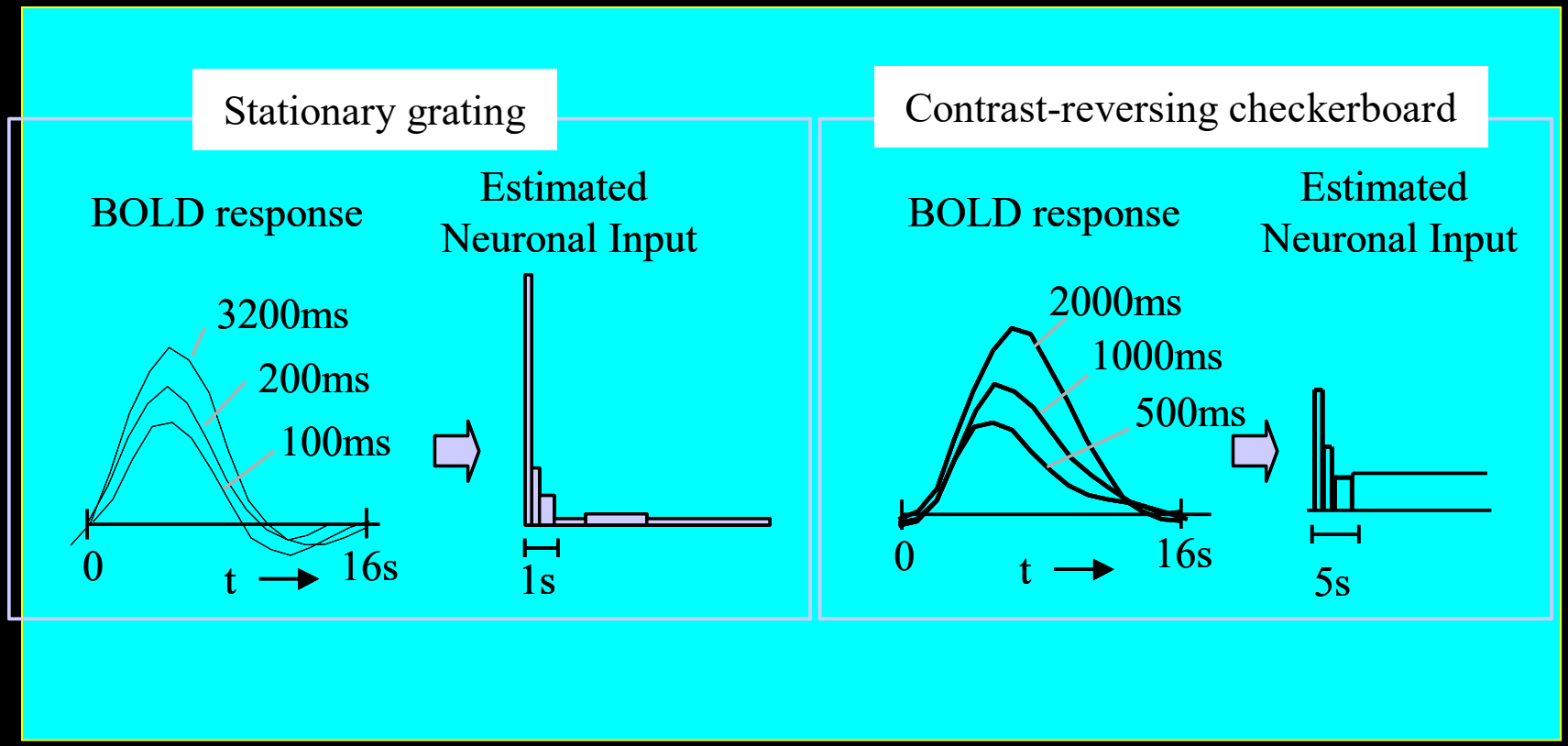
BOLD Correlation with Neuronal Activity

Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157.



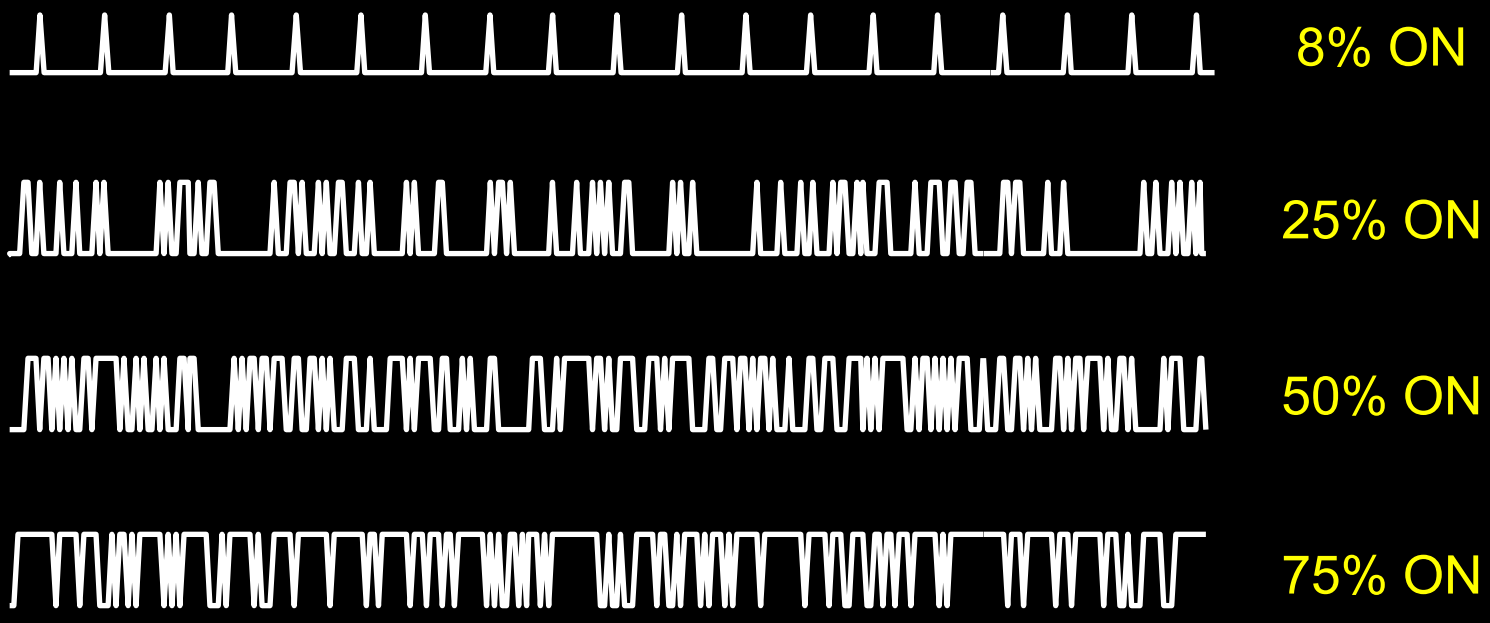
P. A. Bandettini and L. G. Ungerleider, (2001) "From neuron to BOLD: new connections." Nature Neuroscience, 4: 864-866.




Stationary grating
BOLD response
Estimated
Neuronal Input
3200ms
200ms
100ms
0
t
16s
1s
Contrast-reversing checkerboard
BOLD response
Estimated
Neuronal Input
2000ms
1000ms
500ms
0
t
16s
5s

