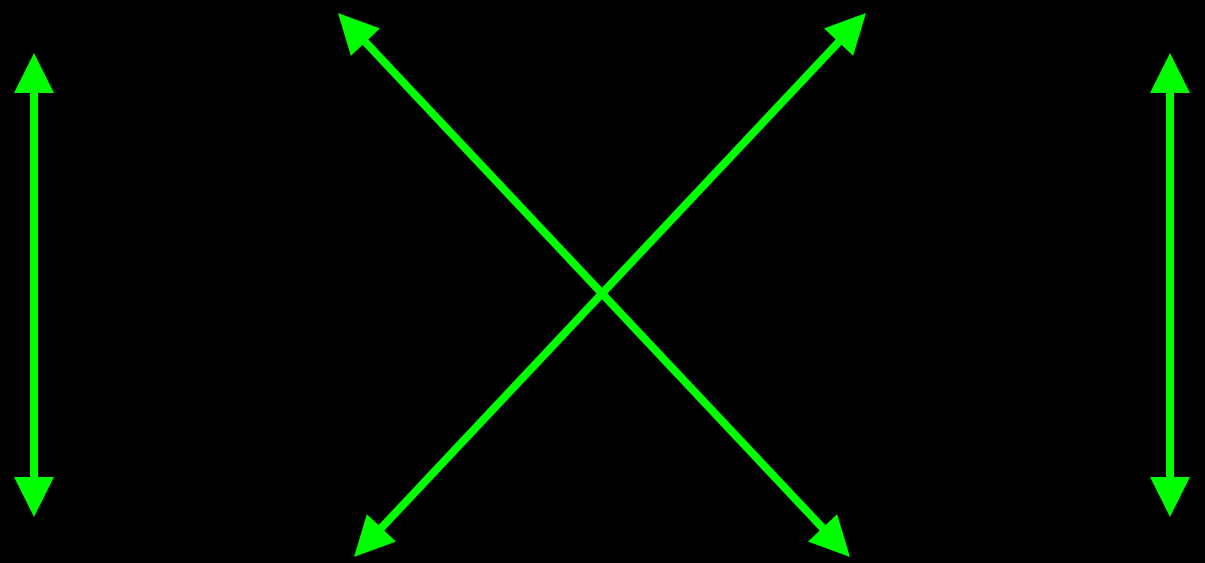
# fMRI: Past, Present, and Future

Peter A. Bandettini, Ph.D

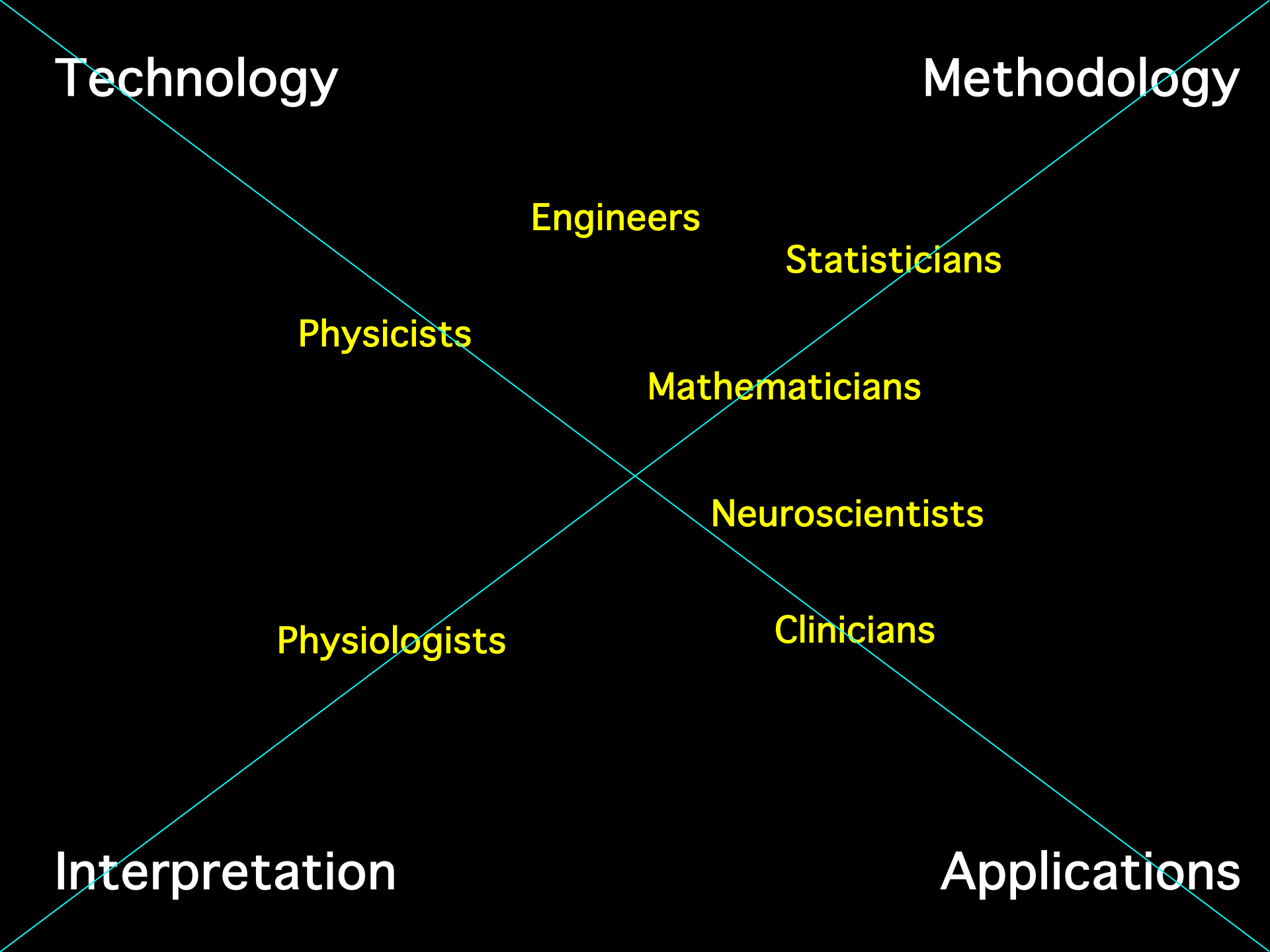
Unit on Functional Imaging Methods
&
3T Neuroimaging Core Facility

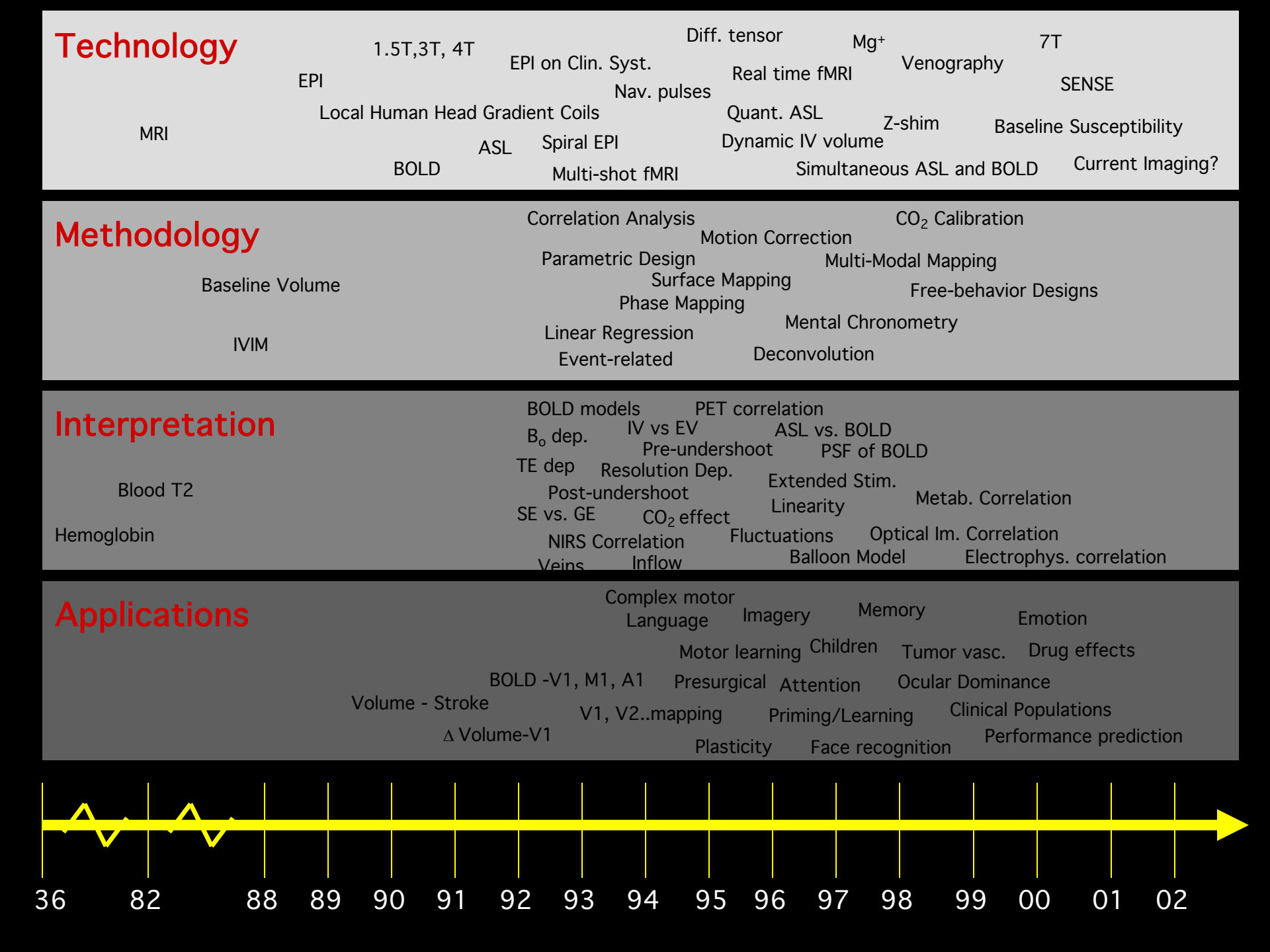
Laboratory of Brain and Cognition
National Institute of Mental Health

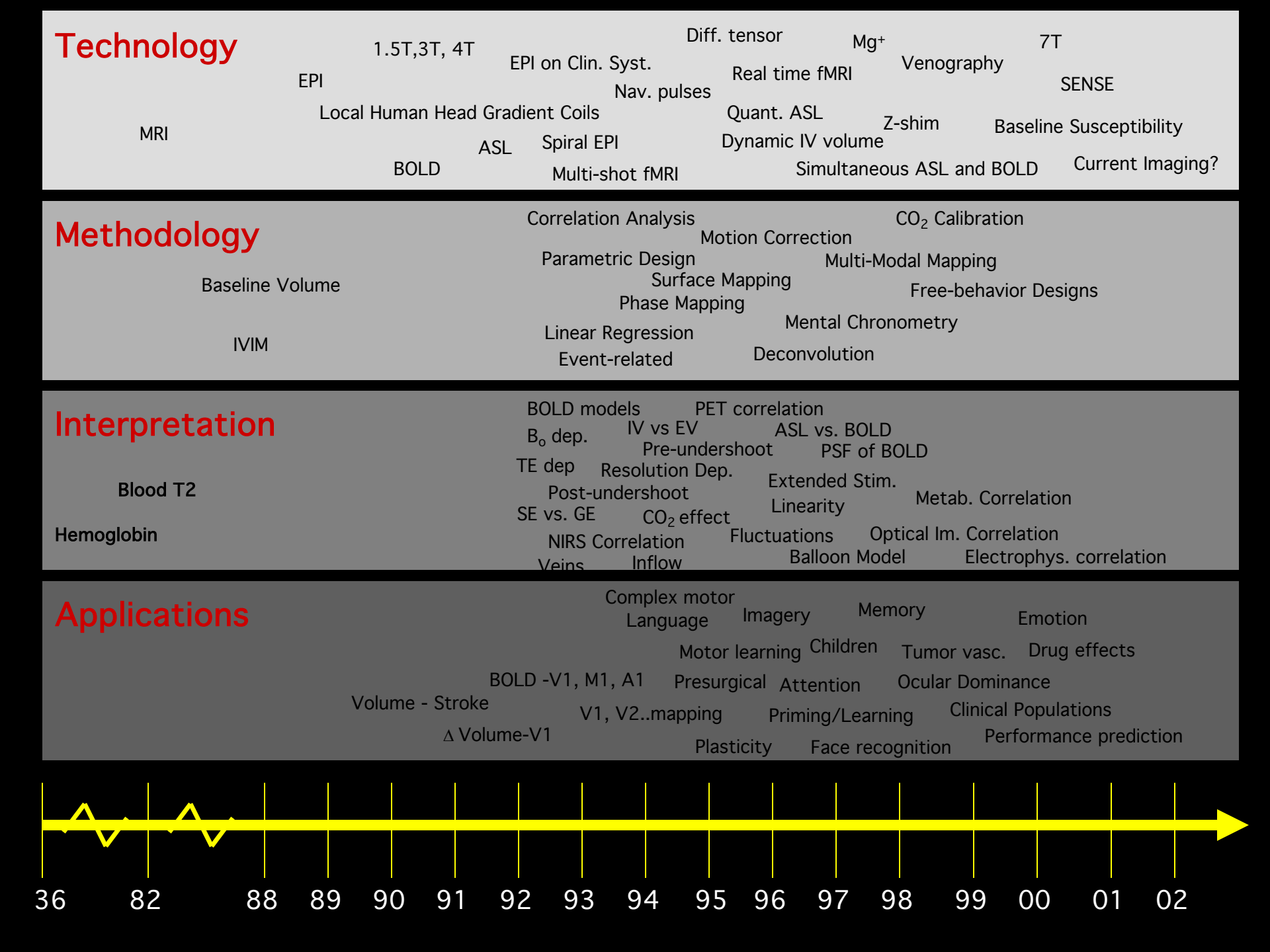
Technology ↔ Methodology



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
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

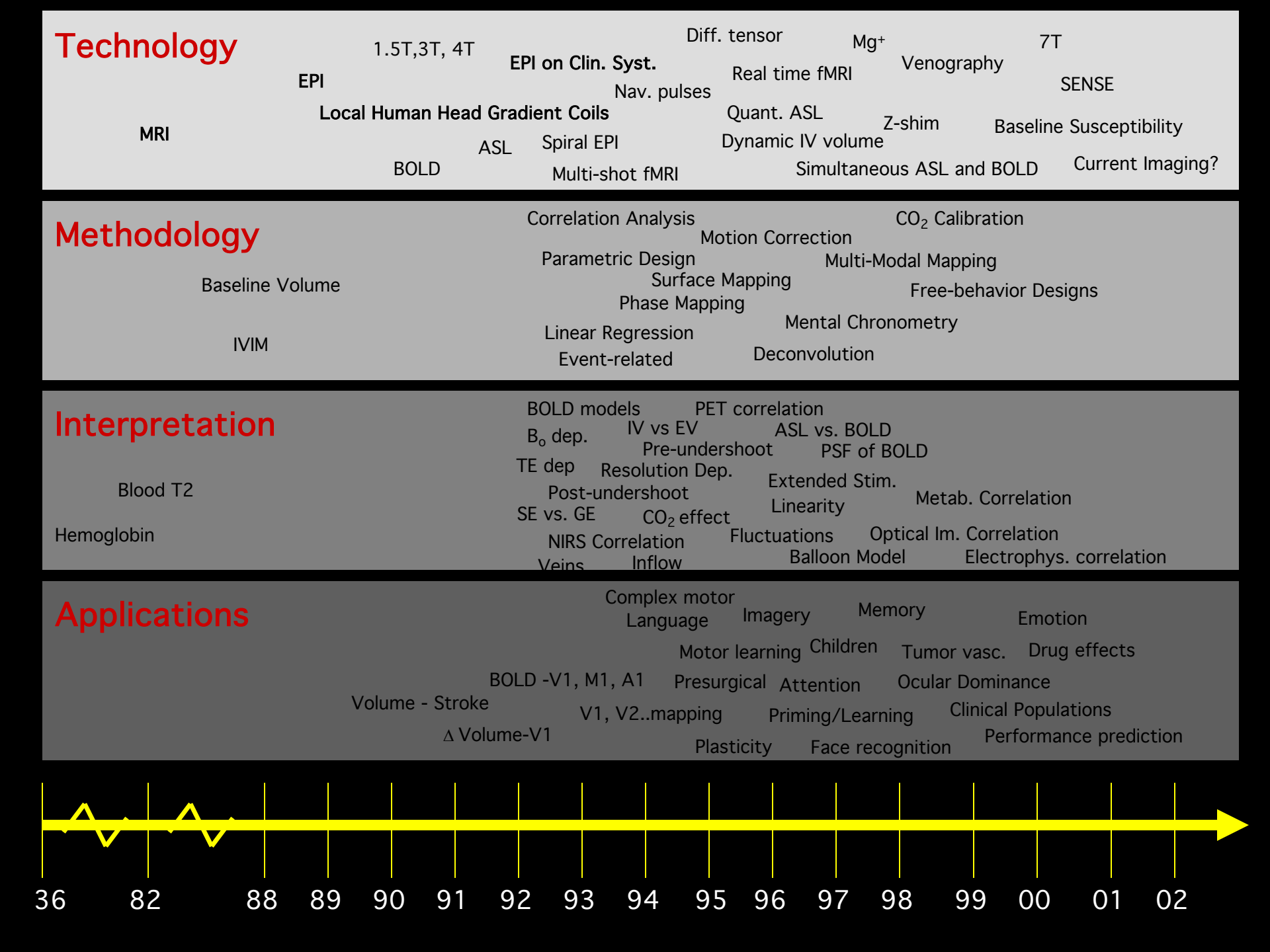

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
Dynamic IV volume
ASL
Spiral EPI
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation Analysis
CO2 Calibration
Motion Correction
Parametric Design
Multi-Modal Mapping
Surface Mapping
Baseline Volume
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
Metab. Correlation
Linearity
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

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.

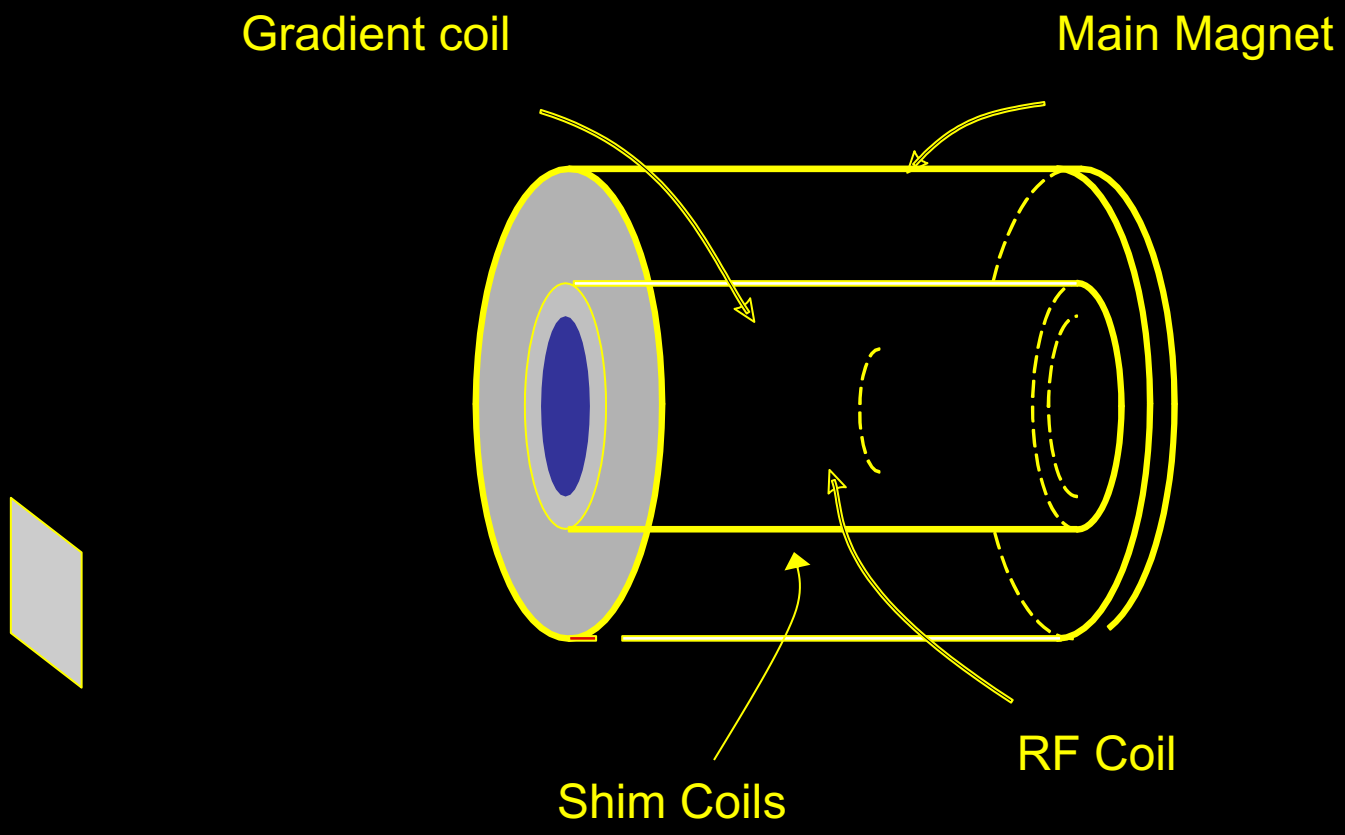

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
Dynamic IV volume
ASL
Spiral EPI
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation 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

$$f_o = \gamma B_o$$

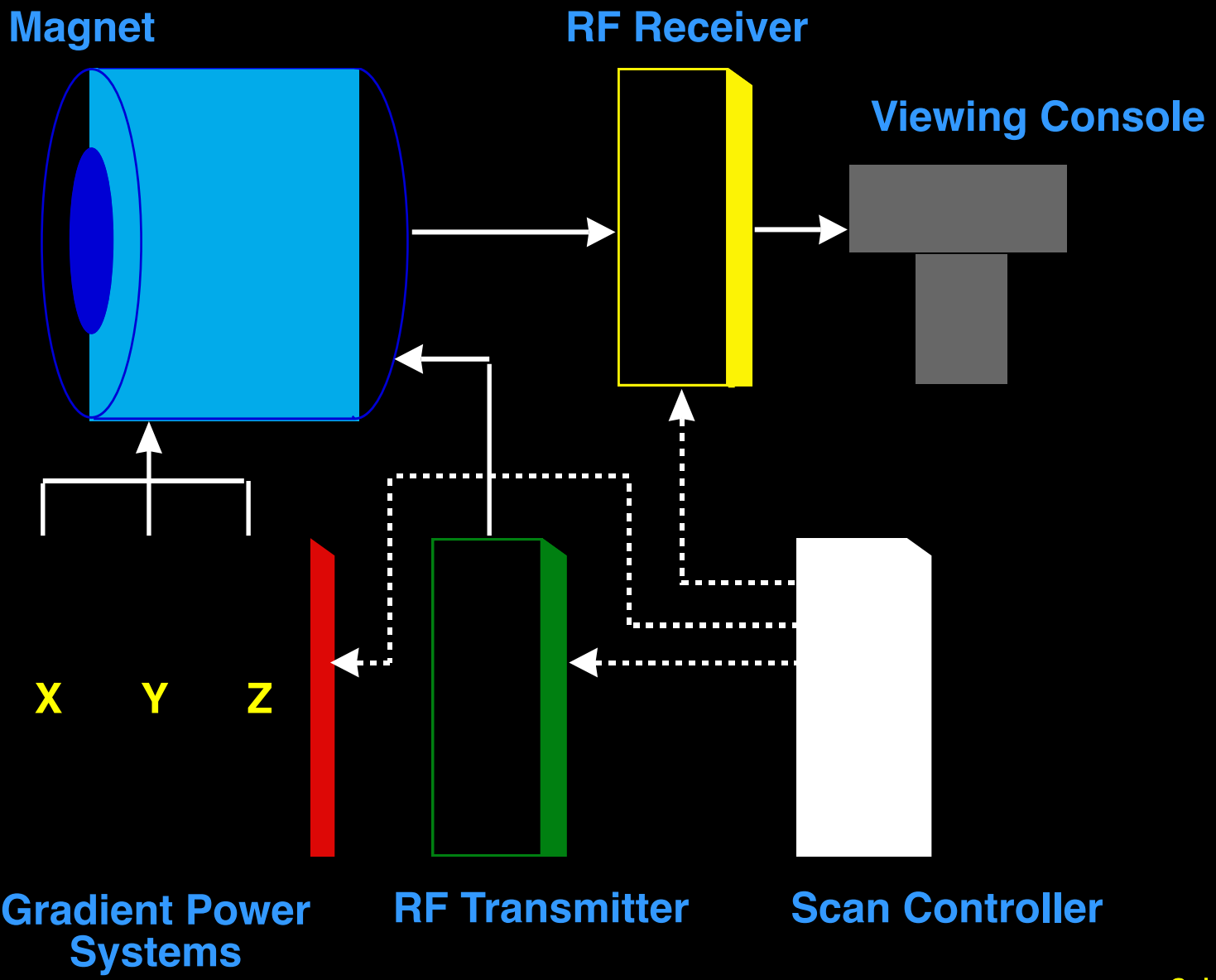
$f_o$ = Larmor frequency

$\gamma$ = gyromagnetic ratio (42.6 MHz/Tesla)

$B_o$ = magnetic field strength (Tesla)

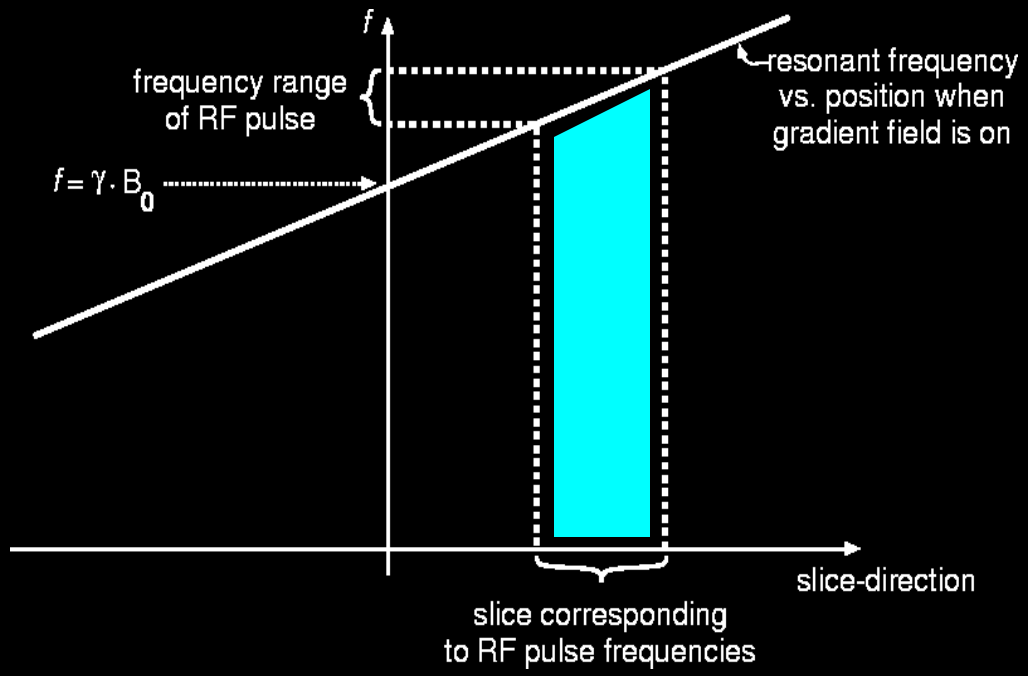

Gradient coil
Main Magnet
RF Coil
Shim Coils

# Imaging System Components

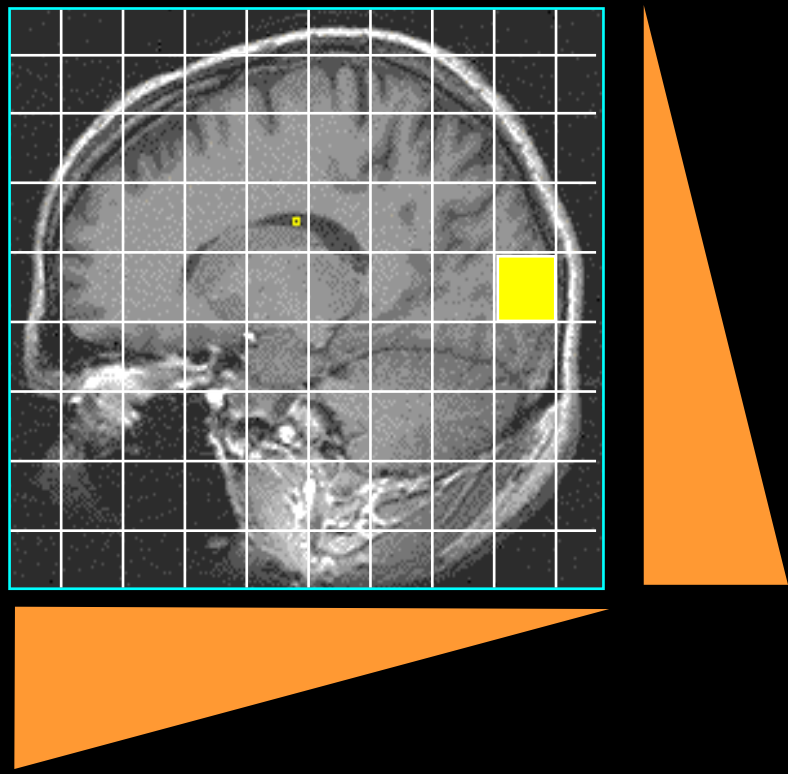



Cohen et al

# Slice Selection

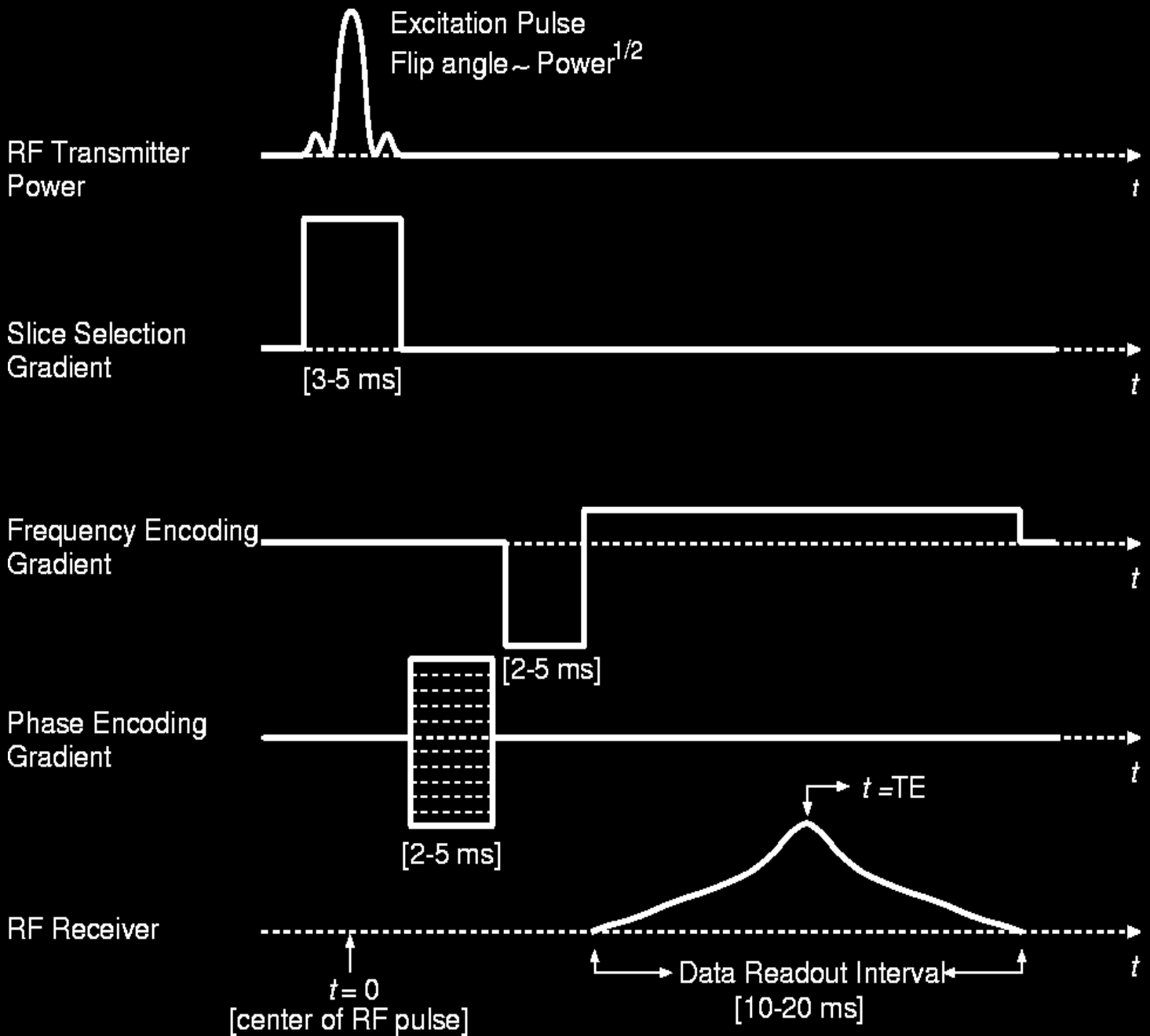



# In – Plane Spatial Localization



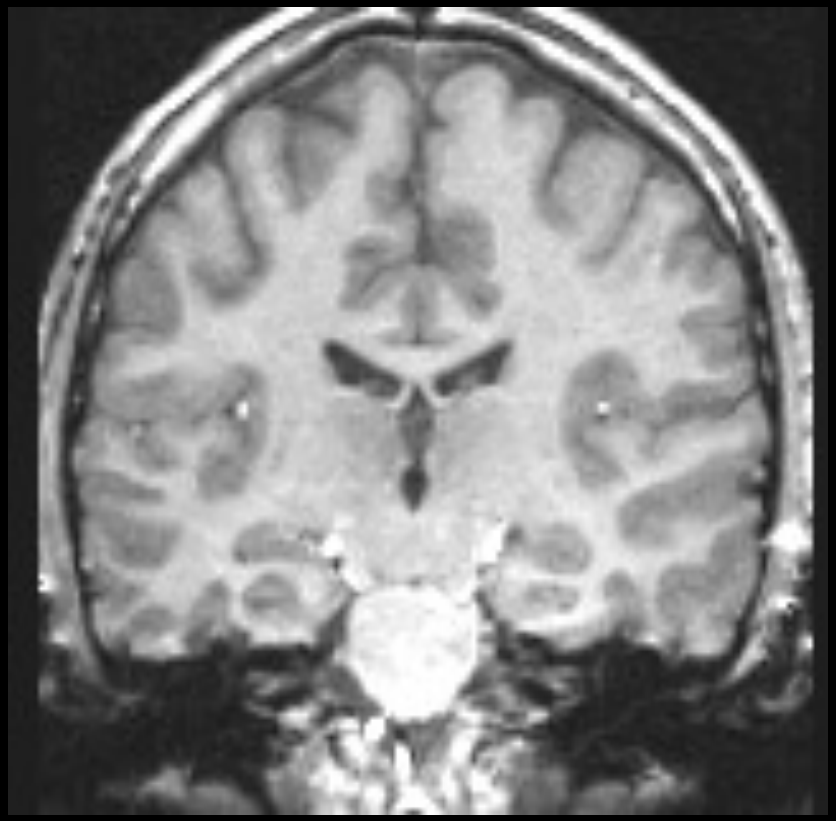
$$f_o = \gamma B_o$$

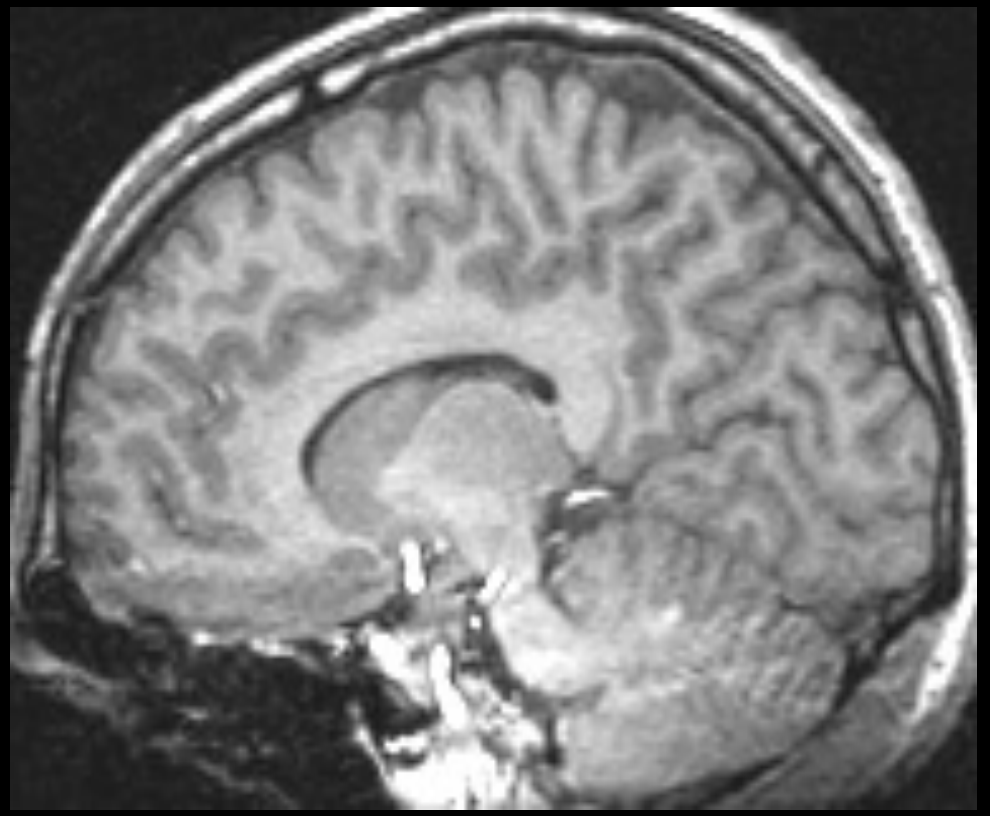
# MRI Pulse Sequence for Gradient Echo Imaging




