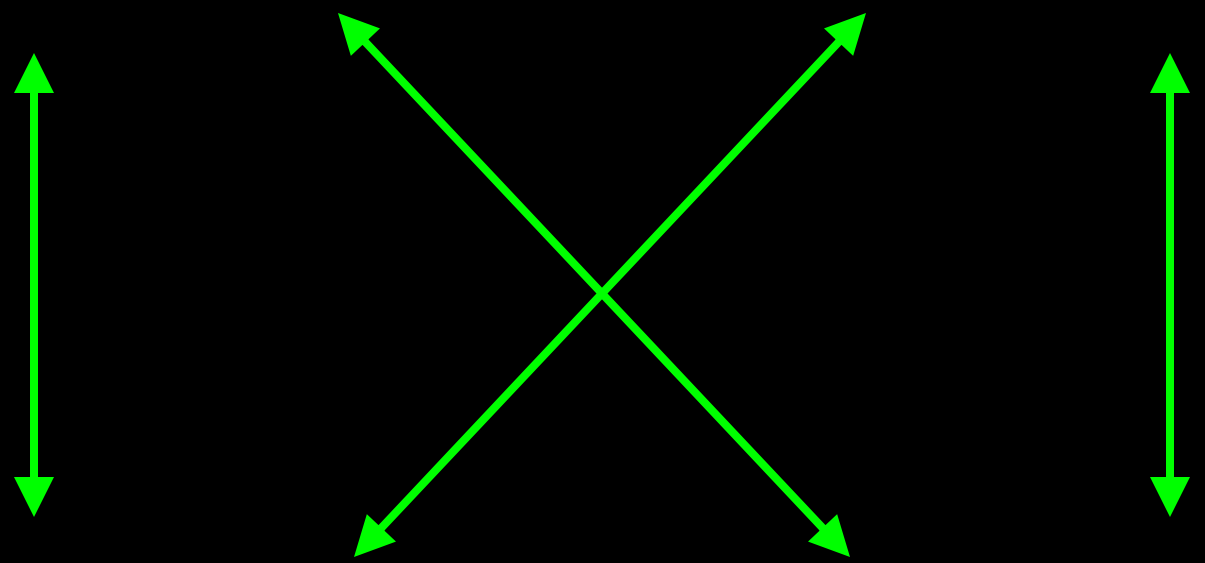
Future Trends

Peter A. Bandettini, Ph.D

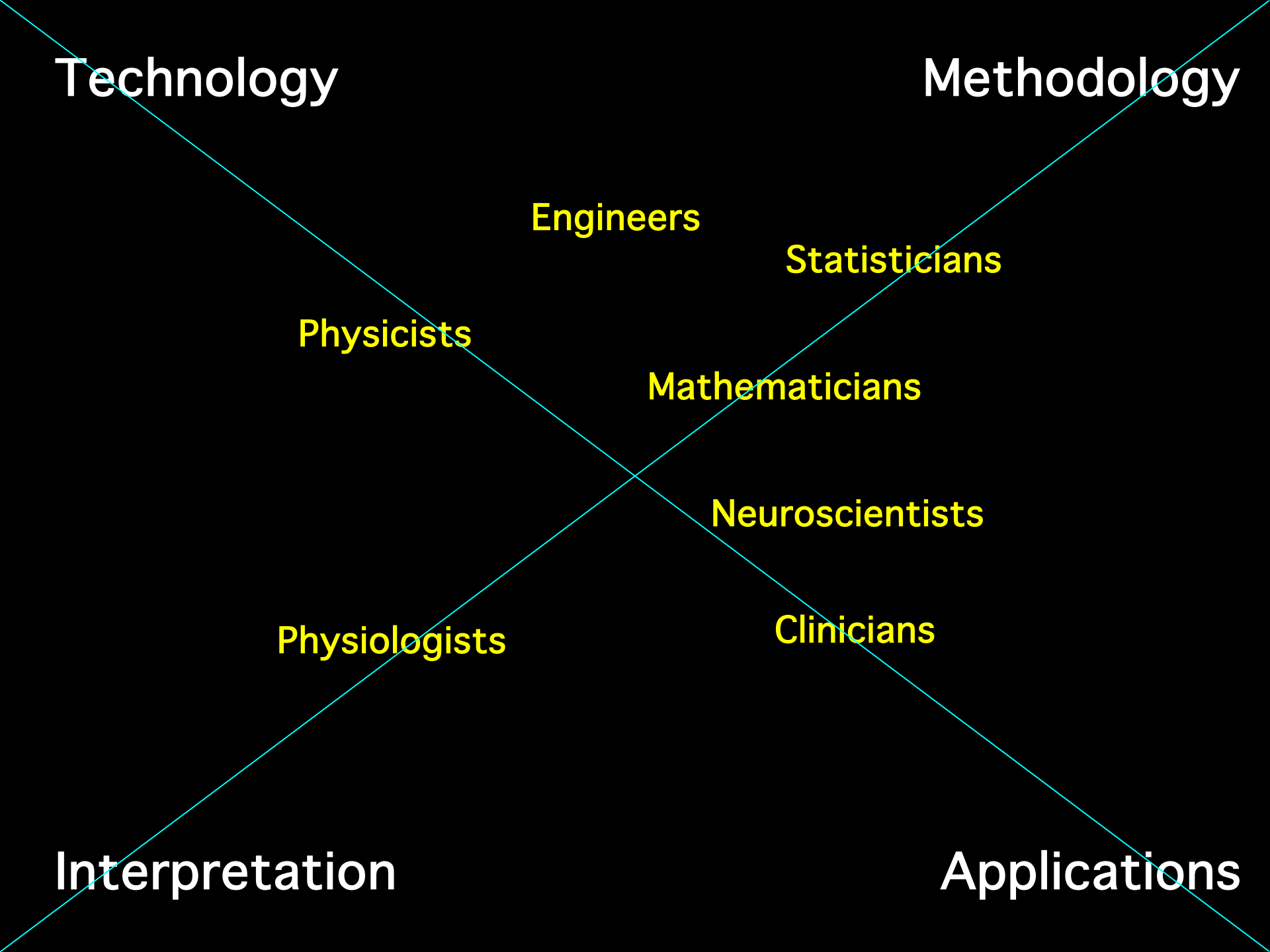
Unit on Functional Imaging Methods
&
3T Neuroimaging Core Facility