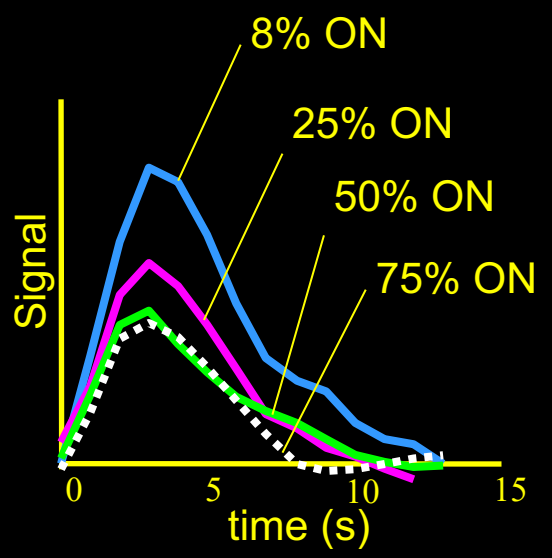
Varying “ON” and “OFF” periods

- *Rapid event-related design with varying ISI*

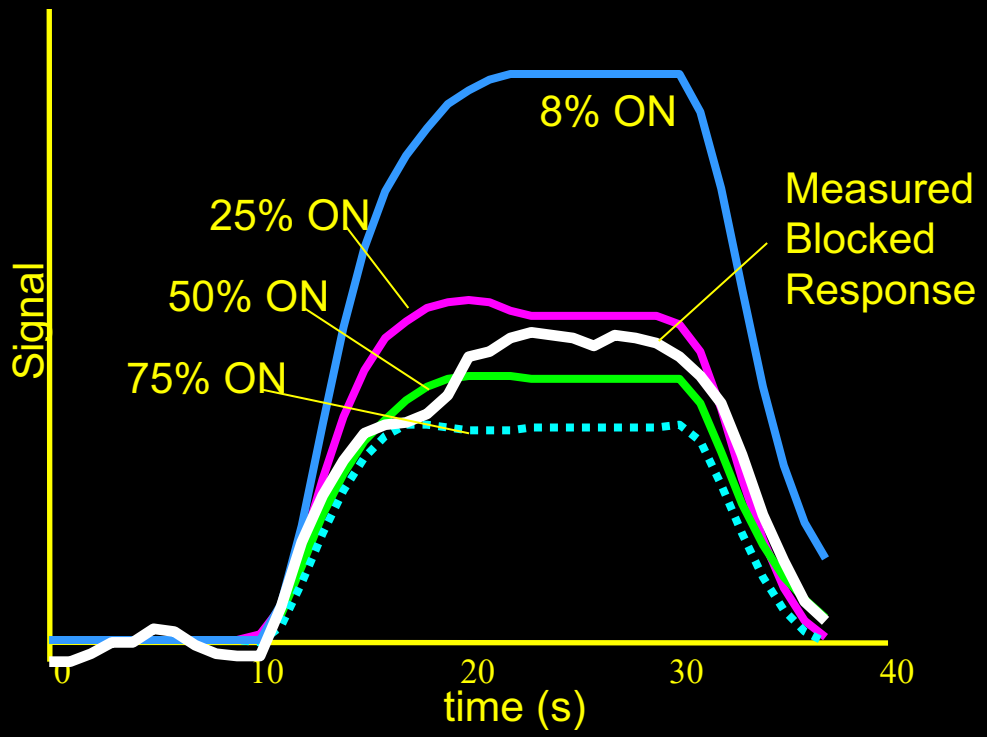


Varying “ON” and “OFF” periods

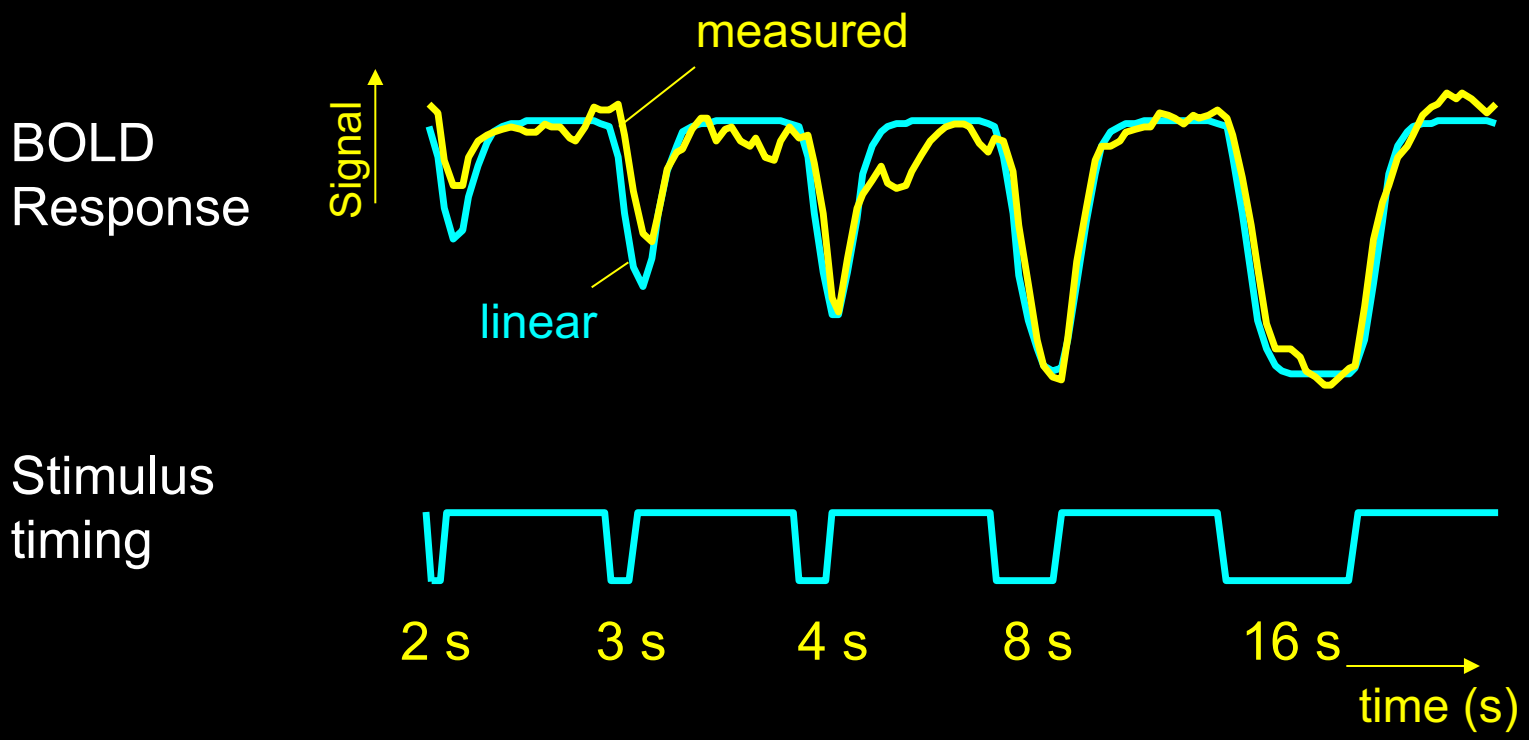
Estimated Impulse Response



Predicted Responses to 20 s stimulation



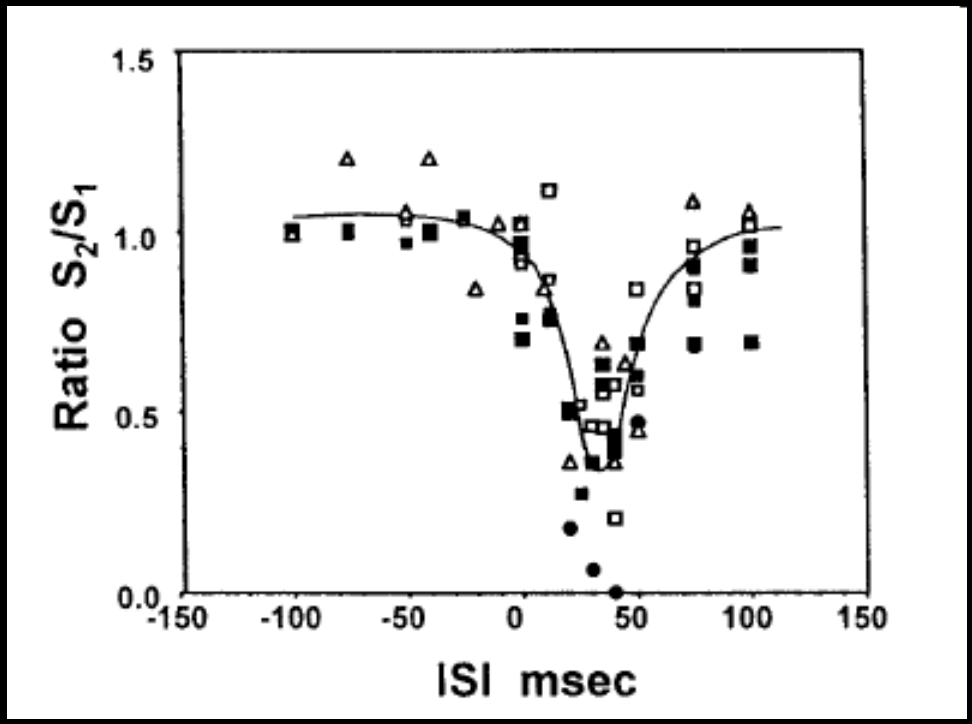
Different stimulus “OFF” periods



Brief stimulus OFF periods produce smaller decreases than expecte

An approach to probe some neural systems interaction by functional MRI at neural time scale down to milliseconds

Seiji Ogawa[†‡], Tso-Ming Lee[†], Ray Stepnoski[†], Wei Chen[§], Xiao-Hong Zhu[§], and Kamil Ugurbil[§]



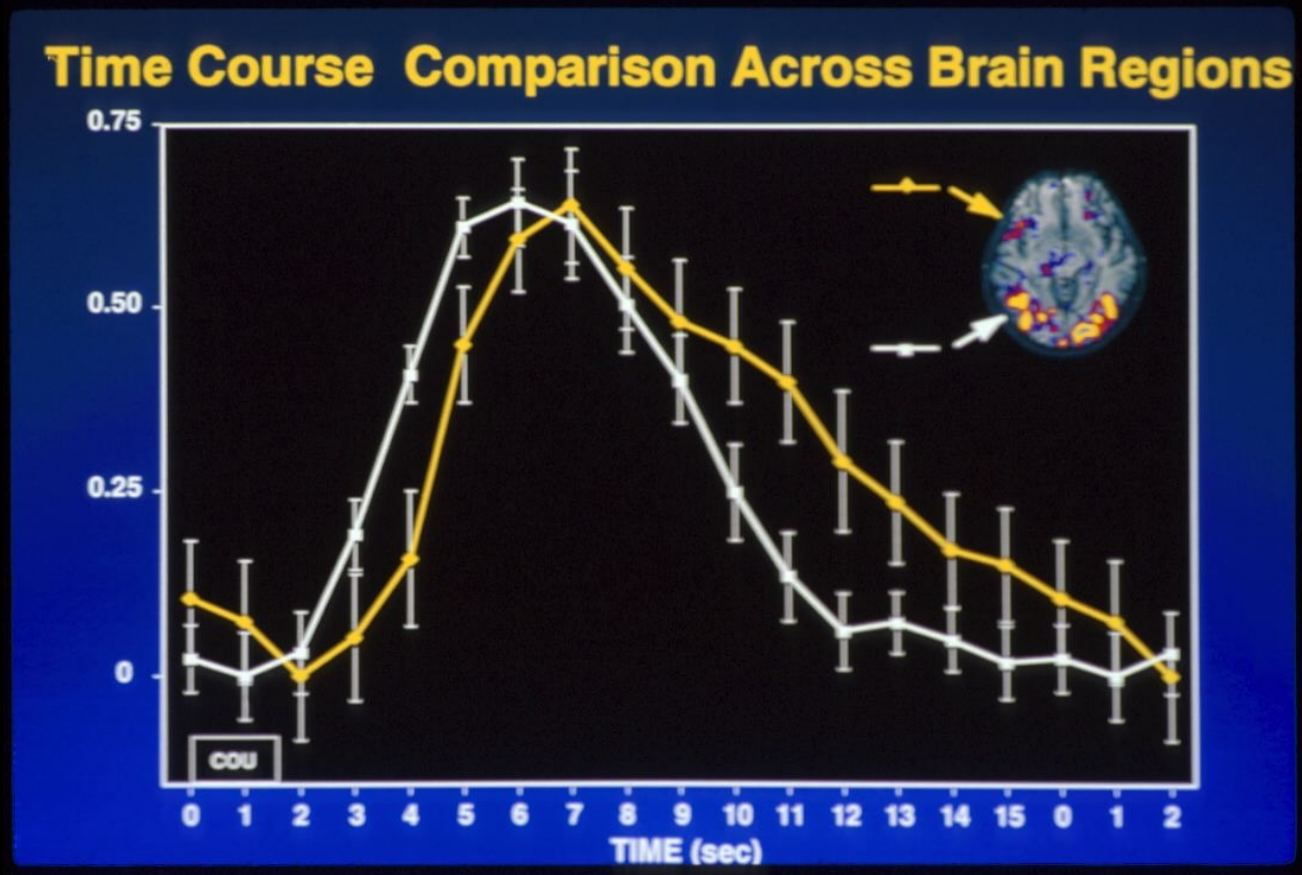
11026–11031 PNAS **September 26, 2000** vol. 97 no. 20