Illustrates sequence of events during scanning

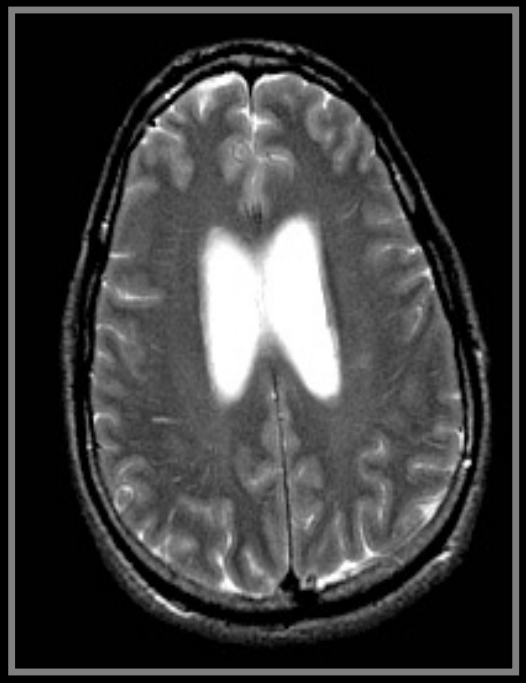
As shown, this method (FLASH) takes 35 ms per RF shot, so would take 2.25 s for a 64×64 image

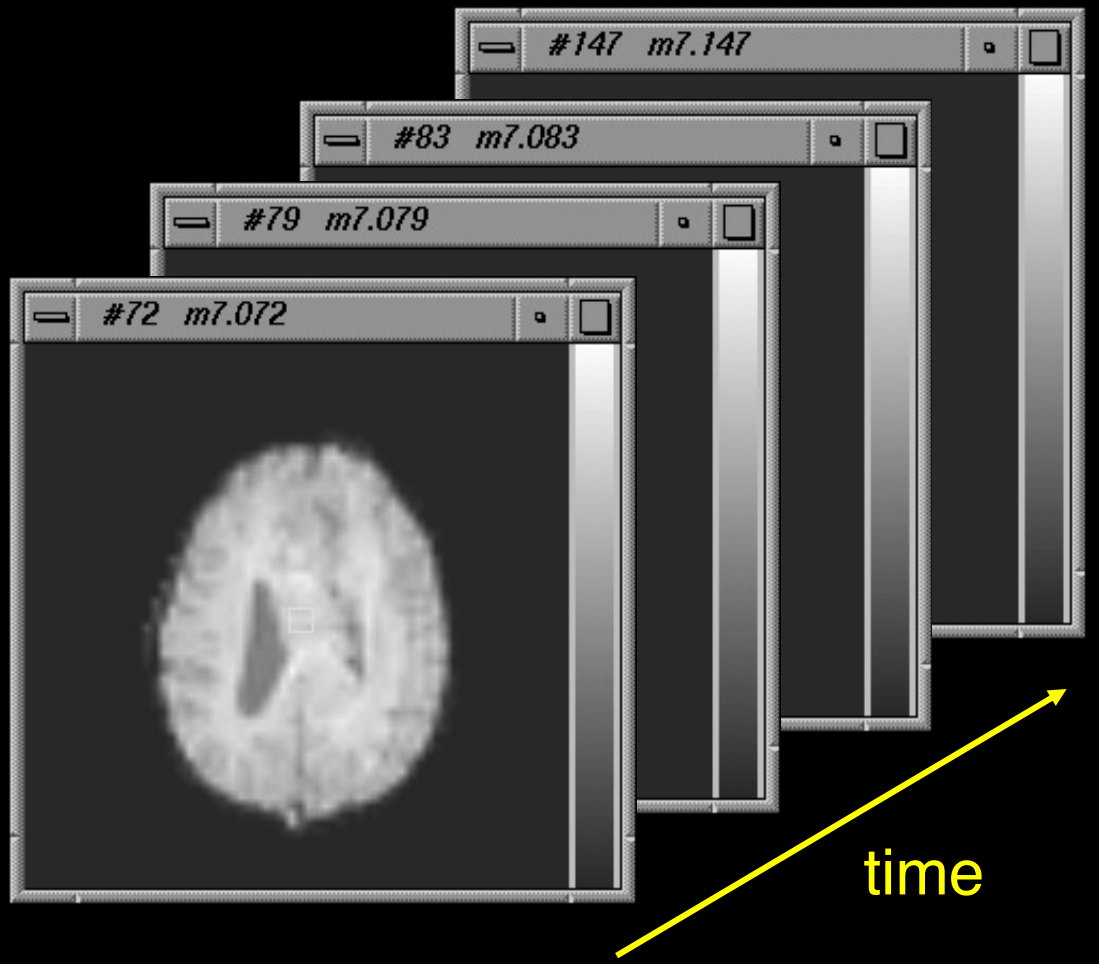




# Souce of Anatomical Contrast: MRI Parameters

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

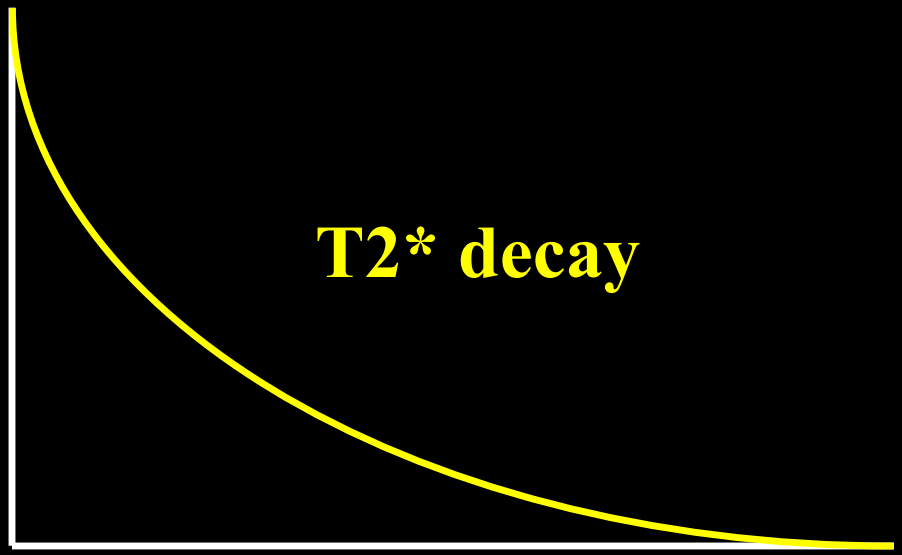


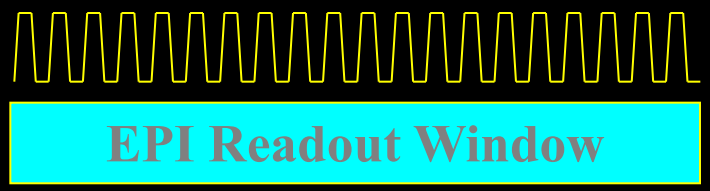



Anatomic

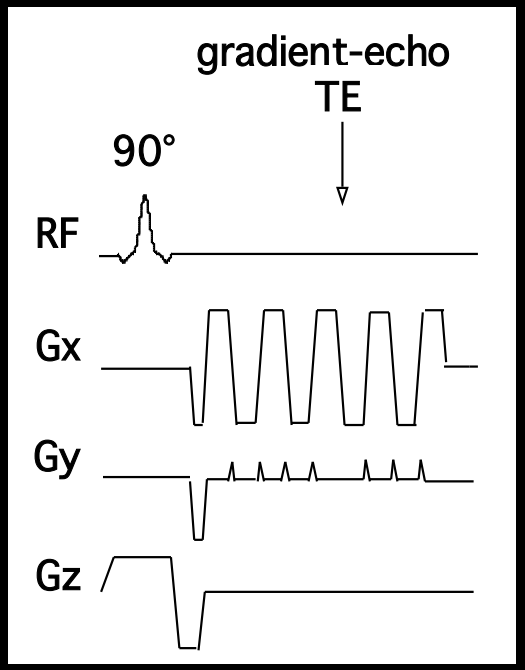
Functional

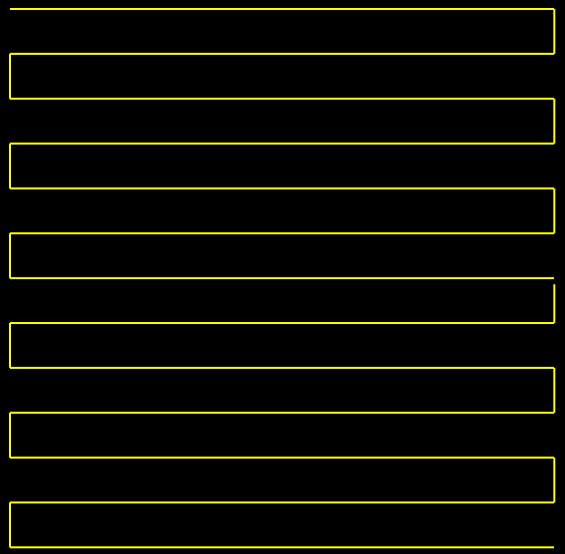
# Single Shot EPI



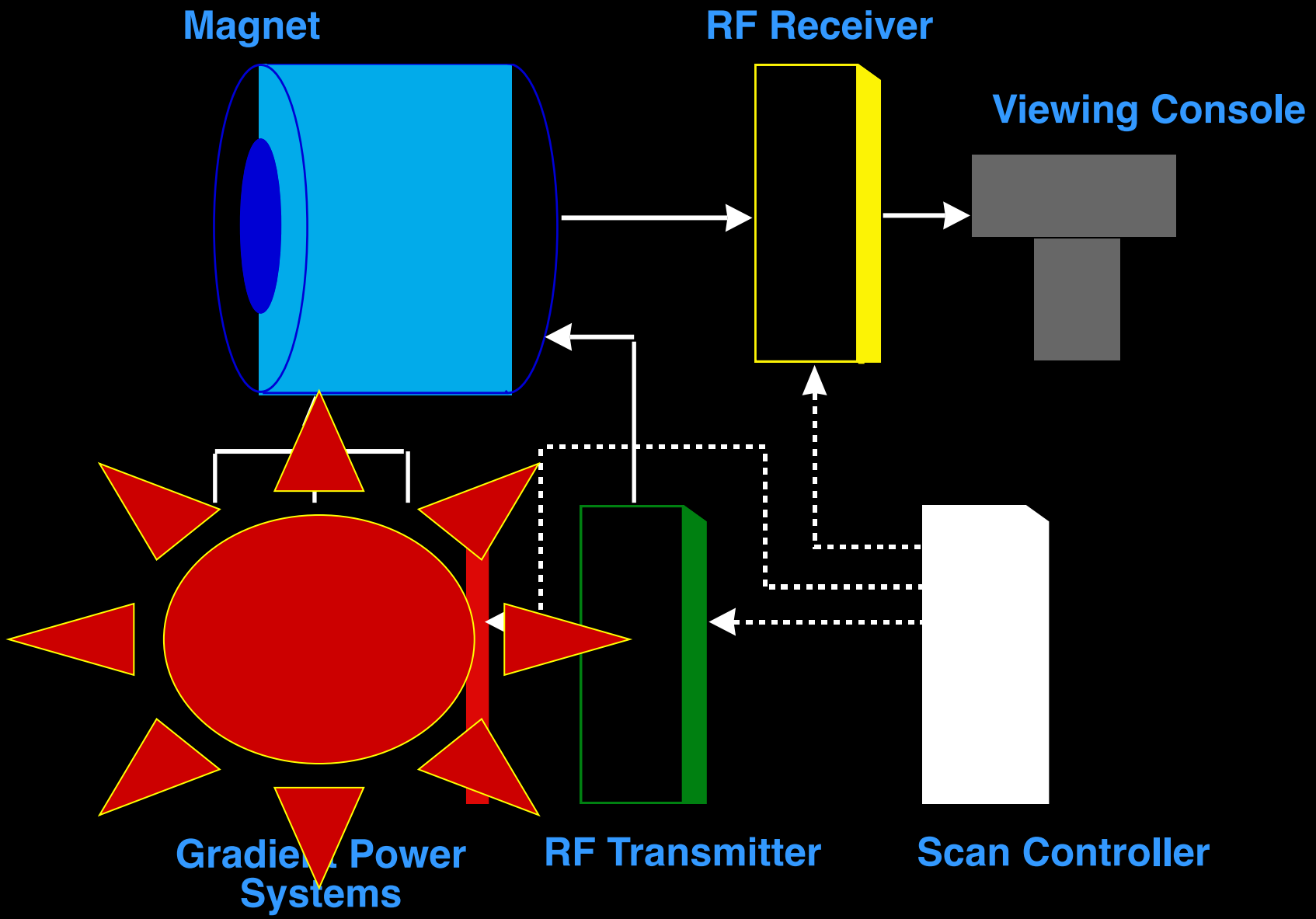




**≈ 20 to 40 ms**

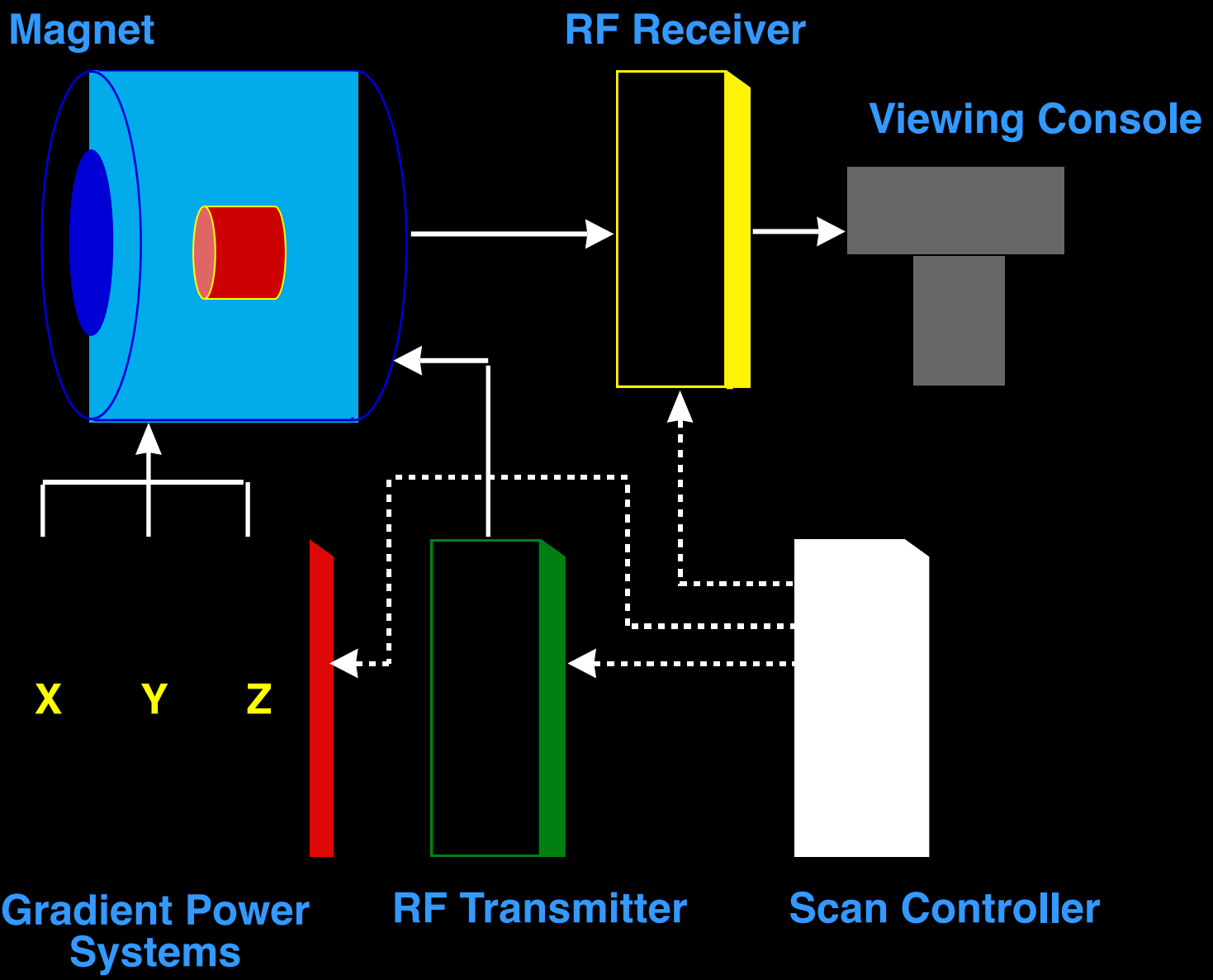


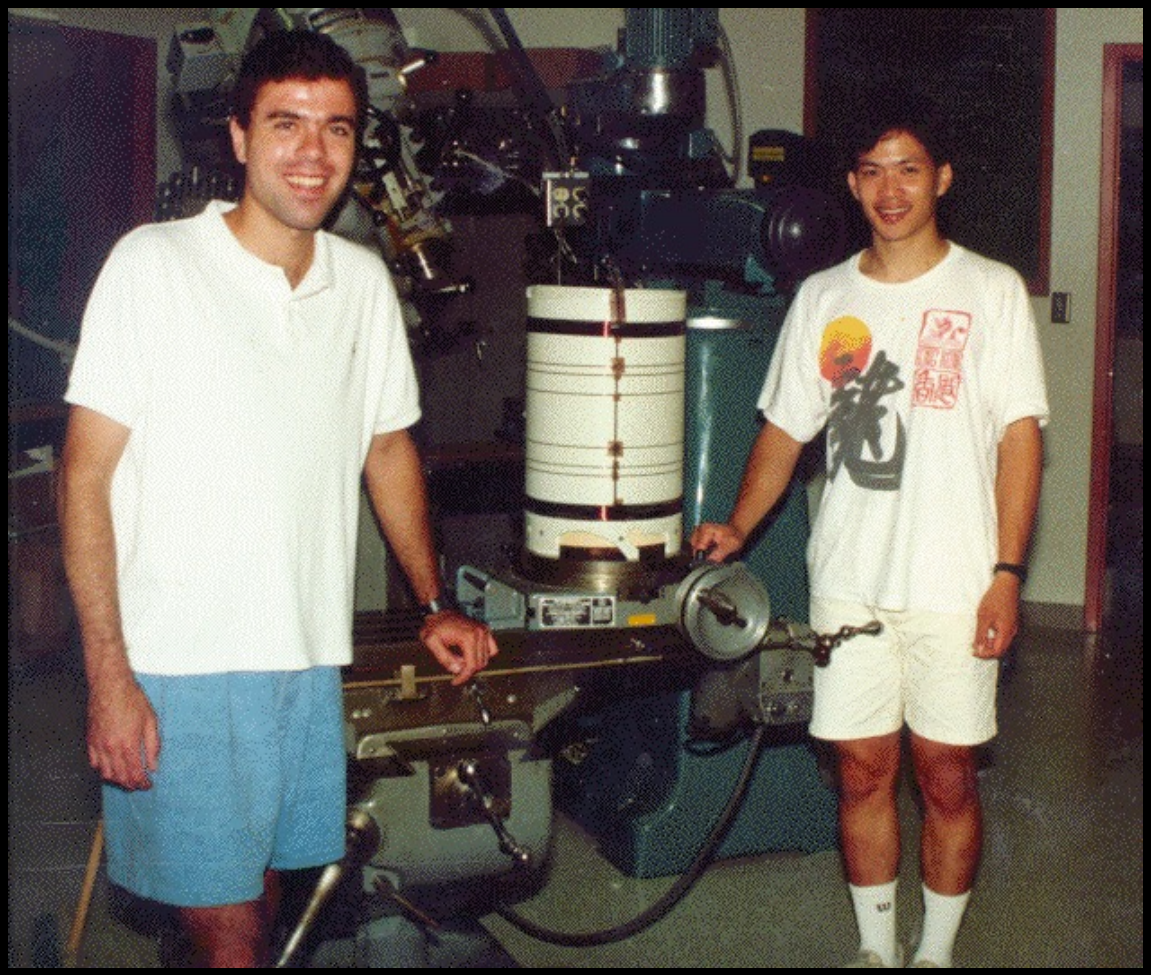
# Imaging System Components



# Imaging System Components



# Local gradients solved the problem



August, 1991

1991-1992

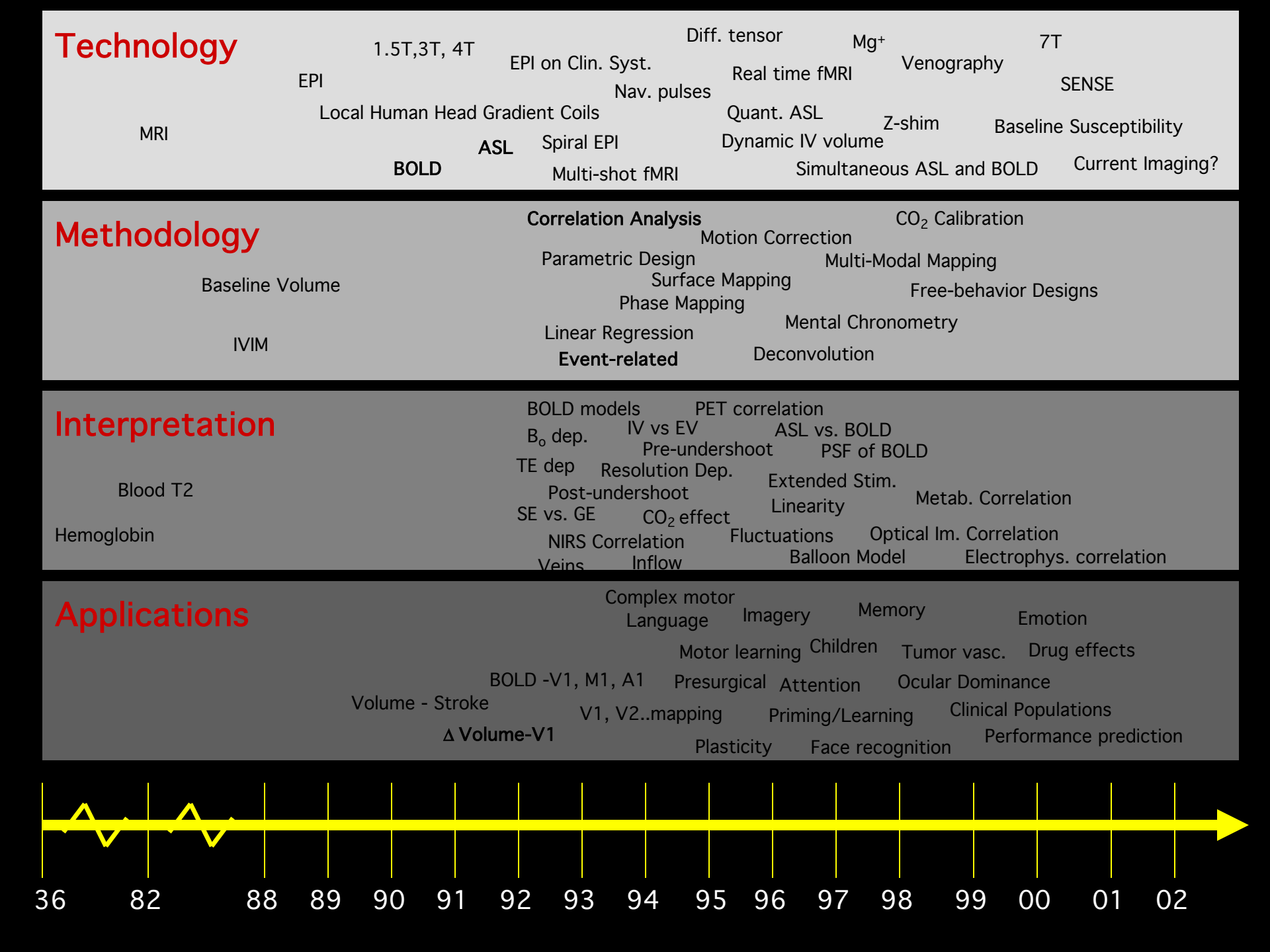
1992-1999

# Functional MRI Methods

Blood Volume Imaging

BOLD Contrast

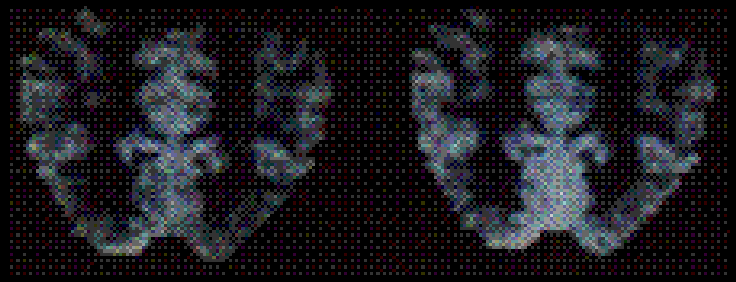
Arterial Spin Labeling

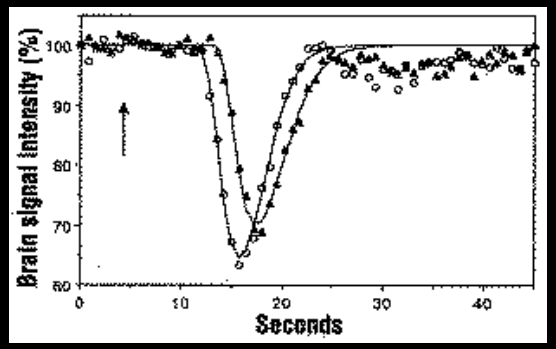

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
ASL
Spiral EPI
Dynamic IV volume
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation Analysis
CO2 Calibration
Motion Correction
Parametric Design
Multi-Modal Mapping
Baseline Volume
Surface Mapping
Free-behavior Designs
Phase Mapping
Mental Chronometry
Linear Regression
IVIM
Event-related
Deconvolution
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
NIRS Correlation
Fluctuations
Optical Im. 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

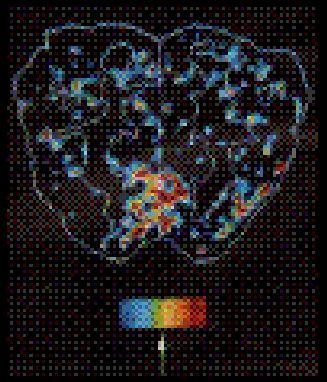
# Blood Volume Imaging

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

Resting Active

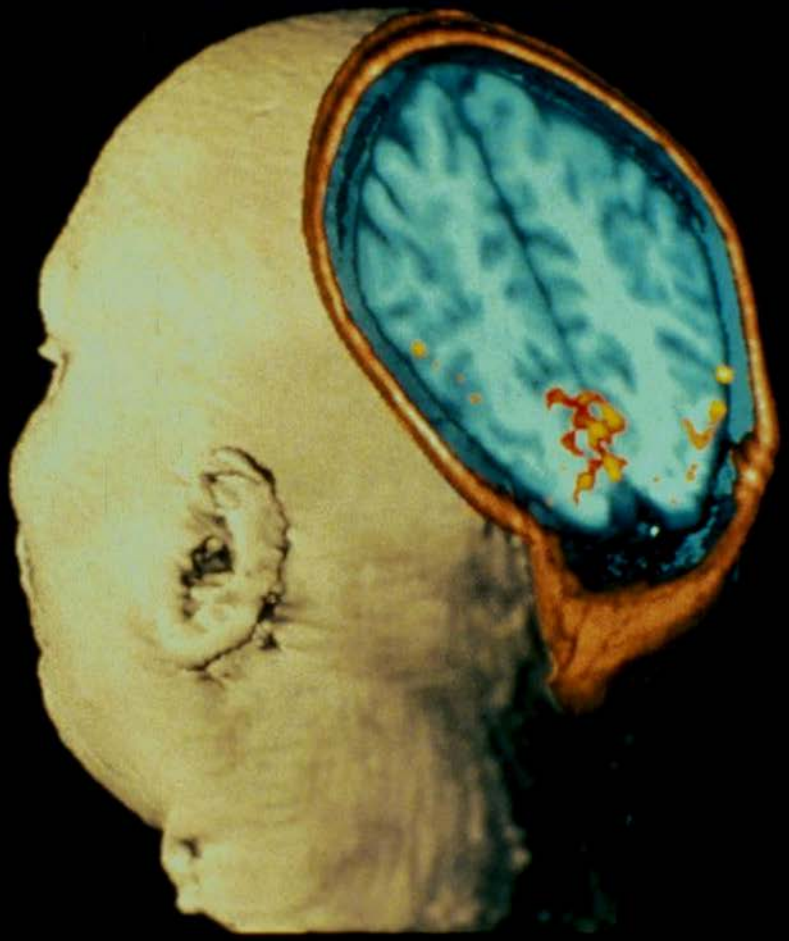




# Blood Volume

**Photic Stimulation**

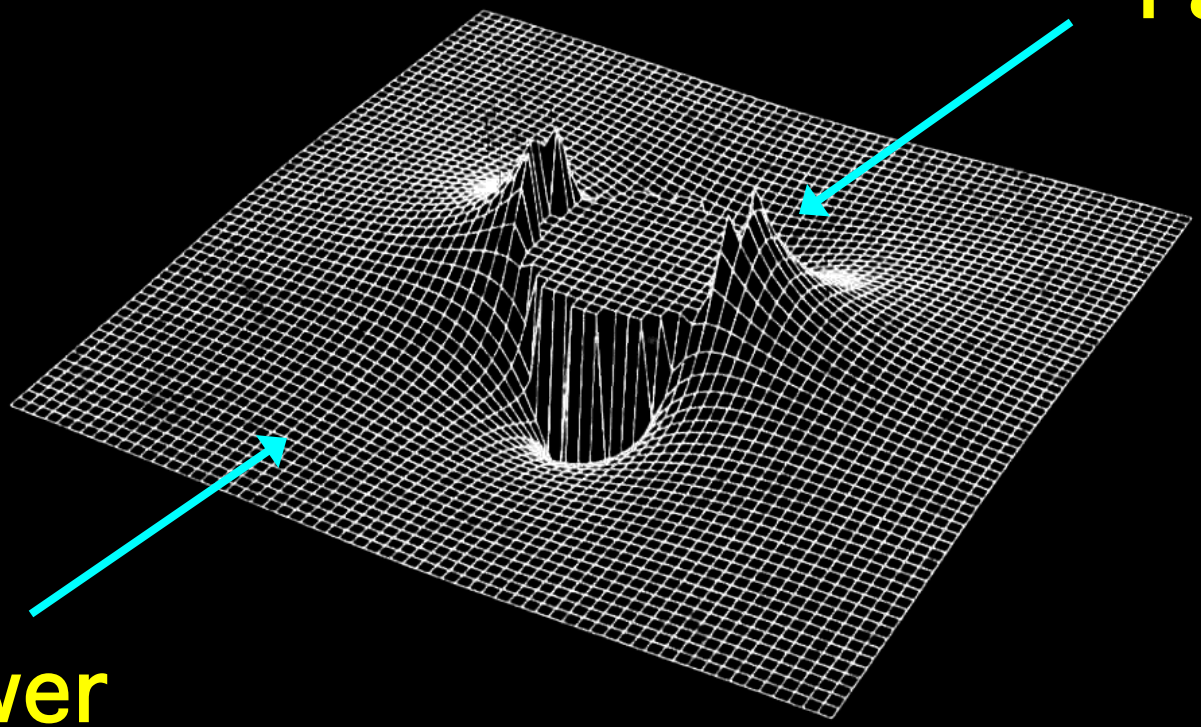


**MRI Image showing activation of the Visual Cortex**

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

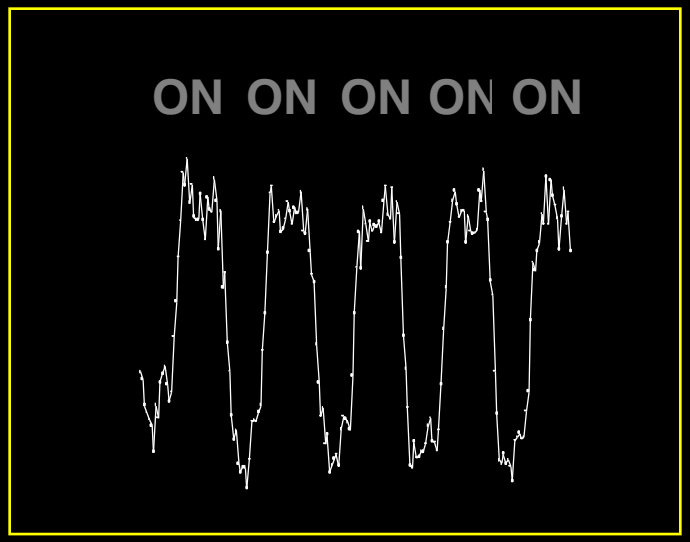

**K. K. Kwong, et al, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.**

**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.**

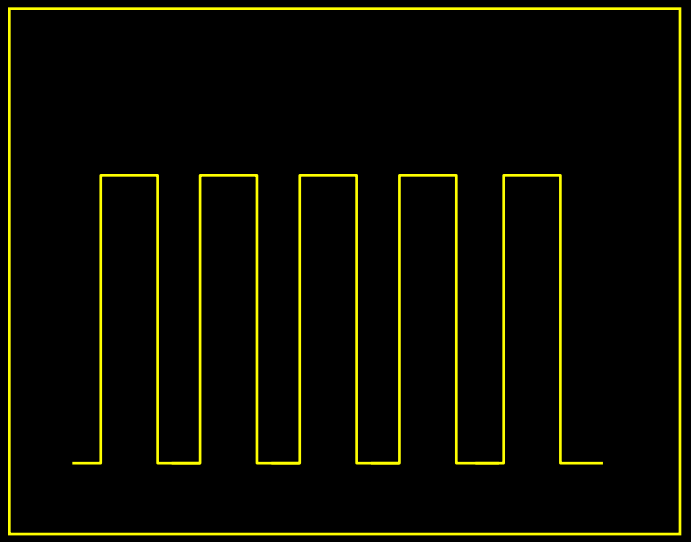
**Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.**

# Creating a Functional Image




Signal Time Course

X

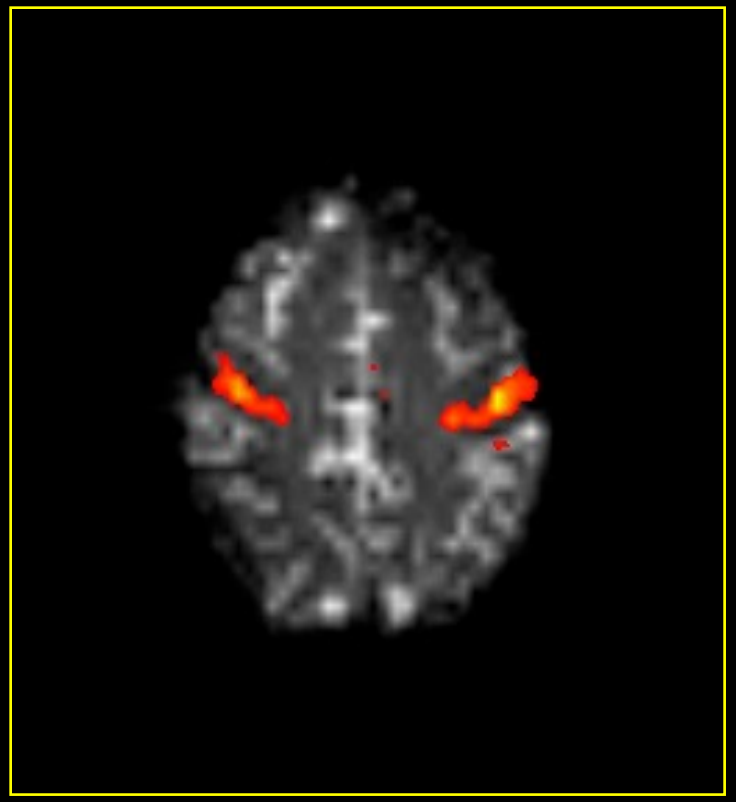


Reference Function

=

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*

↓

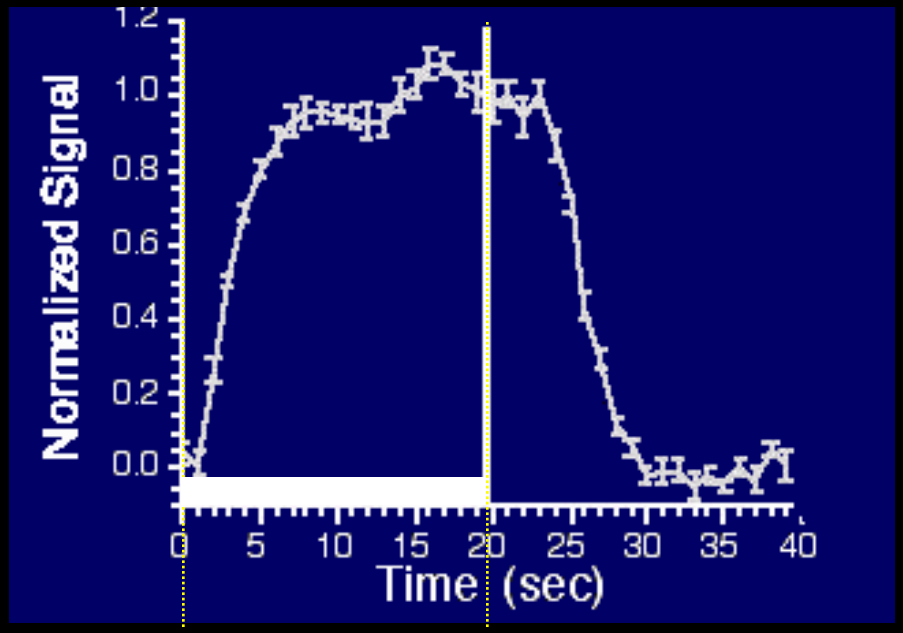
Decrease in susceptibility-related intravoxel dephasing → Increase in T2 and T2*

↓

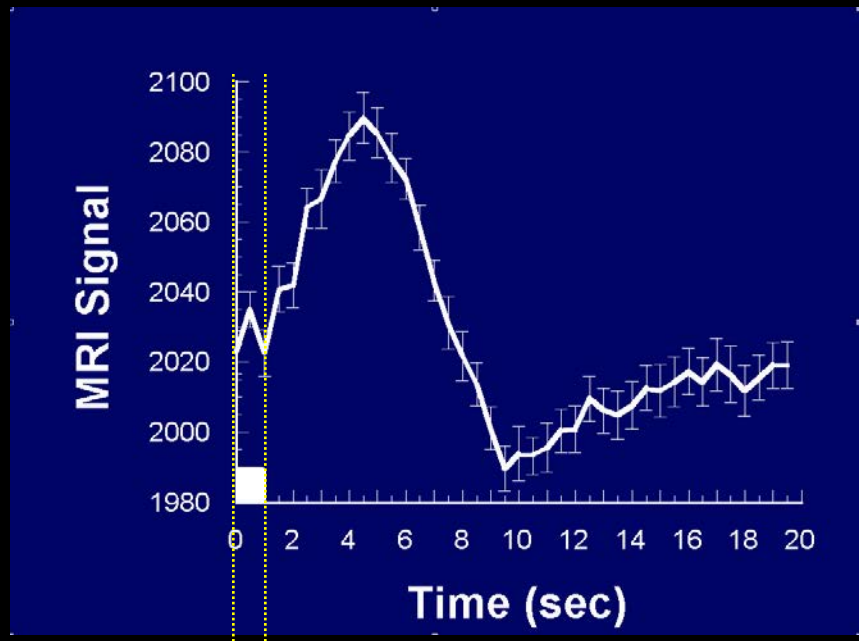
Local Signal Increase in T2 and T2* - weighted sequences