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

Past

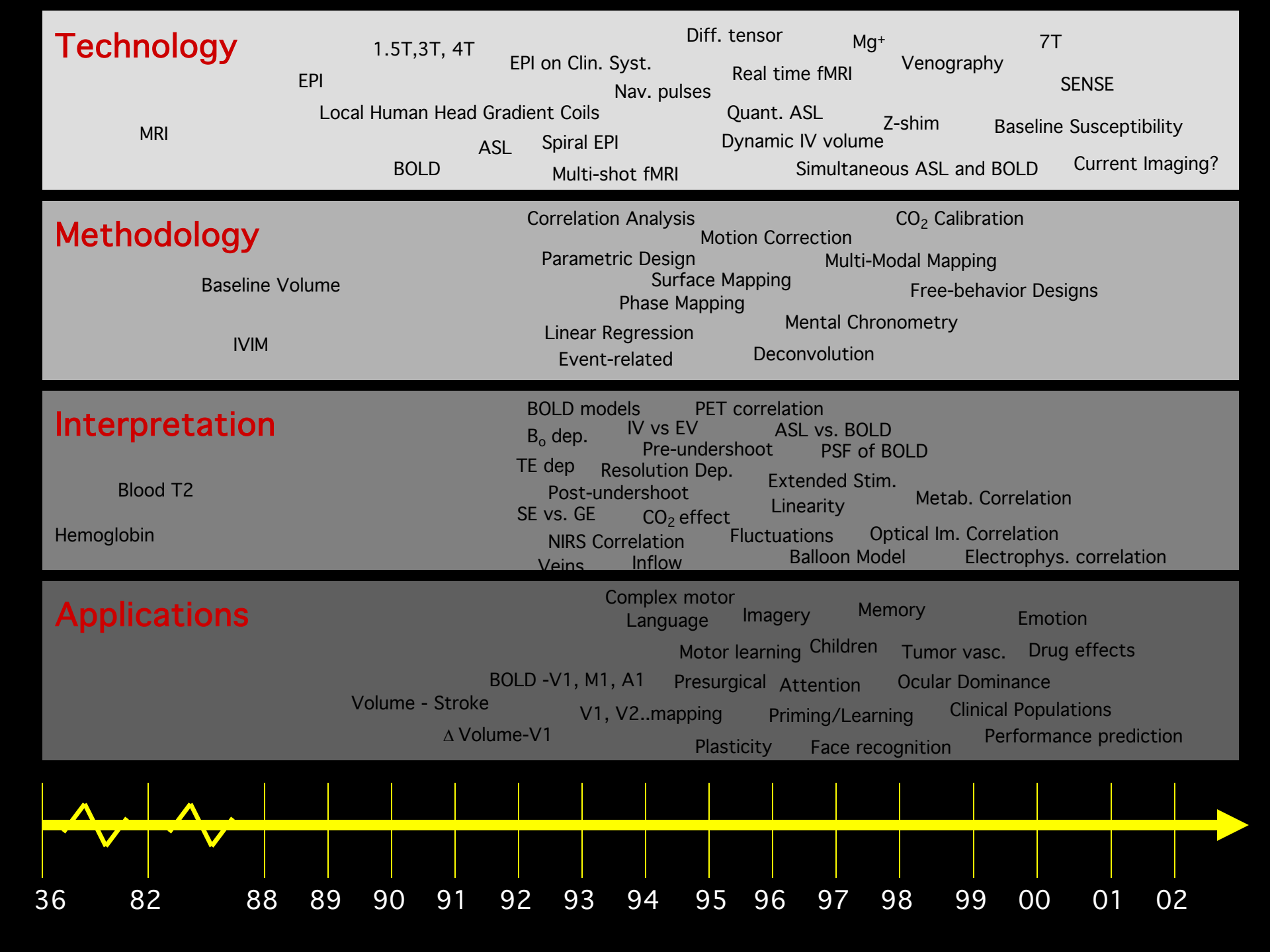
Present

Future

Past

Present

Future


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
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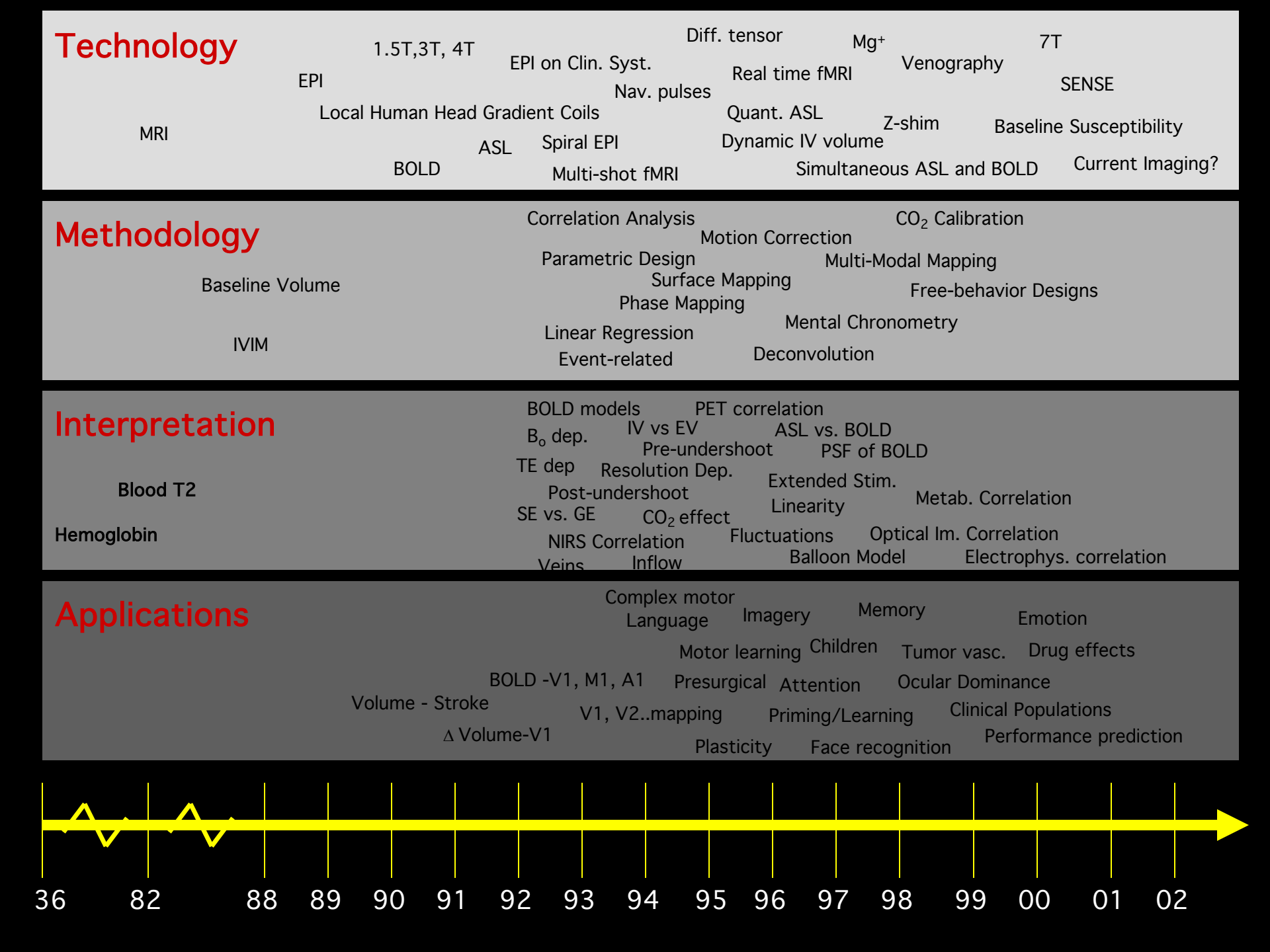
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L. Pauling, C. D. Coryell, (1936) “The magnetic properties and structure of hemoglobin, oxyhemoglobin, and carbonmonoxyhemoglobin.” Proc.Natl. Acad. Sci. USA 22, 210-216.

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.

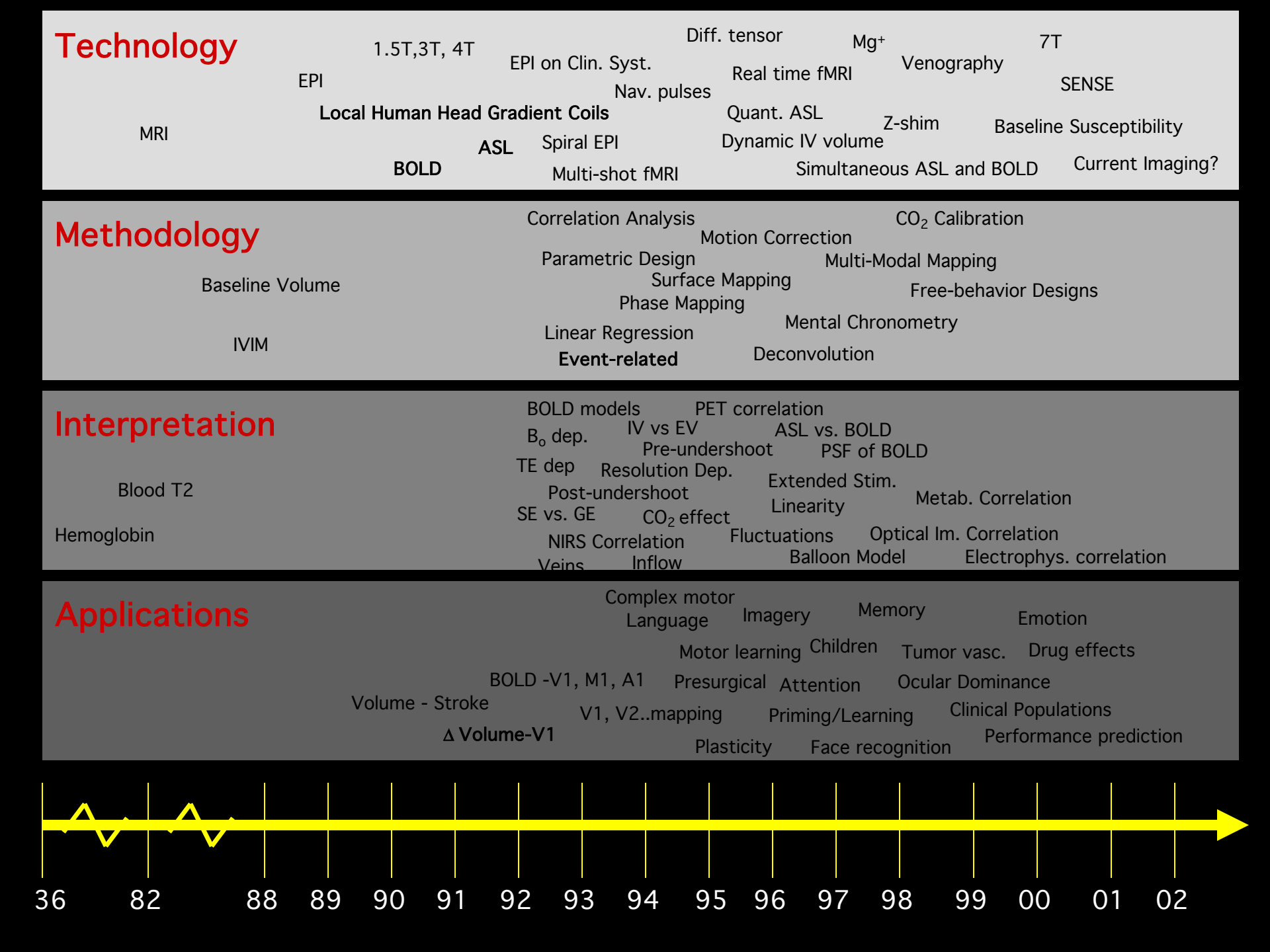
R. Turner, D. LeBihan, C. T. W. Moonen, D. Despres, J. Frank, (1991). Echo-planar time course MRI of cat brain oxygenation changes. Magn. Reson. Med. 27, 159-166.

Functional MRI Methods

Blood Volume Imaging

BOLD Contrast

Arterial Spin Labeling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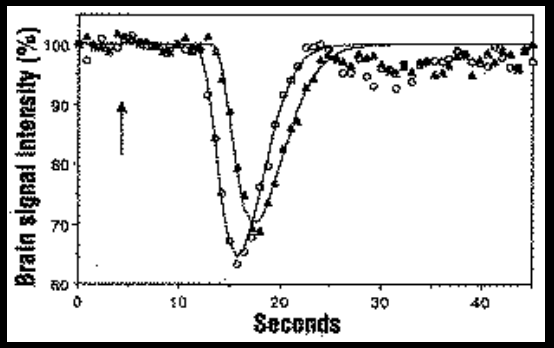
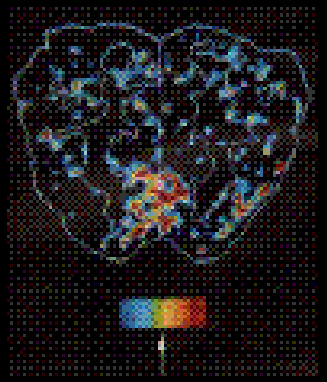
Blood Volume Imaging