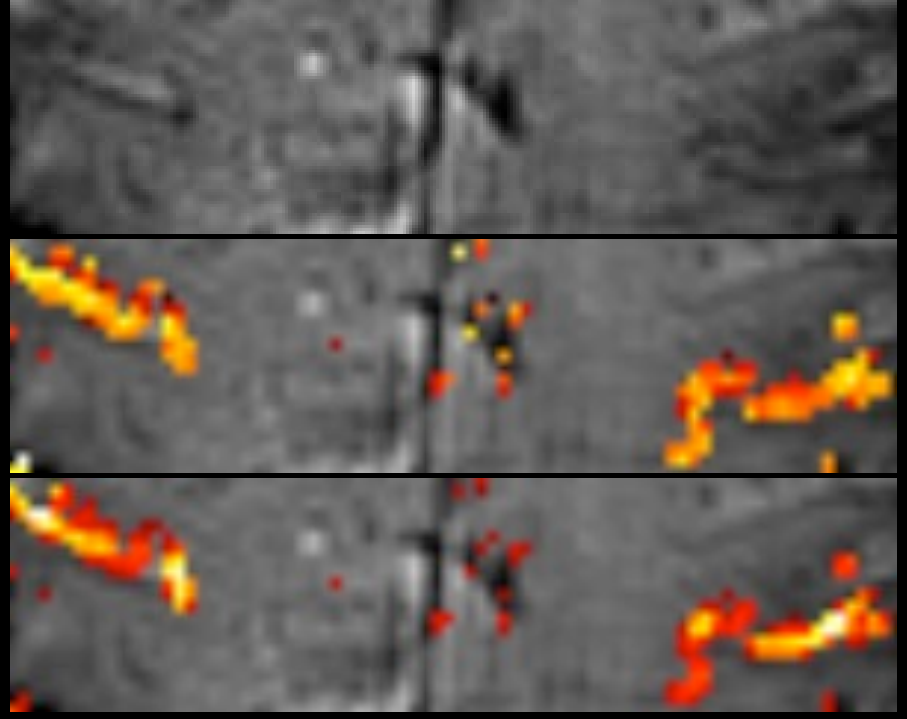
Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 14878–14883, December 1996
Neurobiology

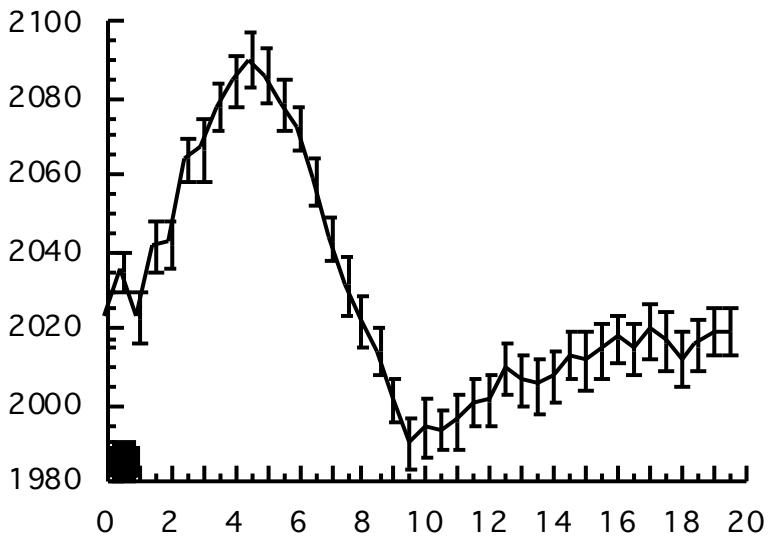
Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging

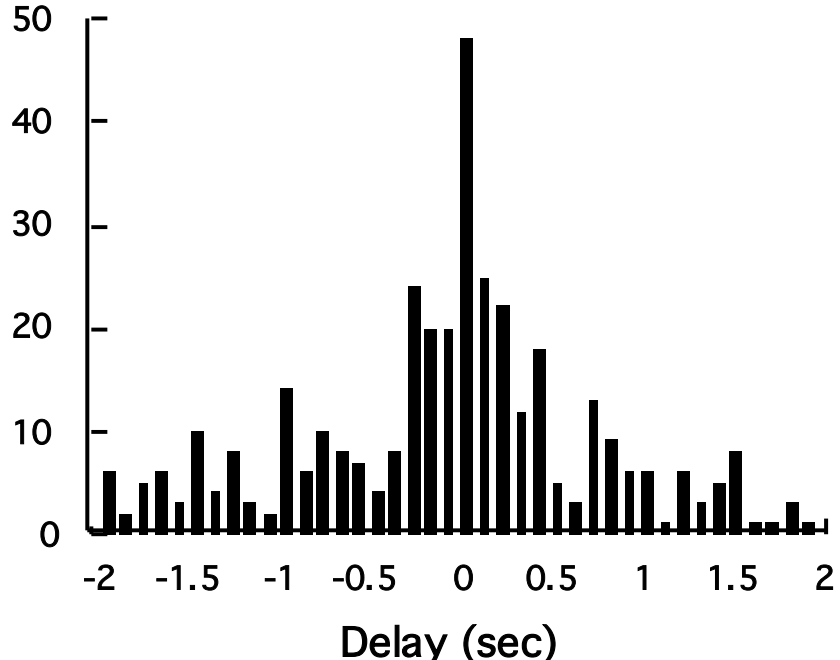
(neuroimaging/single trial/language/prefrontal)

RANDY L. BUCKNER[†‡§¶], PETER A. BANDETTINI[†‡], KATHLEEN M. O'CRAVEN[†‖], ROBERT L. SAVOY[†‖], STEVEN E. PETERSEN[*††], MARCUS E. RAICHLE[§*†††], AND BRUCE R. ROSEN[†‡]