# The BOLD Signal

Blood Oxygenation Level Dependent (BOLD) signal changes

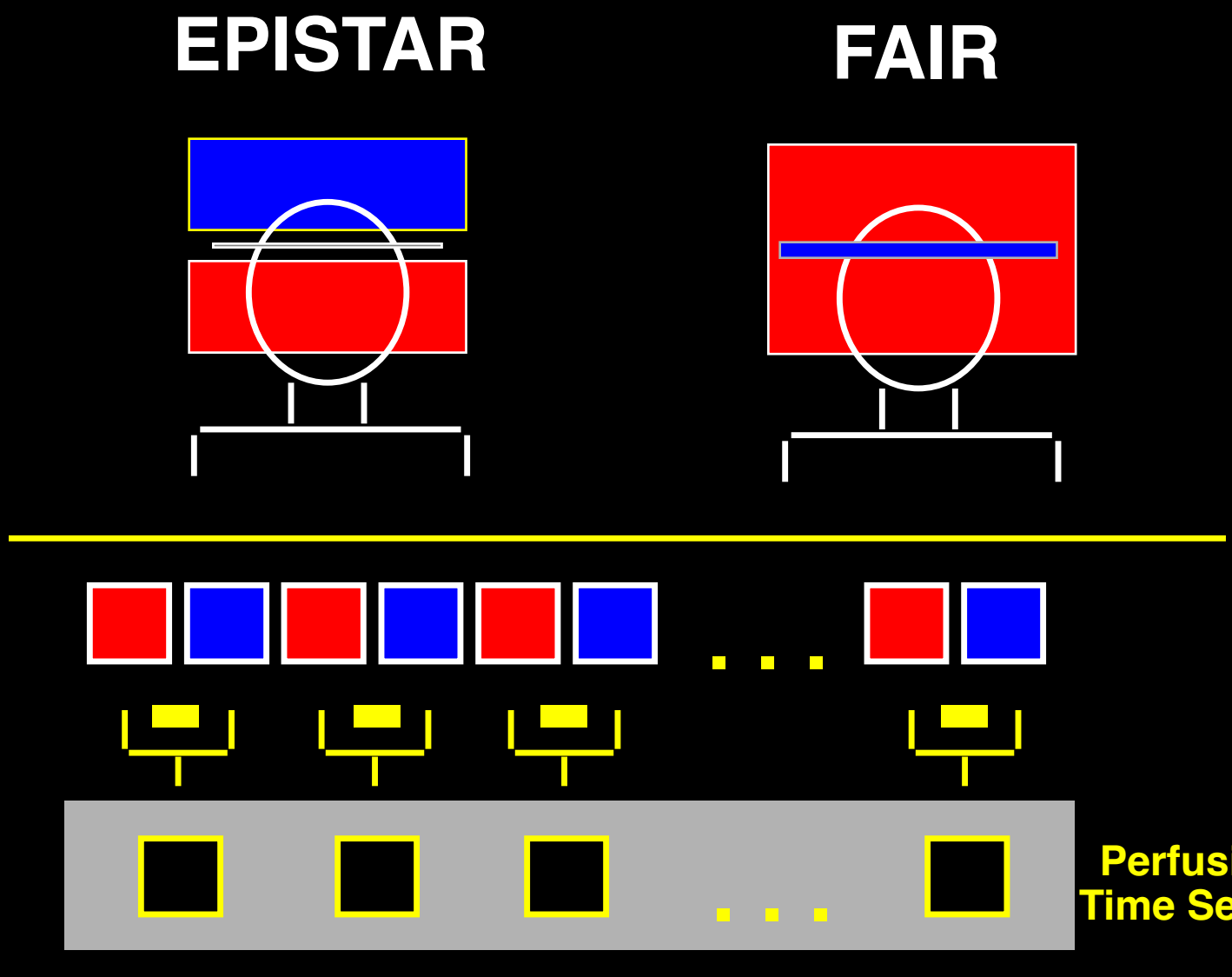


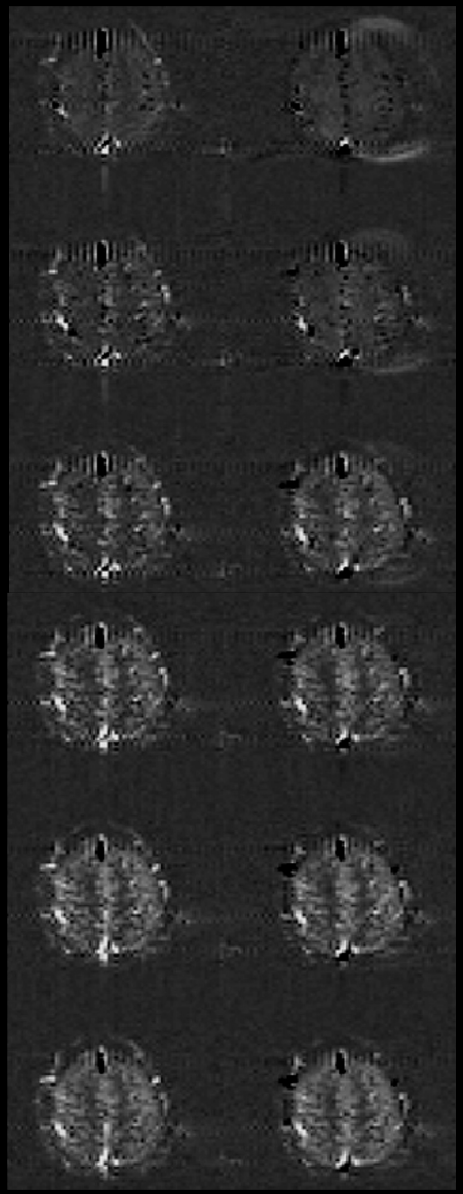

*task*

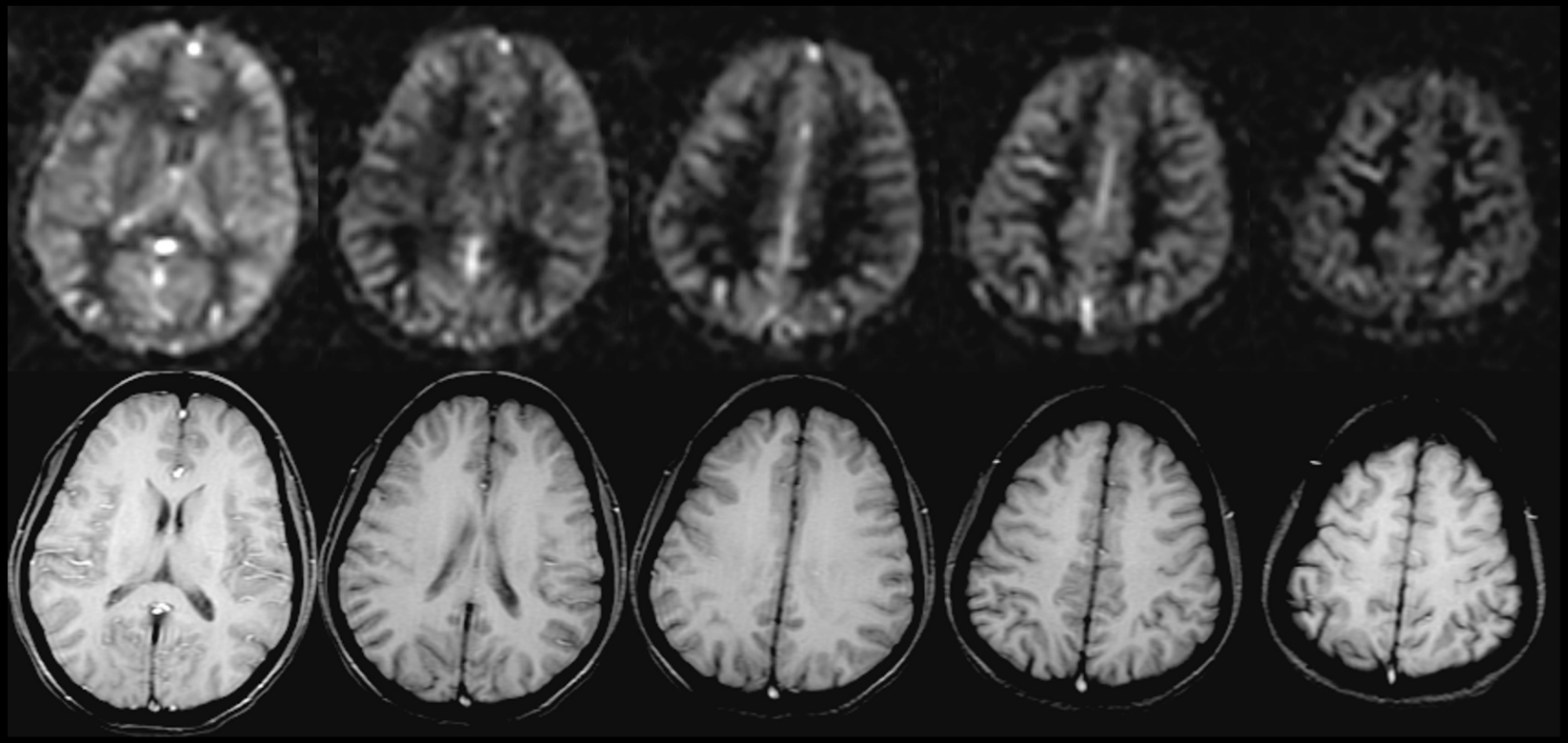



*task*

# Blood Perfusion



| TI (ms) | FAIR | EPISTAR |
|---|---|---|
| 200 |  | |
| 400 | | |
| 600 | | |
| 800 | | |
| 1000 | | |
| 1200 | | |



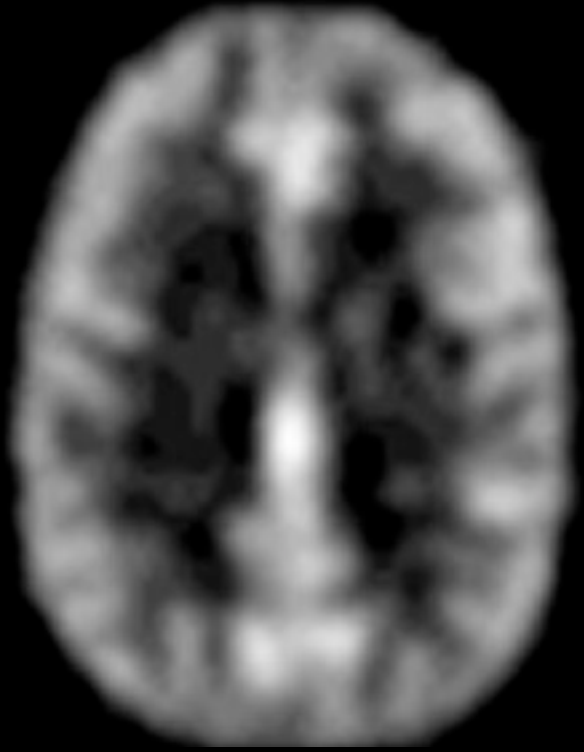
Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) “Magnetic resonance imaging of perfusion using spin-inversion of arterial water.” Proc. Natl. Acad. Sci. USA 89, 212-216.

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.

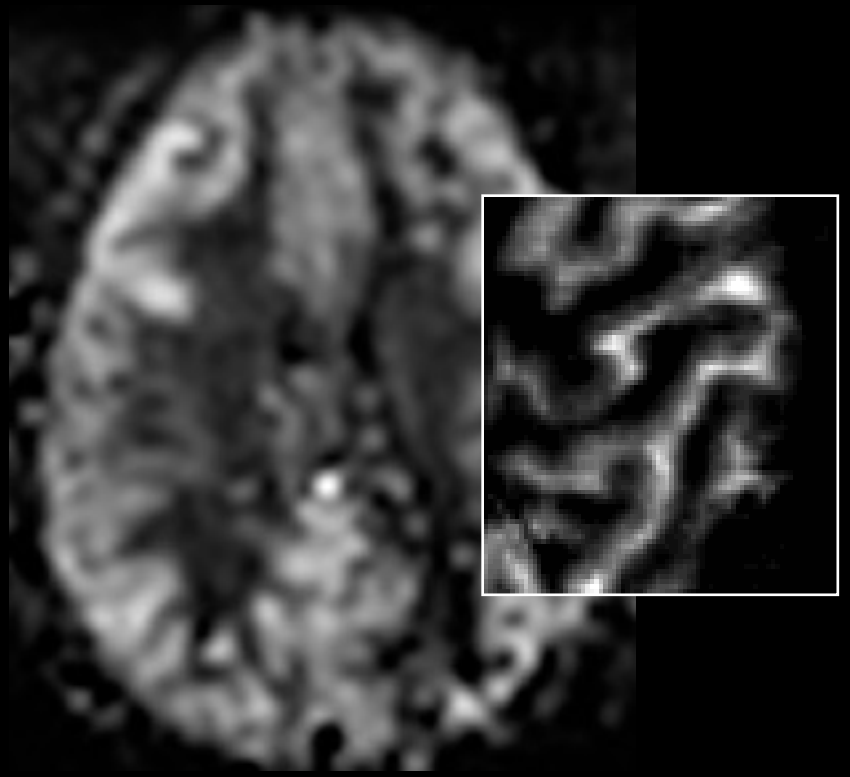
Kim, S.-G. (1995) “Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping.” Magn. Reson. Med. **34**, 293-301.

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

# Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

# Refinements

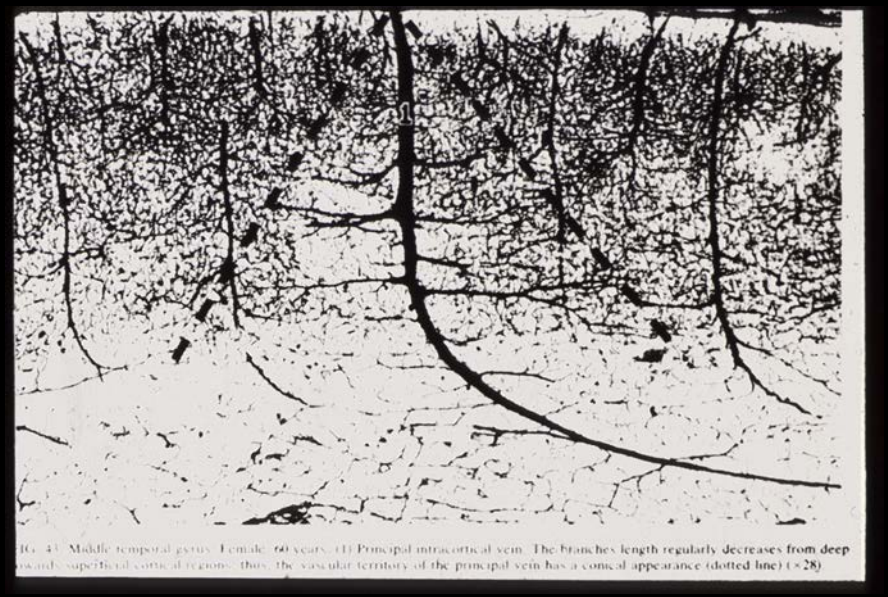
BOLD Contrast Interpretation

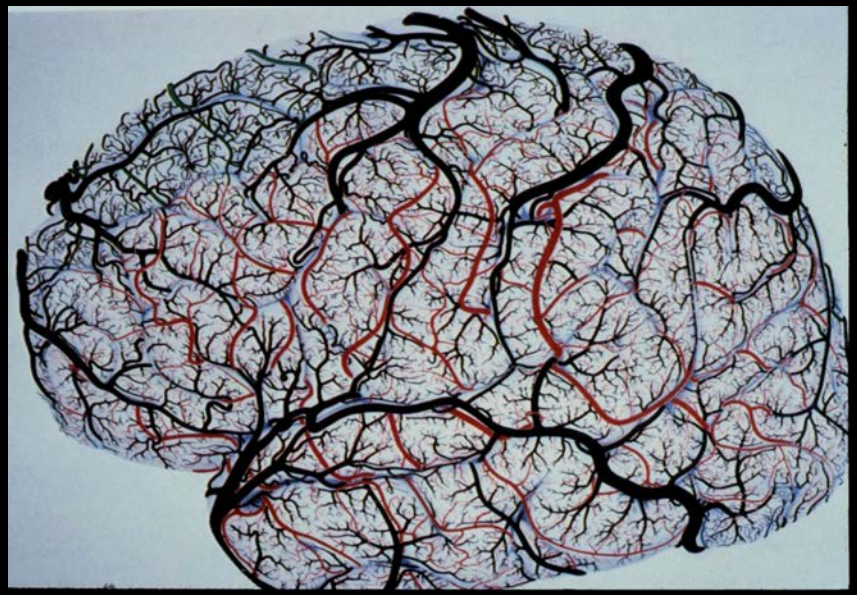
Dynamics, Paradigm Design and Processing

Applications

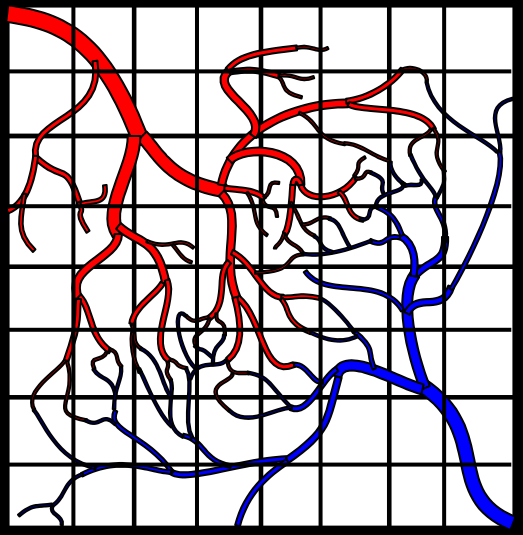
# The Neuroscientists' Challenge:

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





Neuronal Activation



Measured Signal

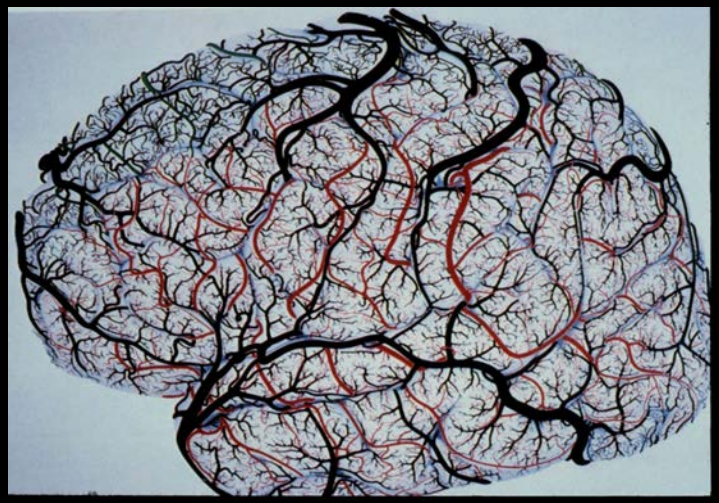
?

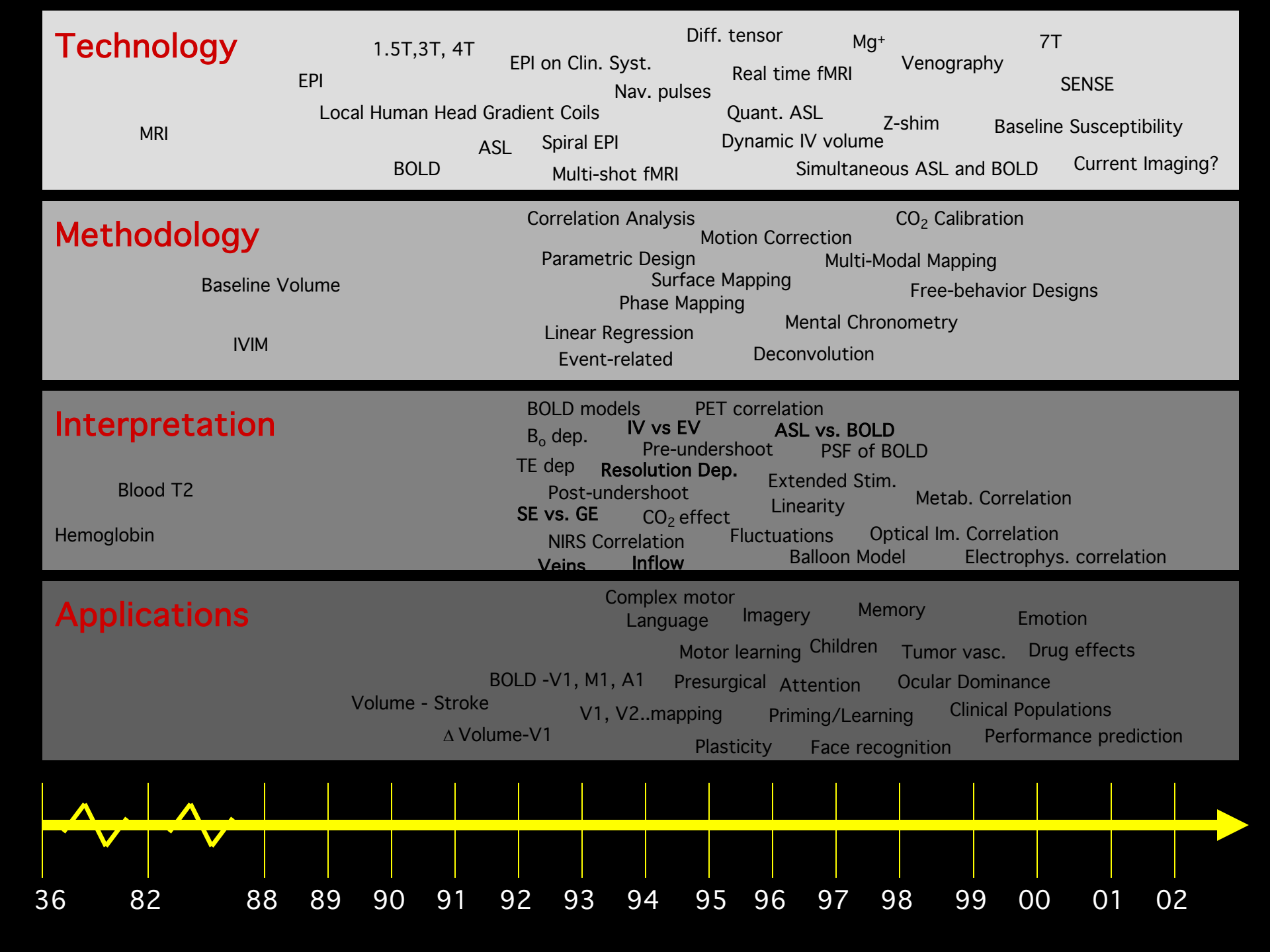
Hemodynamics

?

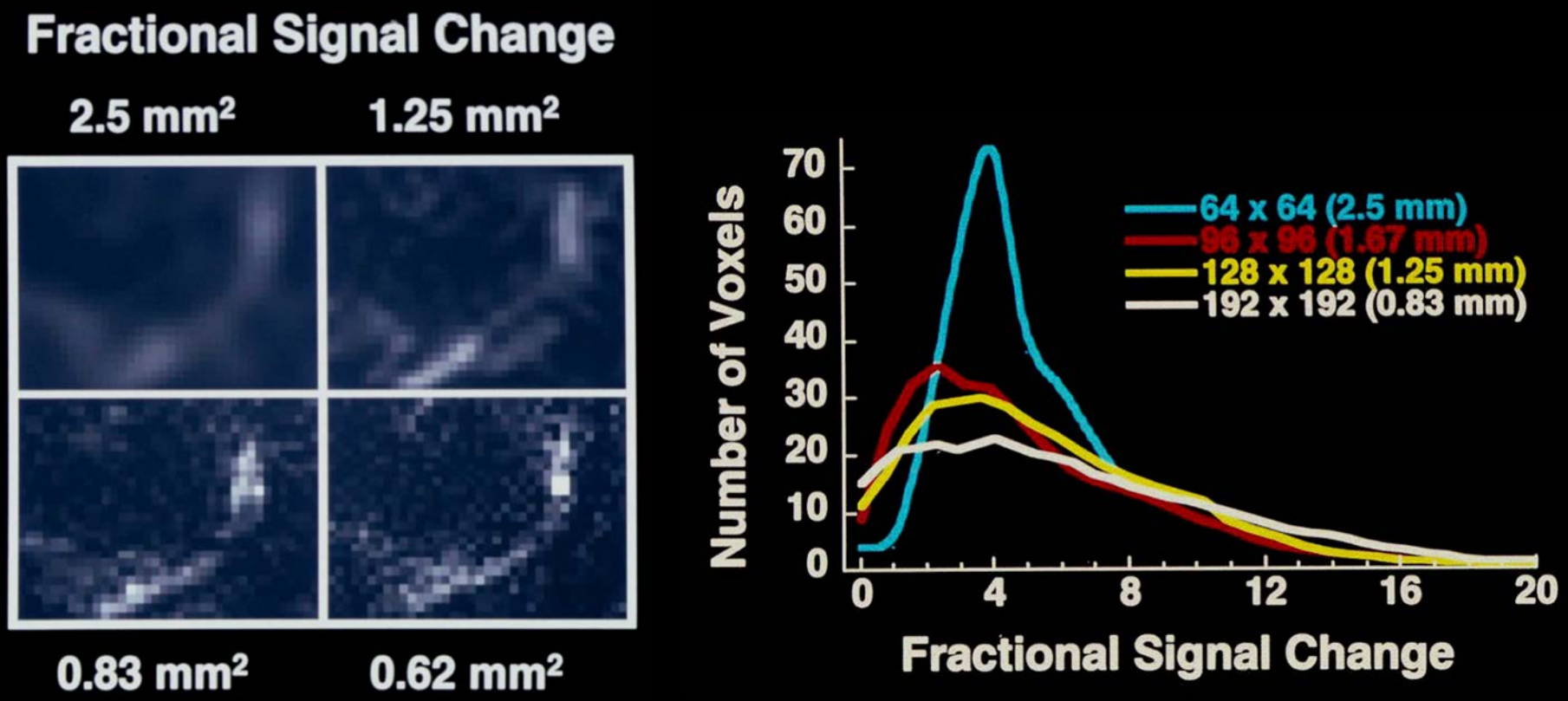
?

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
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
Dynamic IV volume
ASL
Spiral EPI
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
ASL vs. BOLD
B0 dep.
Pre-undershoot
PSF of BOLD
TE dep
Resolution Dep.
Extended Stim.
Blood T2
Post-undershoot
Linearity
Metab. Correlation
SE vs. GE
CO2 effect
Hemoglobin
NIRS Correlation
Fluctuations
Optical Im. 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

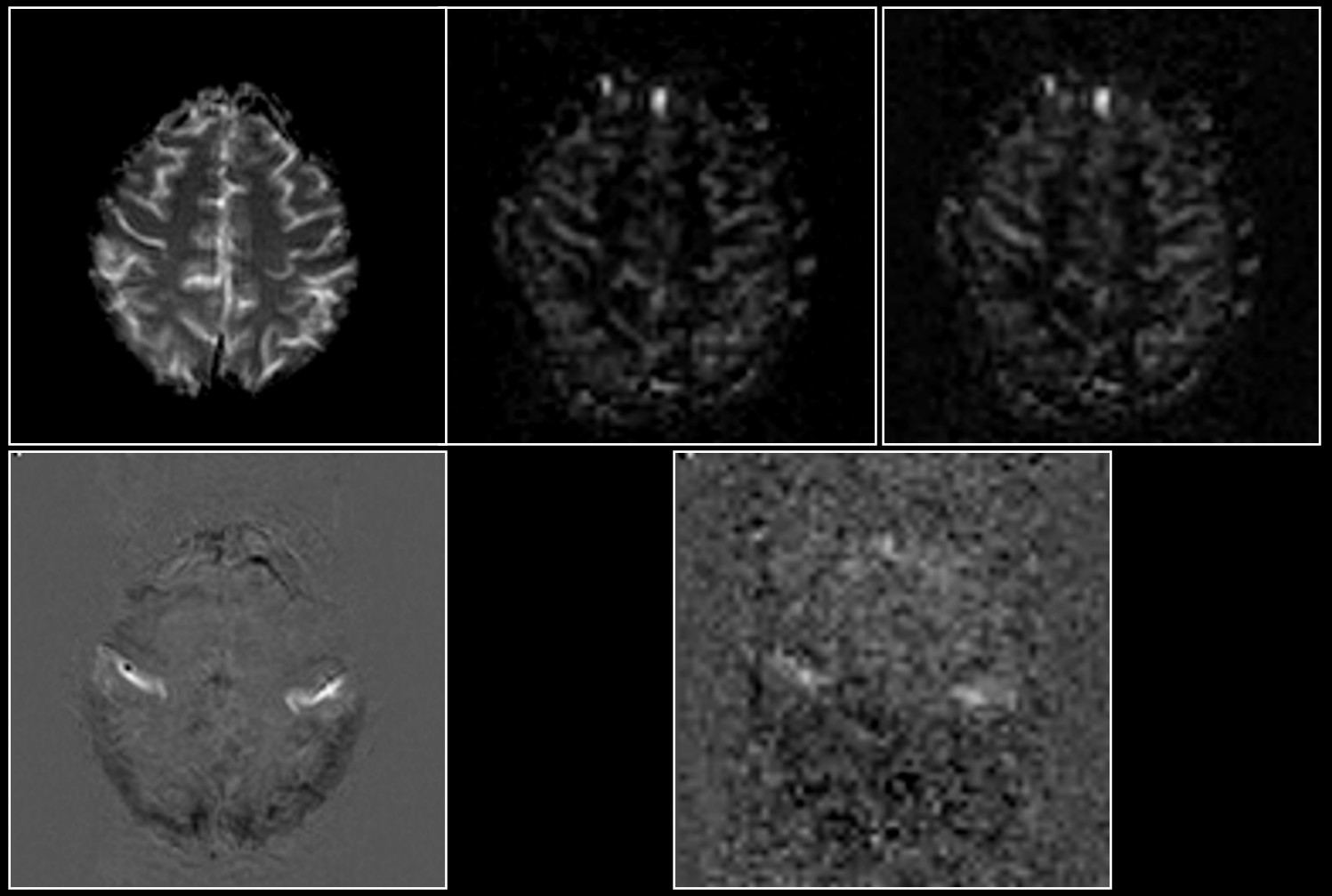
# Partial k-space imaging




**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.**

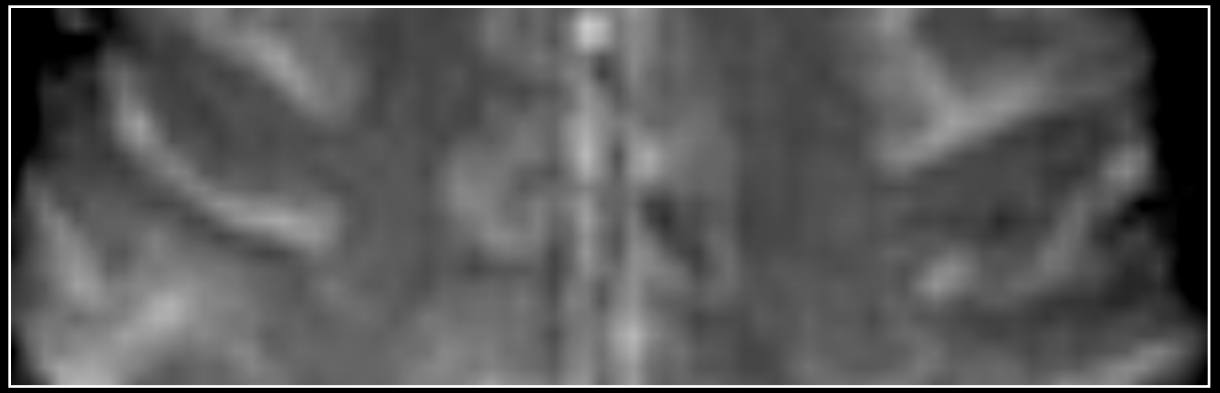
**Perfusion**

**BOLD** *Rest* *Activation*

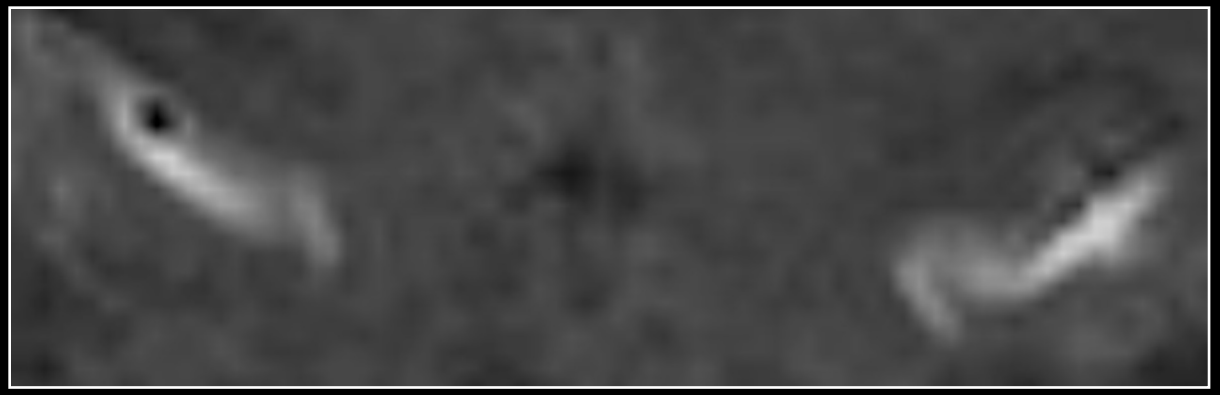


P. A. Bandettini, E. C. Wong, Magnetic resonance imaging of human brain function: principles, practicalities, and possibilities, *in* "Neurosurgery Clinics of North America: Functional Imaging" (M. Haglund, Ed.), p.345-371, W. B. Saunders Co., 1997.

Anatomy

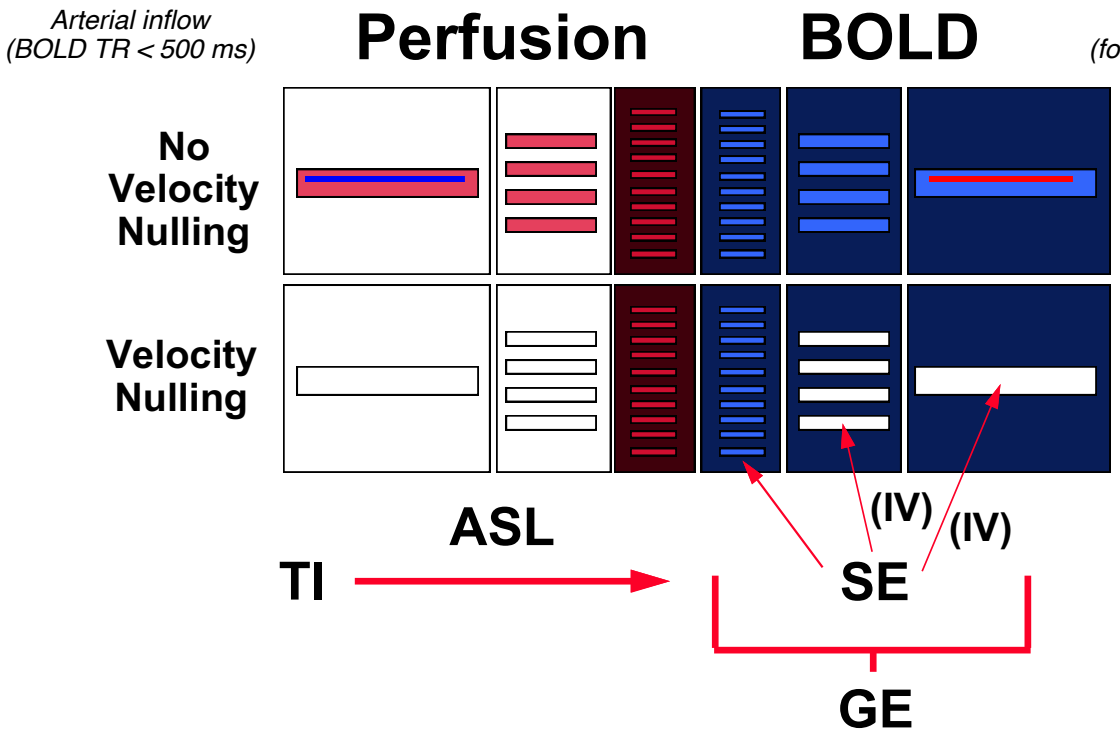


BOLD



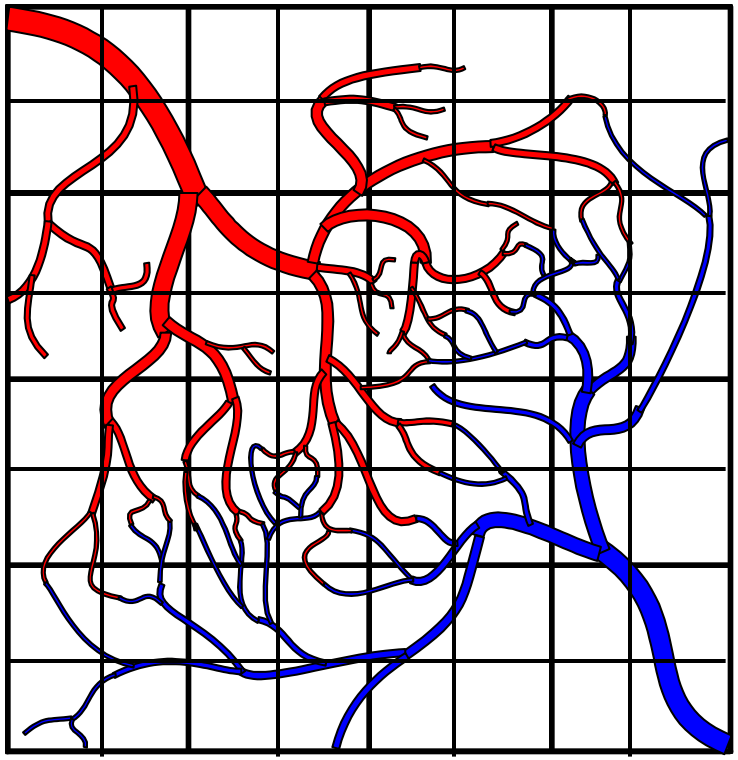
Perfusion

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.