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

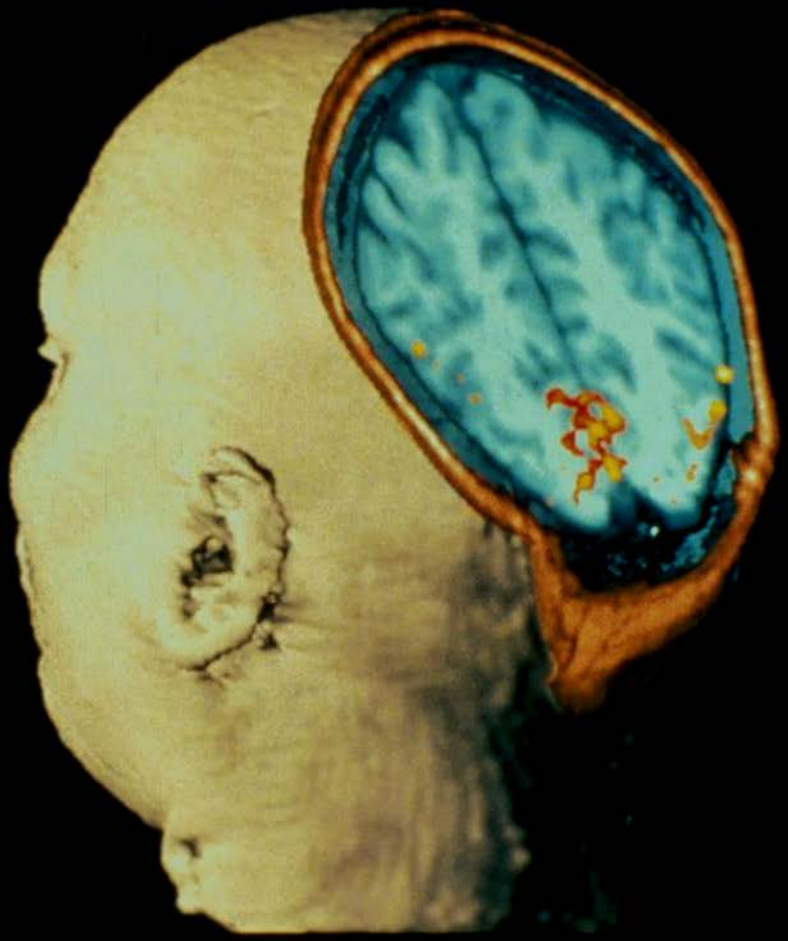
Resting Active





Blood Volume

Photic Stimulation

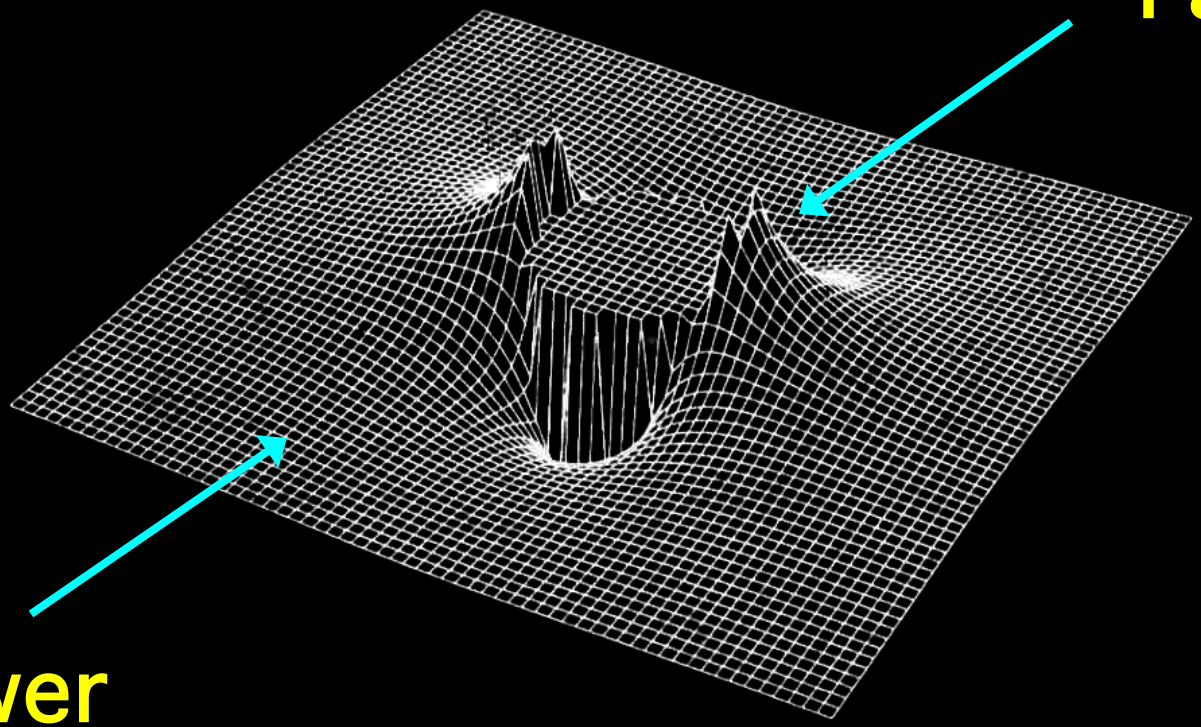


MRI Image showing activation of the Visual Cortex

From Belliveau, et al. Science Nov 1991

Susceptibility Contrast

Susceptibility-Induced Field Distortion in the Vicinity of a Microvessel ⊥ 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.

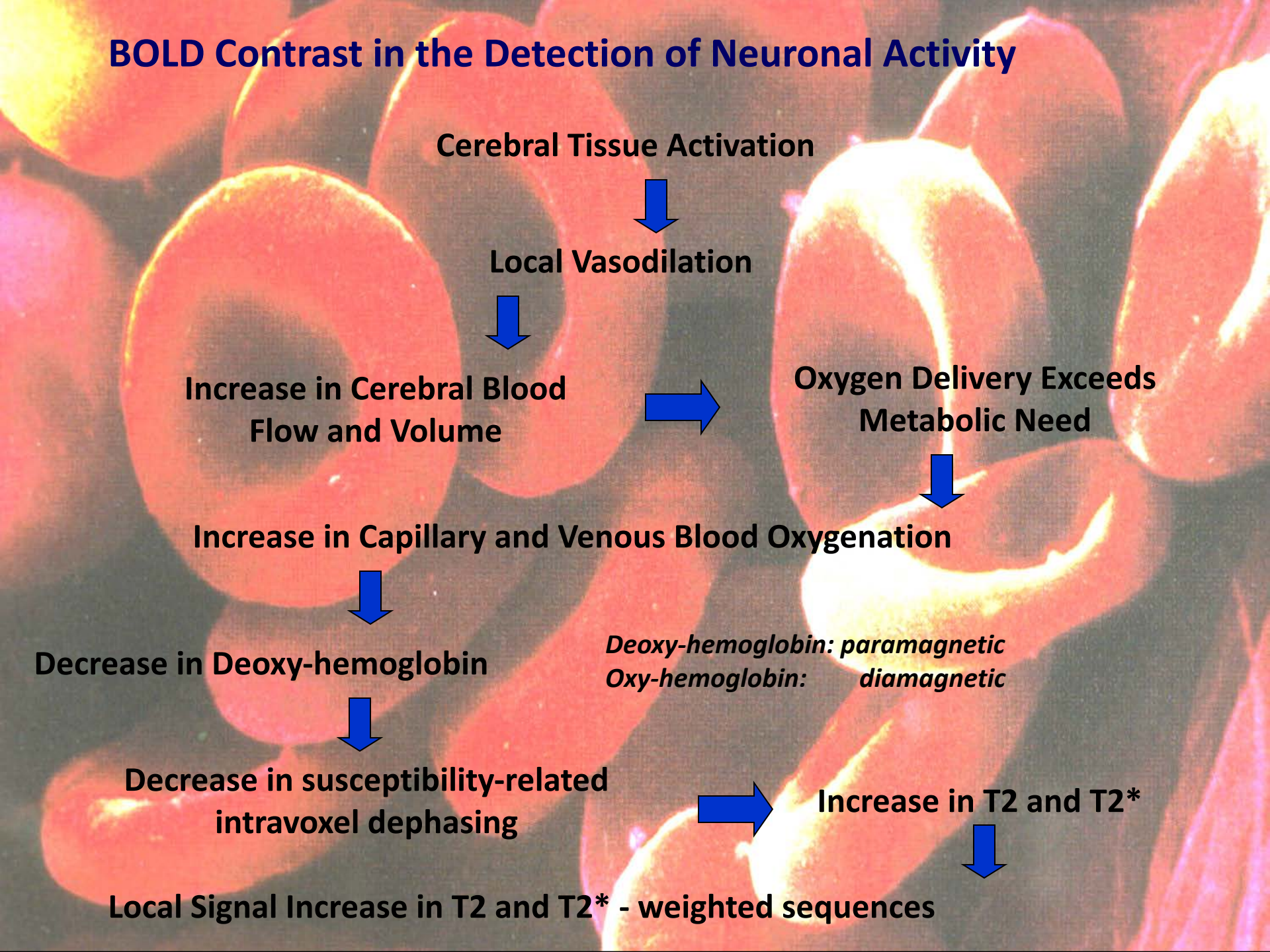
P. A. Bandettini, et al., (1992) "Time course EPI of human brain function during task activation." Magn. Reson. Med 25, 390-397.

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.

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

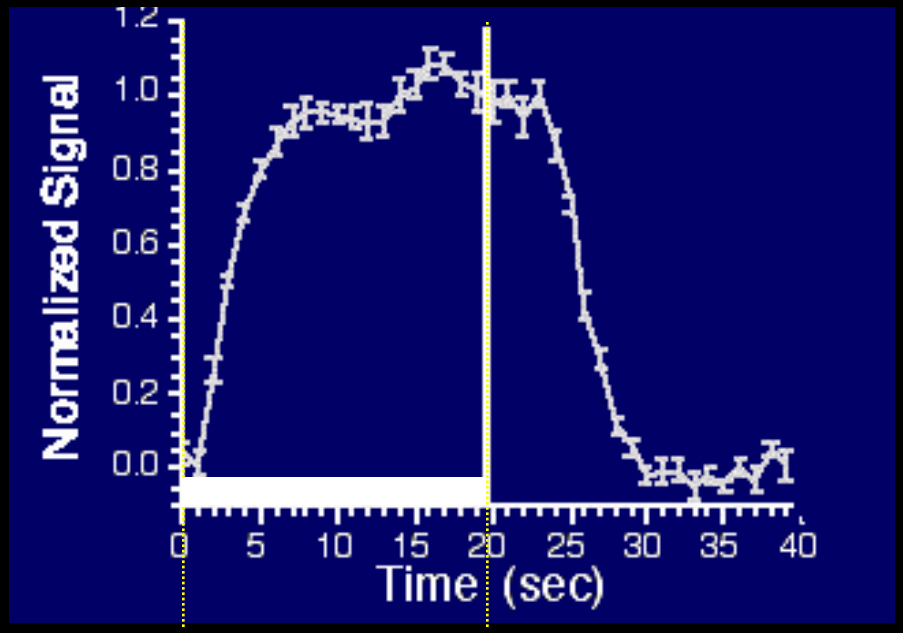
Quality of results and importance of the findings depends on type of question asked, experimental method, and analysis method...