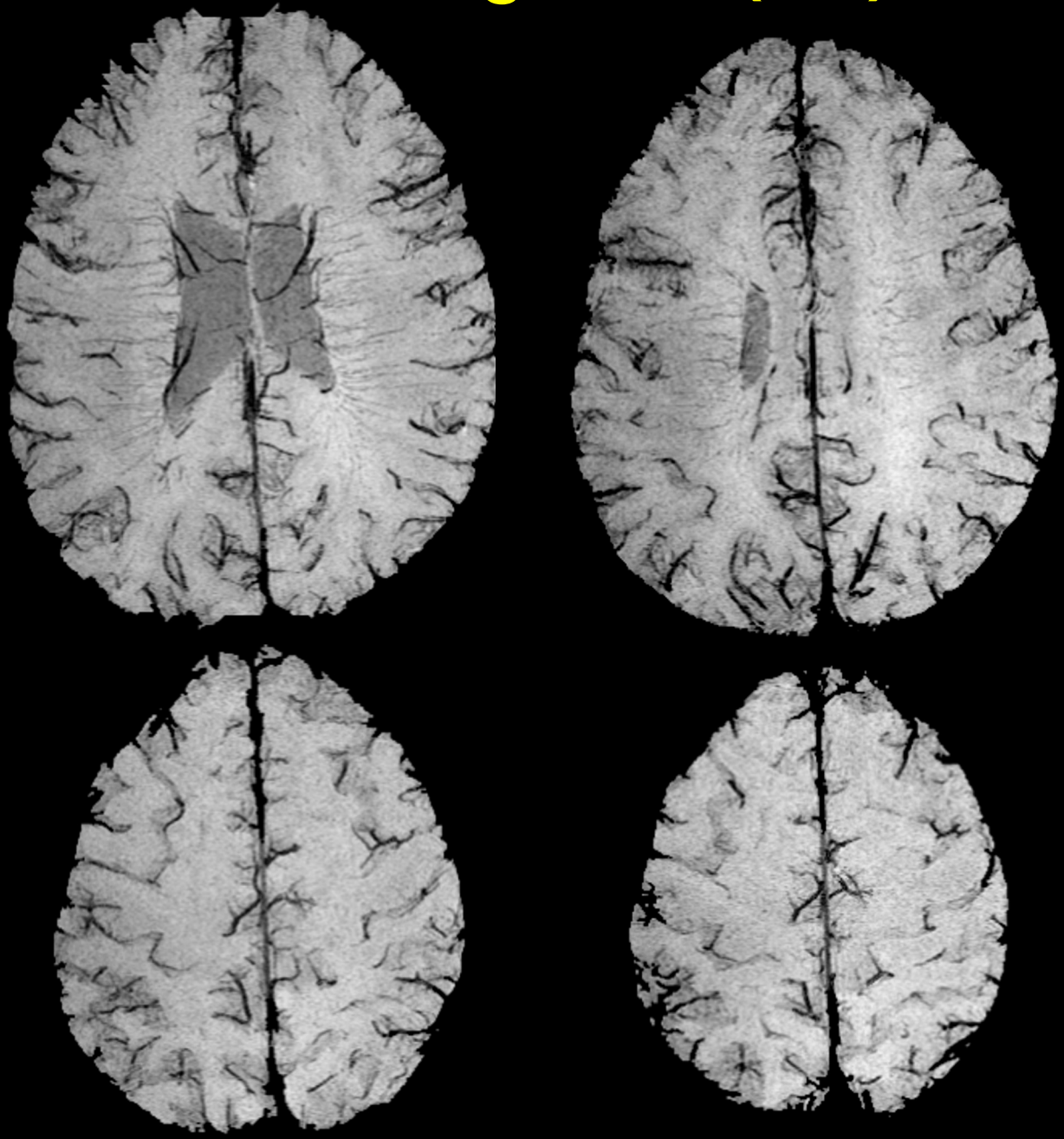


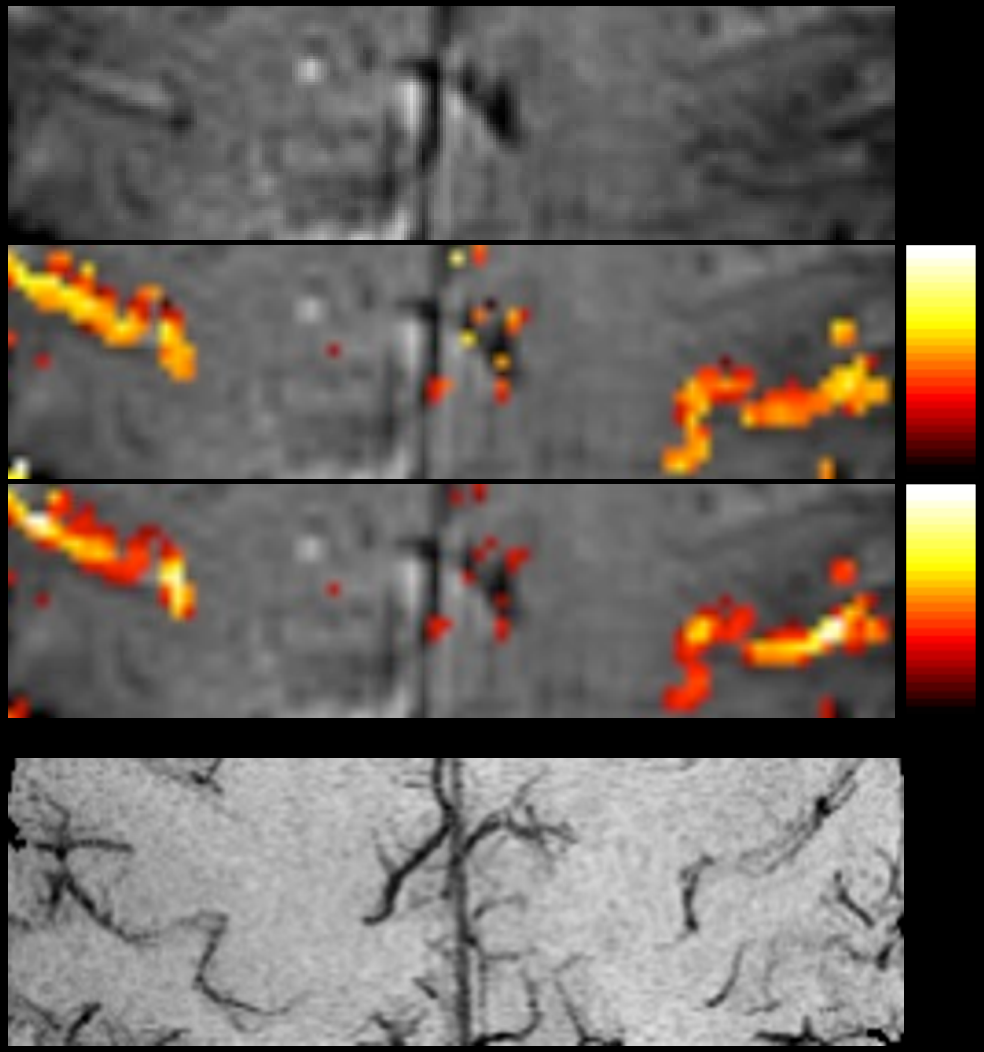

Latency
Magnitude
+ 2 sec
- 2 sec


2100
2080
2060
2040
2020
2000
1980
0 2 4 6 8 10 12 14 16 18 20
Time (sec)


50
40
30
20
10
0
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
Delay (sec)

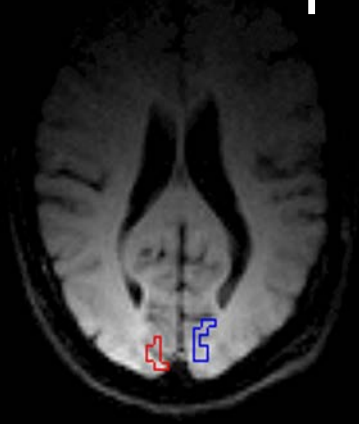
Venograms (3T)



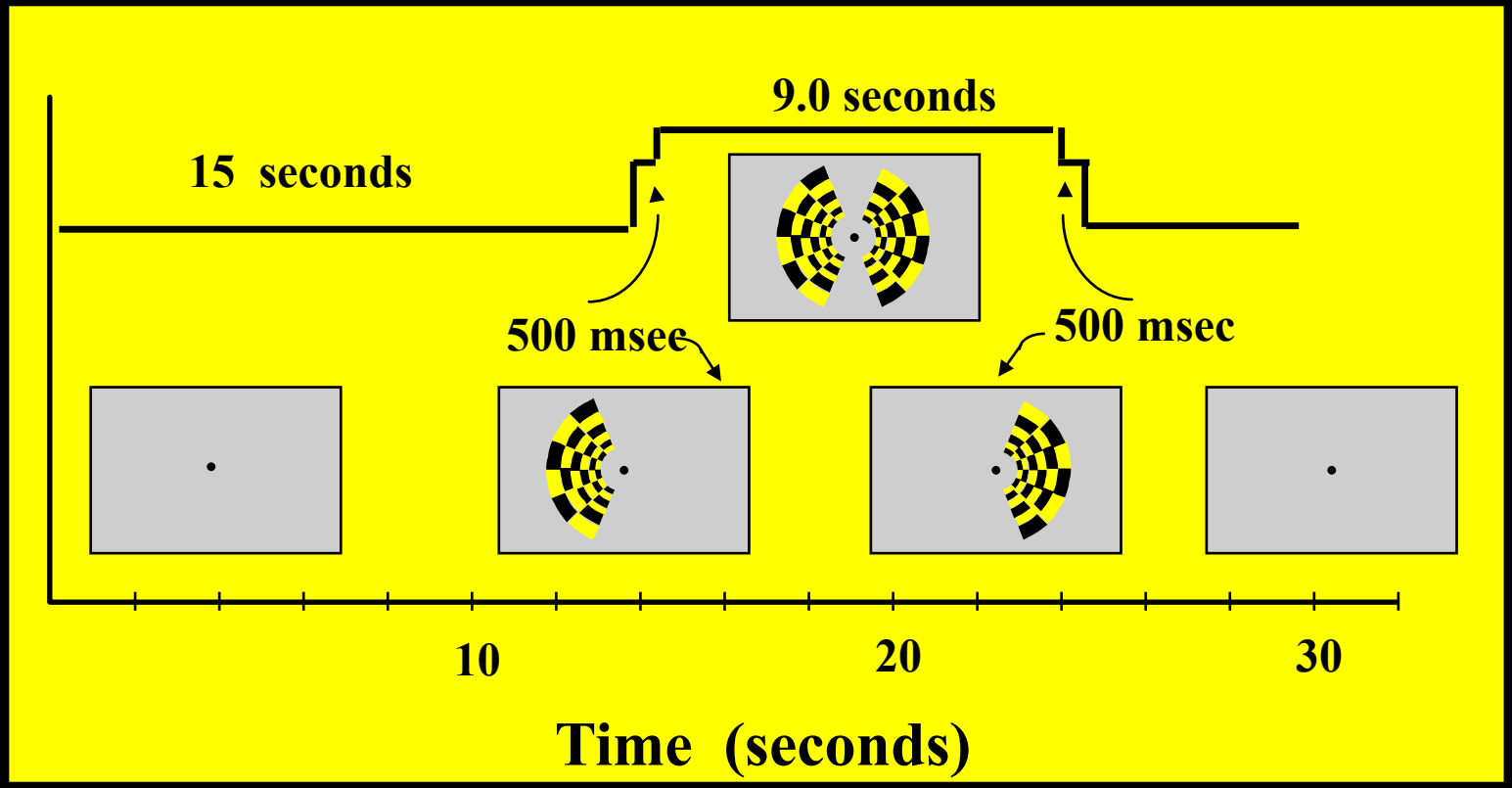


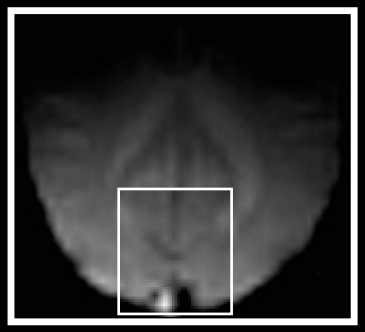
Hemi-Field Experiment

Left Hemisphere



Right Hemisphere



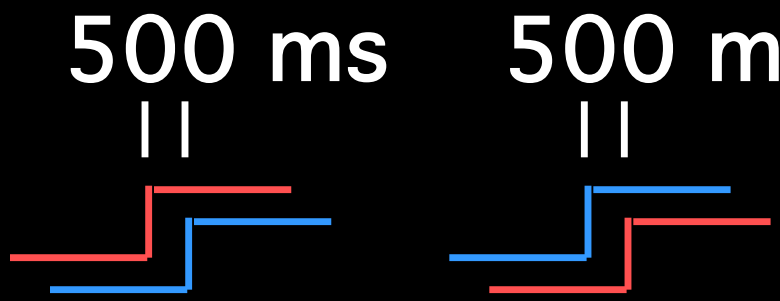


Calibration Techniques.....