Pulse Sequence Sensitivity

Spatial Heterogeneity

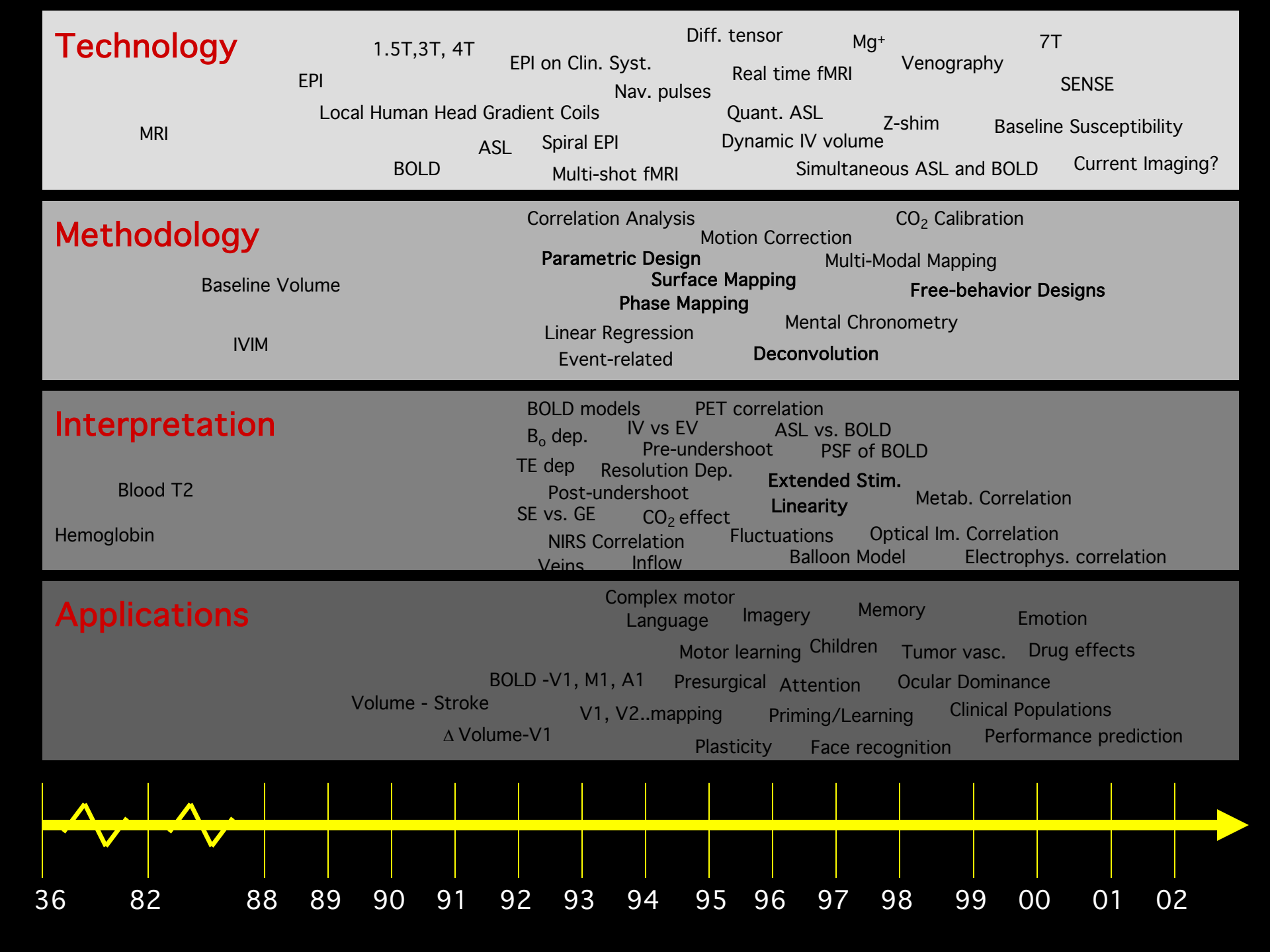


# Refinements

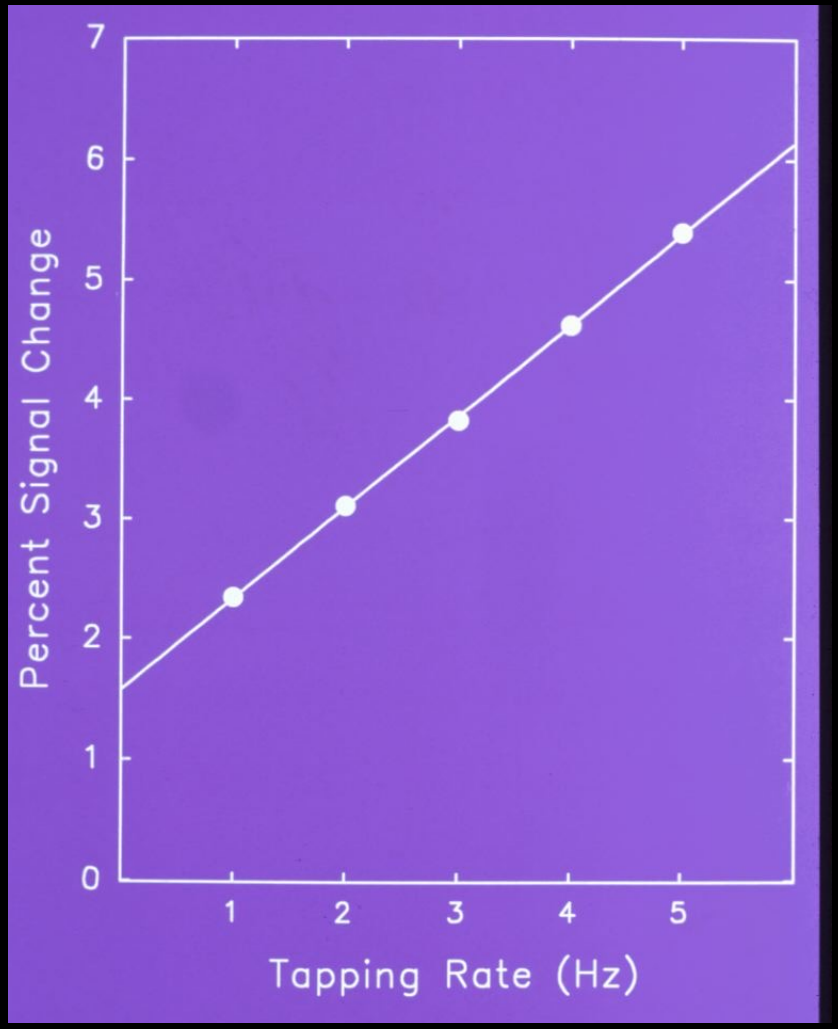
BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

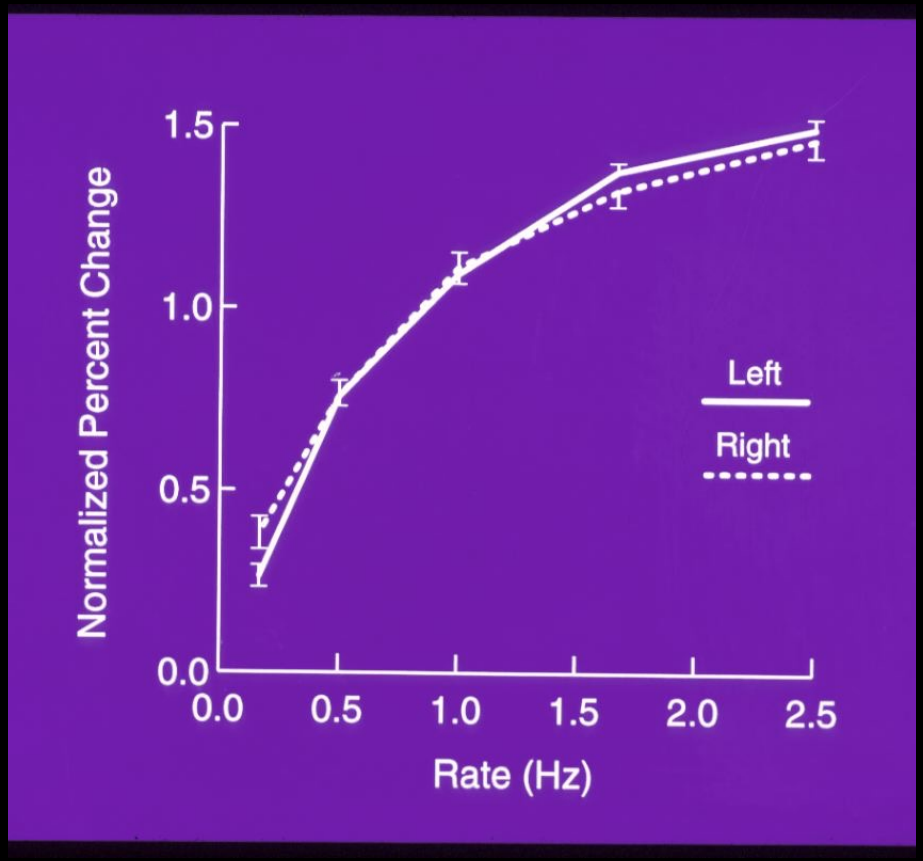

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
ASL
Spiral EPI
Dynamic IV volume
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation Analysis
CO2 Calibration
Motion Correction
Parametric Design
Multi-Modal Mapping
Surface Mapping
Baseline Volume
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
NIRS Correlation
Fluctuations
Optical Im. 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

# Motor Cortex

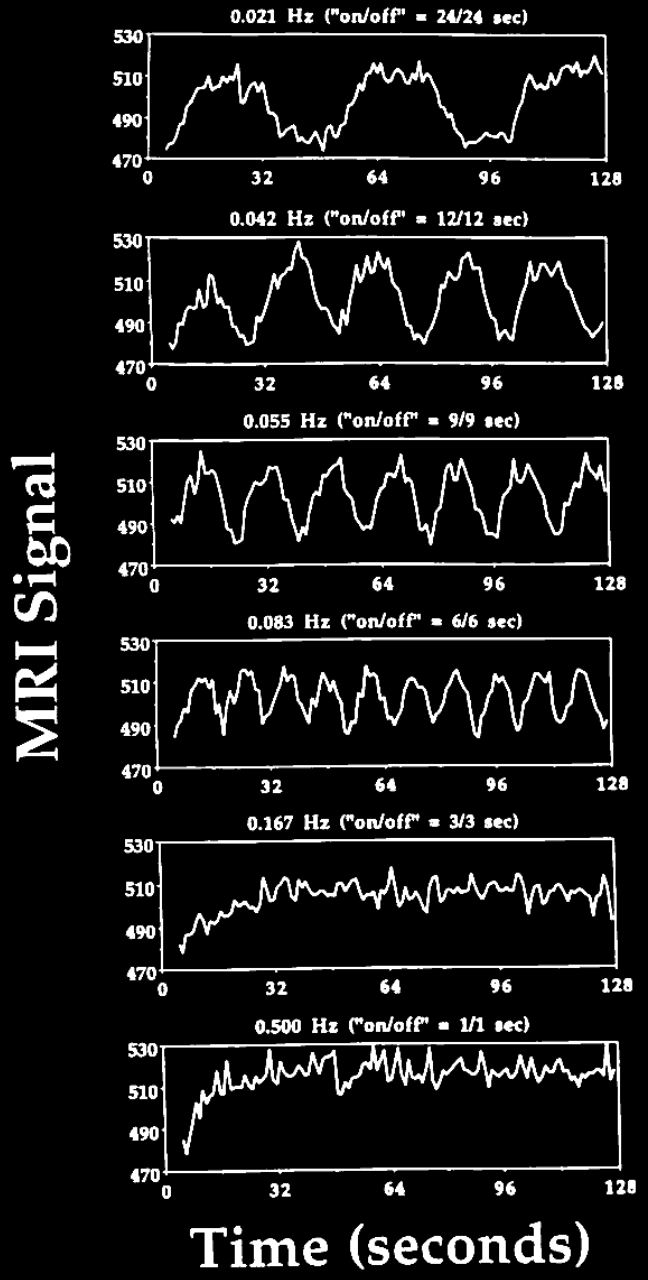


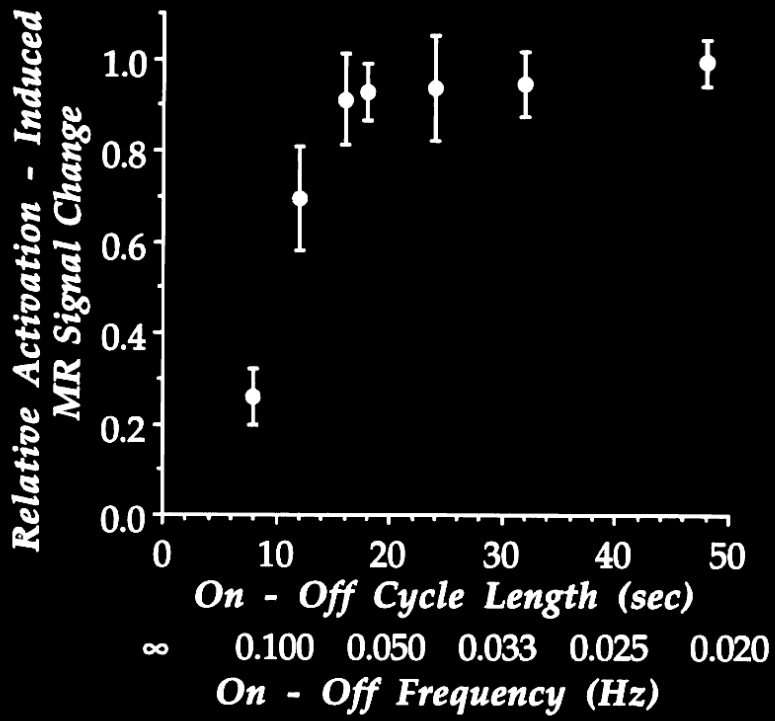

S. M. Rao et al, (1996) "Relationship between finger movement rate and functional magnetic resonance signal change in human primary motor cortex." *J. Cereb. Blood Flow and Met.* 16, 1250-1254.

# Auditory Cortex



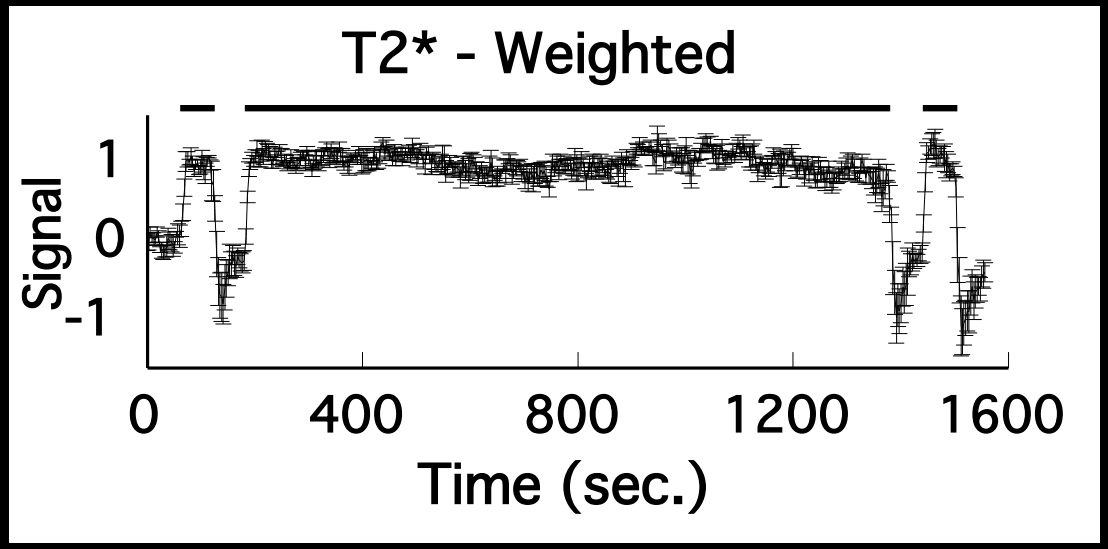

J. R. Binder, et al, (1994). "Effects of stimulus rate on signal response during functional magnetic resonance imaging of auditory cortex." *Cogn. Brain Res.* 2, 31-38



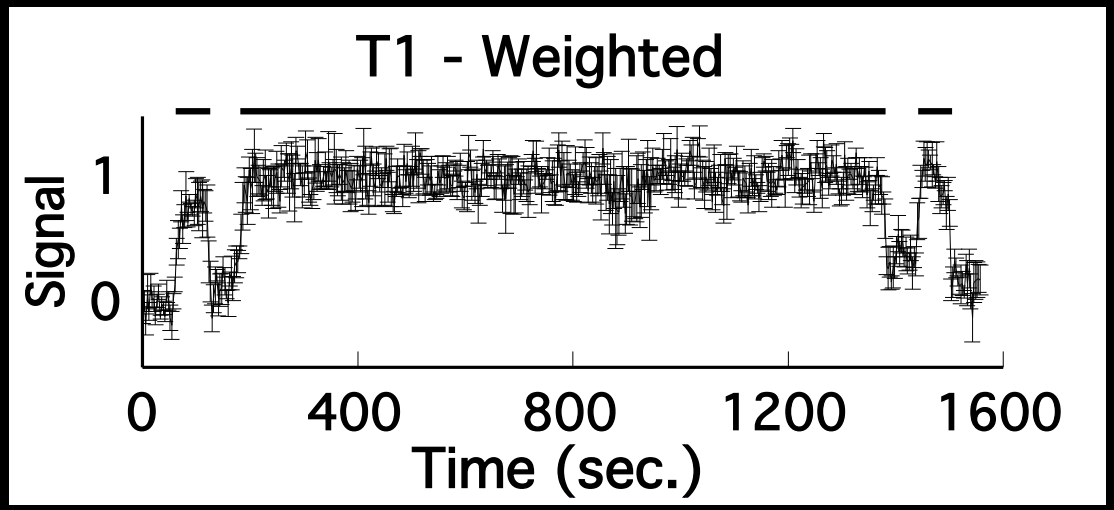




P. A. Bandettini, Functional MRI temporal resolution *in* "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

BOLD

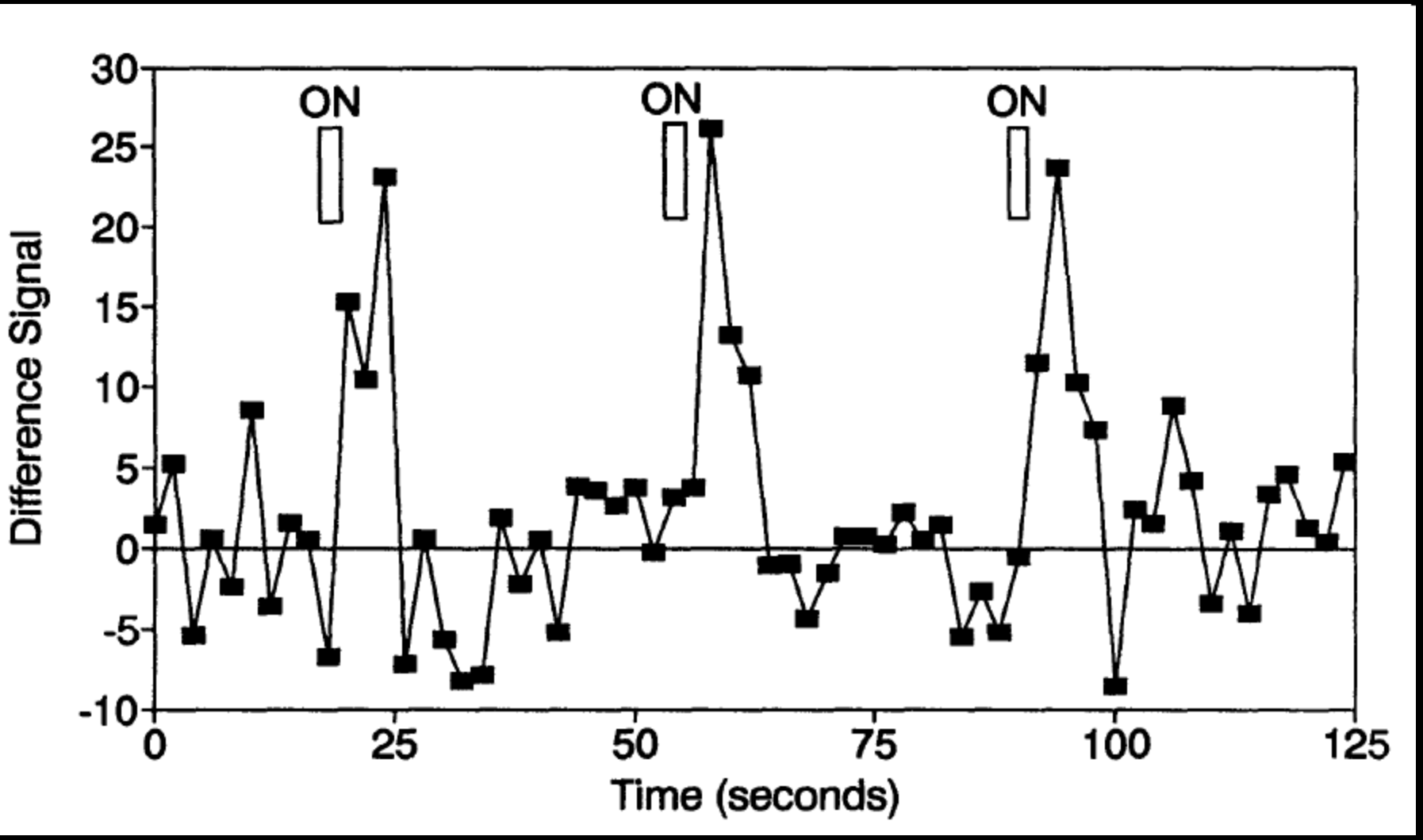



Flow

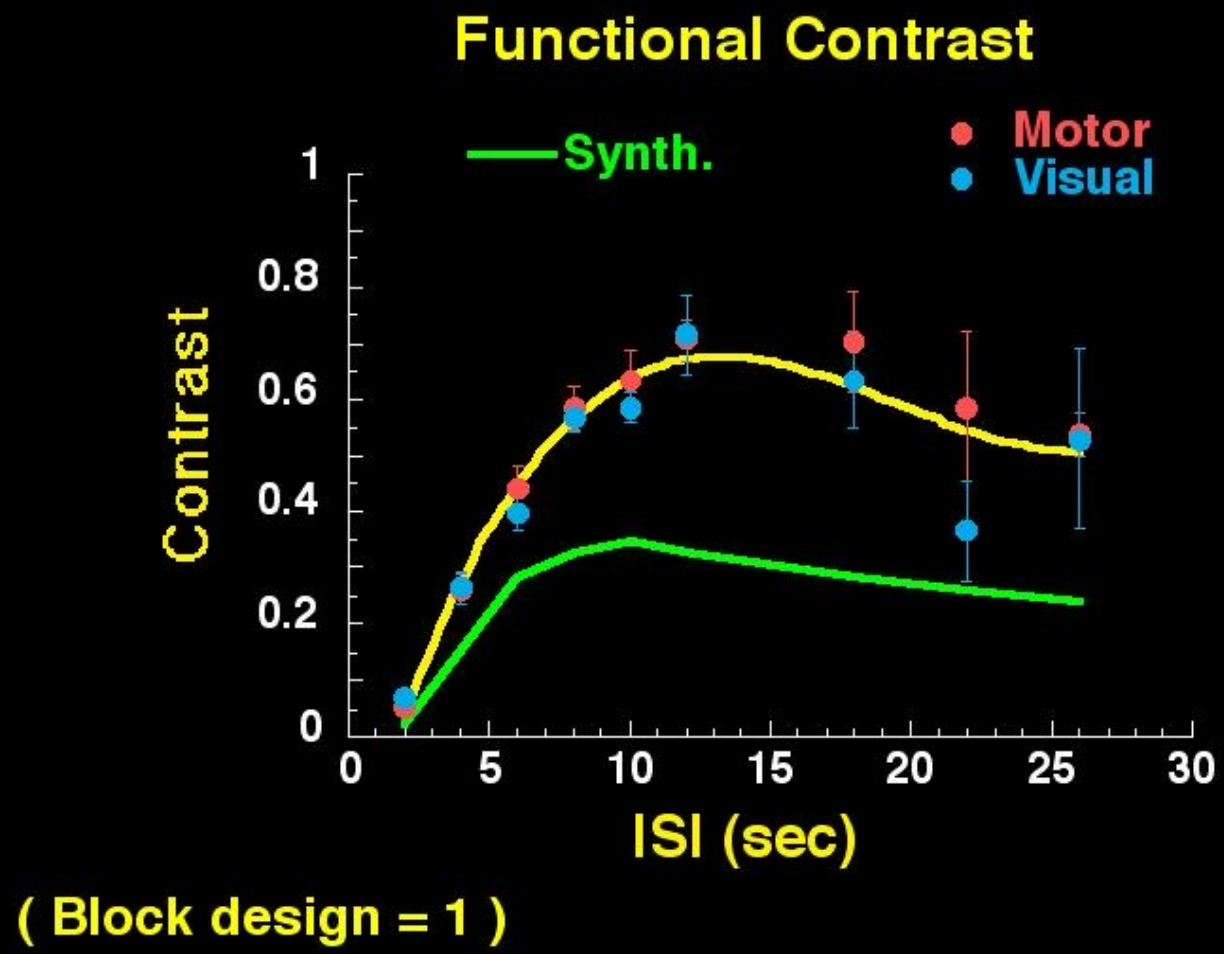



P. A. Bandettini, K. K. Kwong, T. L. Davis, R. B. H. Tootell, E. C. Wong, P. T. Fox, J. W. Belliveau, R. M. Weisskoff, B. R. Rosen, (1997). "Characterization of cerebral blood oxygenation and flow changes during prolonged brain activation." *Human Brain Mapping* 5, 93-109.

# First Event-related fMRI Results

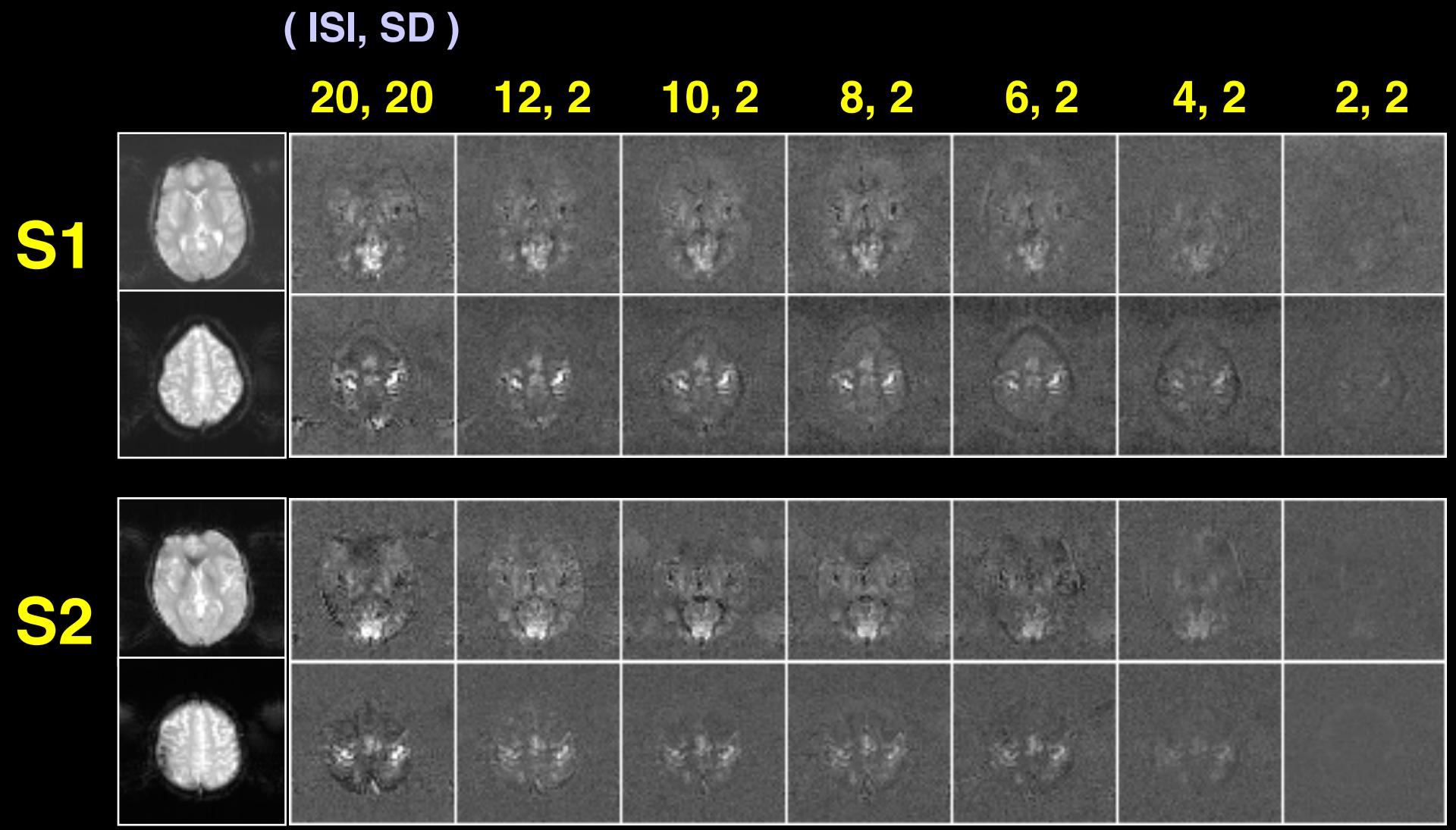



Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

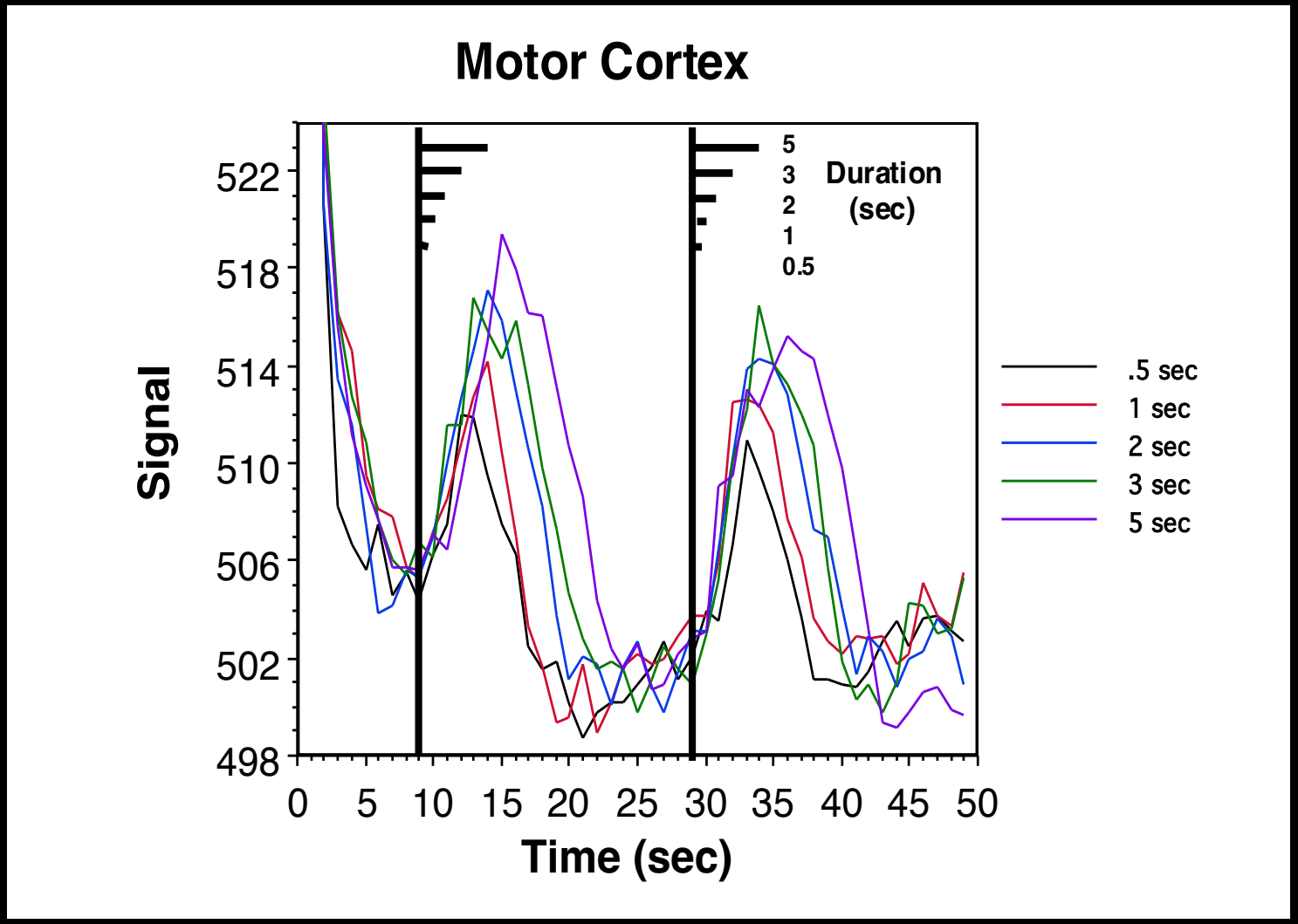



P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* 43: 540-548 (2000).

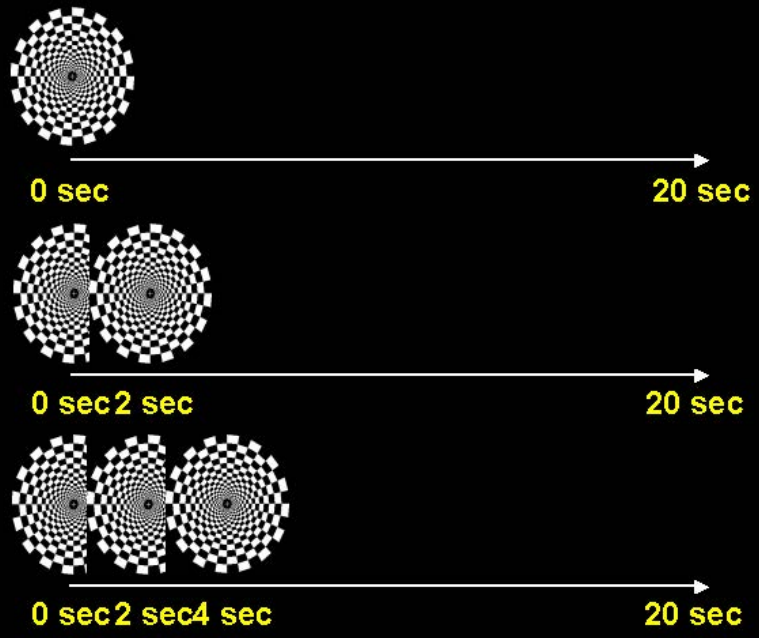
# Contrast to Noise Images




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).



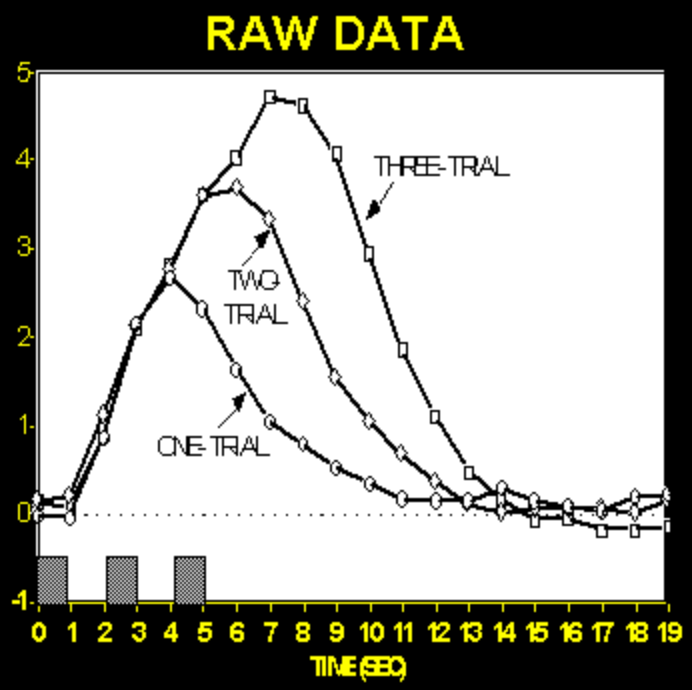

Bandettini, et al., The functional dynamics of blood oxygenation level contrast in the motor cortex, 12'th Proc. Soc. Magn. Reson. Med., New York, p. 1382. (1993).