BOLD Contrast in the Detection of Neuronal Activity

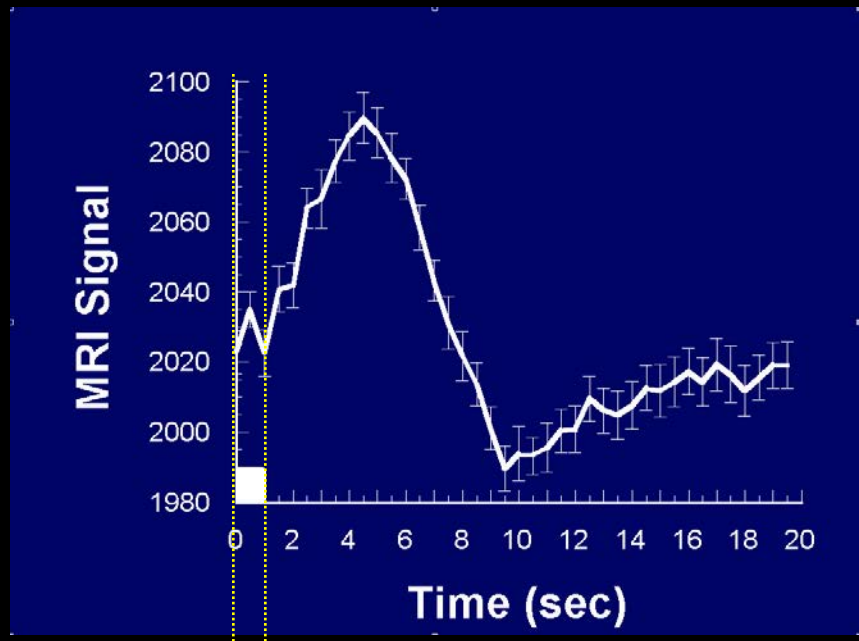


The BOLD Signal

Blood Oxygenation Level Dependent (BOLD) signal changes

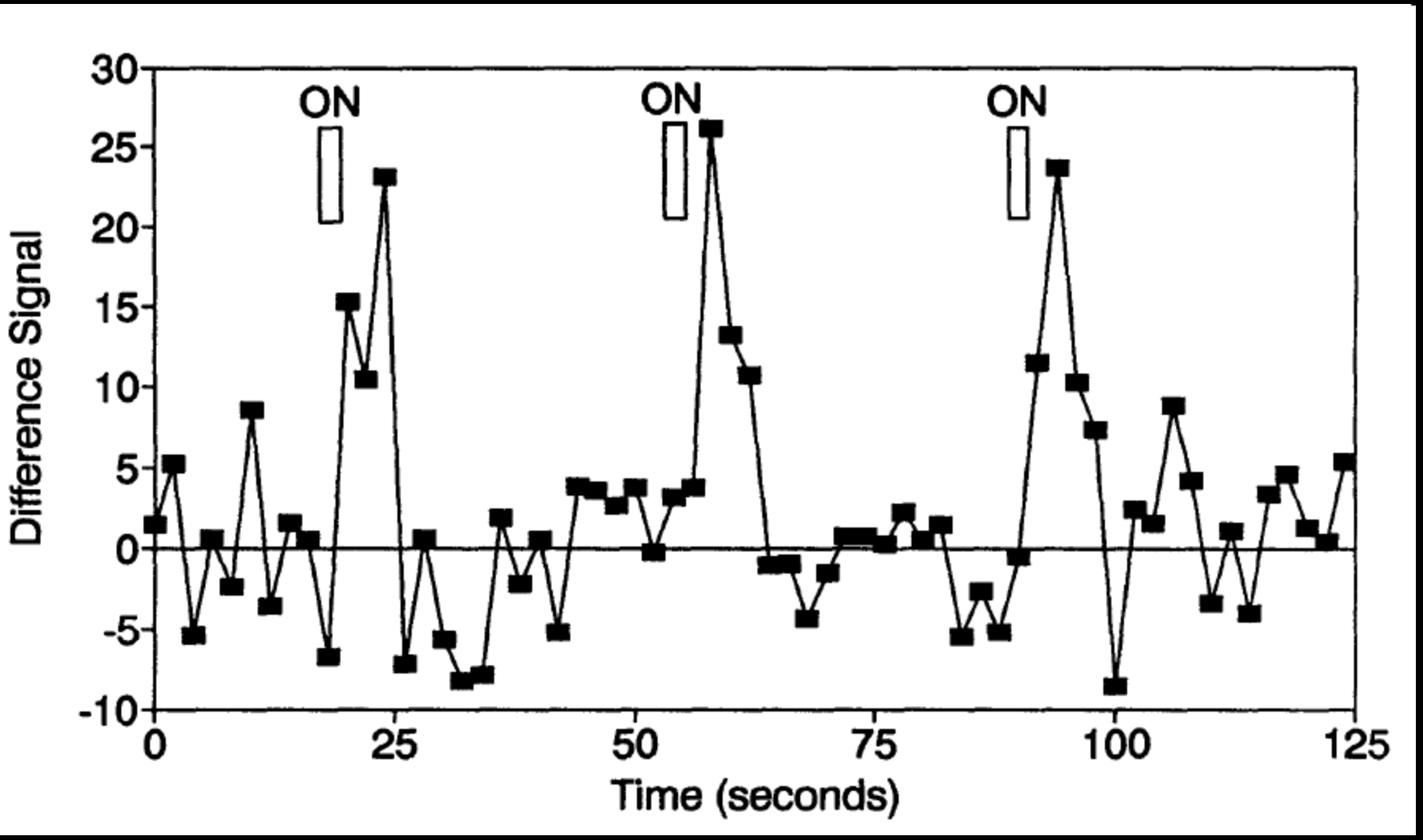


task



task

First Event-related fMRI Results

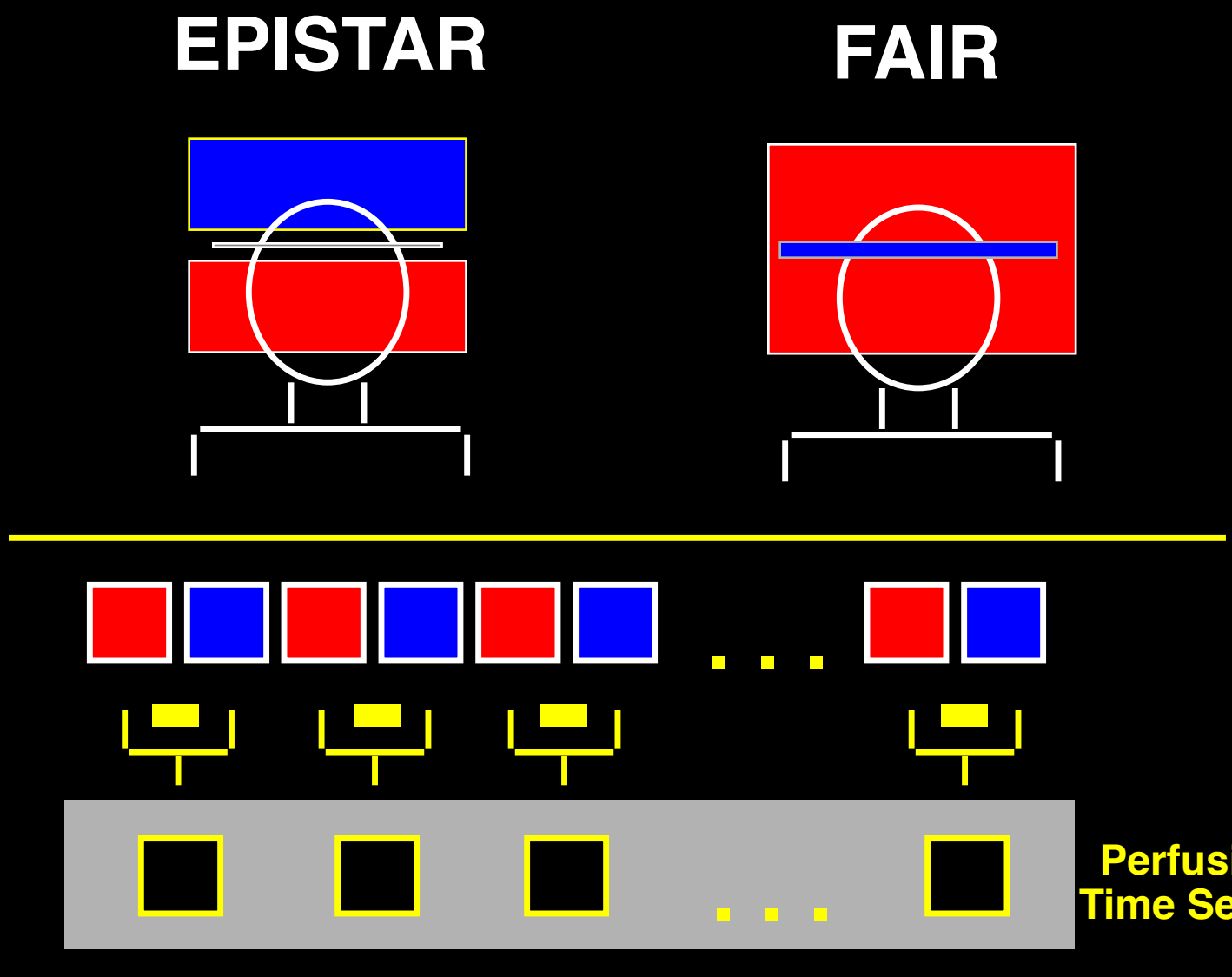


Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

1991-1992

1992-1999

Blood Perfusion



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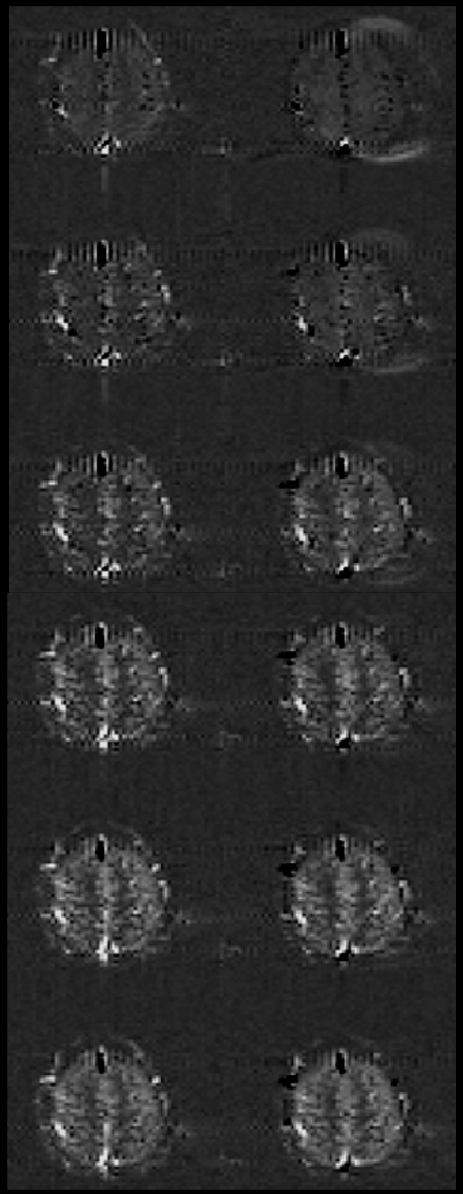
200		
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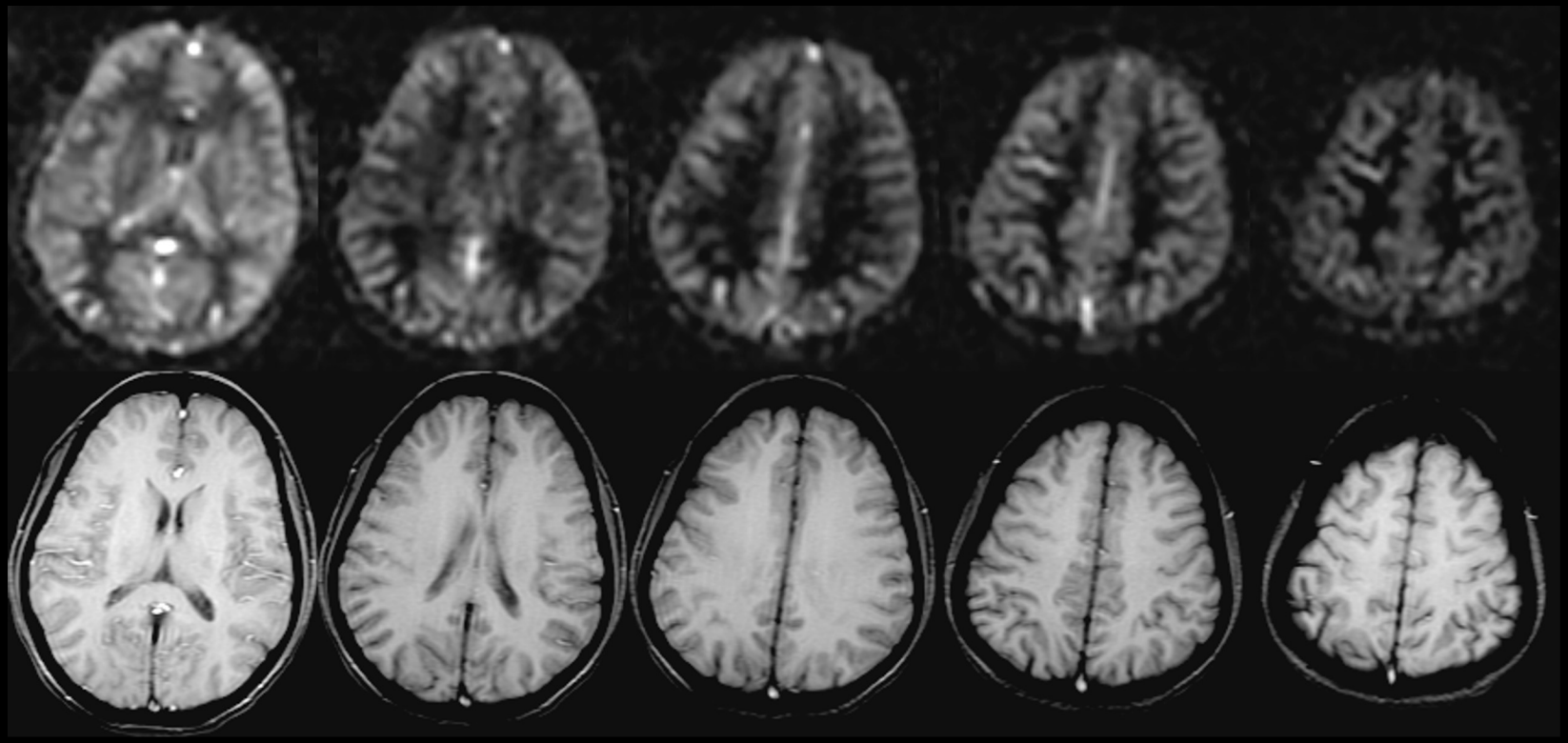


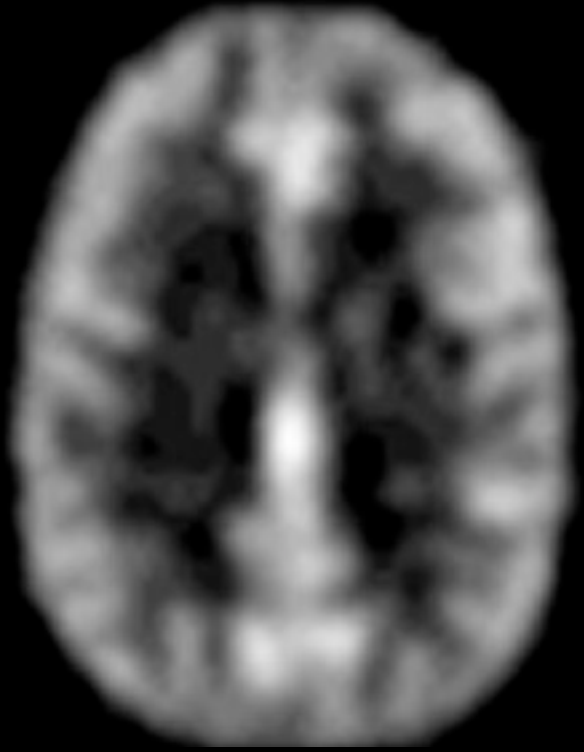
Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) “Magnetic resonance imaging of perfusion using spin-inversion of arterial water.” Proc. Natl. Acad. Sci. USA 89, 212-216.