500 ms 500 ms

Right Hemifield

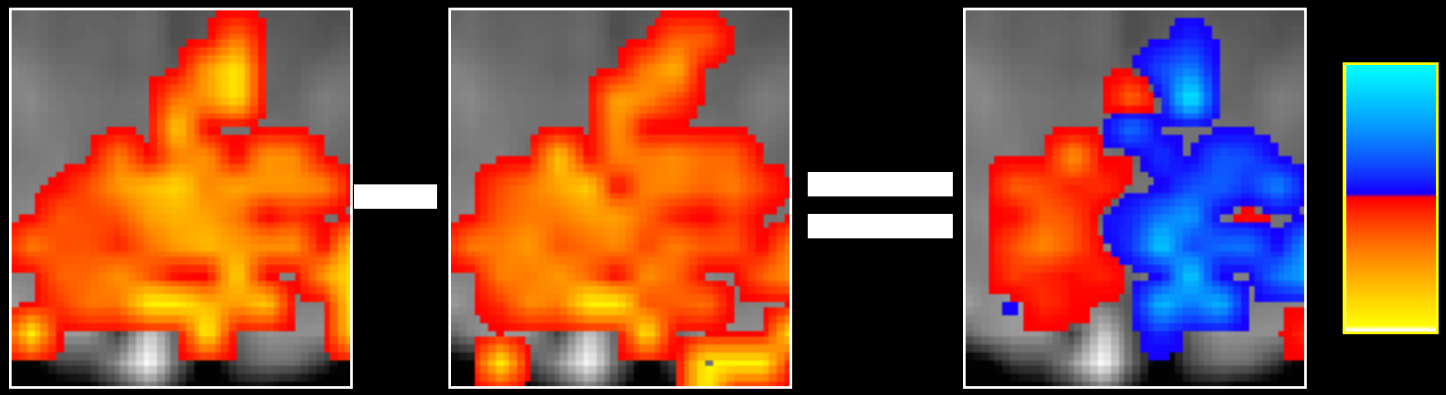
Left Hemifield



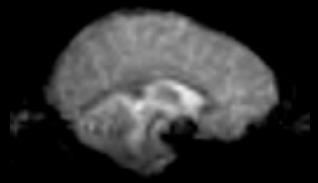
+ 2.5 s

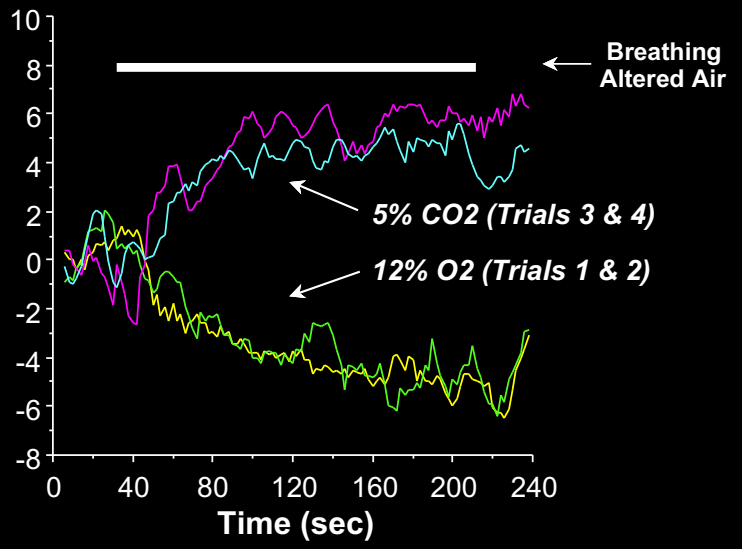
0 s

- 2.5 s

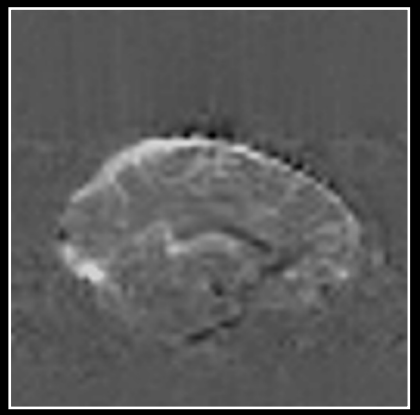


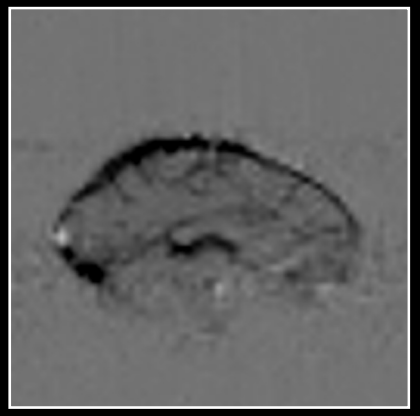
Hemdodynamic Stress Calibration





5% CO2





12% O2

P. A. Bandettini, E. C. Wong, A hypercapnia - based normalization method for improved spatial localization of human brain activation with fMRI. *NMR in Biomedicine* 10, 197-203 (1997).

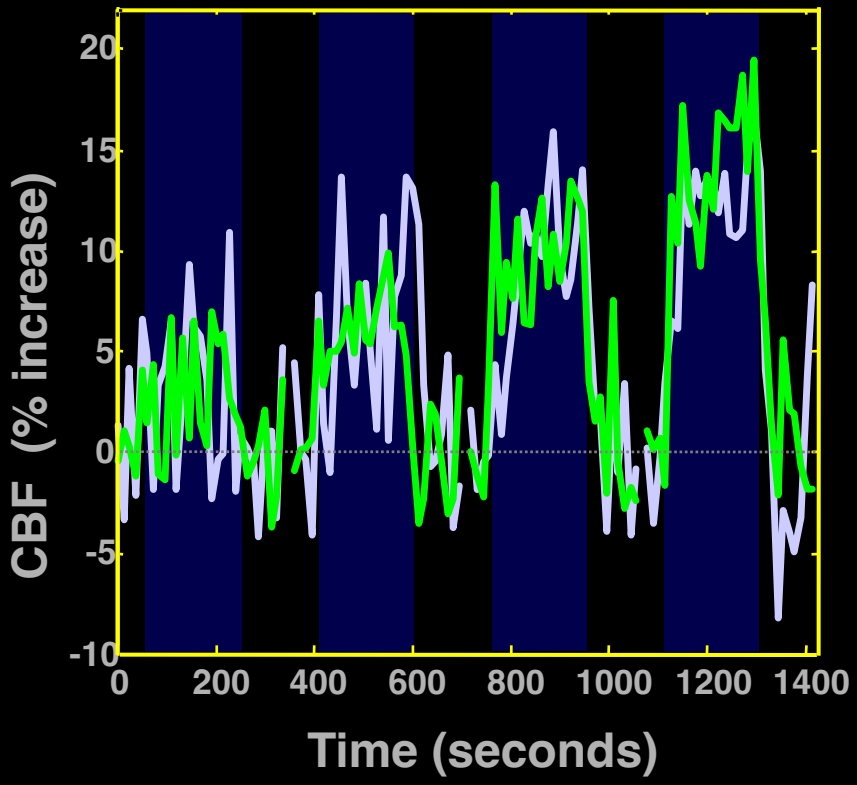
Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 9403–9408, August 1999
Neurobiology

Linear coupling between cerebral blood flow and oxygen consumption in activated human cortex

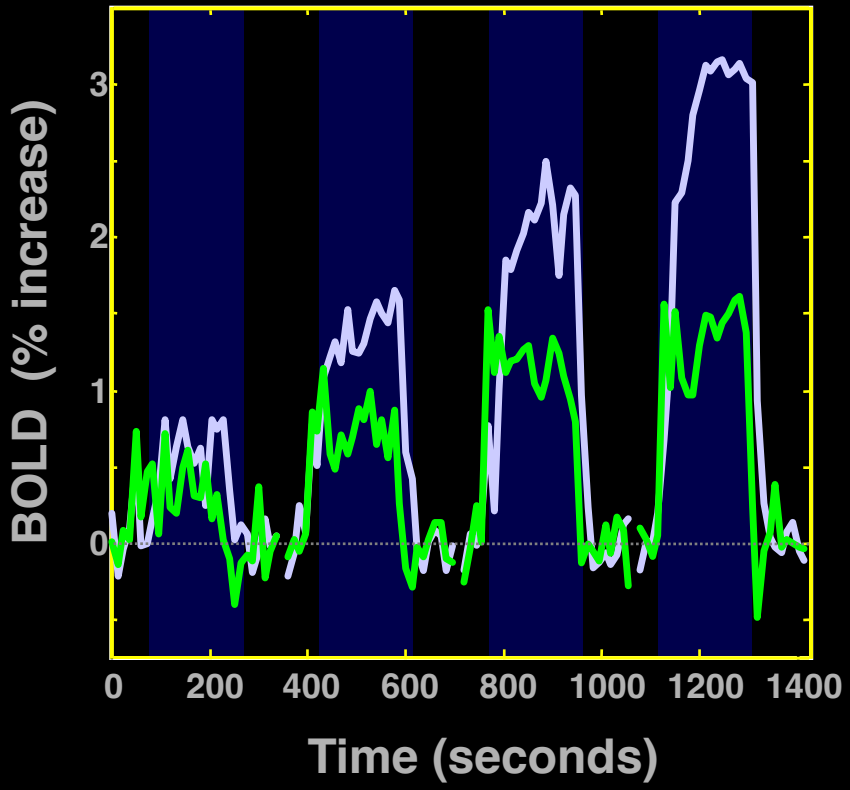
RICHARD D. HOGE*†, JEFF ATKINSON*, BRAD GILL*, GÉRARD R. CRELIER*, SEAN MARRETT‡, AND G. BRUCE PIKE*