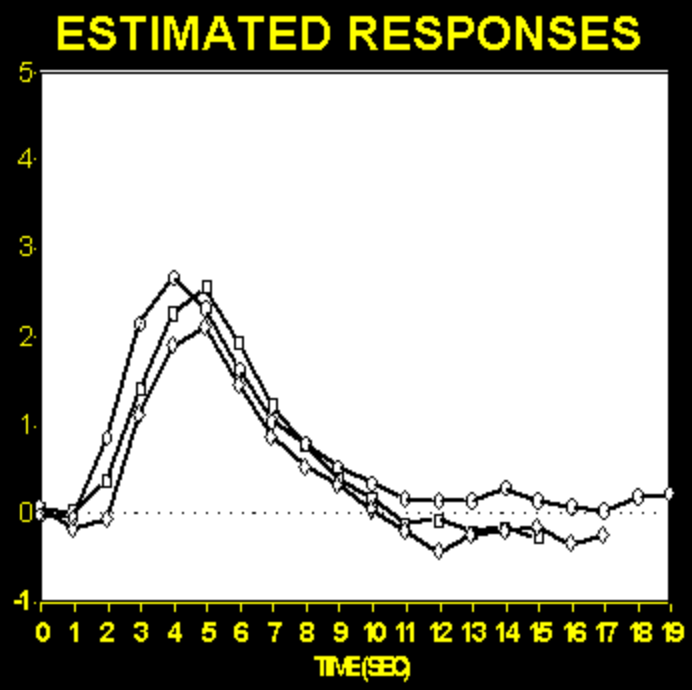


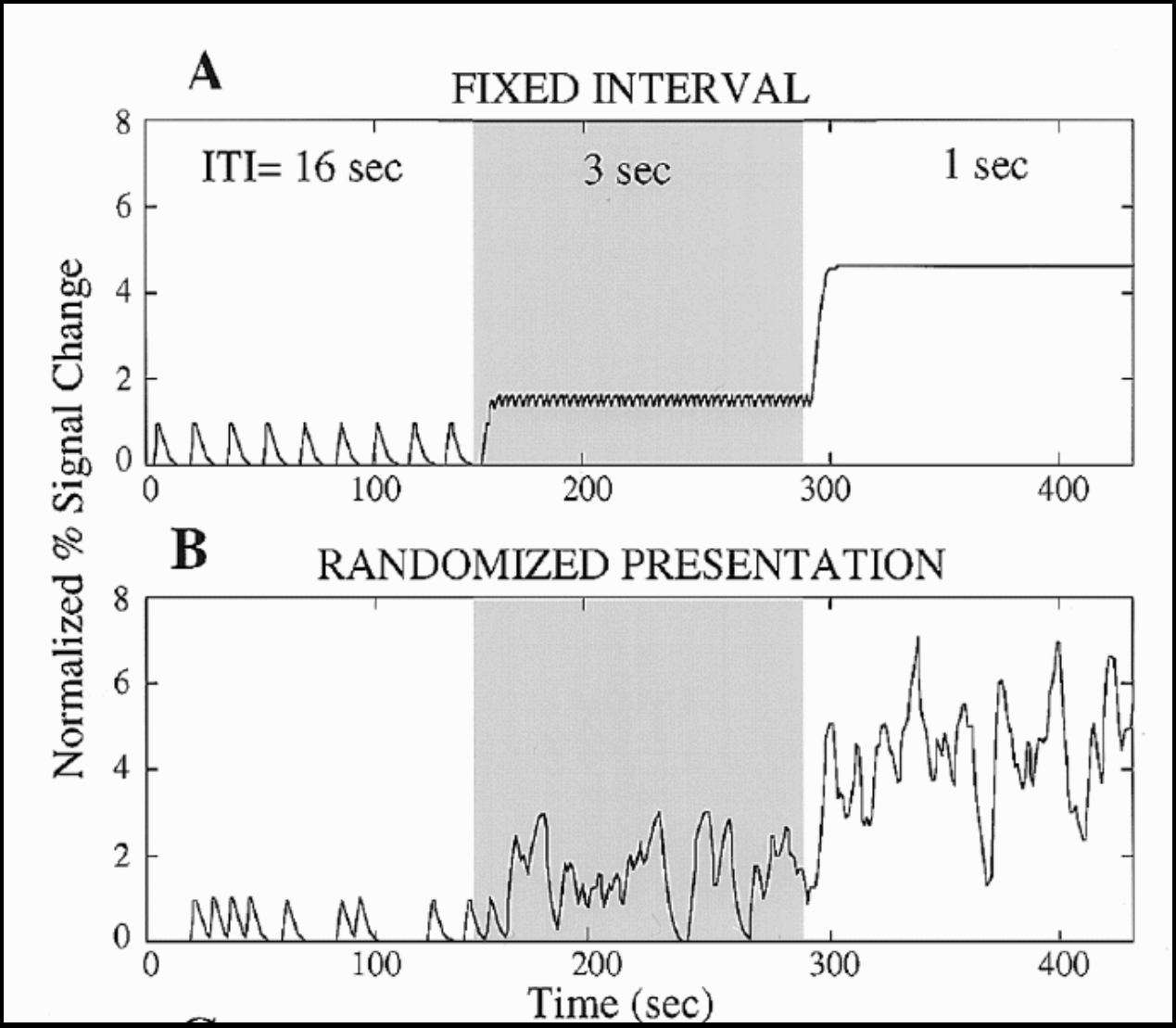

Human Brain Mapping 5:329–340(1997)

## Selective Averaging of Rapidly Presented Individual Trials Using fMRI

Anders M. Dale* and Randy L. Buckner



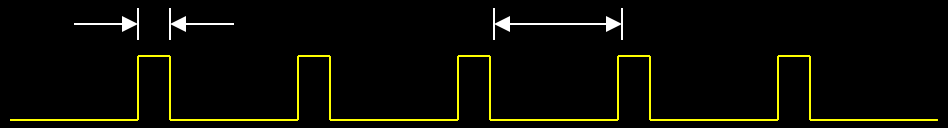


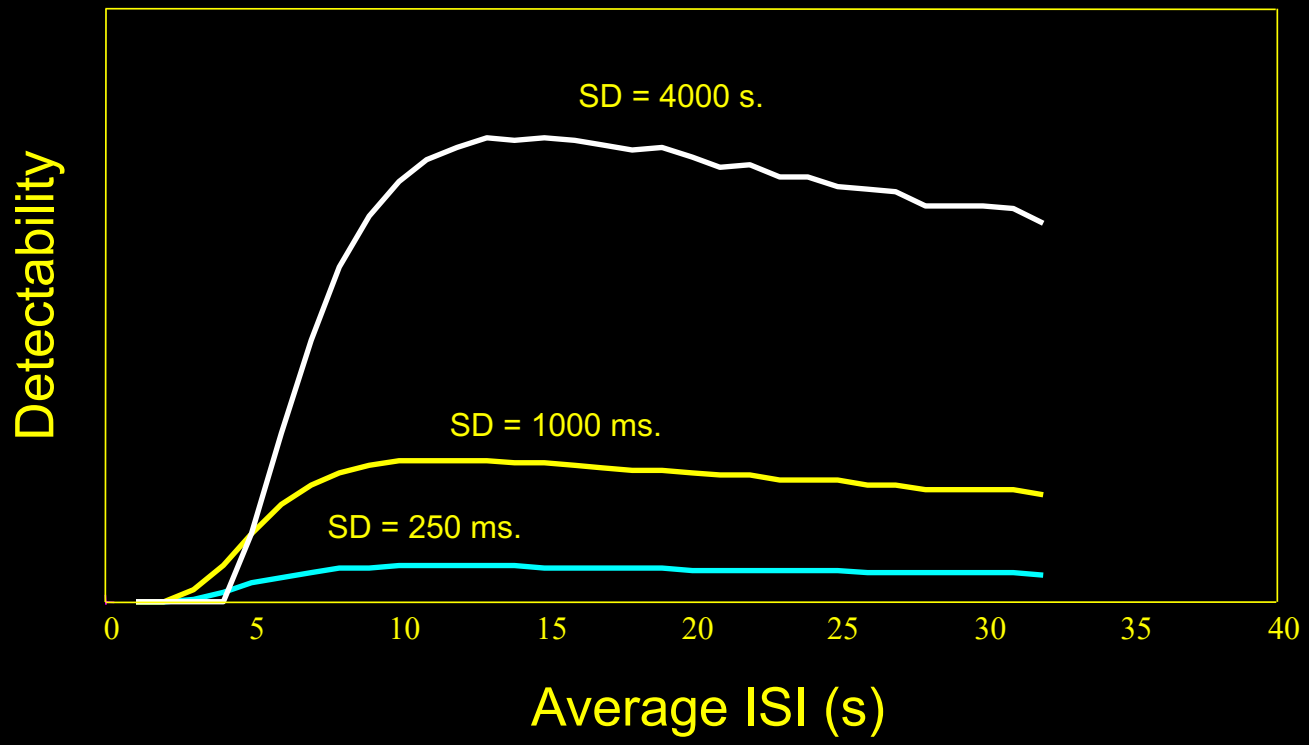

M.A. Burock et al. *NeuroReport*, 9, 3735-9 (1998)

# Detectability – constant ISI

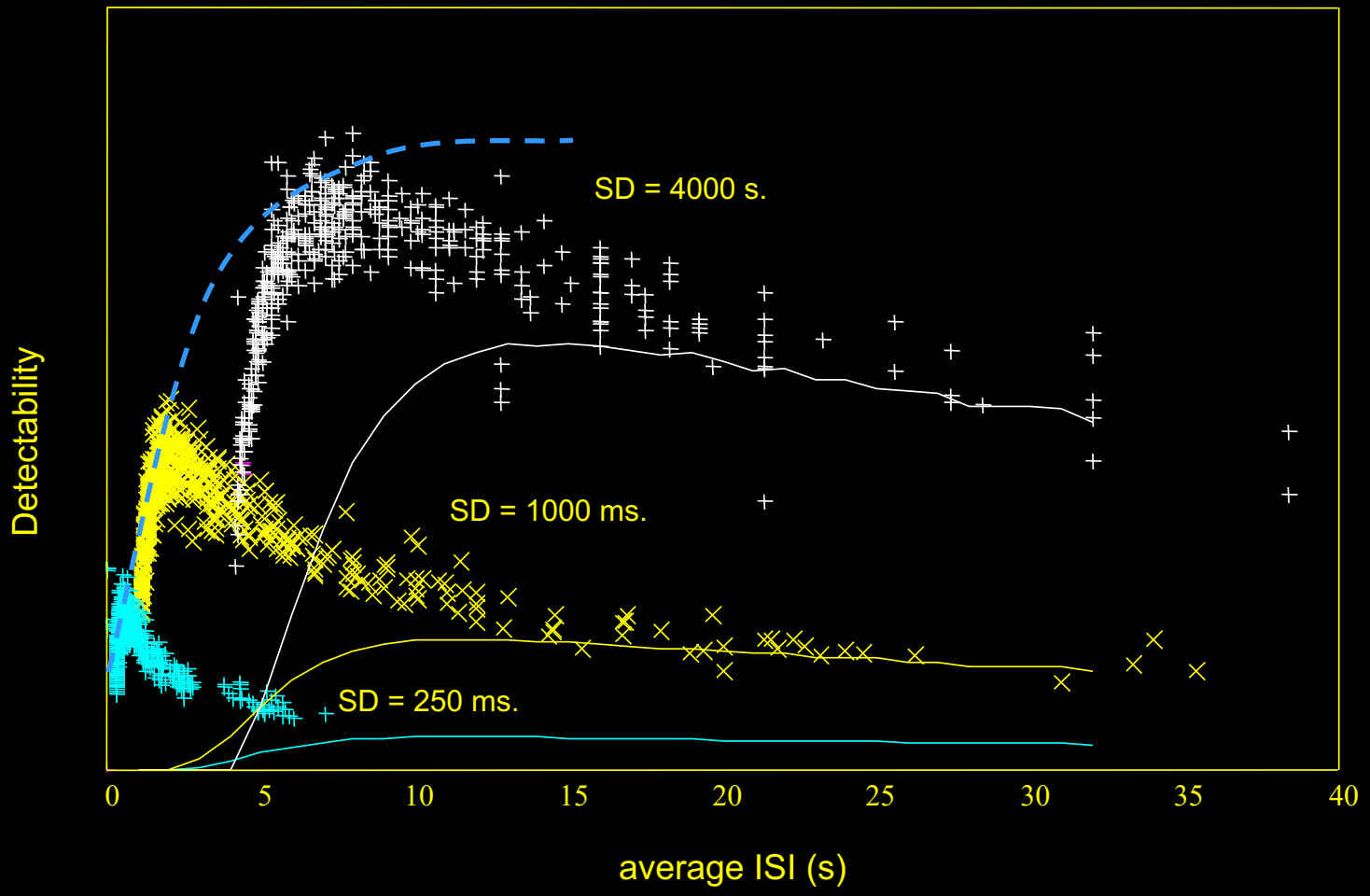
SD – stimulus duration

ISI – inter-stimulus interval



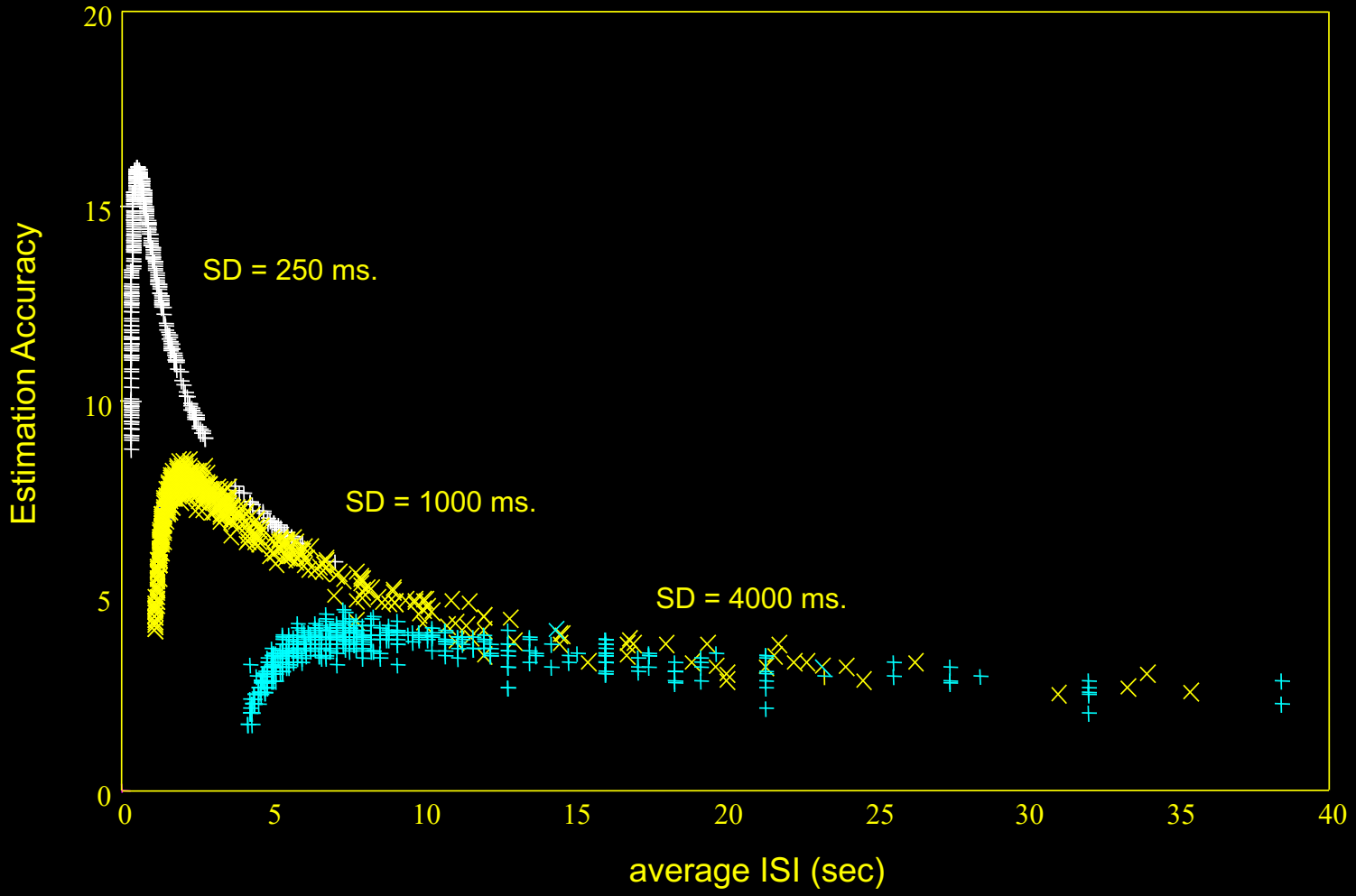


# Detectability vs. Average ISI

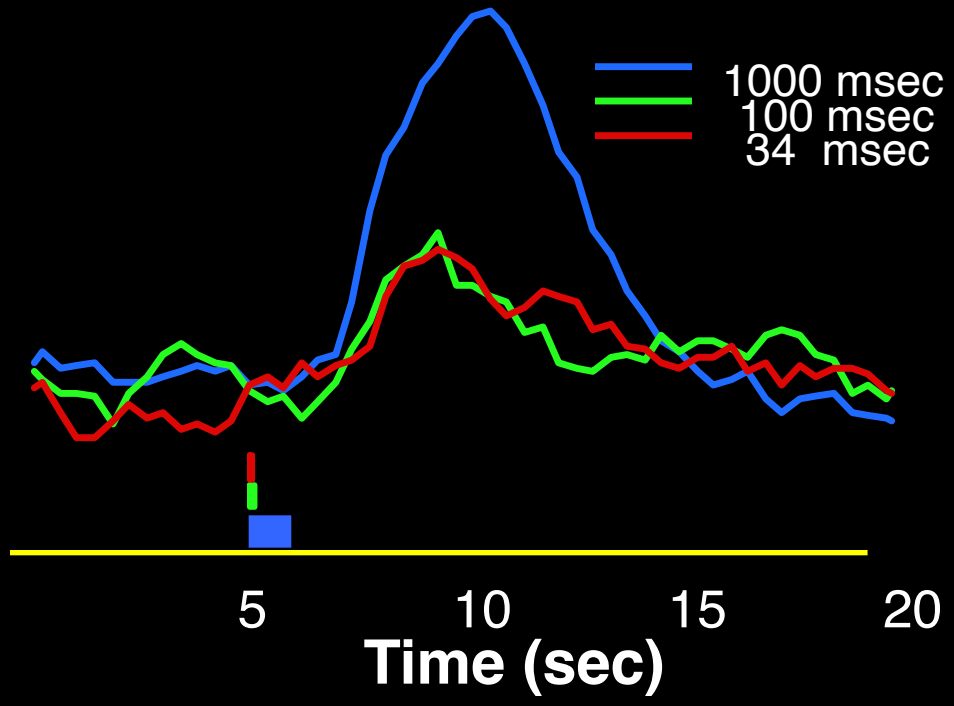



**R. M. Birn, R. W. Cox, P. A. Bandettini, Detection versus estimation in Event-Related fMRI: choosing the optimal stimulus timing. *NeuroImage* 15: 262-264, (2002).**

# 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).**



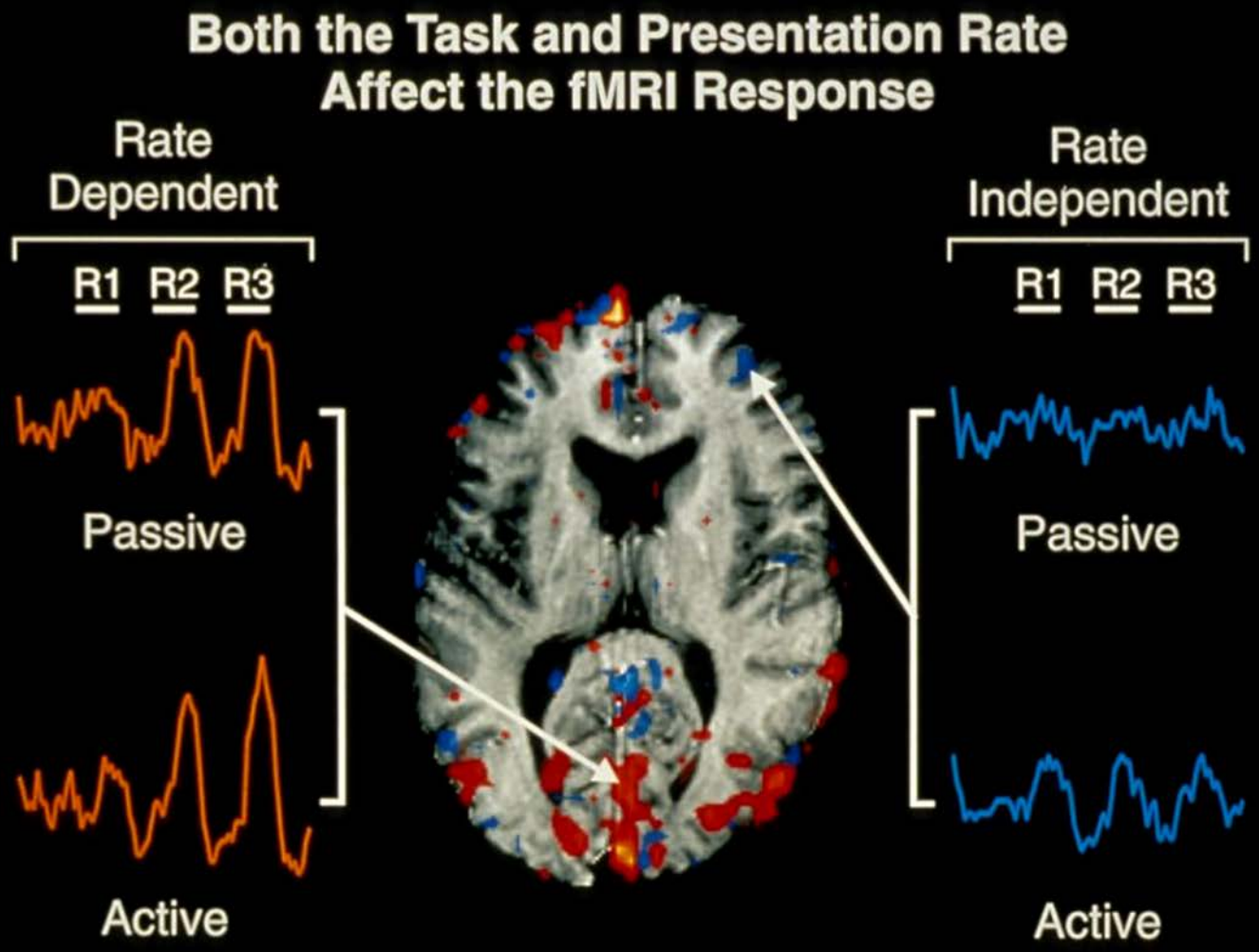

R. L. Savoy, et al., Pushing the temporal resolution of fMRI: studies of very brief visual stimuli, onset variability and asynchrony, and stimulus-correlated changes in noise [oral], 3'rd Proc. Soc. Magn. Reson., Nice, p. 450. (1995).

# 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

# Neuronal Activation Input Strategies

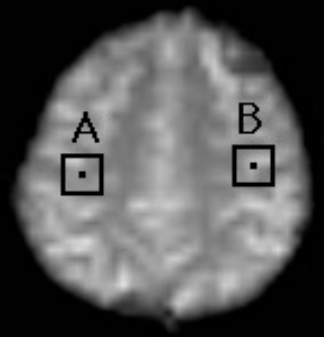
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. Phase Encoding
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

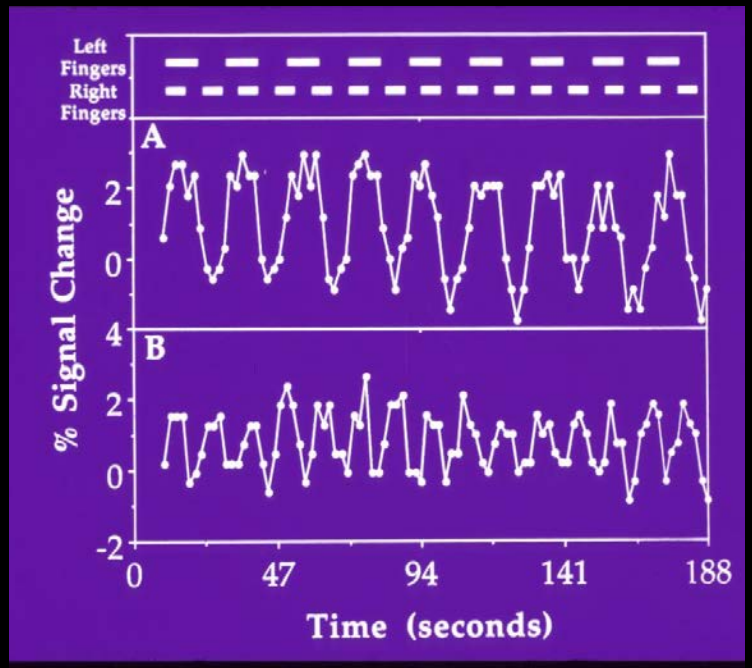


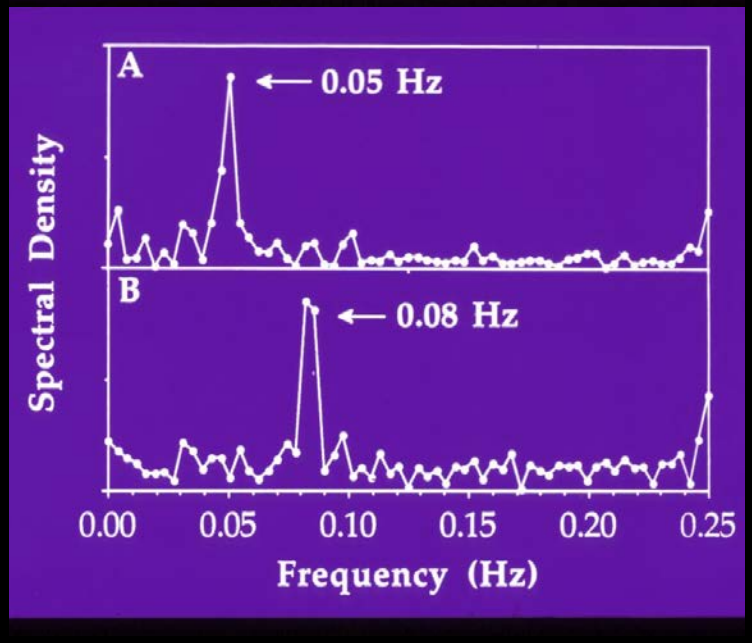

E. A. DeYoe, P. A. Bandettini, J. Nietz, D. Miller, P. Winas, Methods for functional magnetic resonance imaging (FMRI). *J. Neuroscience Methods* 54, 171-187 (1994).

# Neuronal Activation Input Strategies

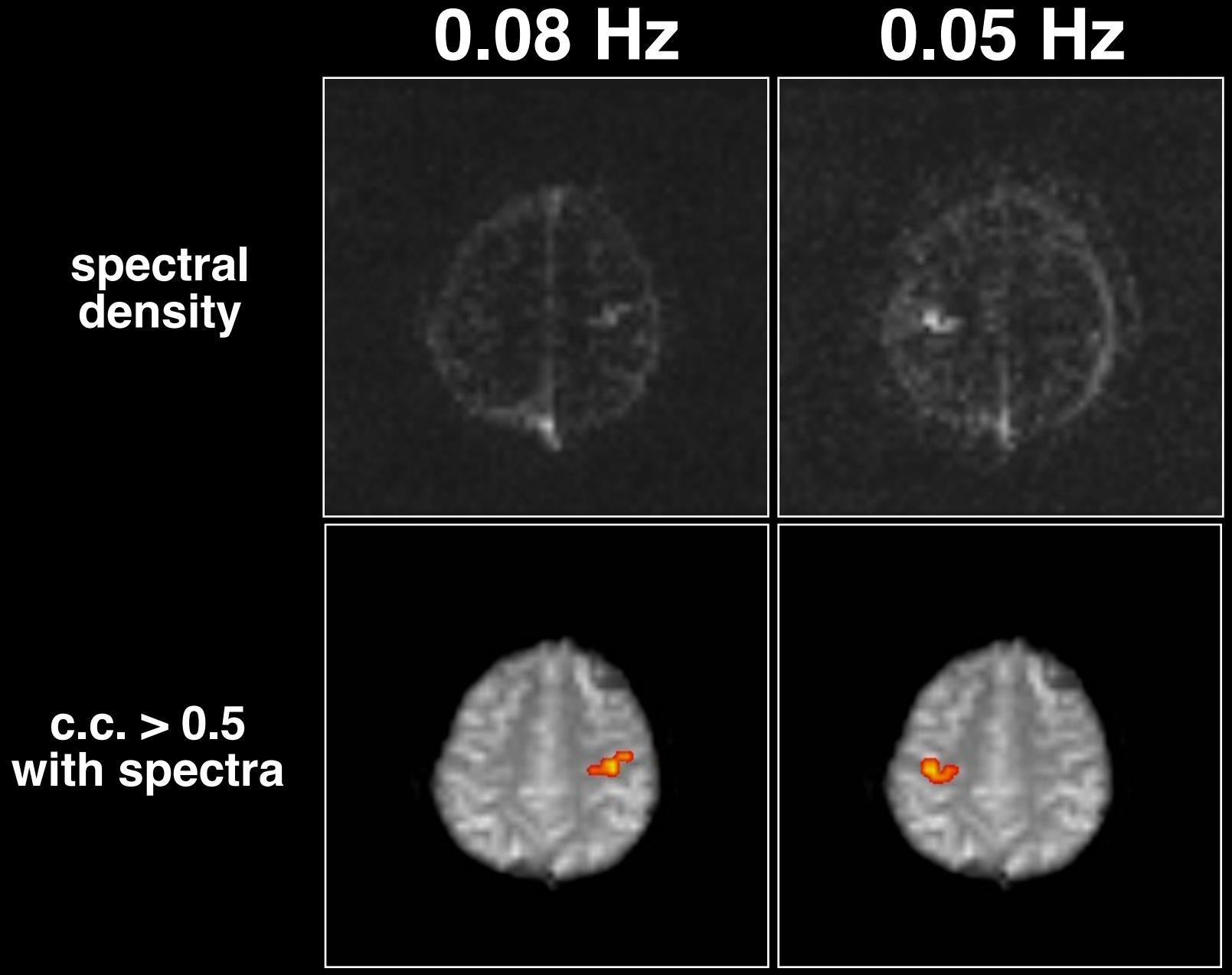
1. Block Design
2. Parametric Design
3. **Frequency Encoding**
4. Phase Encoding
5. Event Related
6. Orthogonal Design
7. Free Behavior Design




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).

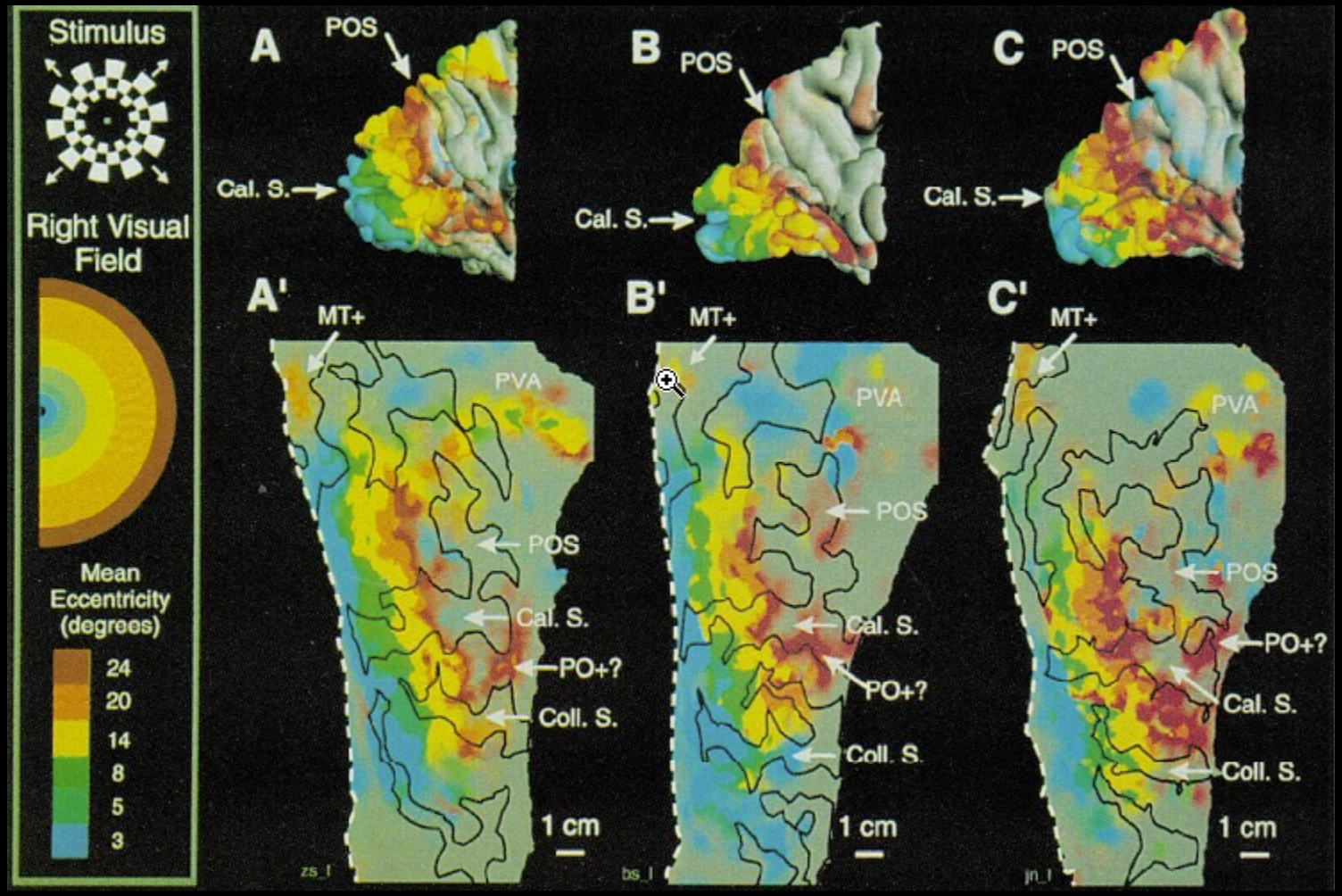
# Neuronal Activation Input Strategies

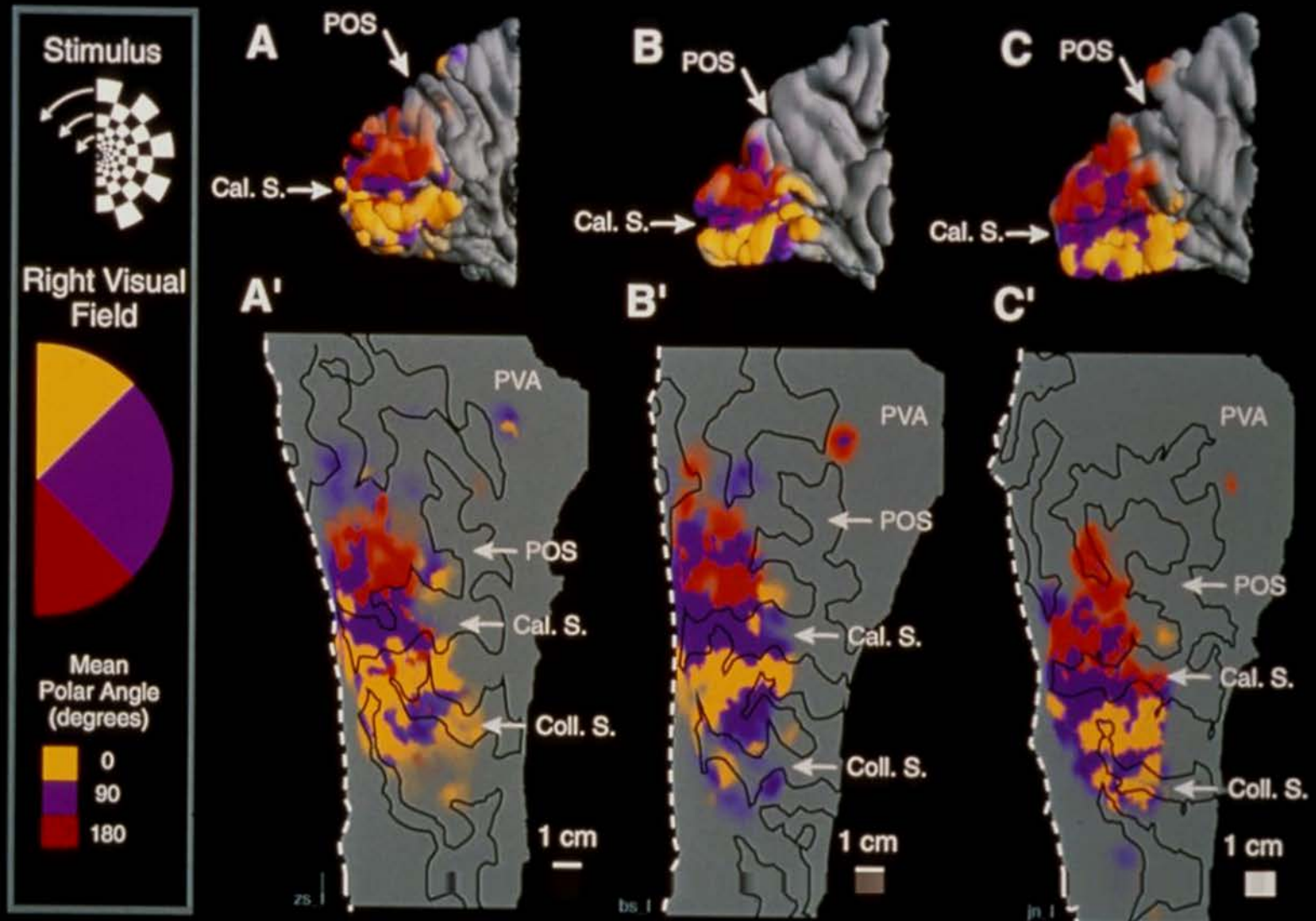
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. **Phase Encoding**
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

*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

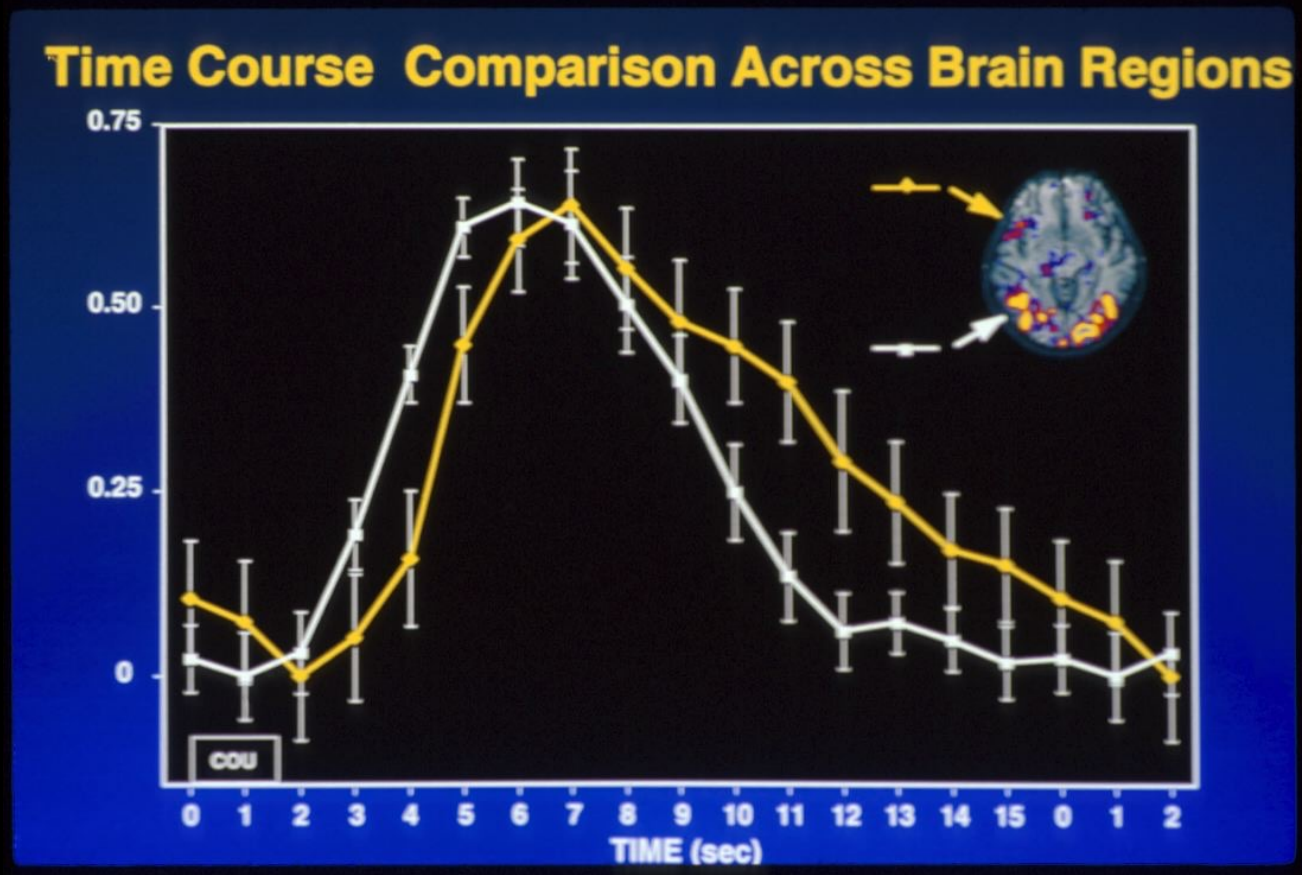
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. Phase Encoding
5. **Event Related**
6. Orthogonal Design
7. Free Behavior Design

*Proc. Natl. Acad. Sci. USA*
Vol. 93, pp. 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)