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.

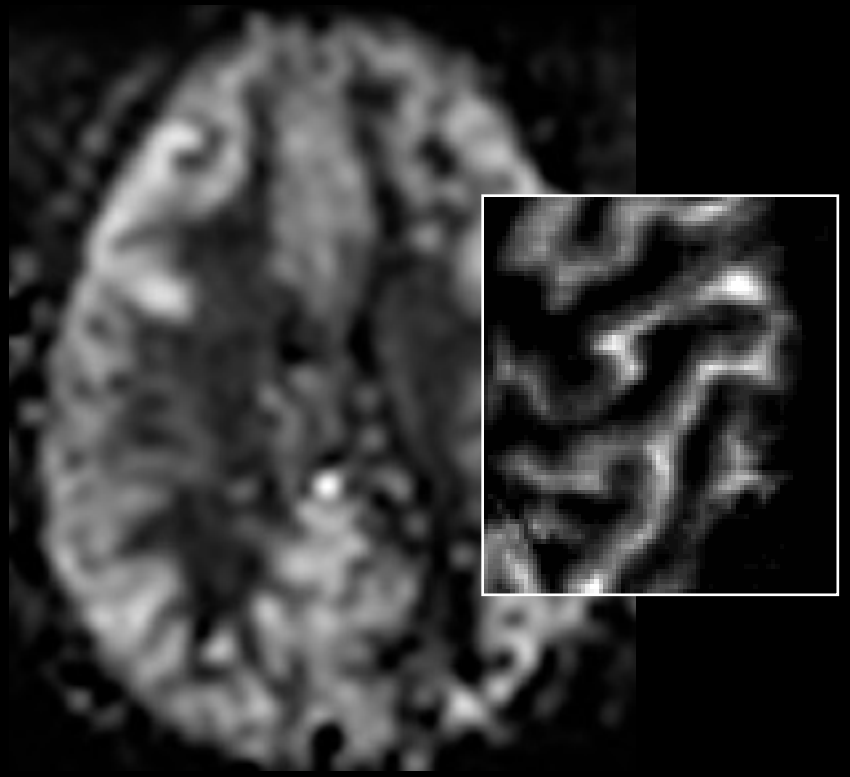
Kim, S.-G. (1995) “Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping.” Magn. Reson. Med. **34**, 293-301.

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

Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

Refinements

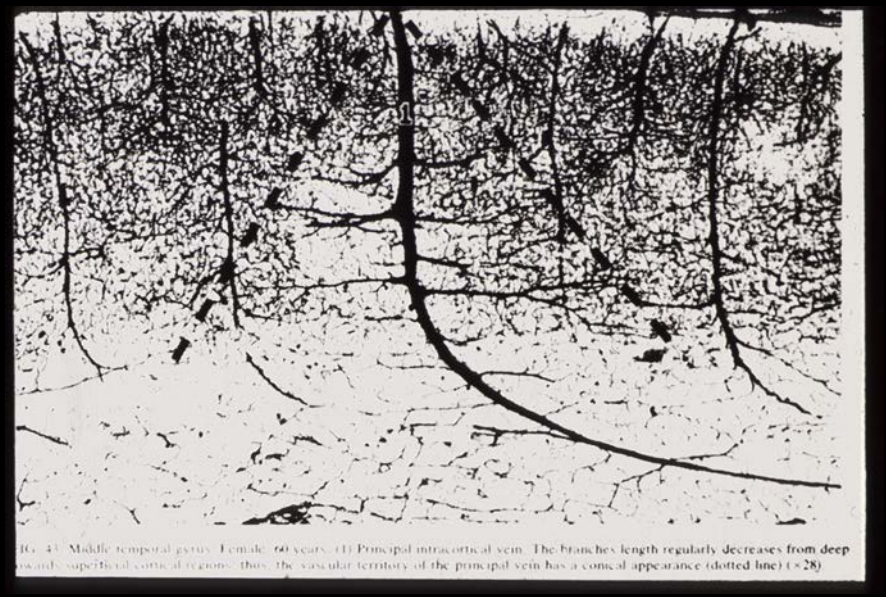
BOLD Contrast Interpretation

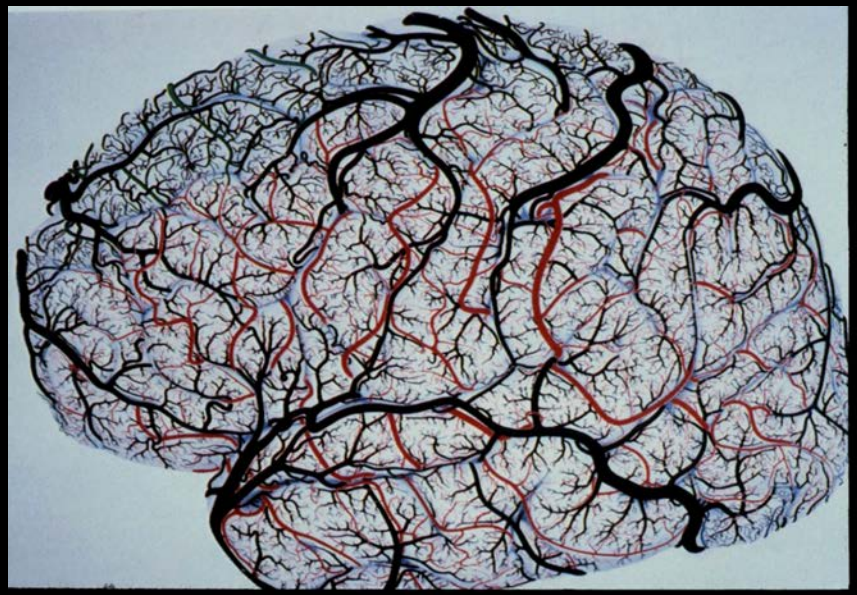
Dynamics, Paradigm Design and Processing

Applications

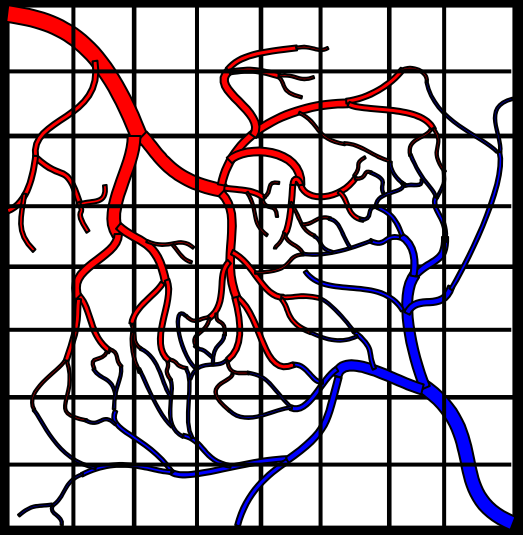
The Neuroscientists' Challenge:

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





Neuronal Activation



Measured Signal

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Hemodynamics

?