*Room WB325, McConnell Brain Imaging Centre, Montreal Neurological Institute, Quebec, Canada H3A 2B4; and ‡Nuclear Magnetic Resonance Center, Massachusetts General Hospital, Building 149, 13th Street, Charlestown, MA 02129

CBF



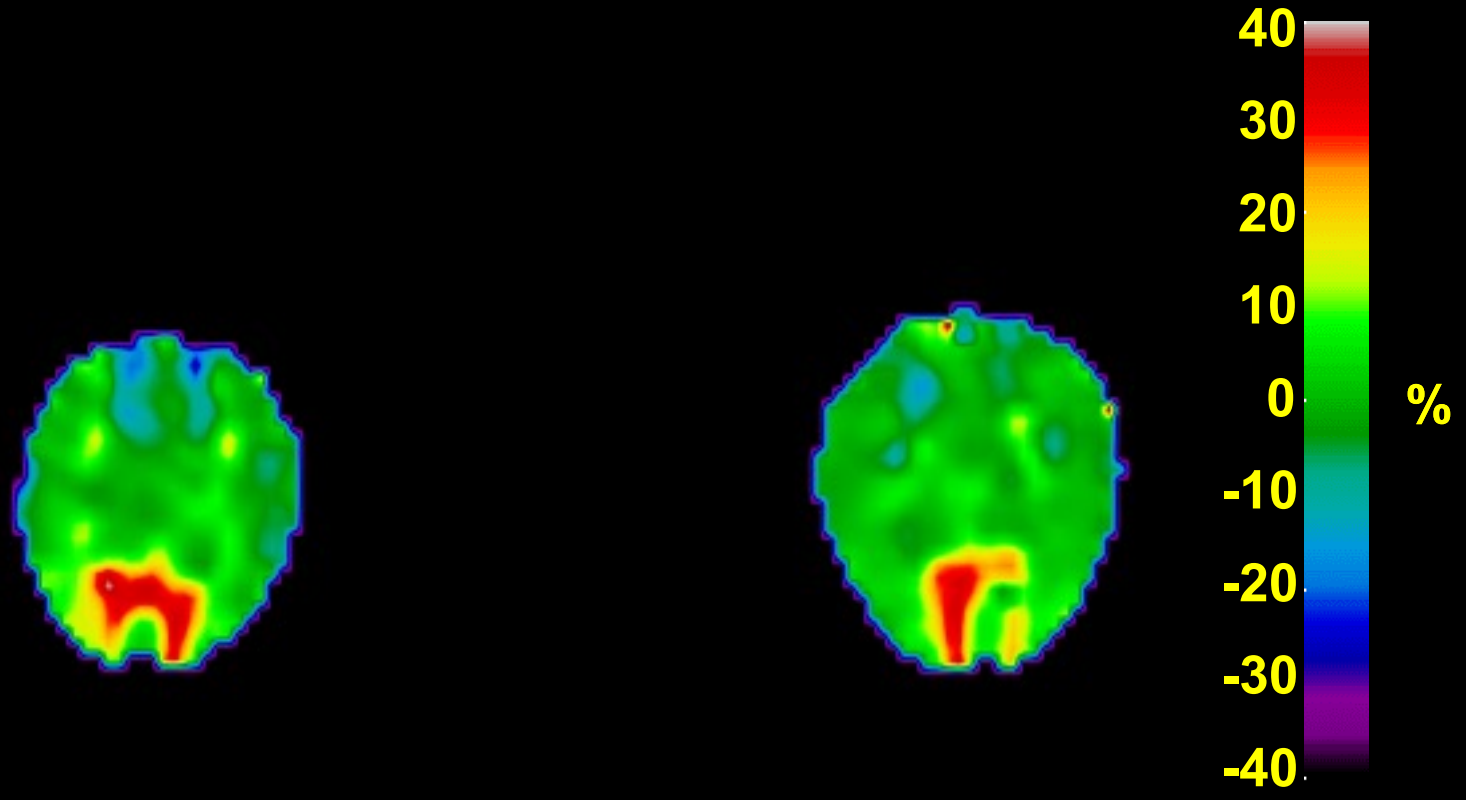
BOLD



Simultaneous Perfusion and BOLD imaging during graded visual activation and hypercapnia

N=12

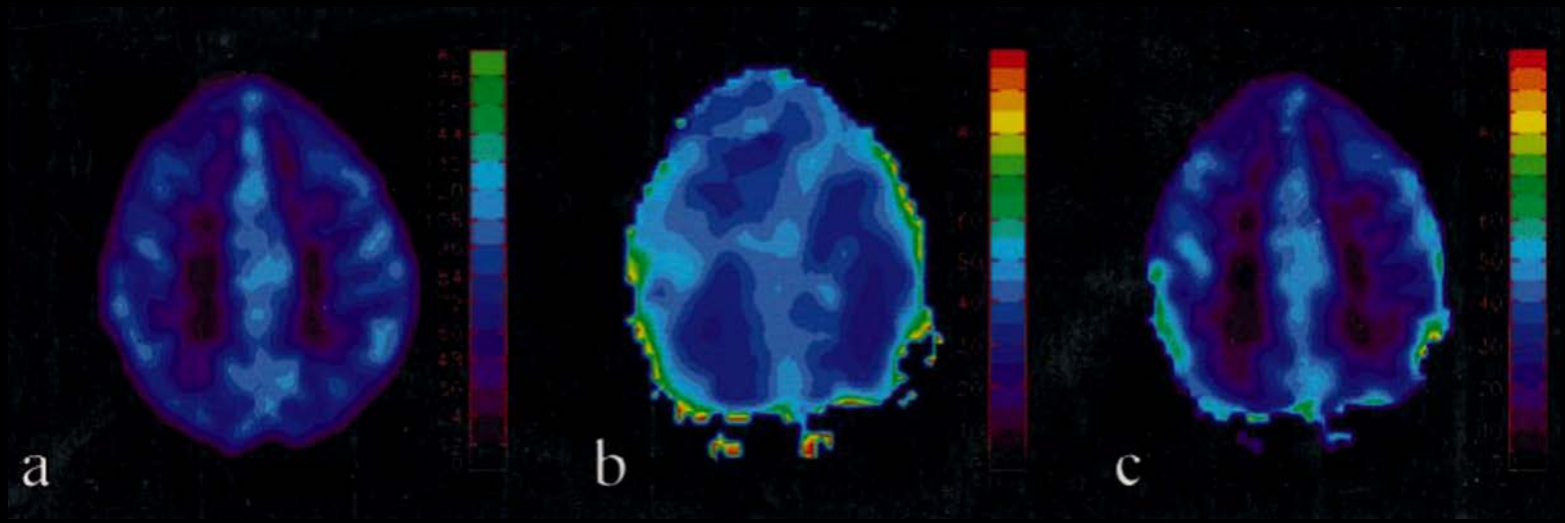
Computed $CMRO_2$ Changes



NMR IN BIOMEDICINE
NMR Biomed. 2001;**14**:441–447
DOI:10.1002/nbm.717

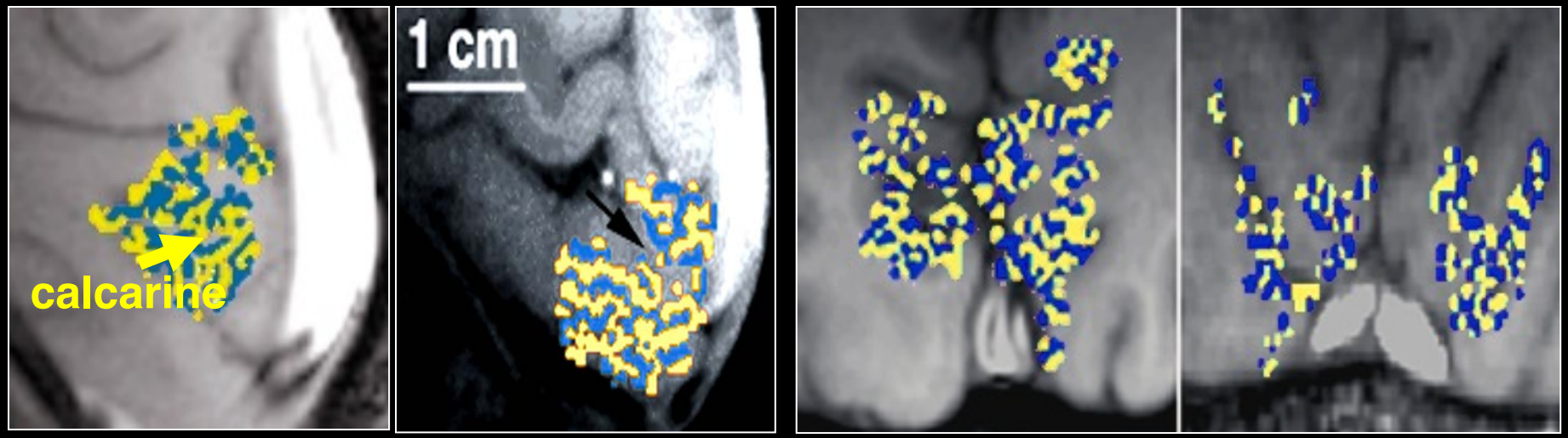
Quantitative measurements of cerebral metabolic rate of oxygen utilization using MRI: a volunteer study

Hongyu An,[1] Weili Lin,[2]* Azim Celik[3] and Yueh Z. Lee[2]

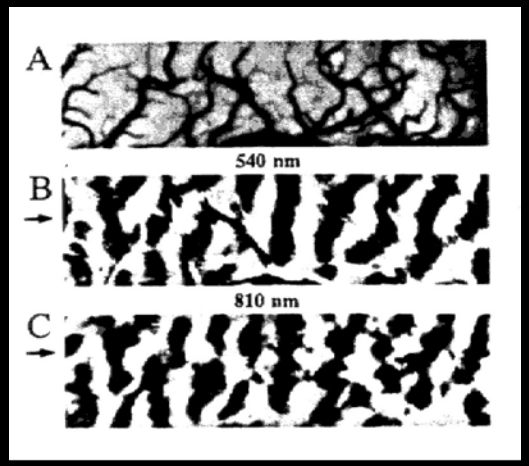


CBF OEF $CMRO_2$

Ocular Dominance Column Mapping using fMRI



Menon, R. S., S. Ogawa, et al. (1997). "Ocular dominance in human V1 demonstrated by functional magnetic resonance imaging." J Neurophysiol 77(5): 2780-7.