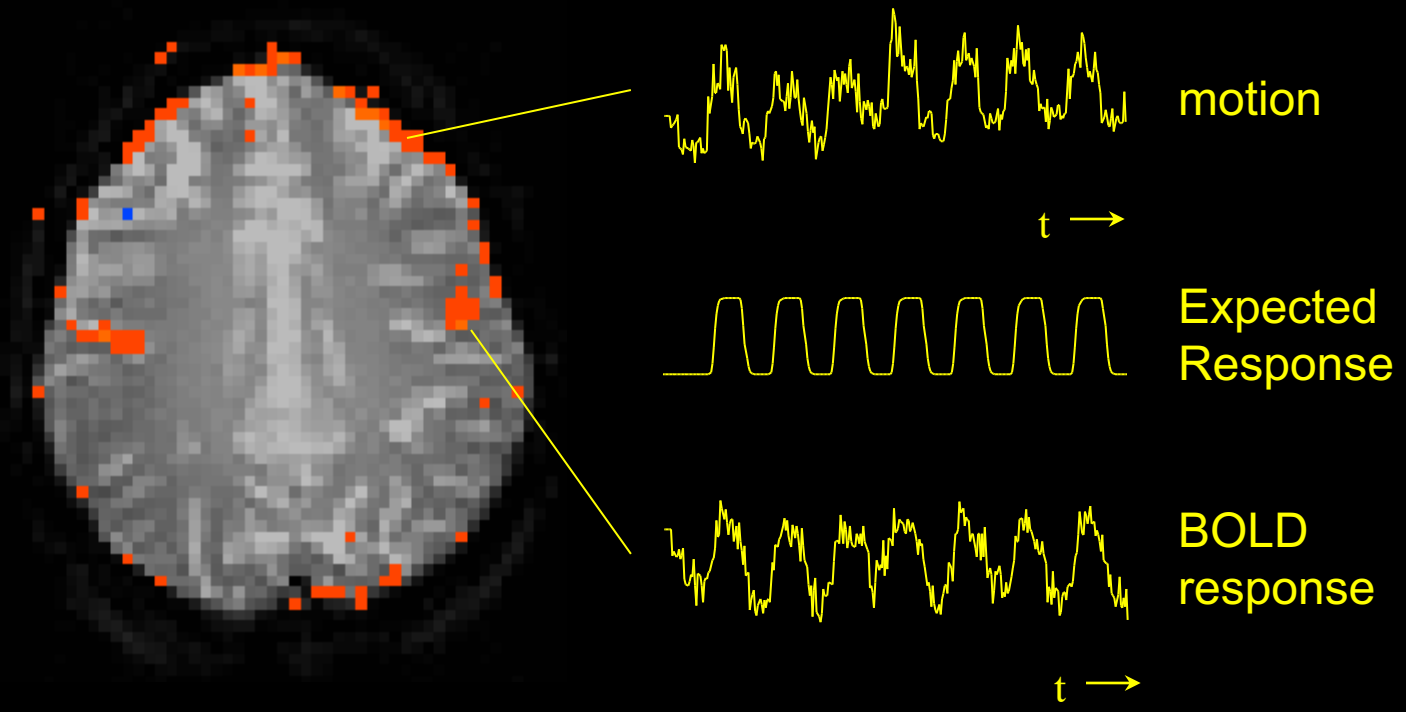
RANDY L. BUCKNER[†‡§¶], PETER A. BANDETTINI[†‡], KATHLEEN M. O'CRAVEN[†‖], ROBERT L. SAVOY[†‖], STEVEN E. PETERSEN[*††], MARCUS E. RAICHLE[§*†††], AND BRUCE R. ROSEN[†‡]



# Event Related Advantages

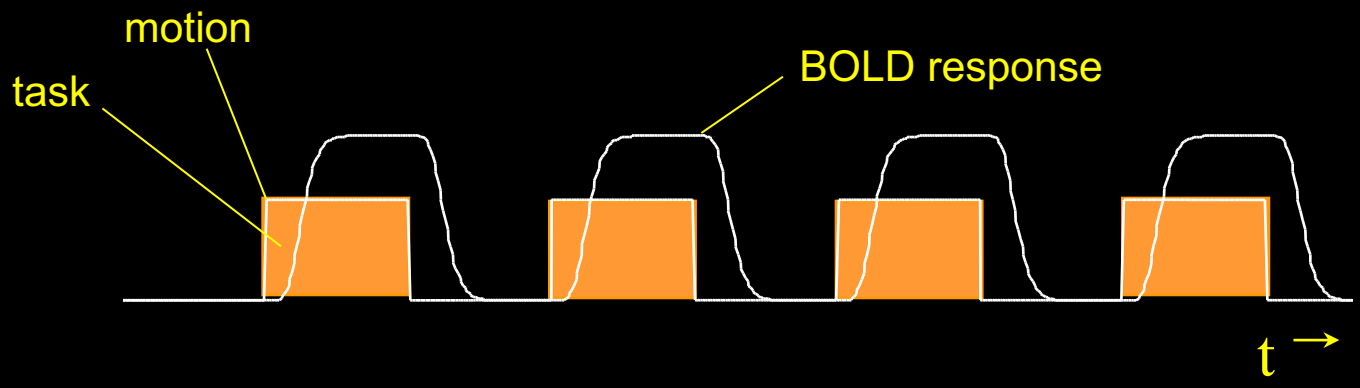
- Task Randomization
- Post acquisition, Performance-based, data binning
- Natural presentation
- Reduction of habituation effects
- Overt responses
- Reduction of scanner noise effects
- More precise estimation of hemodynamic respons

# Speaking - Blocked Trial

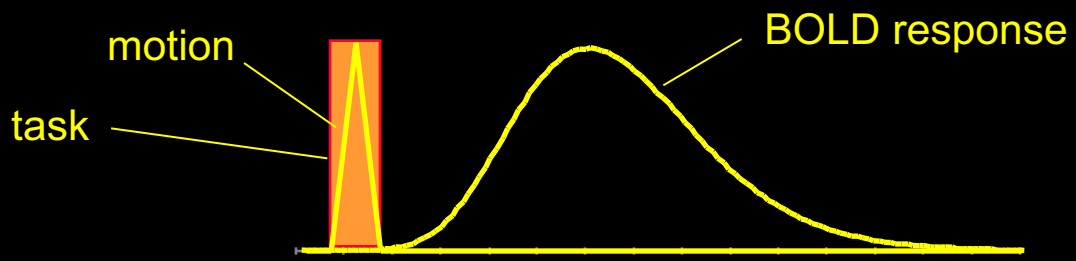


# fMRI during tasks that involve brief motion

## Blocked Design

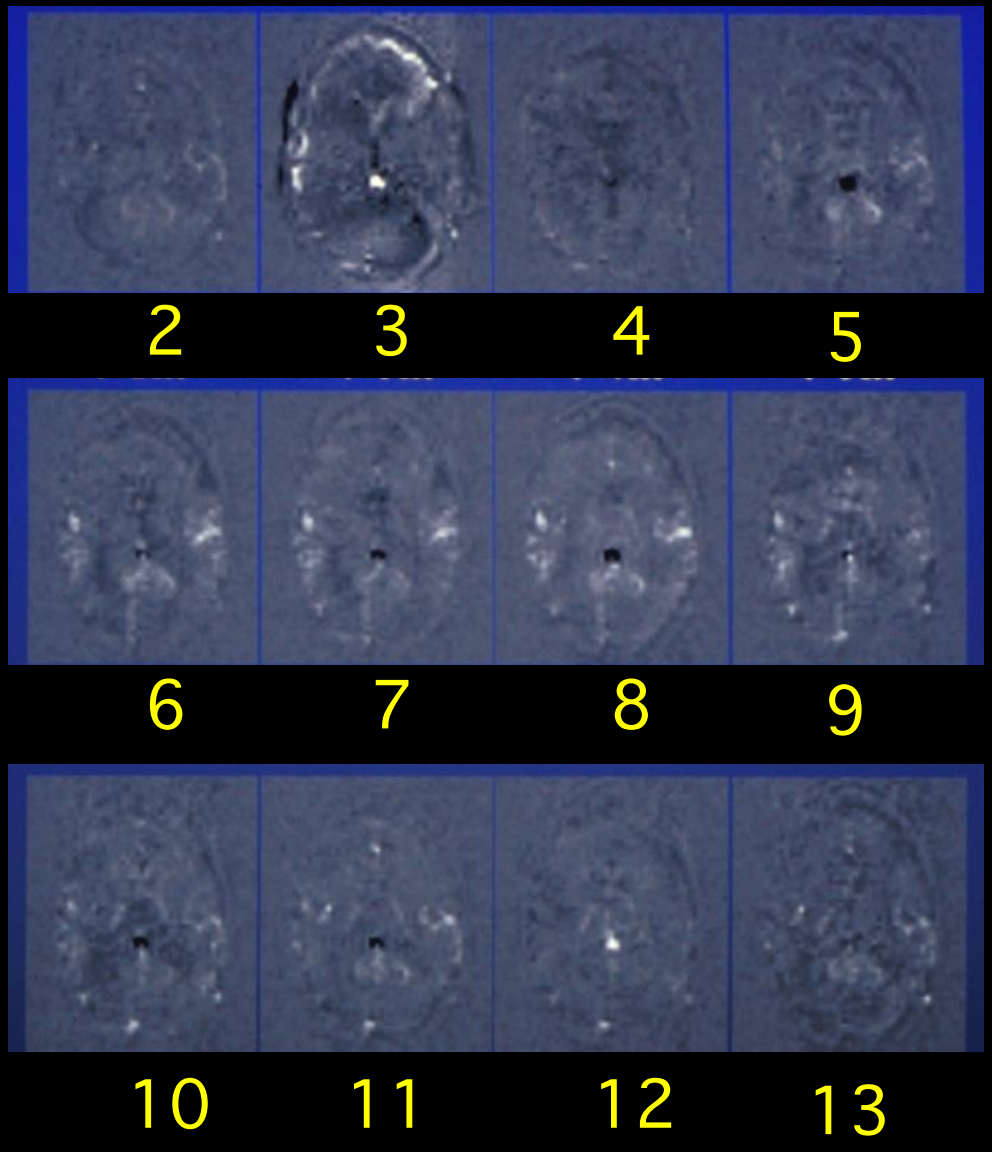



## Event-Related Design



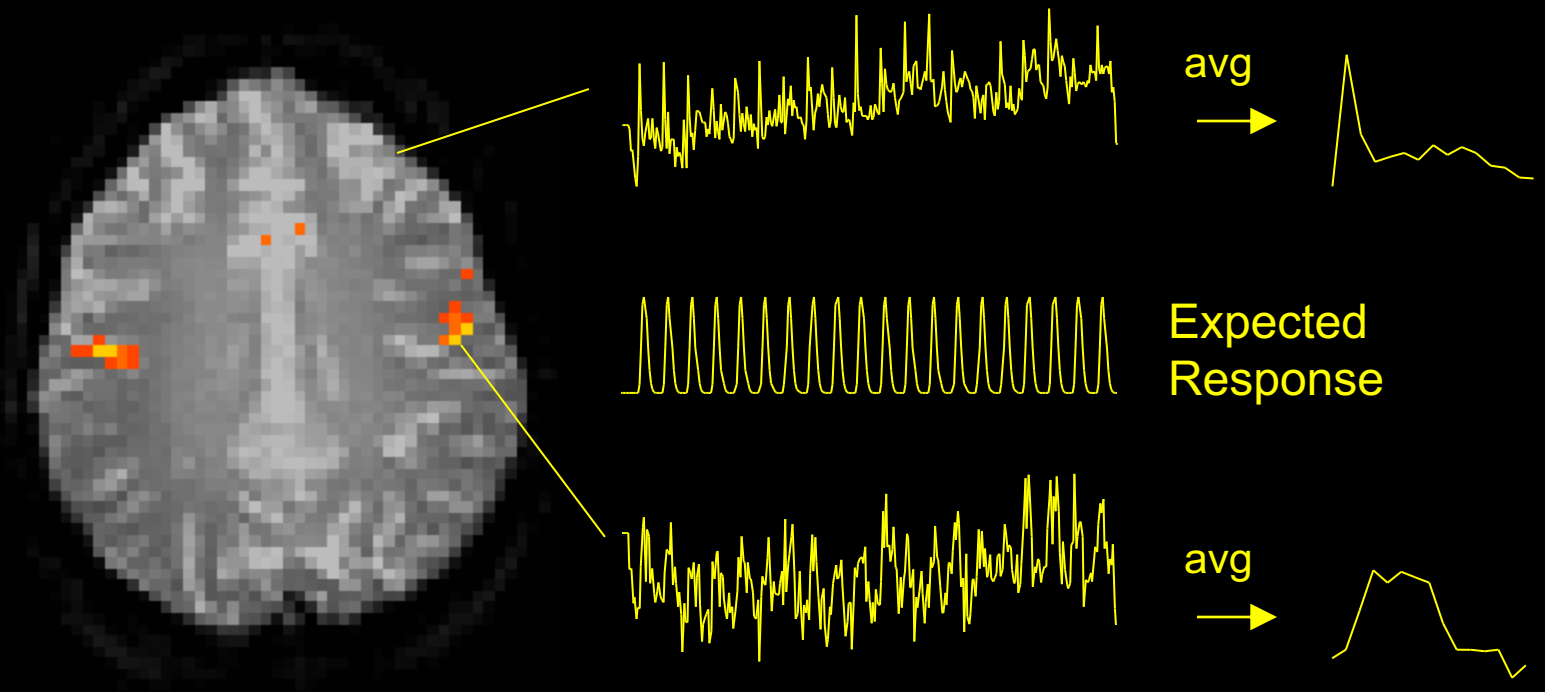

R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

# Overt Word Production



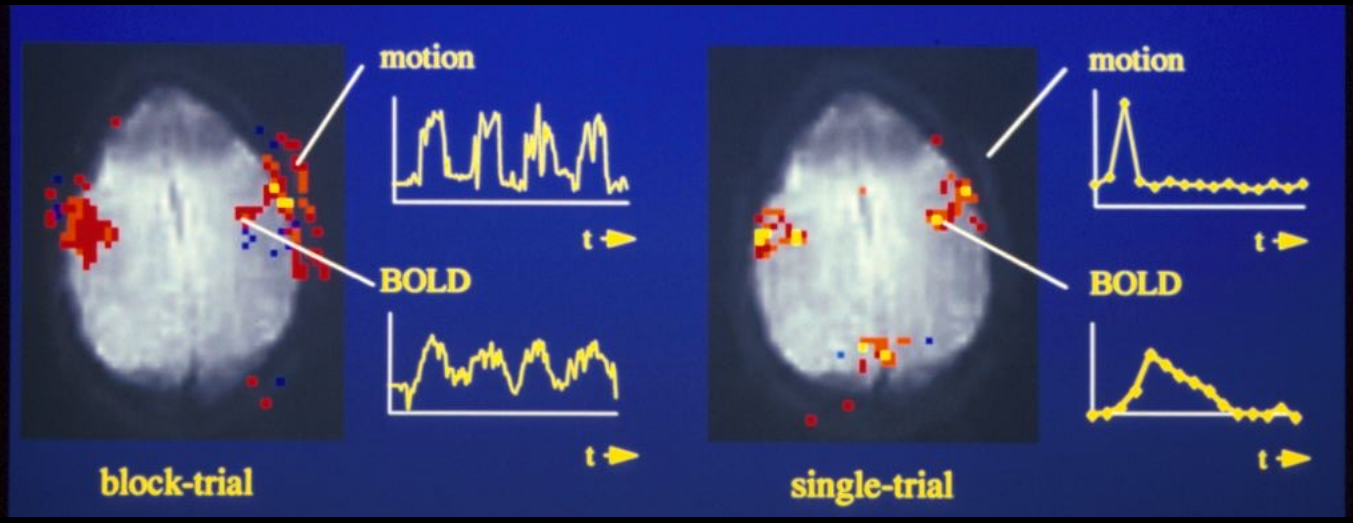

R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

# Speaking - ER-fMRI

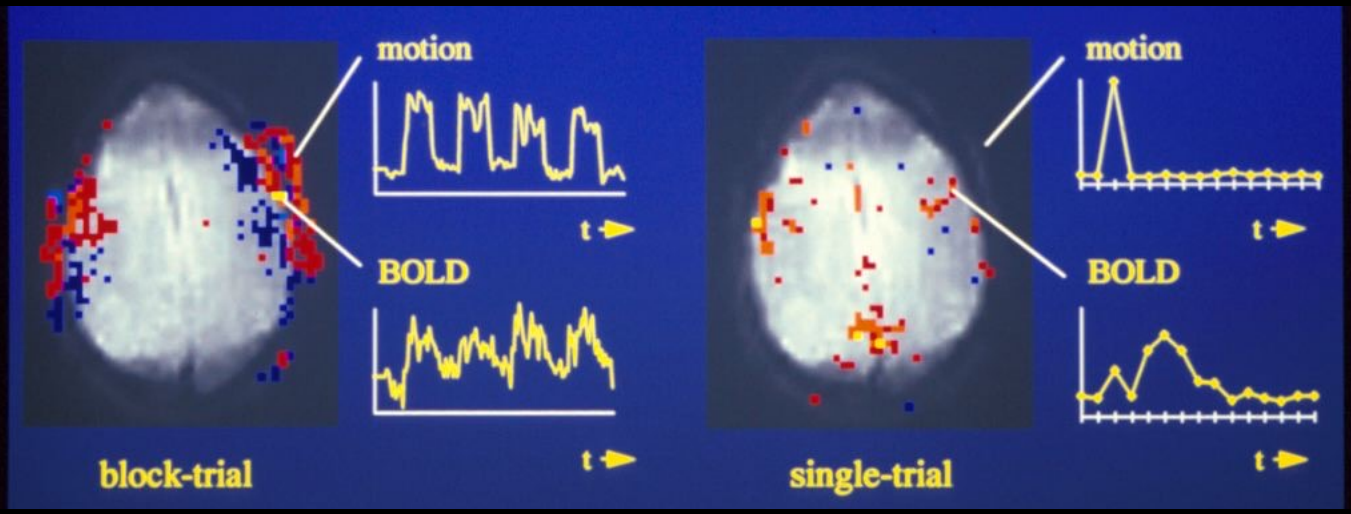



R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

# Tongue Movement




# Jaw Clenching



# 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

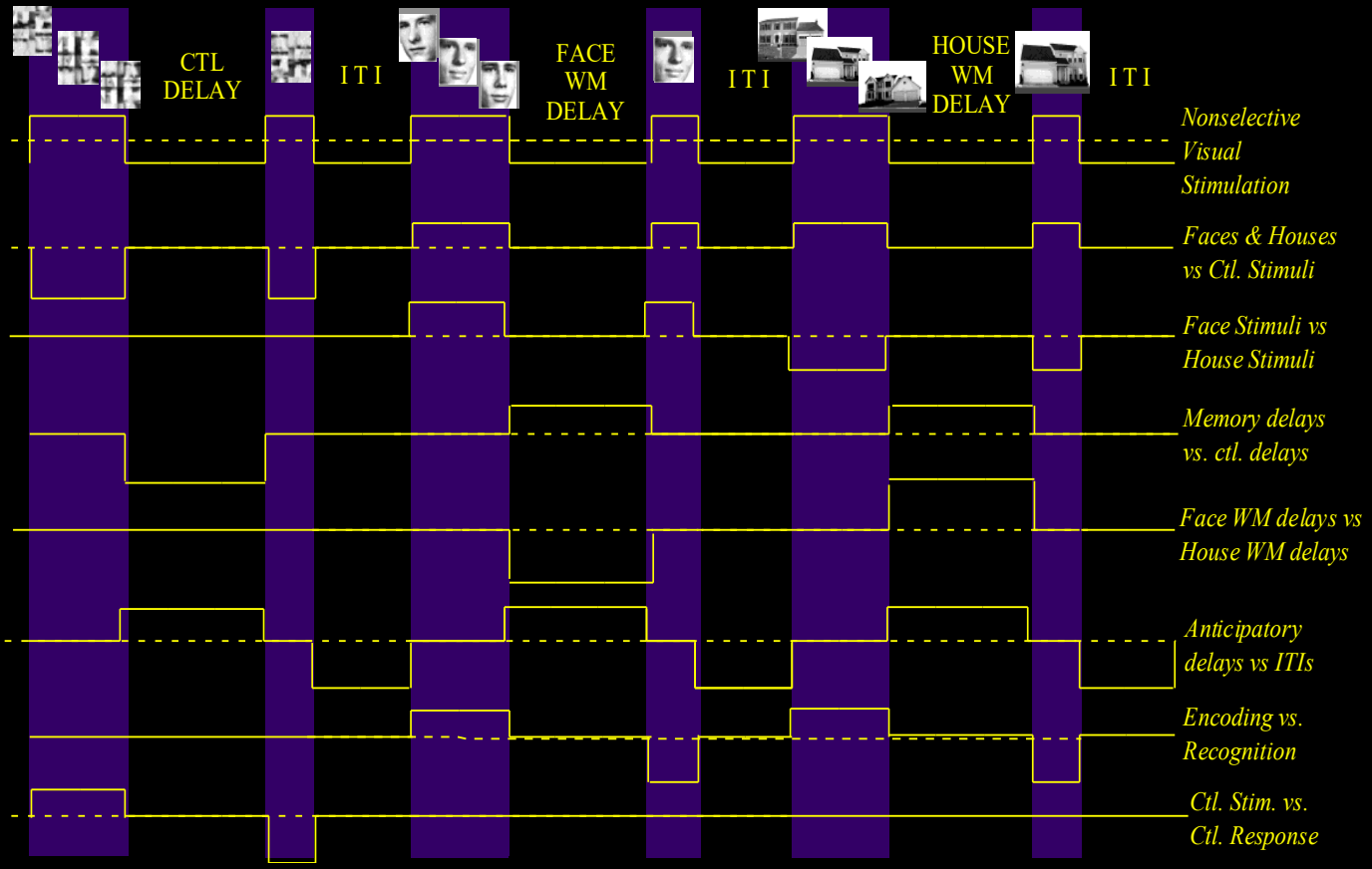
Bypass?
- Paradigm timing strategies..
- Gating (with T1-correction)

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

# 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

# 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

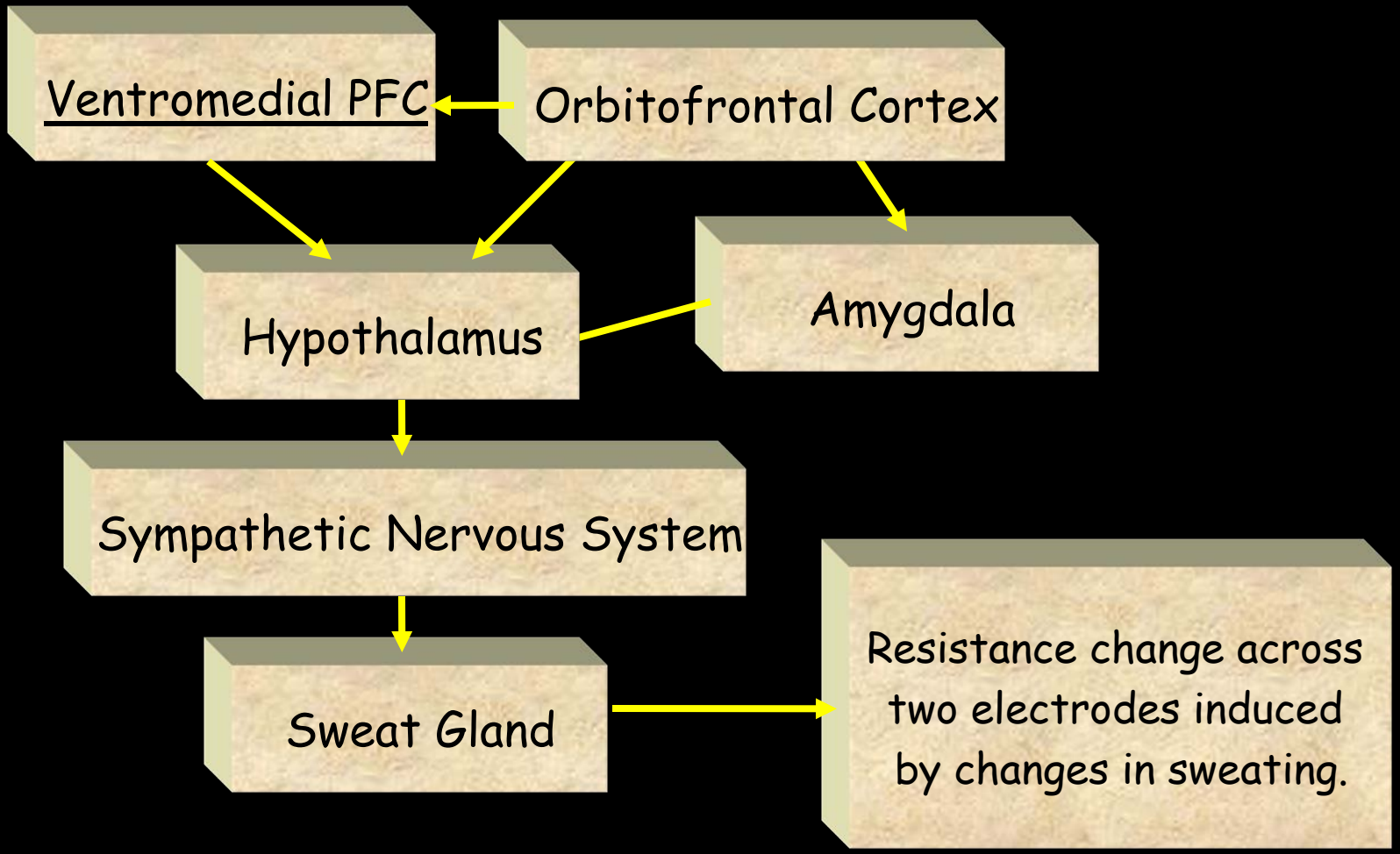
1. Block Design
2. Parametric Design
3. Frequency Encoding
4. Phase Encoding
5. Event Related
6. Orthogonal Design
7. Free Behavior Design

# Free Behavior Design

Use a continuous measure as a reference function:

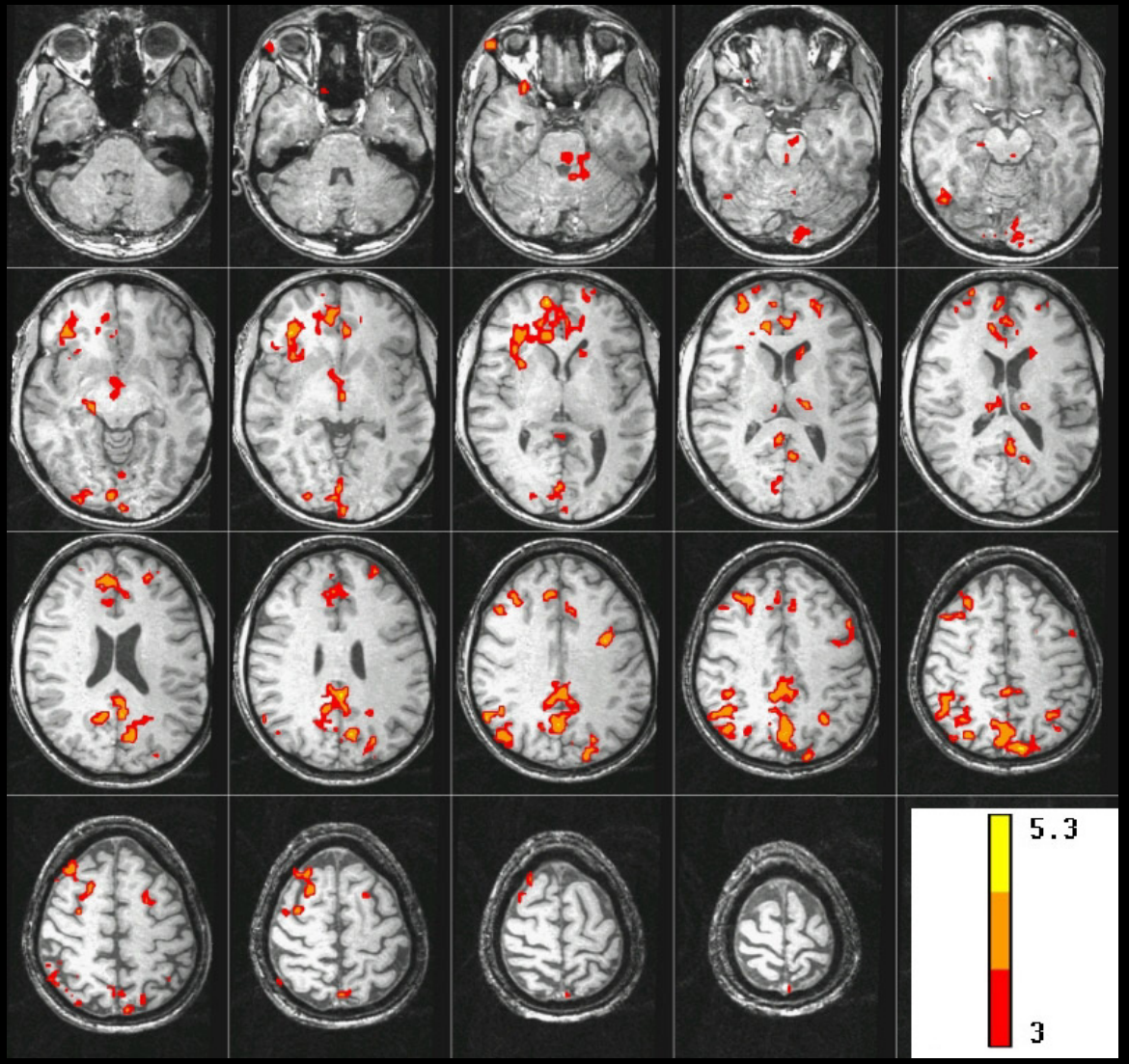
- Task performance
- Skin Conductance
- Heart, respiration rate..
- Eye position
- EEG

# The Skin Conductance Response (SCR)



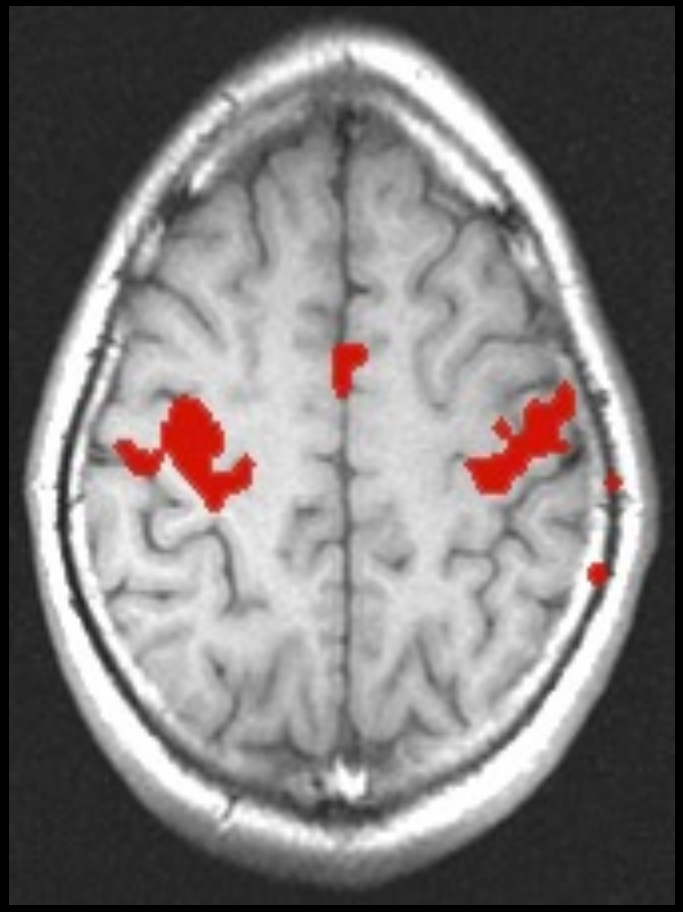

Patterson et al. (submitted)

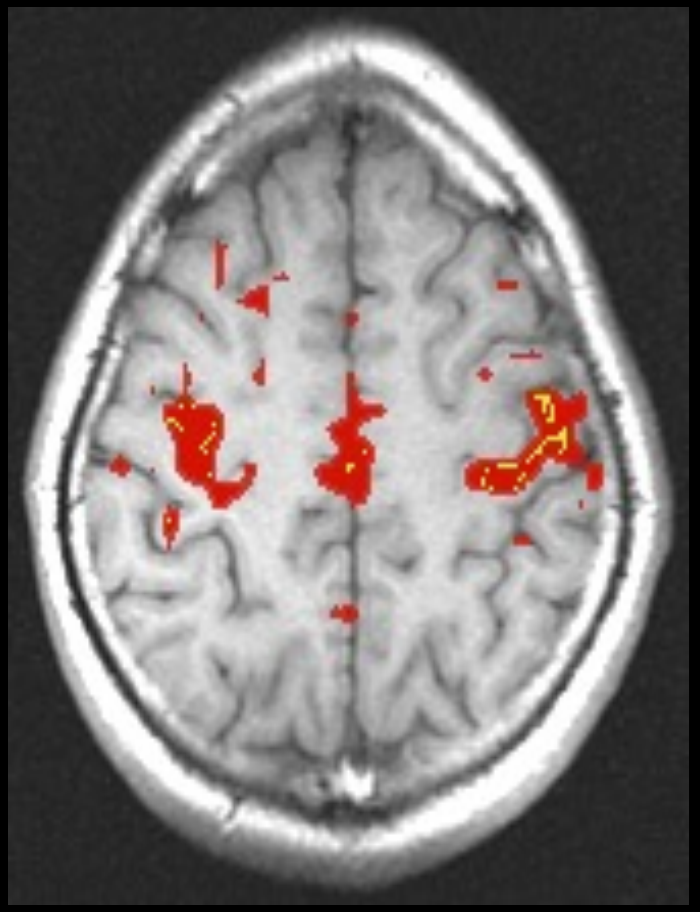
# Brain activity correlated with SCR during "Rest"




Patterson et al. (submitted)

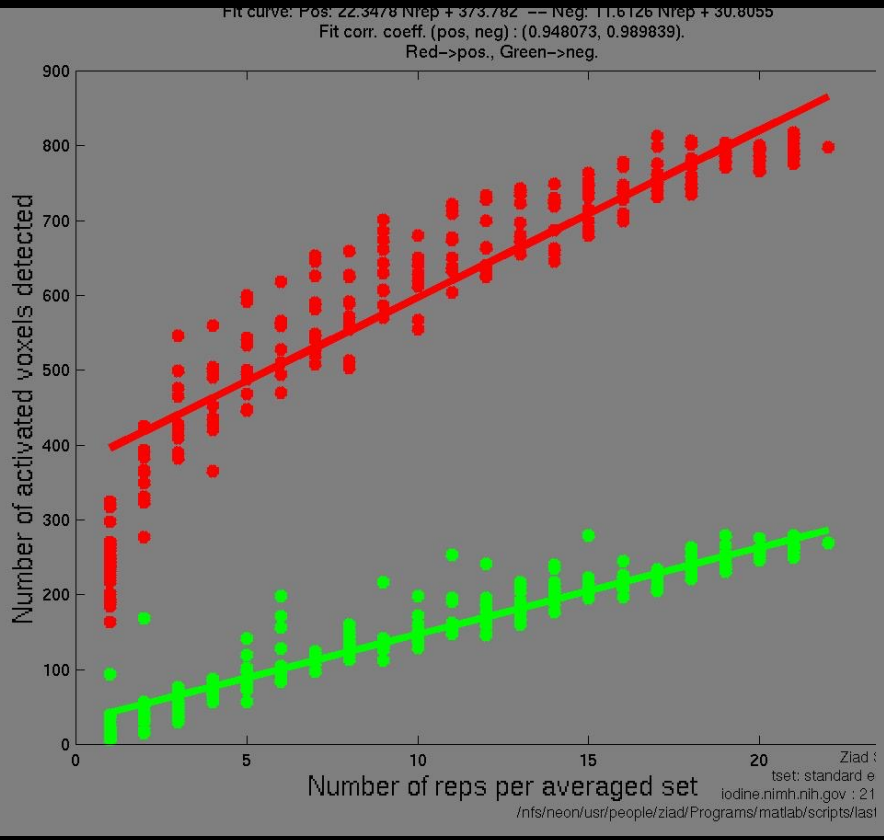
# Resting Hemodynamic Autocorrelations





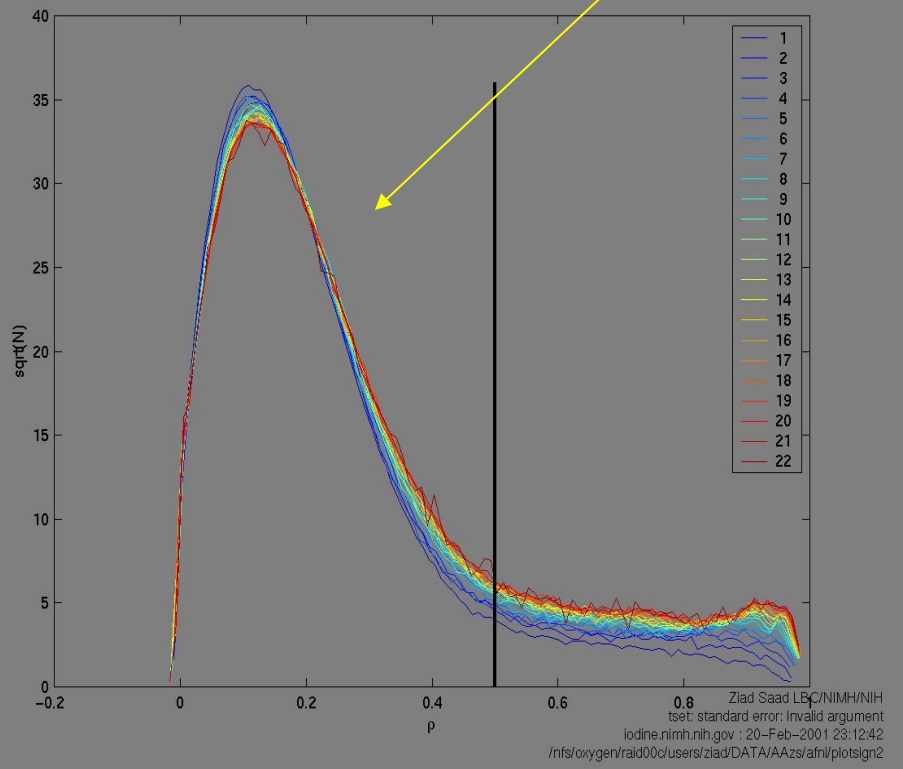
B. Biswal *et al*., MRM, 34:537 (1995)