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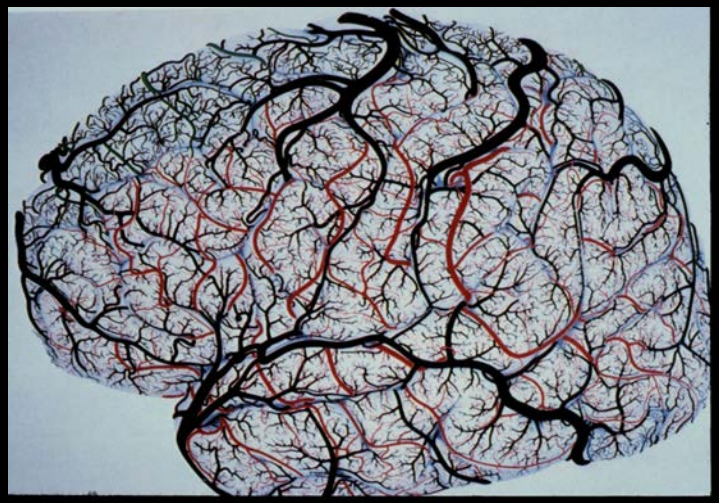
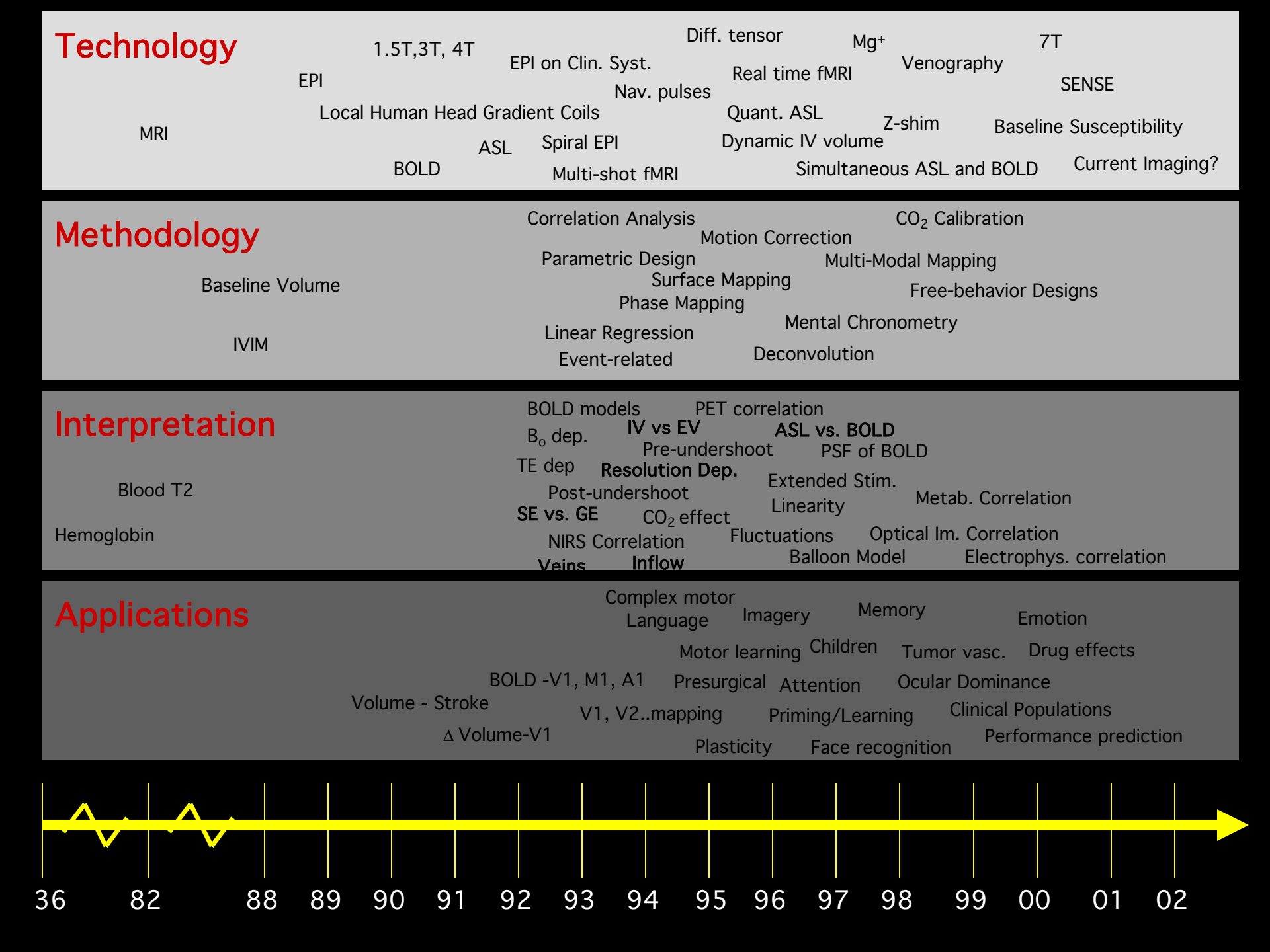
Noise

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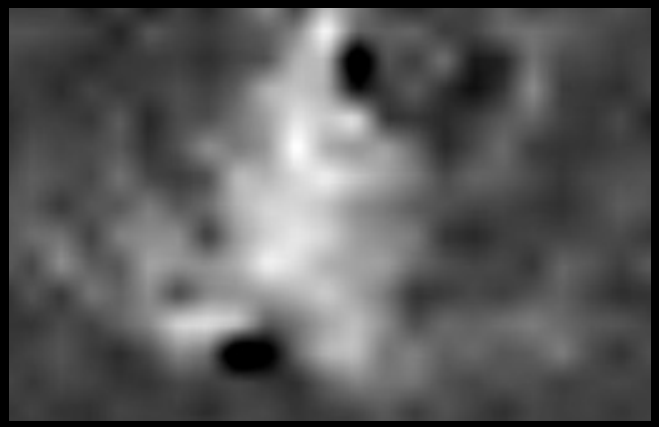
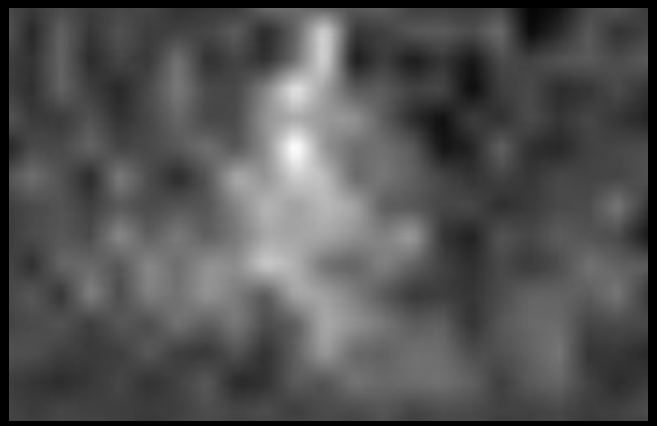
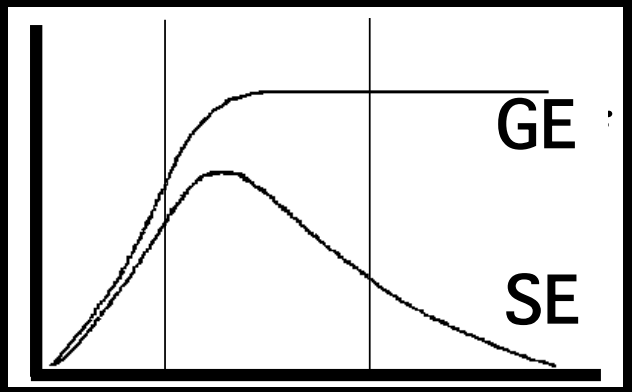