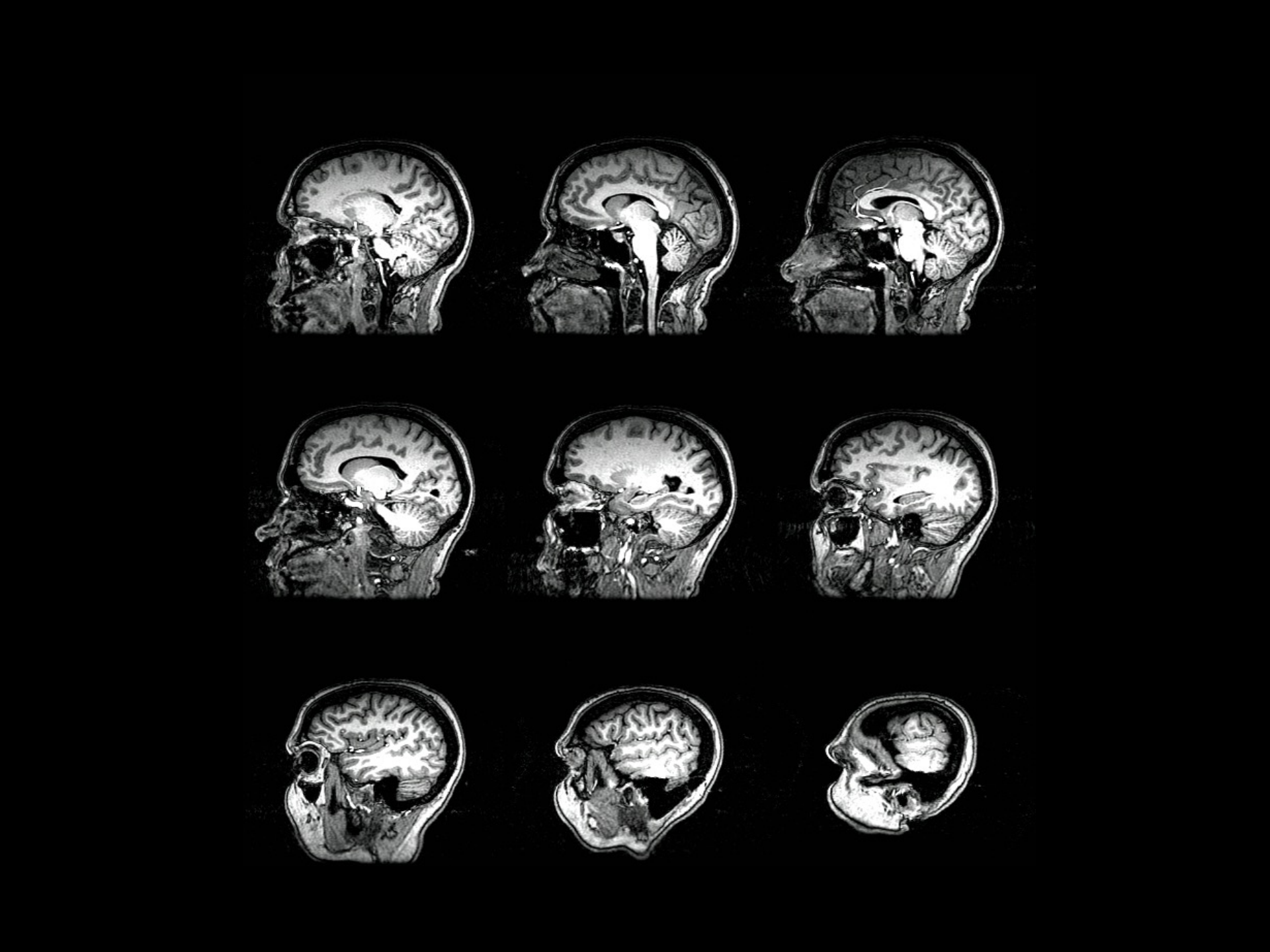


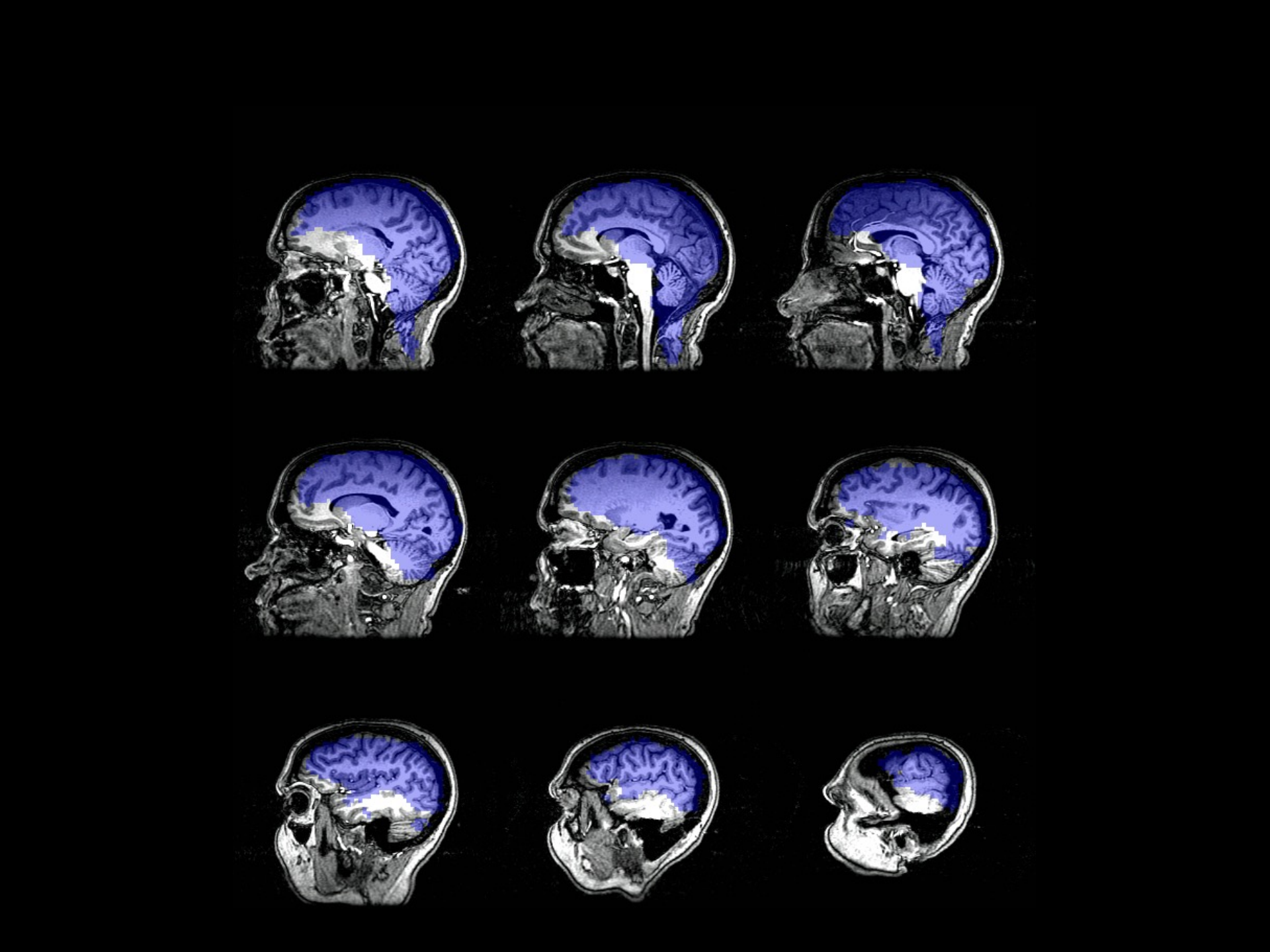
Optical Imaging

R. D. Frostig et. al, PNAS 87: 6082-6086, (1990).

Future....