# Continuously Growing Activation Area




# CC Histogram

Inflection Point



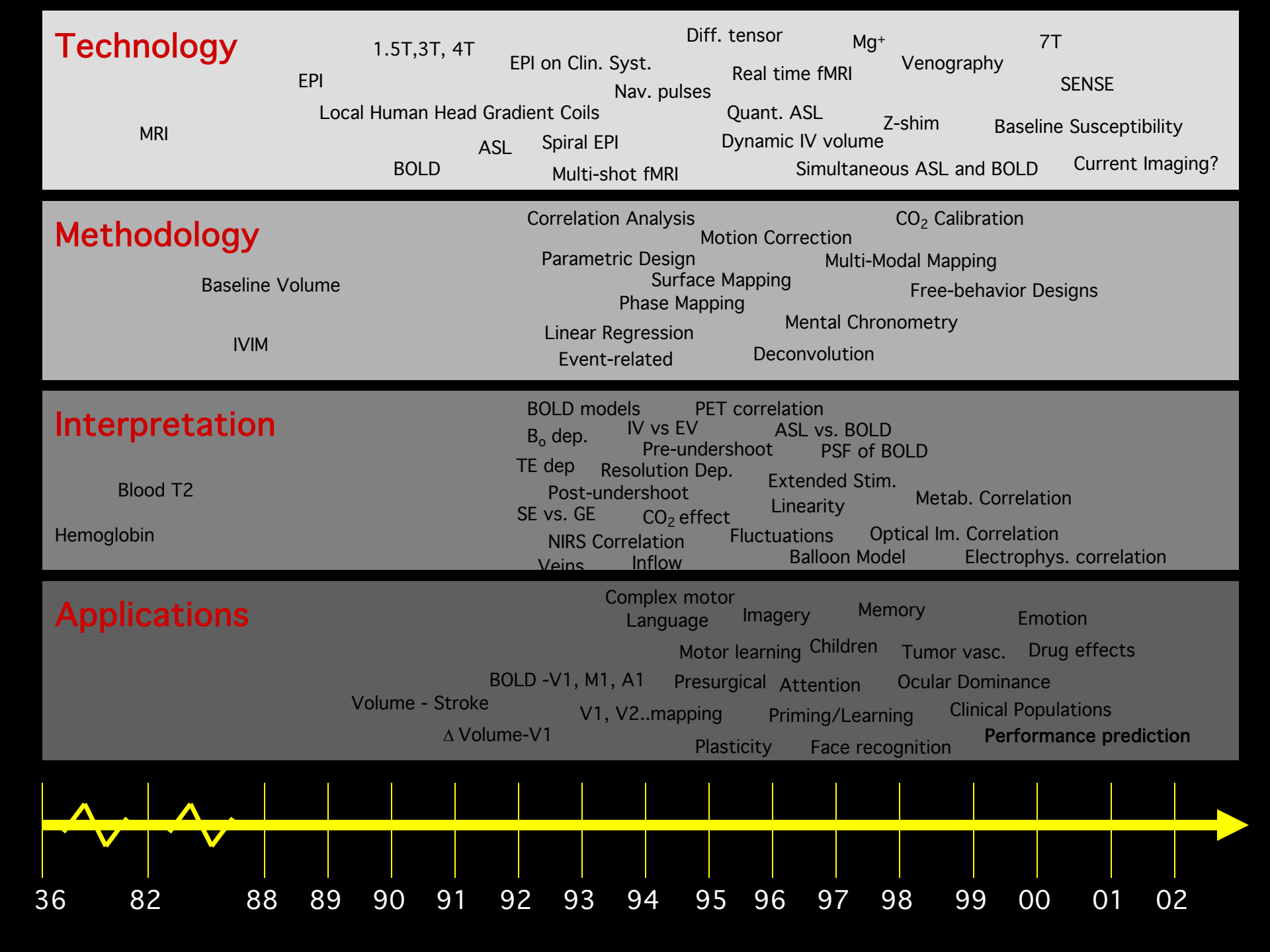

Ziad Saad, et al (Submitted)

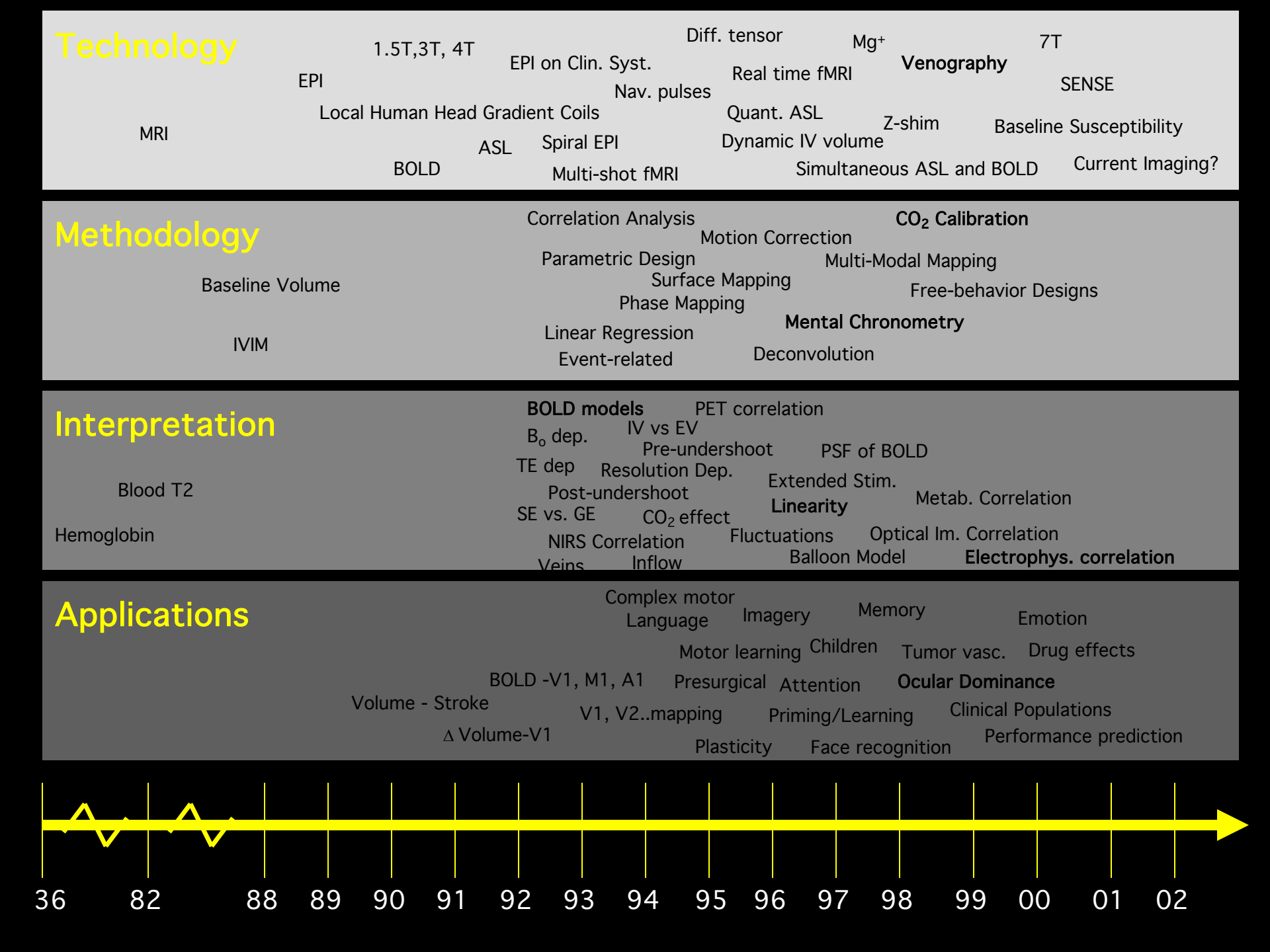
# Refinements

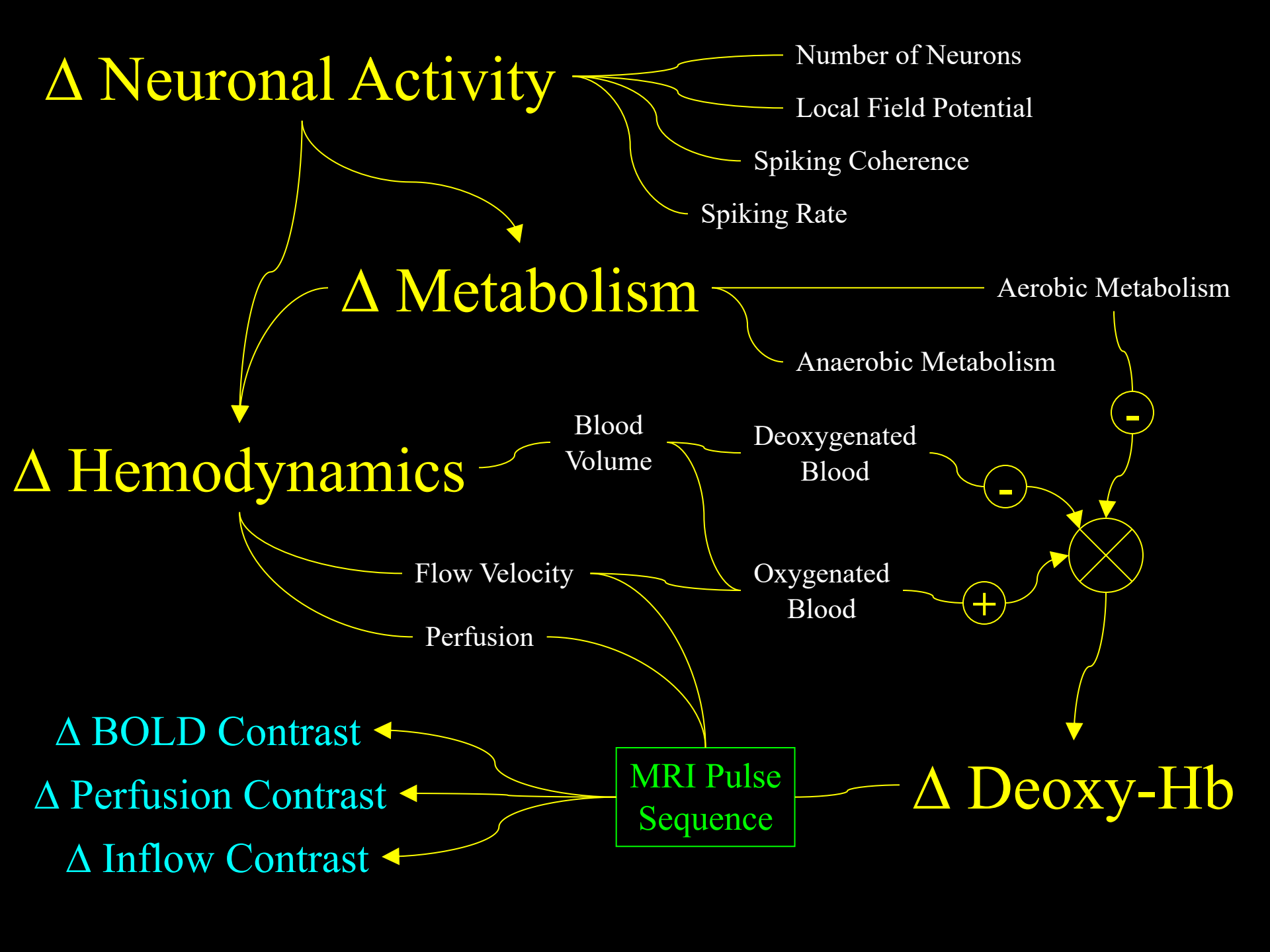
BOLD Contrast Interpretation

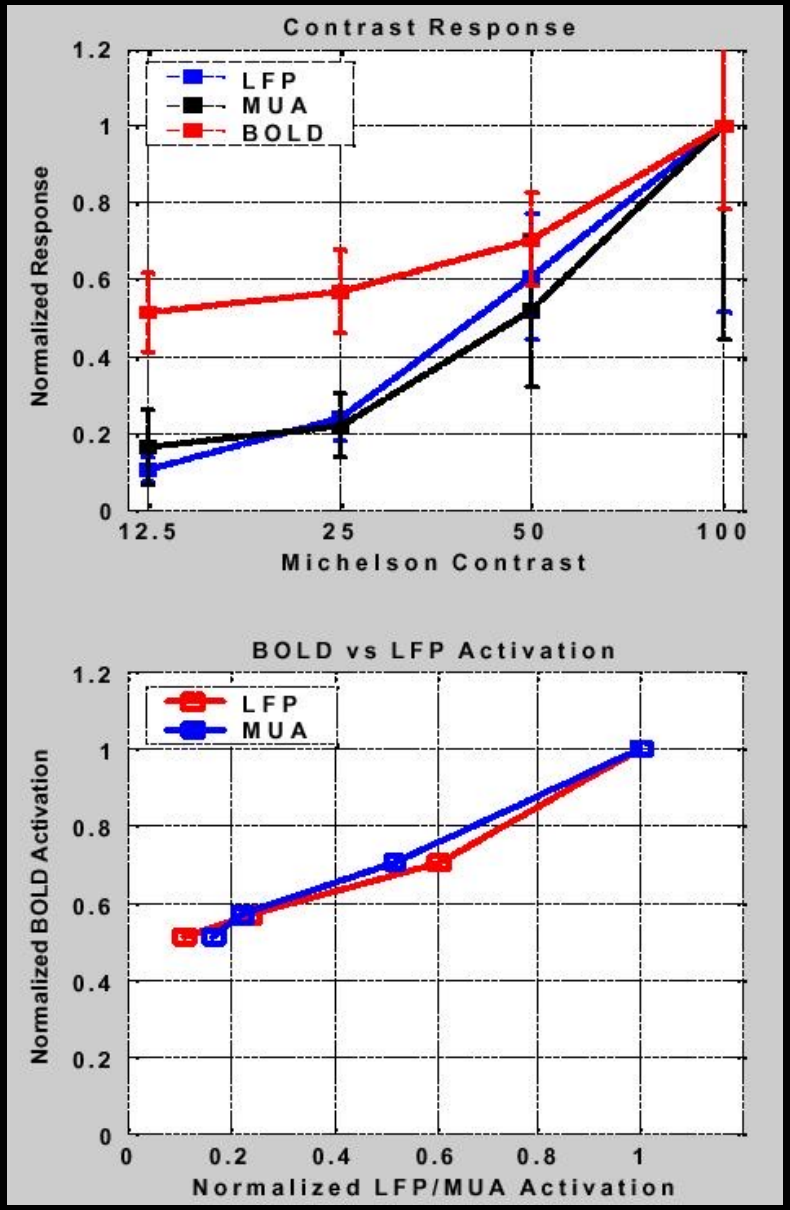
Dynamics, Paradigm Design and Processing

Applications

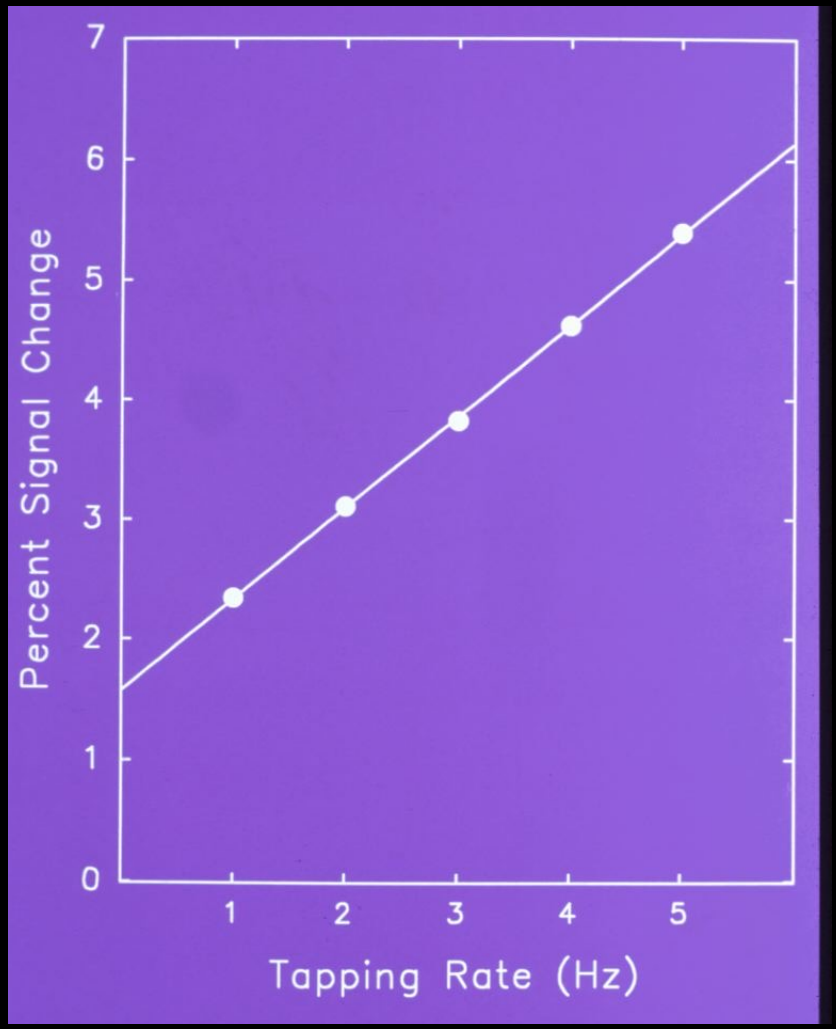

Technology
1.5T,3T, 4T
Diff. tensor
Mg+
7T
EPI on Clin. Syst.
Venography
EPI
Real time fMRI
SENSE
Nav. pulses
Local Human Head Gradient Coils
Quant. ASL
Z-shim
Baseline Susceptibility
MRI
ASL
Spiral EPI
Dynamic IV volume
BOLD
Multi-shot fMRI
Simultaneous ASL and BOLD
Current Imaging?
Methodology
Correlation 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


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.
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


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



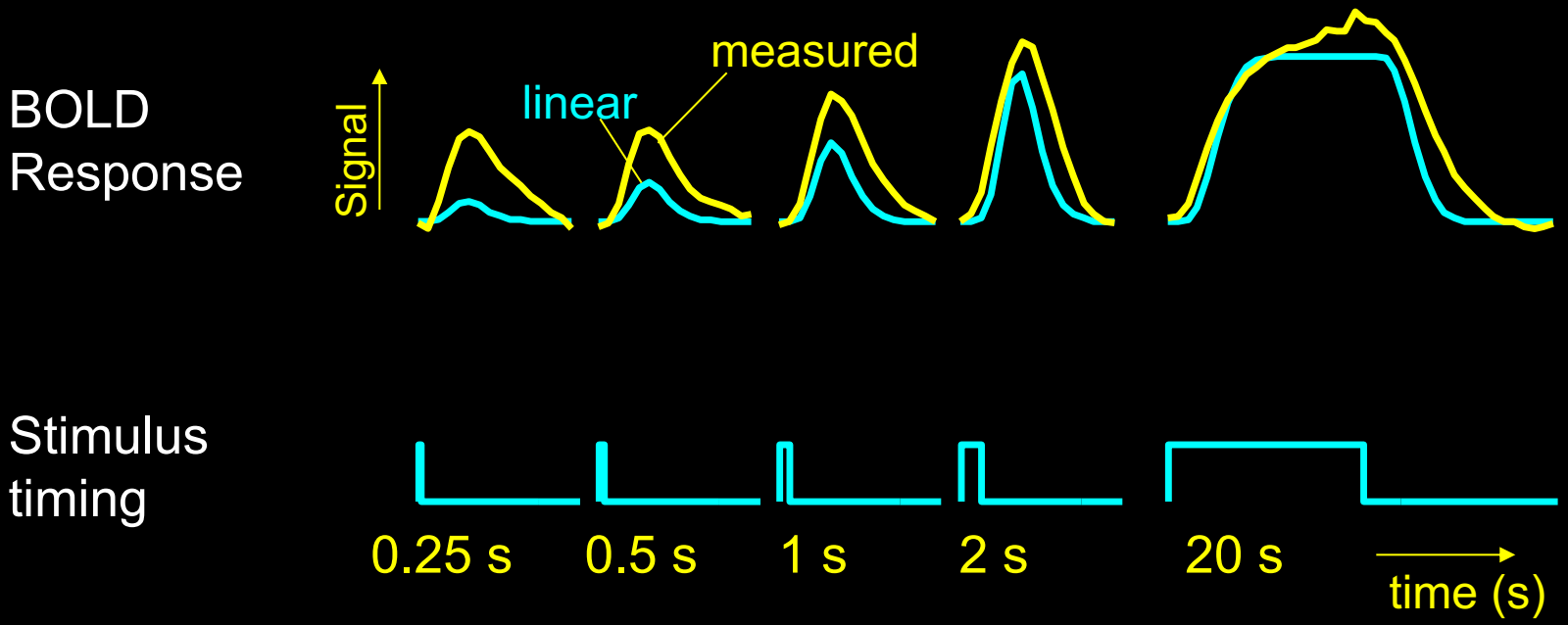

Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157




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

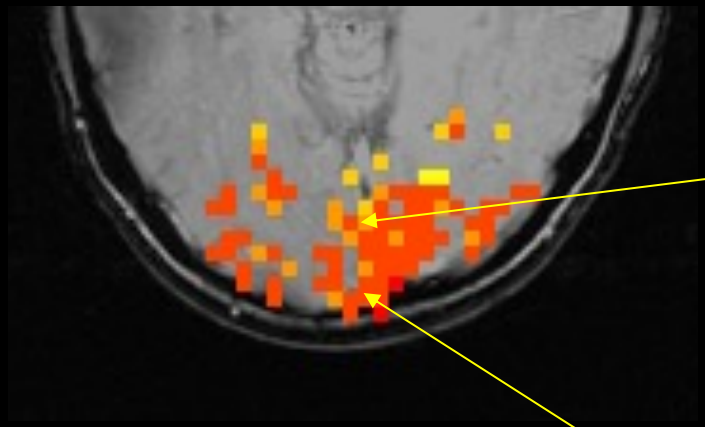
## Different stimulus "ON" periods

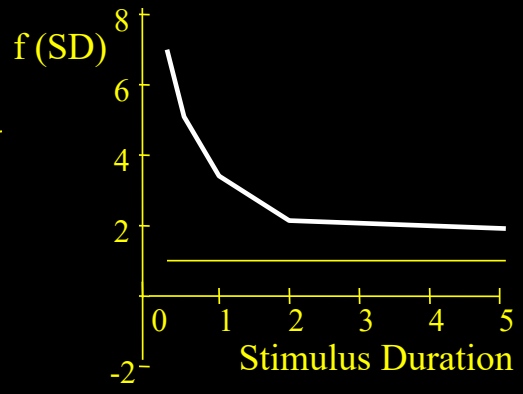


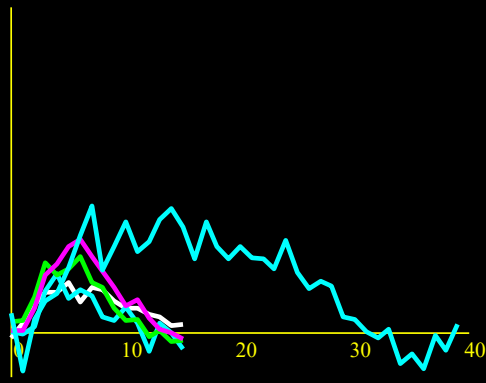

*Brief stimuli produce larger responses than expected*

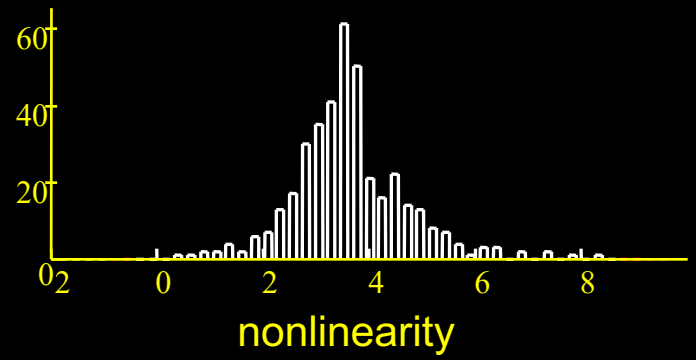
**R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.**

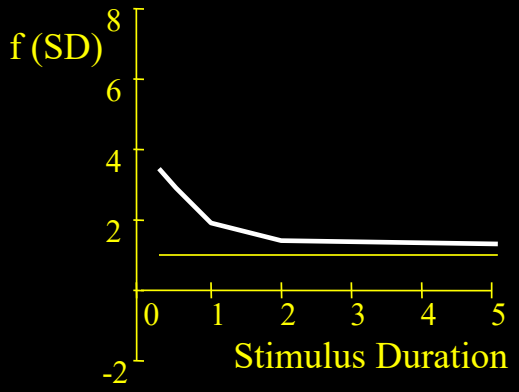
# Spatial Heterogeneity of BOLD Nonlinearity

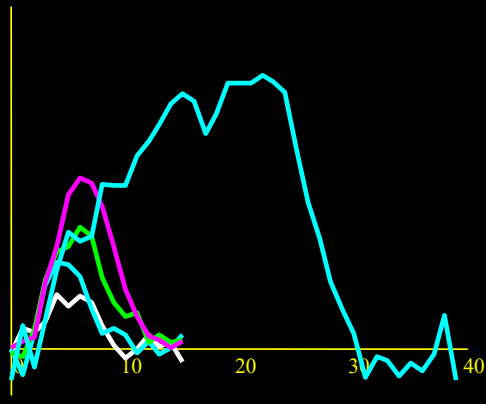




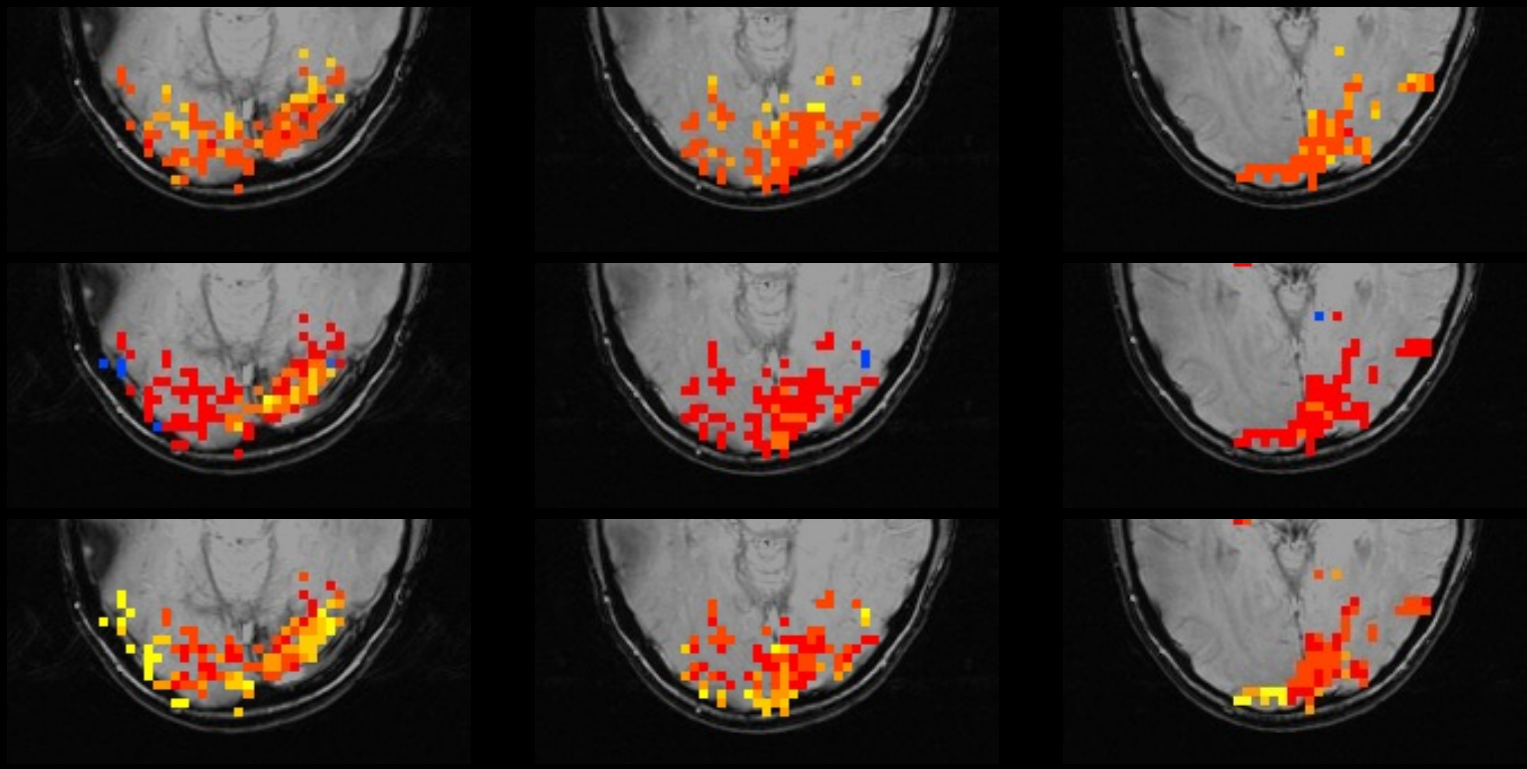

**R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.**

# Results – visual task

Nonlinearity

Magnitude

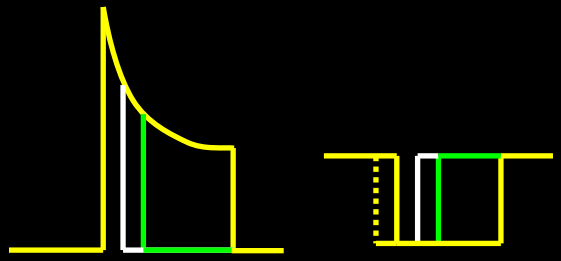
Latency



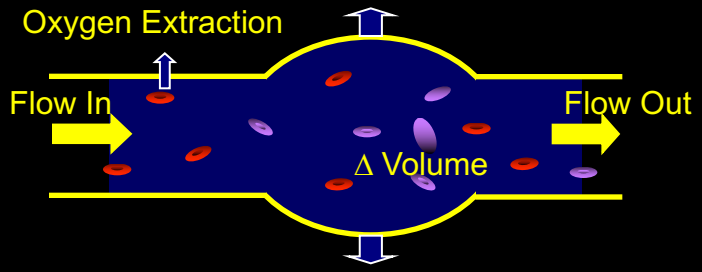
**R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.**

# Sources of this Nonlinearity

- Neuronal

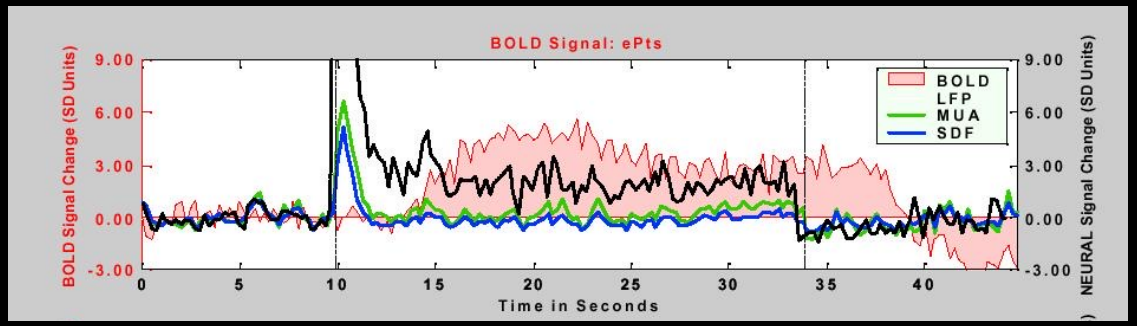


- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics

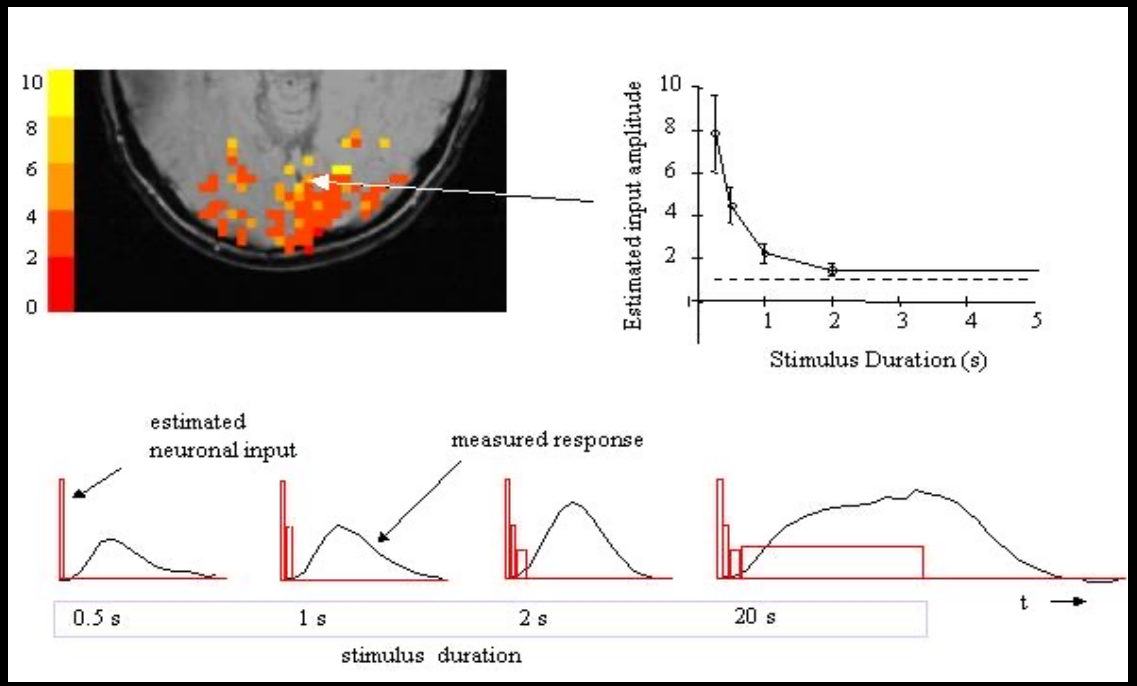


# BOLD Correlation with Neuronal Activity

**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.**

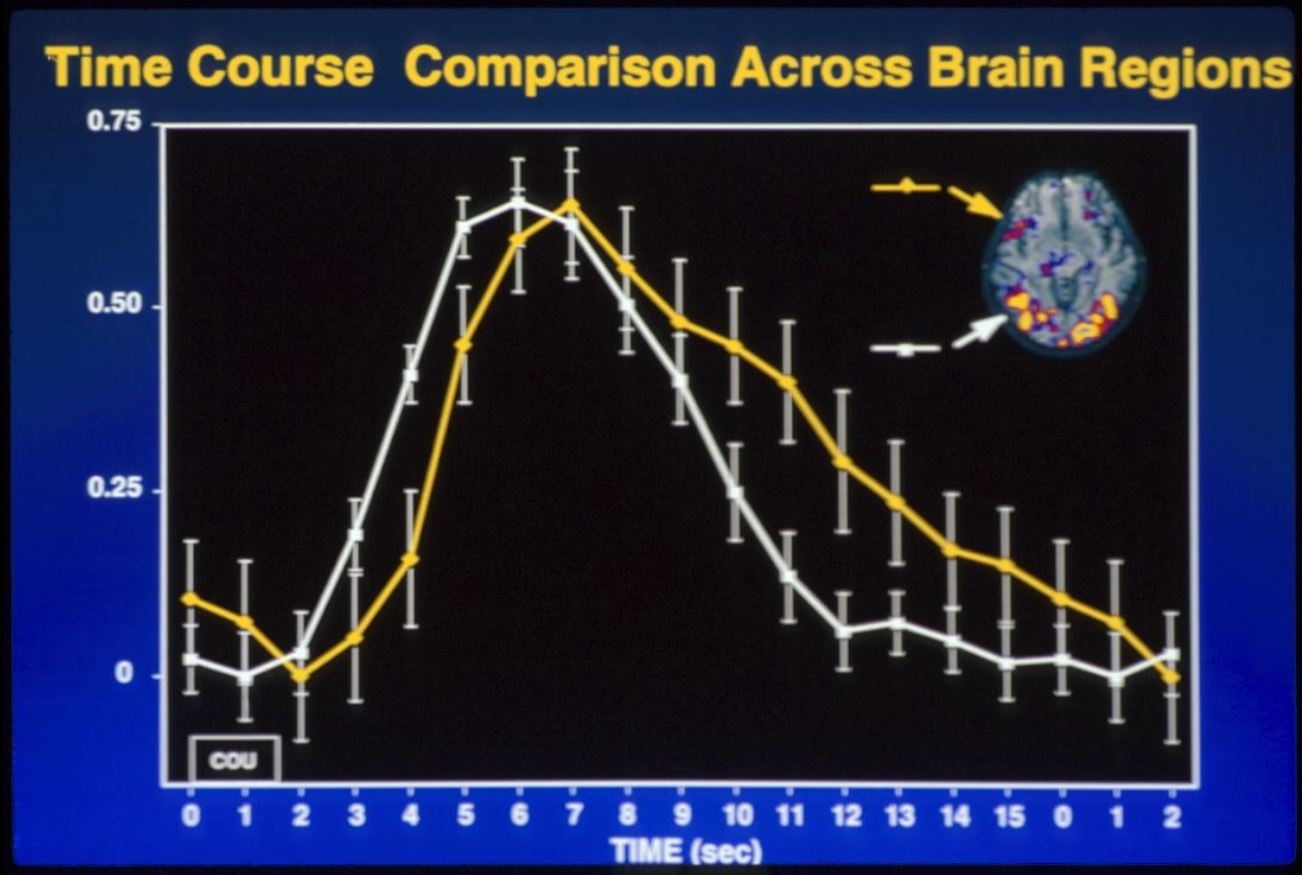


*Proc. Natl. Acad. Sci. USA*
Vol. 93, pp. 14878–14883, December 1996
Neurobiology

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

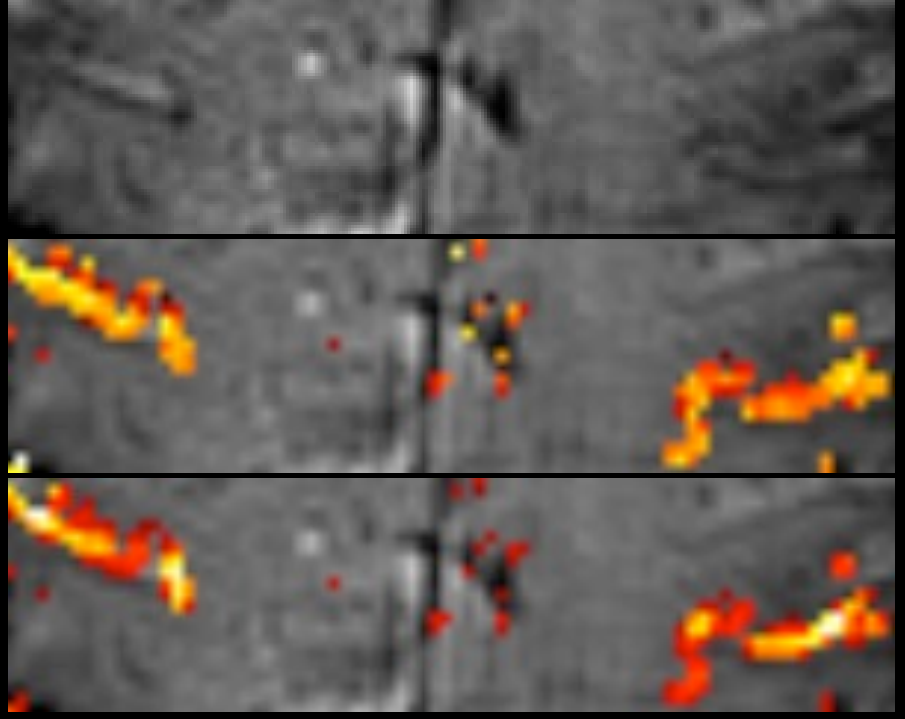
(neuroimaging/single trial/language/prefrontal)