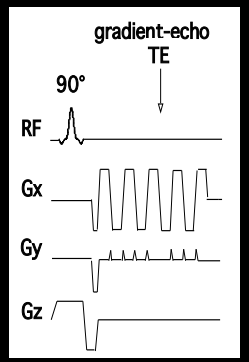
Contrast

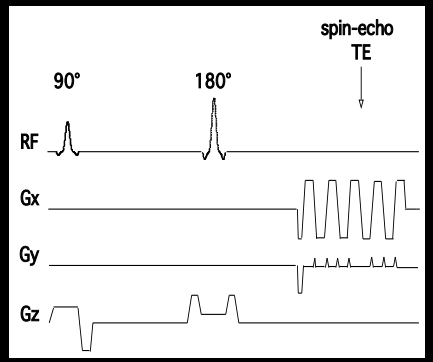


2.5 to 3 μm 3 to 15 μm 15 to ∞ μm

compartment size

Gradient - Echo





Spin - Echo

T1 - weighted

Flow weighted

T2* weighted

BOLD weighted

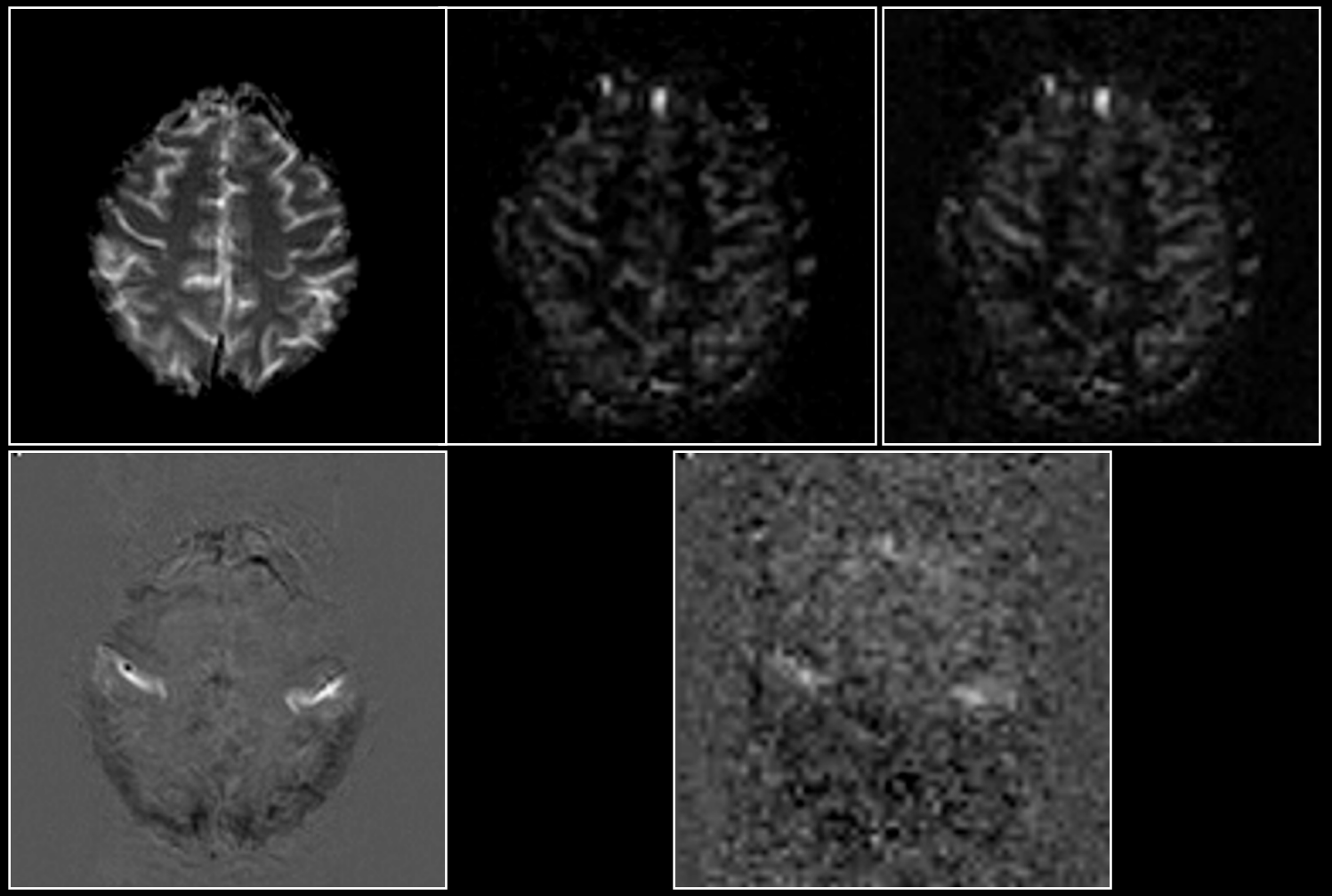
T1 and T2* weighted

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

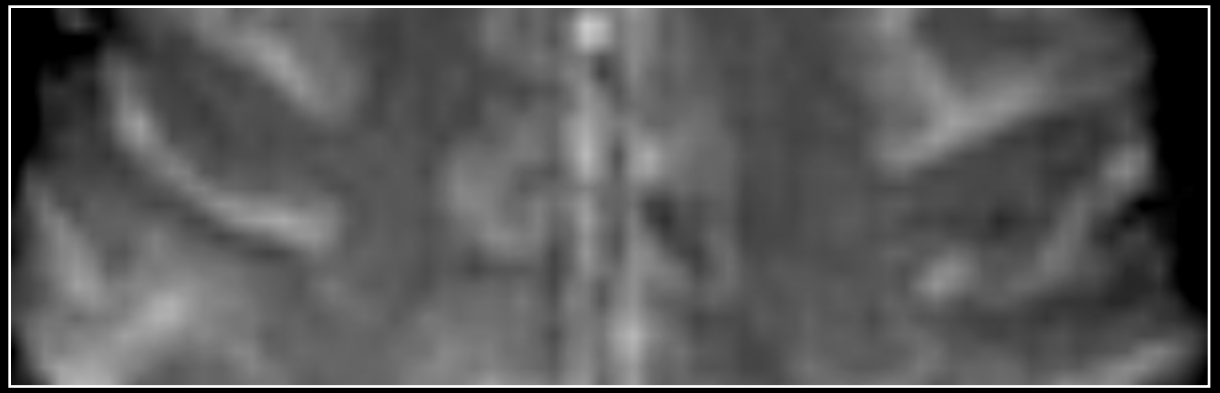
Perfusion

BOLD *Rest* *Activation*

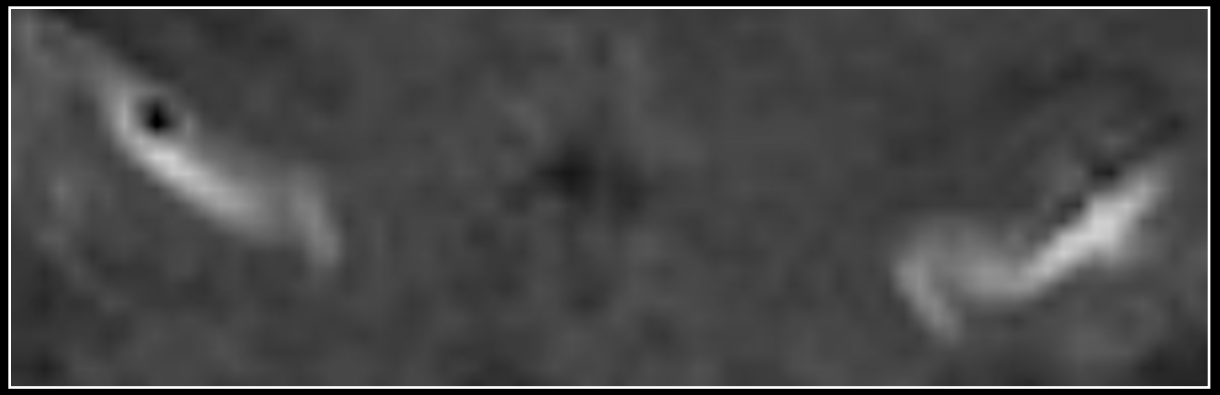


P. A. Bandettini, E. C. Wong, Magnetic resonance imaging of human brain function: principles, practicalities, and possibilities, *in* "Neurosurgery Clinics of North America: Functional Imaging" (M. Haglund, Ed.), p.345-371, W. B. Saunders Co., 1997.