- Shimming
- Acoustic Noise
- Multishot Techniques
- Increased Gradient Performance
- Higher Field Strengths
- Surface Coil Arrays
- Calibration / Quantification
- Embedded Functional Contrast
- Noise / Fluctuations
- Direct Neuronal Current Imaging
- Clinical Populations
- Neuronal,Vascular, and Metabolic Informatic

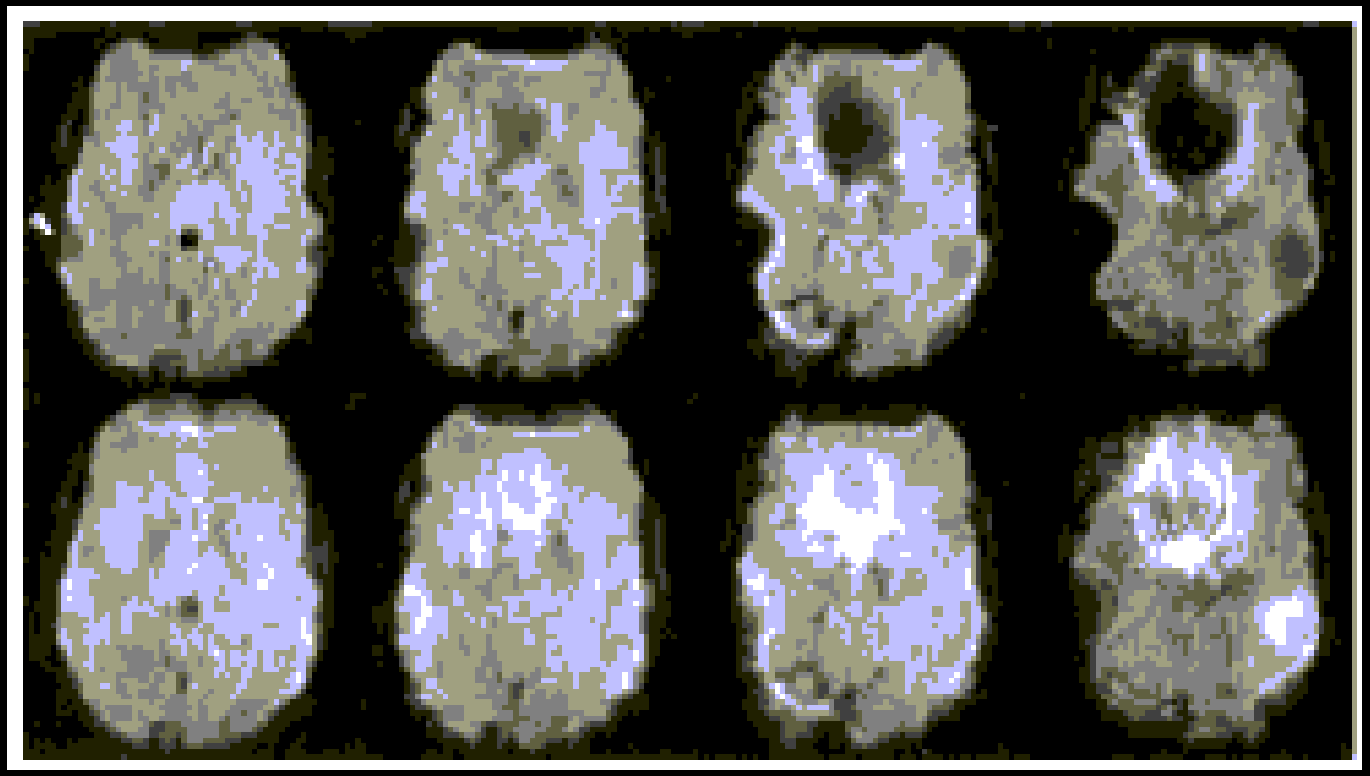




Magnetic Resonance in Medicine 42:290–299 (1999)

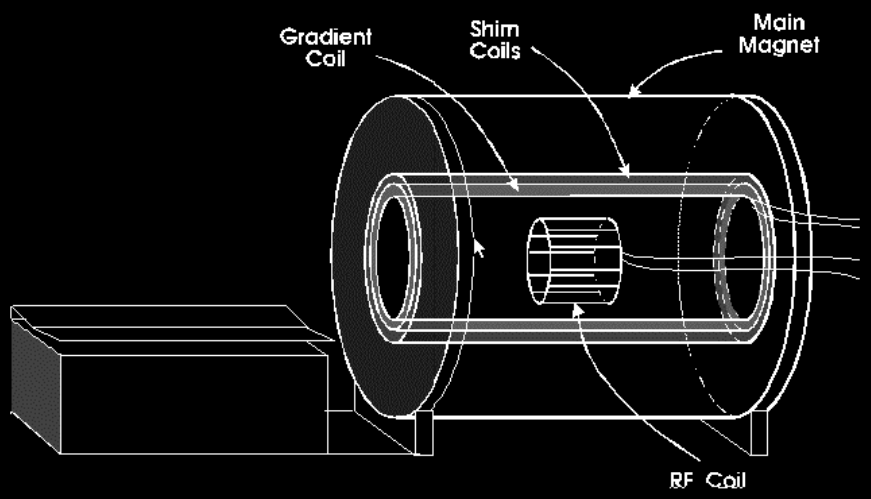
3D z-Shim Method for Reduction of Susceptibility Effects in BOLD fMRI

Gary H. Glover*



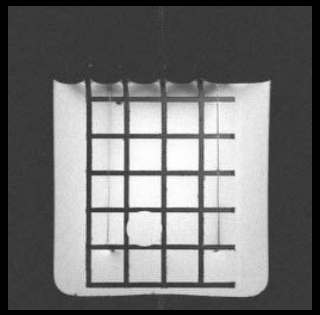
2 G/cm, 350 T/m/s

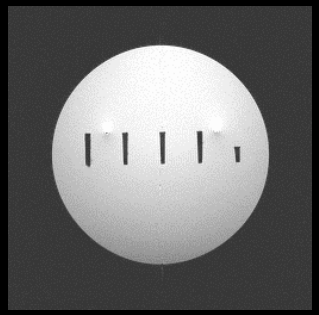
4 G/cm, 150 T/m/s



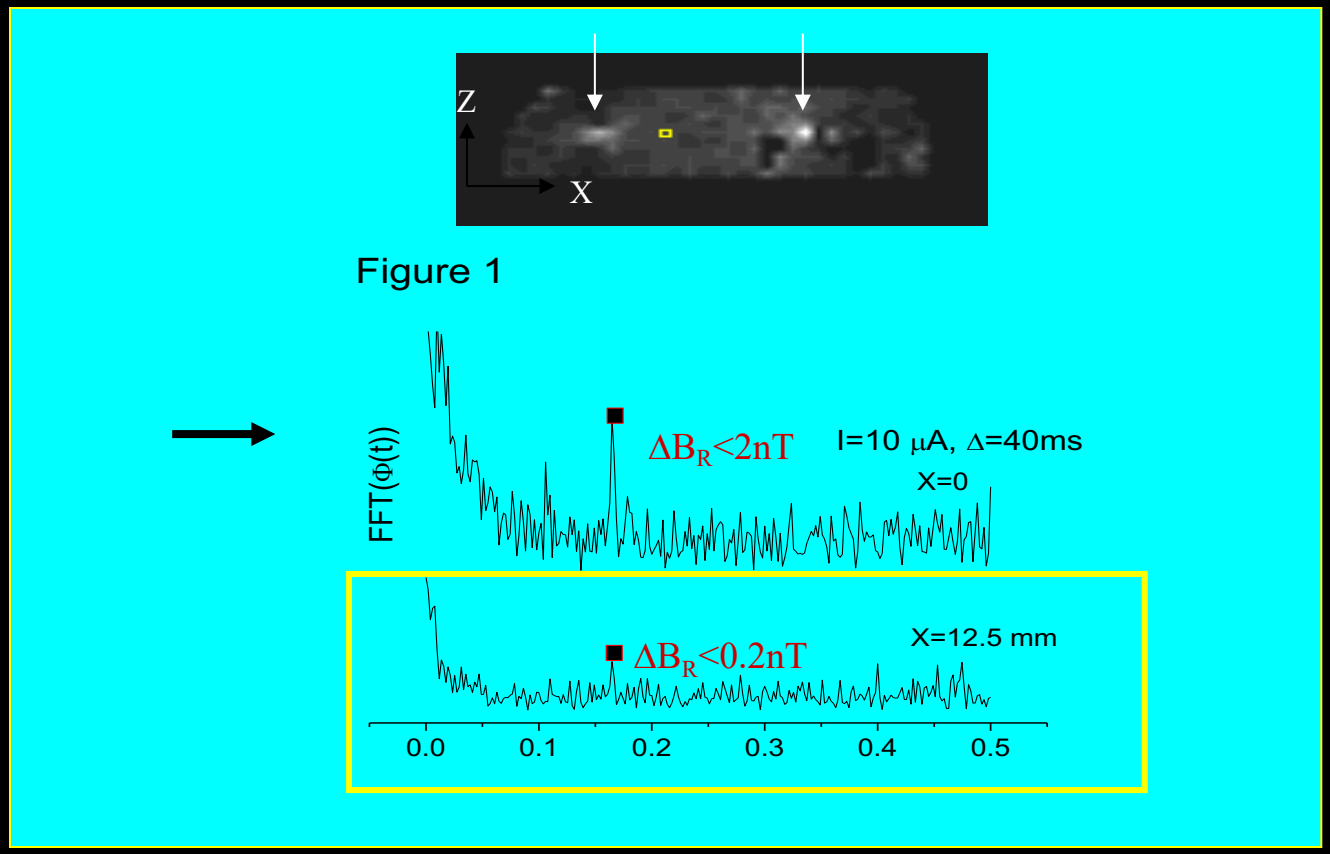
10 G/cm, 1000 T/m/s

Diffusion imaging
Faster imaging
Higher resolution





Neuronal Current Imaging



J. Bodurka, P. A. Bandettini. Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes, Magn. Reson. Med. .

FIM Unit & FMRI Core Facility

Director:

Peter Bandettini

Staff Scientists:

Sean Marrett

Jerzy Bodurka

Frank Ye

Wen-Ming Luh

Computer Specialist:

Adam Thomas

Post Docs:

Rasmus Birn

Hauke Heekeren

David Knight

Patrick Bellgowan

Ziad Saad

Graduate Student:

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Post-Back. IRTA Students:

Elisa Kapler

August Tuan

Dan Kelley

Visiting Fellows:

Sergio Casciaro

Marta Maieron

Guosheng Ding

Clinical Fellow:

James Patterson

Psychologist:

Julie Frost

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Courtney Kemps

Douglass Ruff

Carla Wettig

Kang-Xing Jin

Program Assistant:

Kay Kuhns

Scanning Technologists:

Karen Bove-Bettis

Paula Rowser