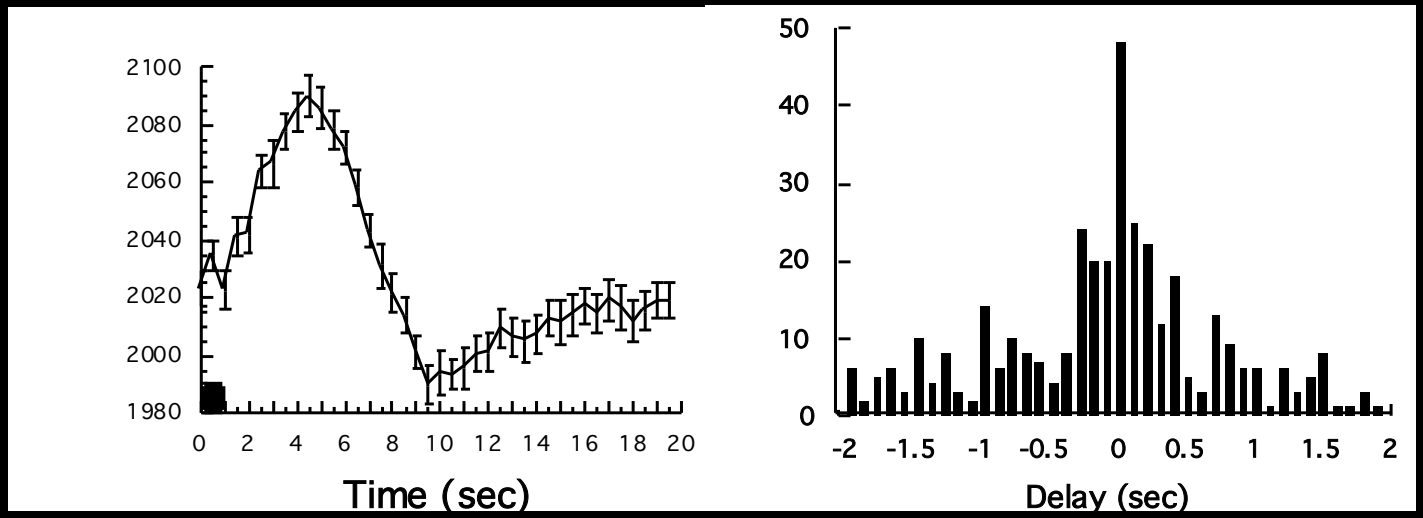
RANDY L. BUCKNER[†‡§¶], PETER A. BANDETTINI[†‡], KATHLEEN M. O'CRAVEN[†‖], ROBERT L. SAVOY[†‖], STEVEN E. PETERSEN[*††], MARCUS E. RAICHLE[§*†††], AND BRUCE R. ROSEN[†‡]



Latency

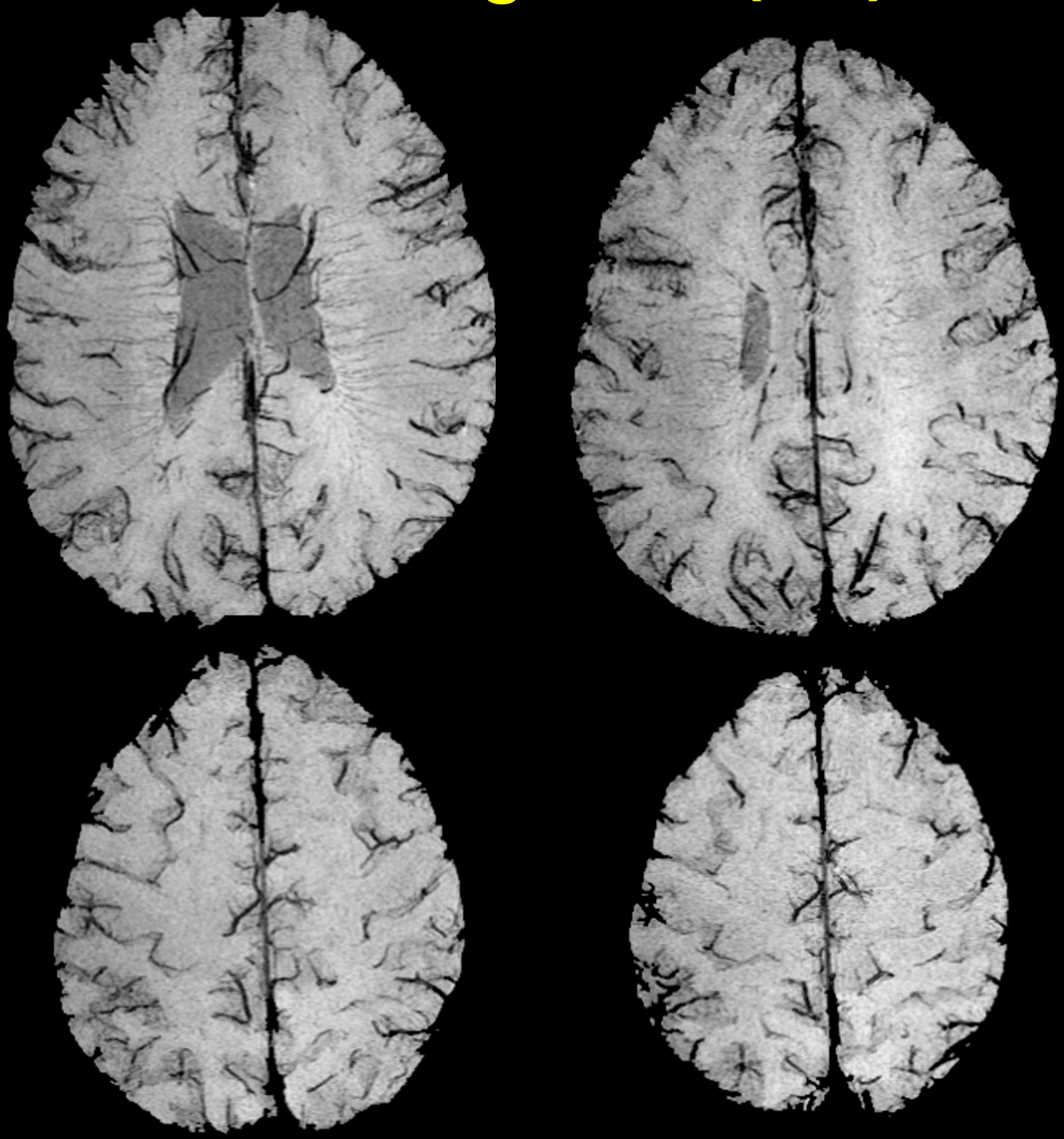
Magnitude

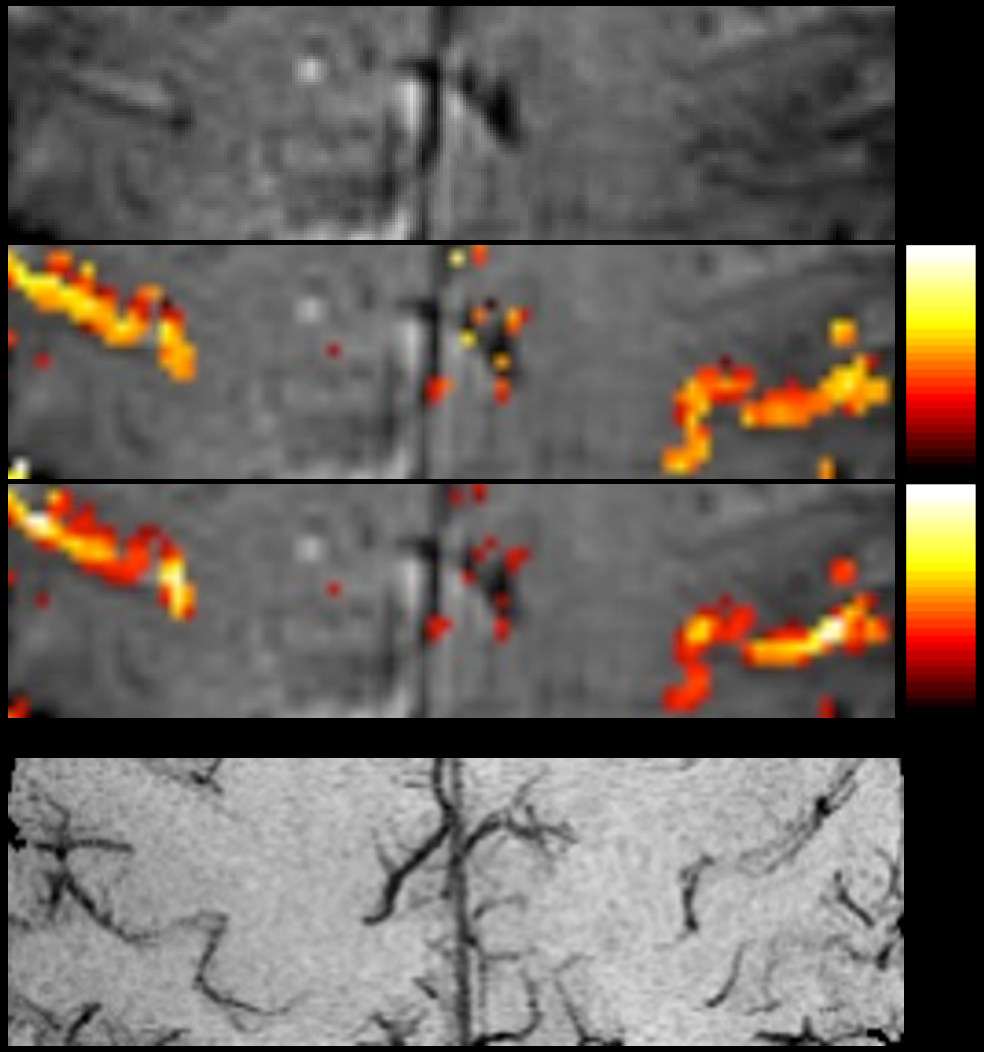



P. A. Bandettini, The temporal resolution of Functional MRI *in* "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

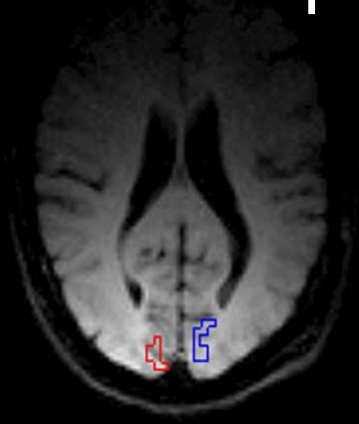
# Venograms (3T)



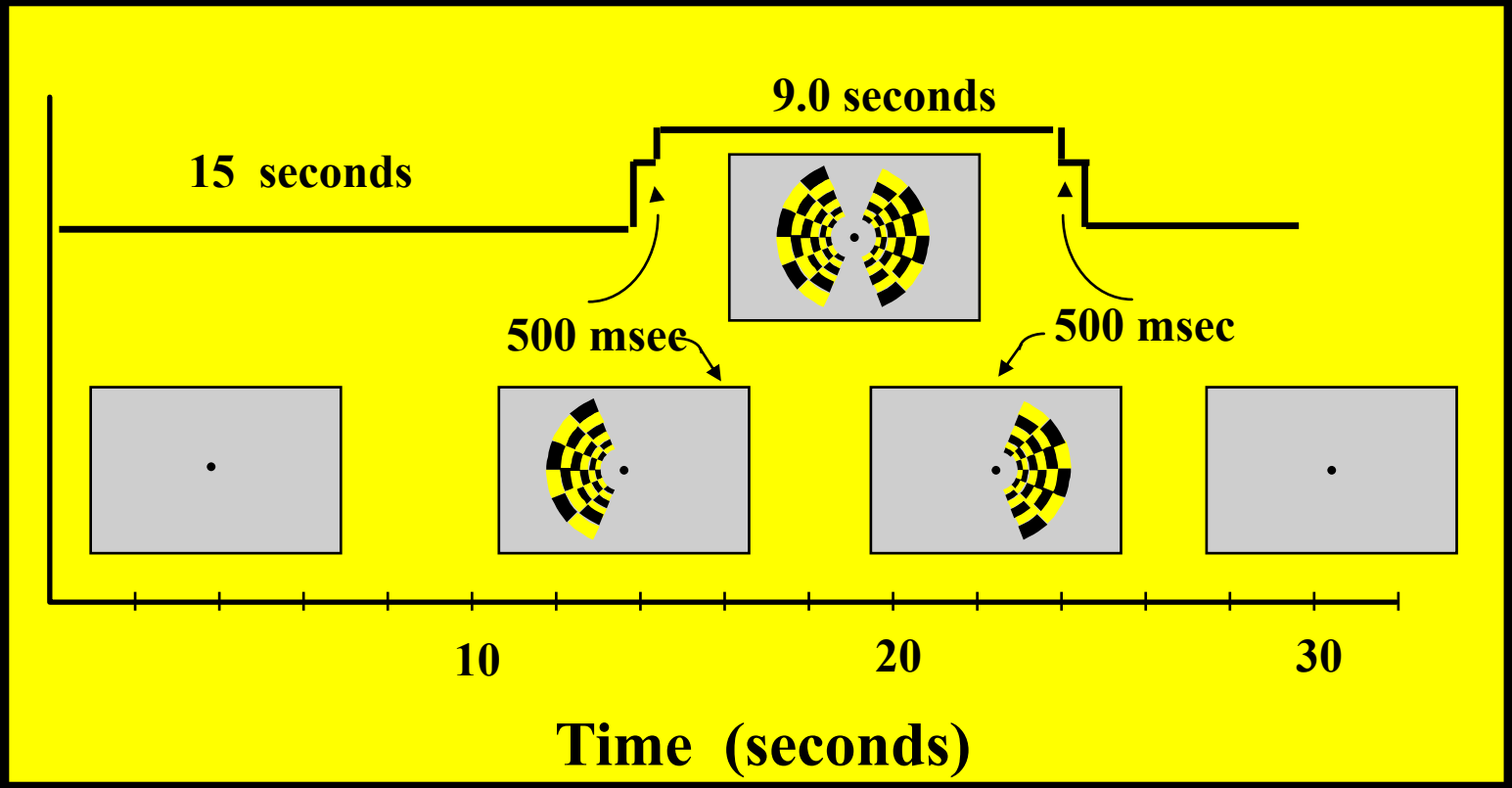


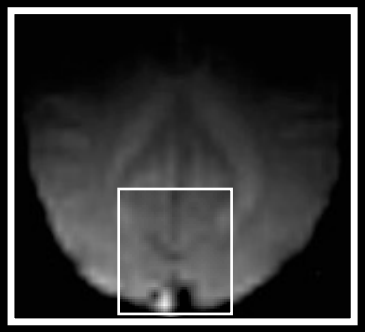
# Hemi-Field Experiment

Left Hemisphere

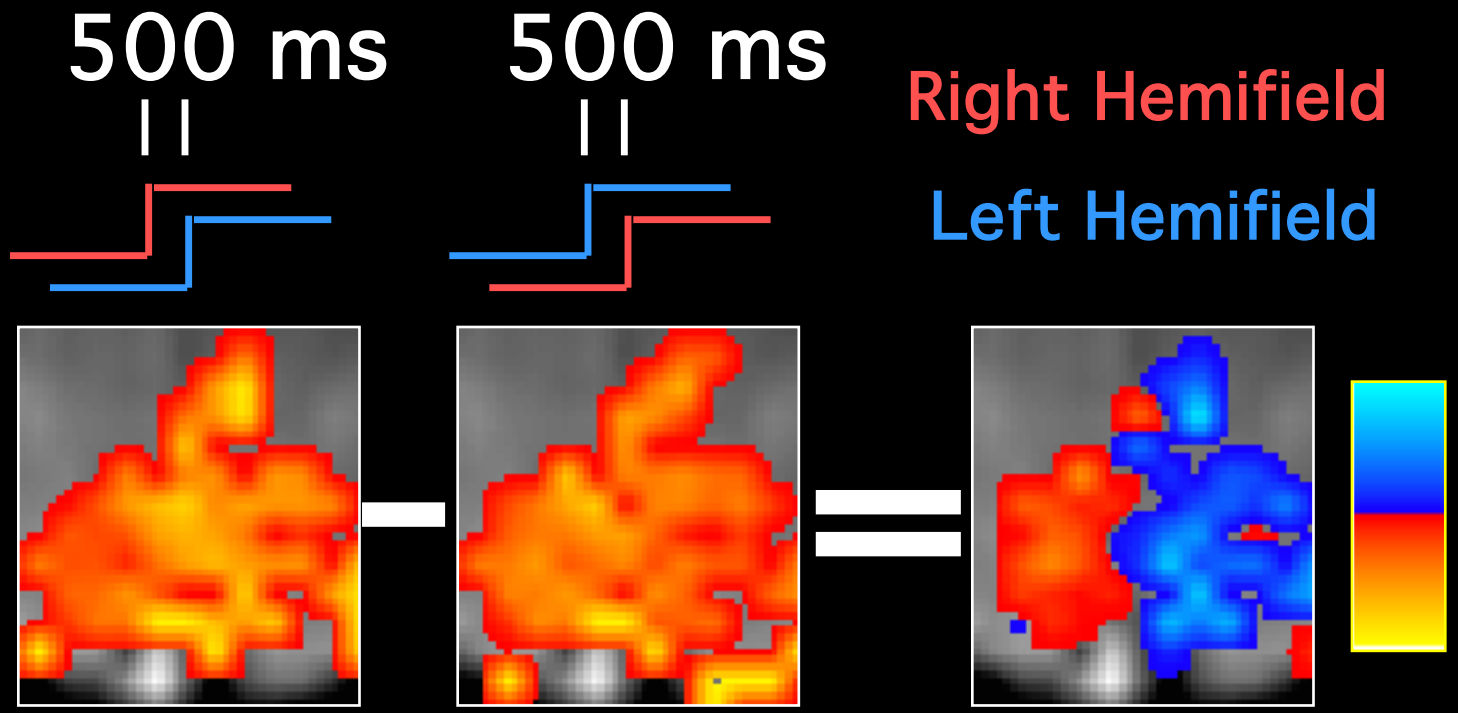


Right Hemisphere





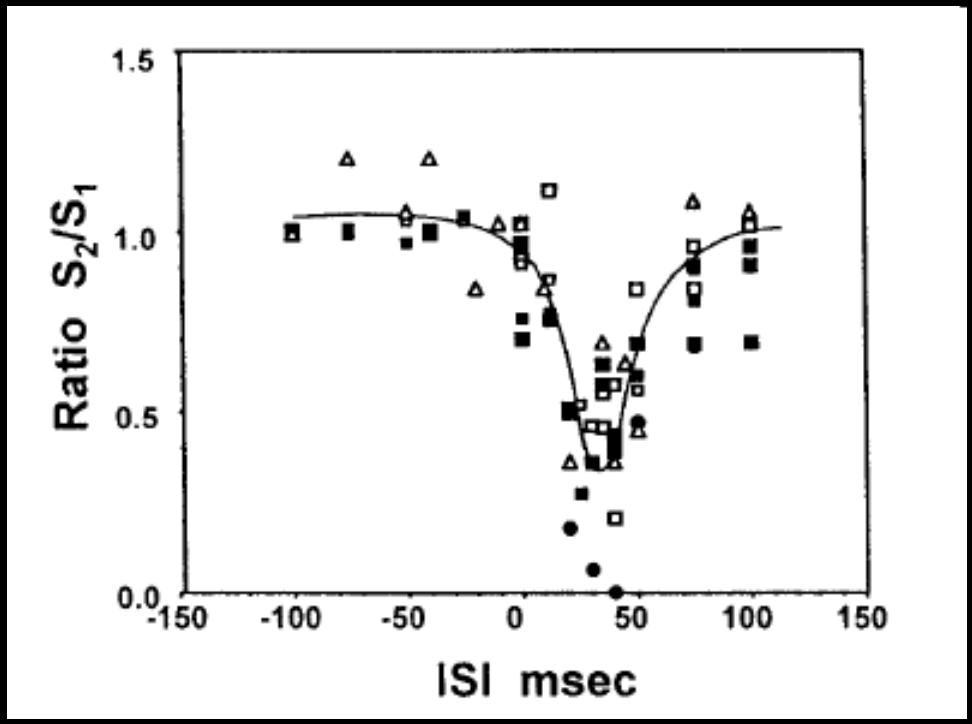
# Calibration Techniques.....




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

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

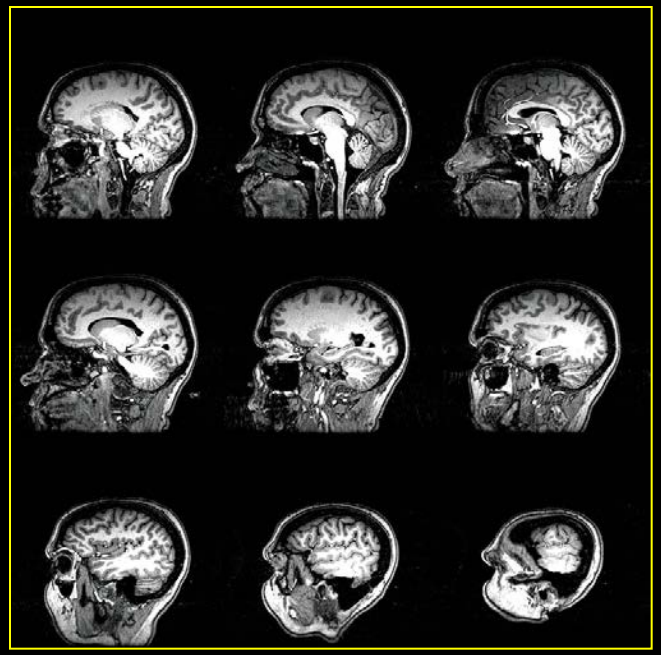
Seiji Ogawa[†‡], Tso-Ming Lee[†], Ray Stepnoski[†], Wei Chen[§], Xiao-Hong Zhu[§], and Kamil Ugurbil[§]

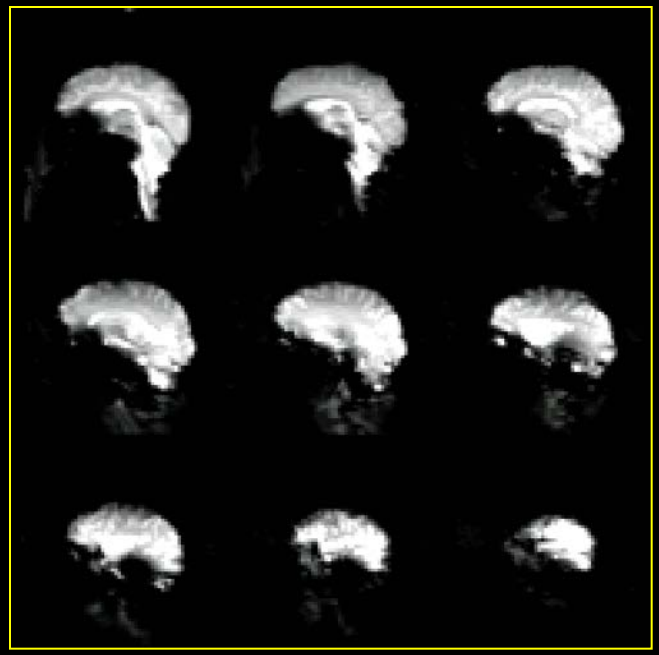


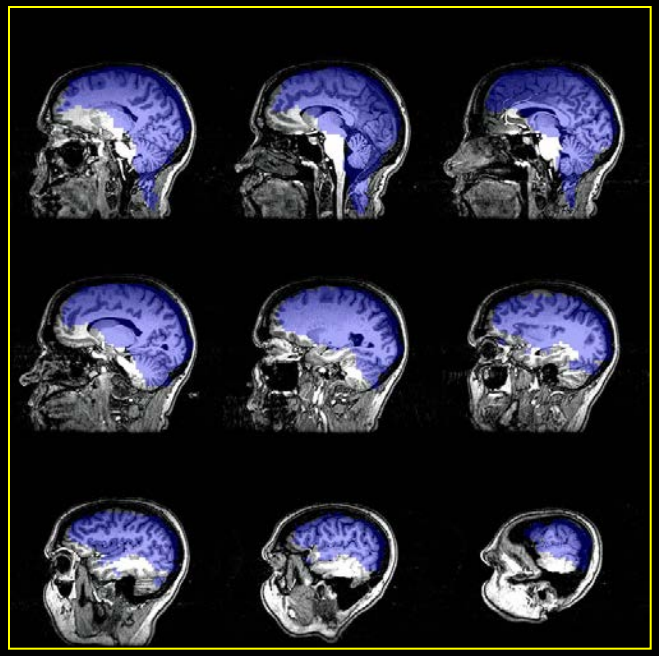

**11026–11031** PNAS **September 26, 2000** vol. 97 no. 20

# 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



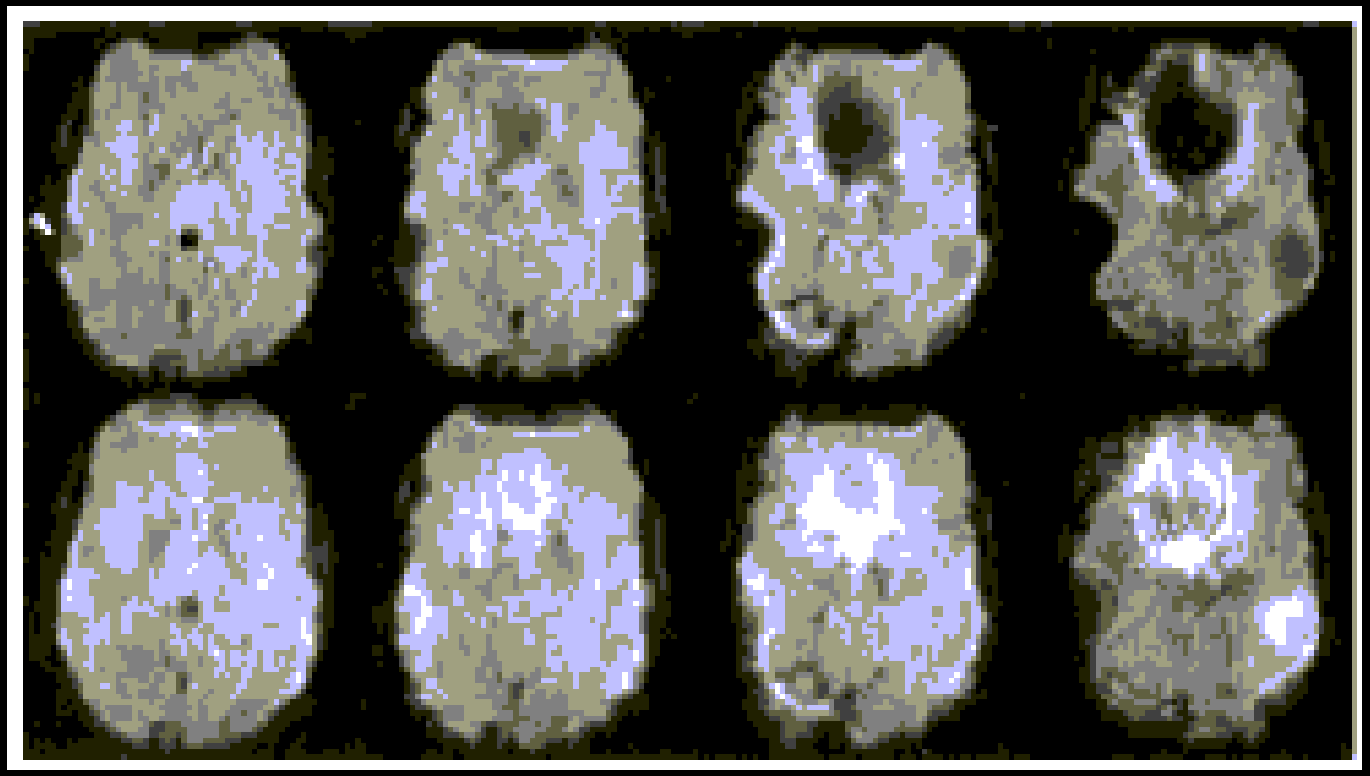




Magnetic Resonance in Medicine 42:290–299 (1999)

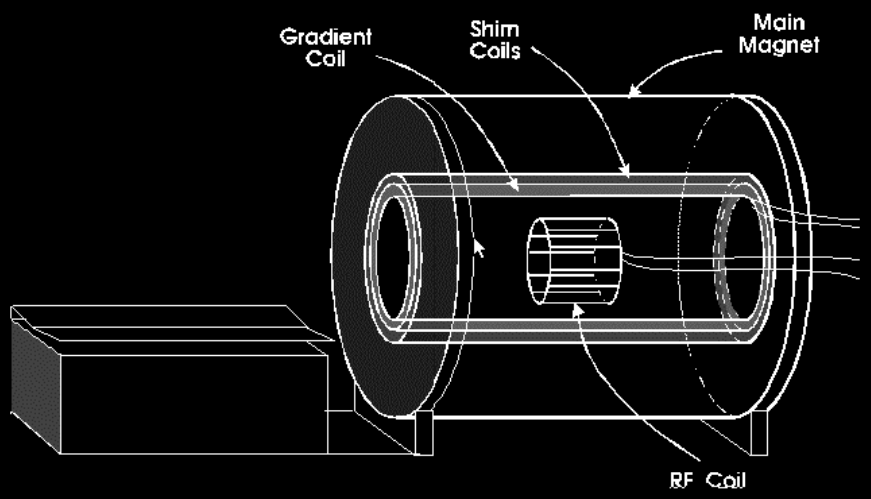
# 3D z-Shim Method for Reduction of Susceptibility Effects in BOLD fMRI

Gary H. Glover*



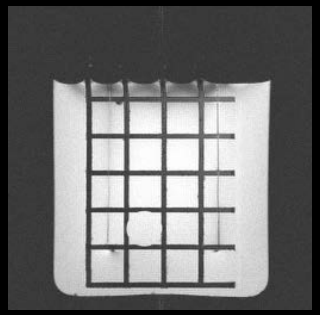
2 G/cm, 350 T/m/s

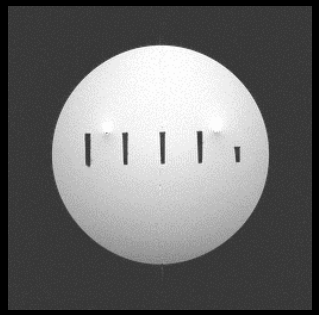
4 G/cm, 150 T/m/s



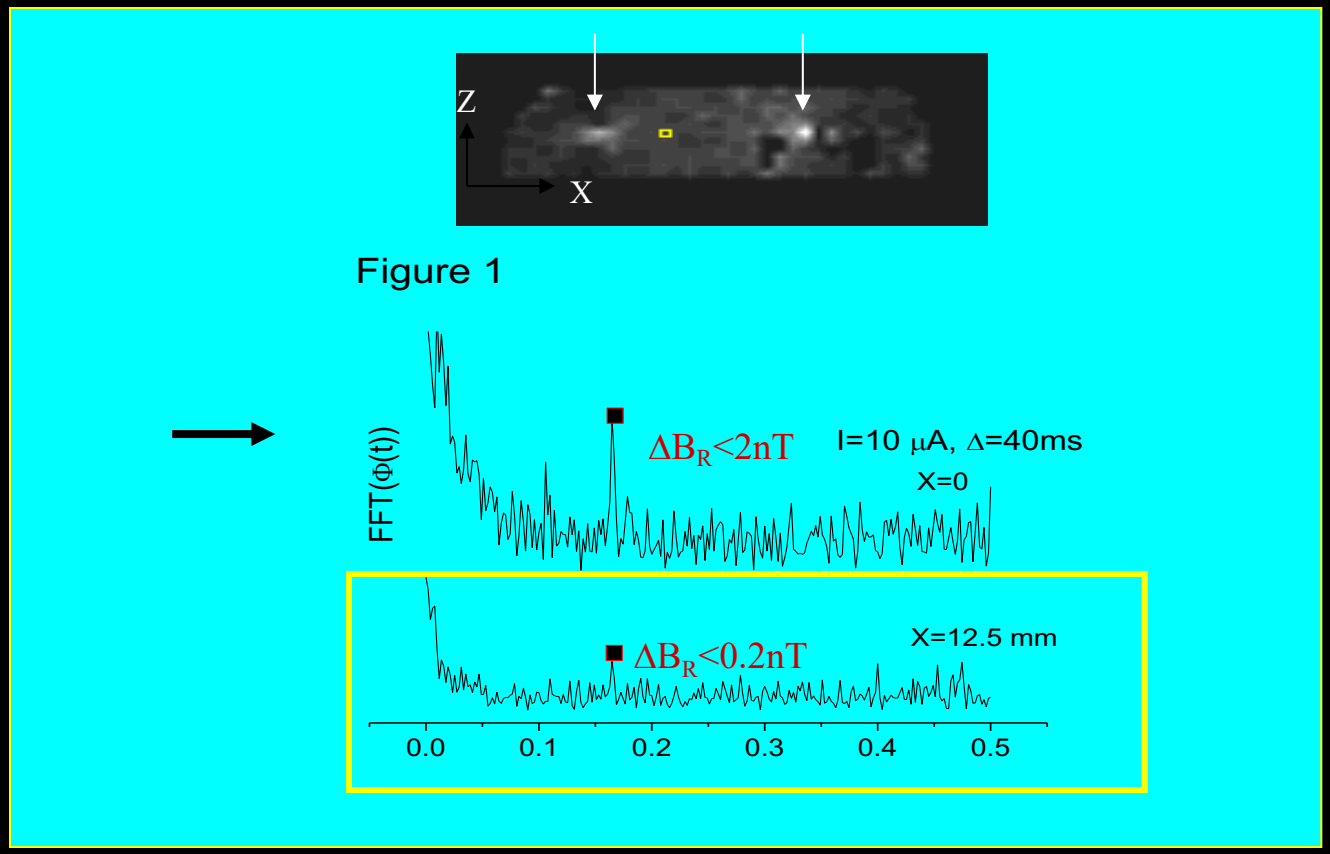

10 G/cm, 1000 T/m/s

Diffusion imaging
Faster imaging
Higher resolution

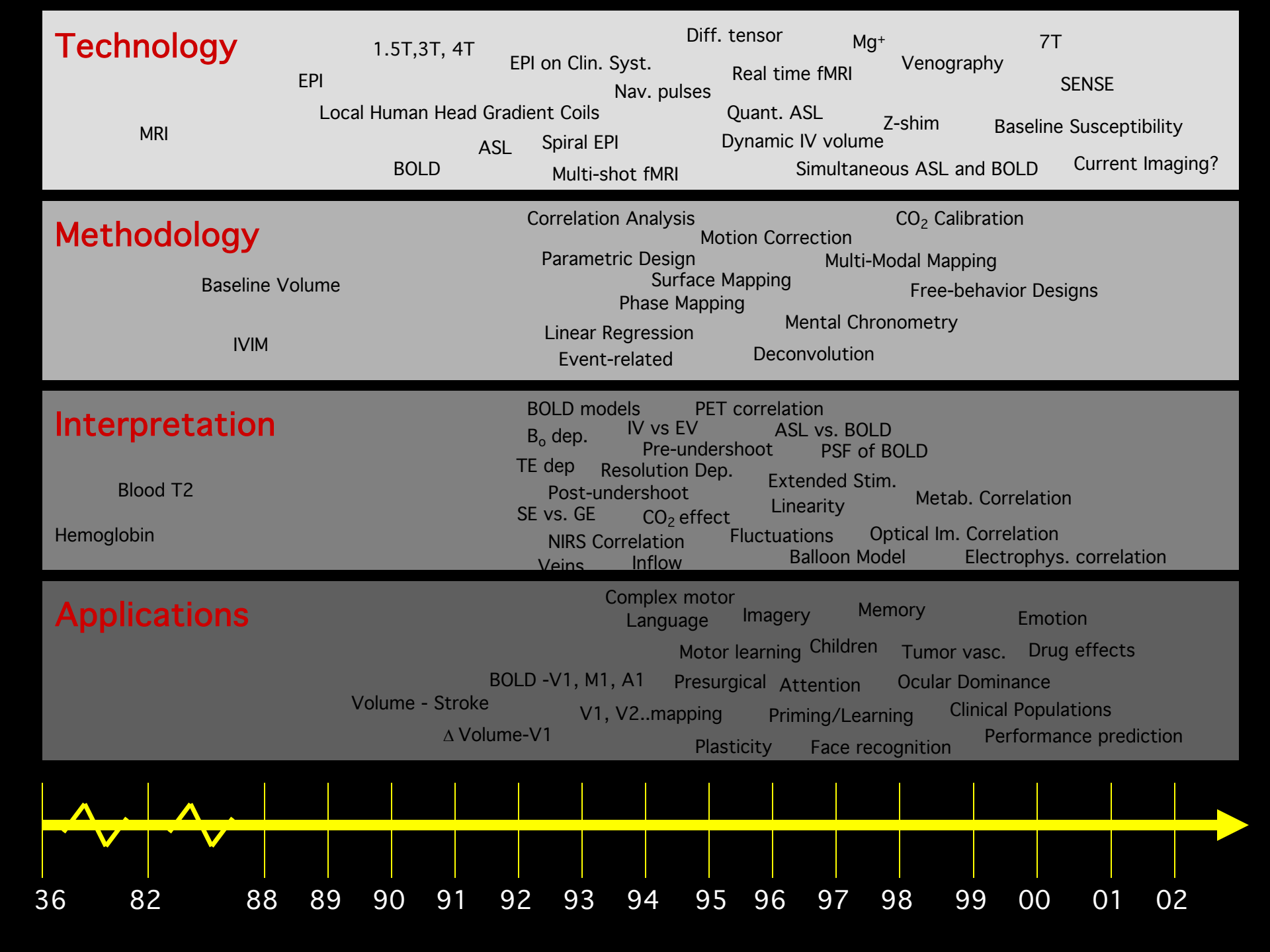




# Neuronal Current Imaging




J. Bodurka, P. A. Bandettini. Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes, *Magn. Reson. Med* 47: 1052-1058, (2002)


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

# 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:**

Natalia Petridou

**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

**Summer Students:**

Hannah Chang

Courtney Kemps

Douglass Ruff

Carla Wettig

Kang-Xing Jin

**Program Assistant:**

Kay Kuhns

**Scanning Technologists:**

Karen Bove-Bettis

Paula Rowser