Anatomy



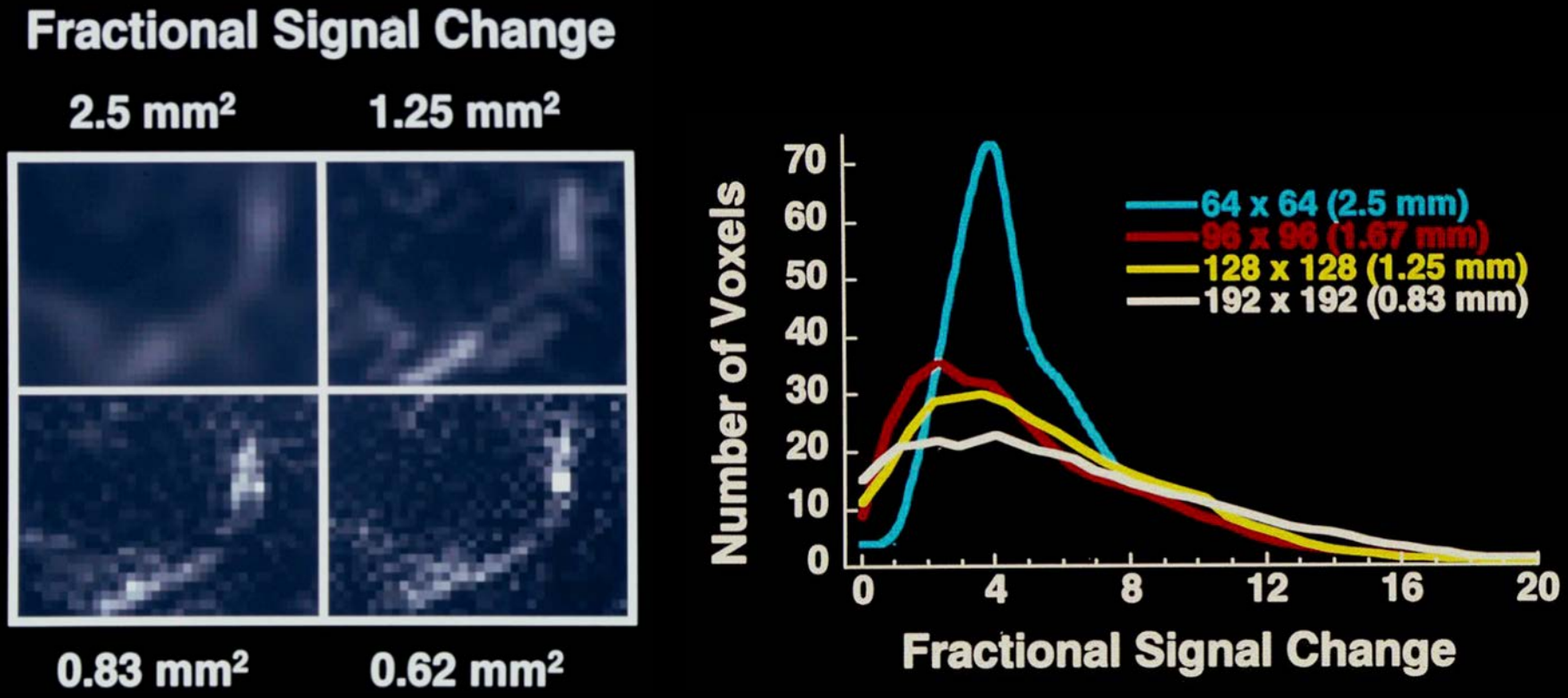
BOLD



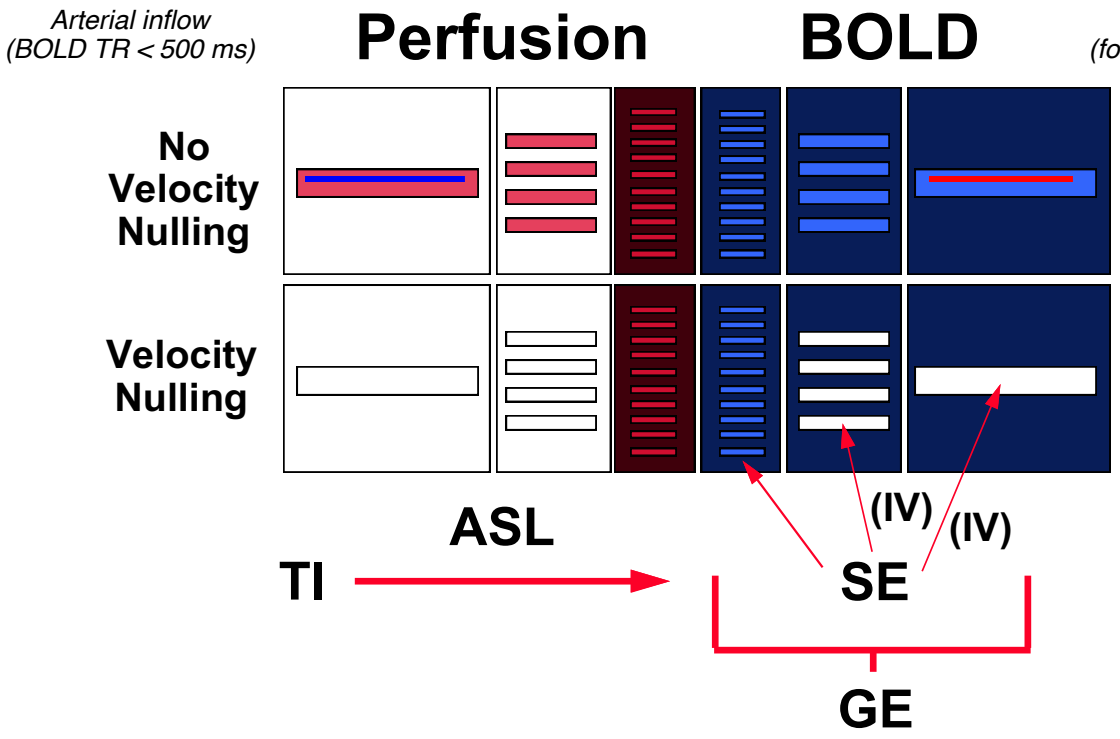
Perfusion

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

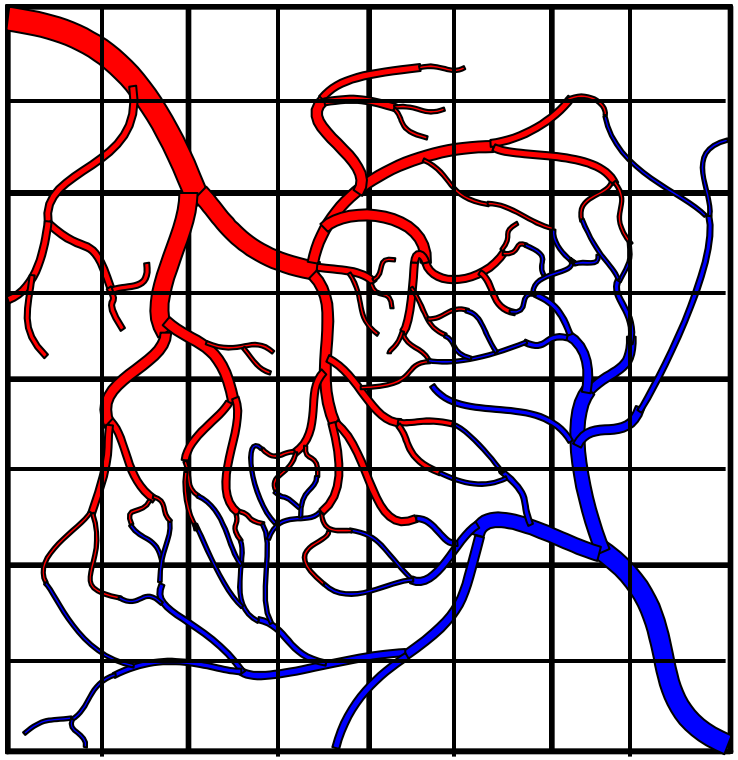


Jesmanowicz, P. A. Bandettini, J. S. Hyde, (1998) "Single shot half k-space high resolution EPI for fMRI at 3T." *Magn. Reson. Med.* 40, 754-762.



Pulse Sequence Sensitivity

Spatial Heterogeneity

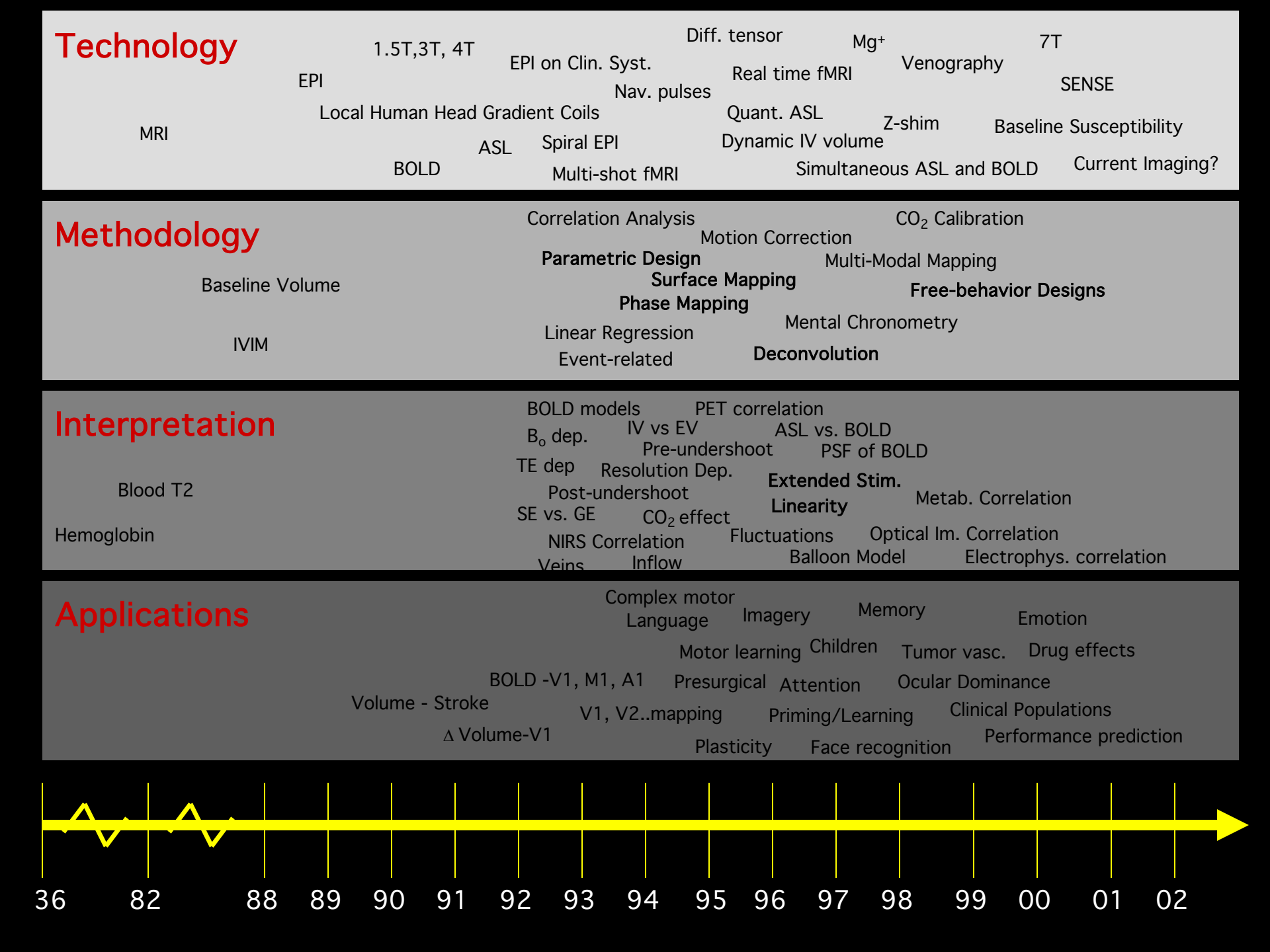


Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications


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
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CO2 Calibration
Motion Correction
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Multi-Modal Mapping
Surface Mapping
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Free-behavior Designs
Phase Mapping
Mental Chronometry
Linear Regression
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Deconvolution
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Performance prediction
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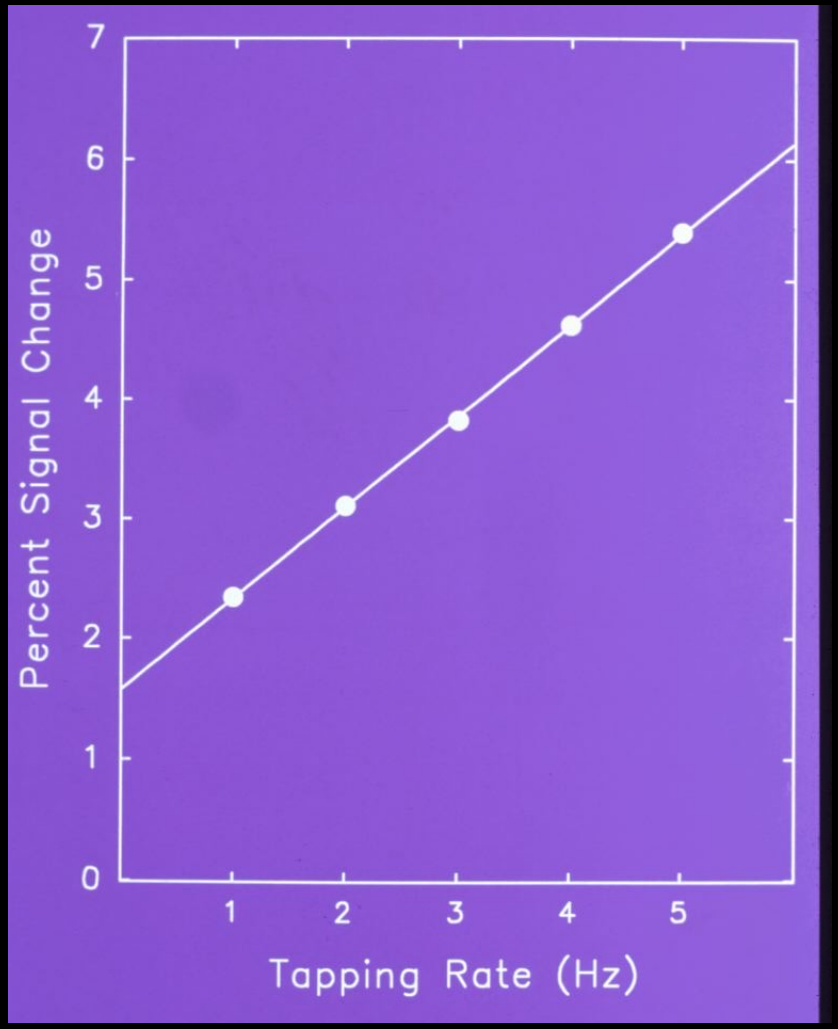
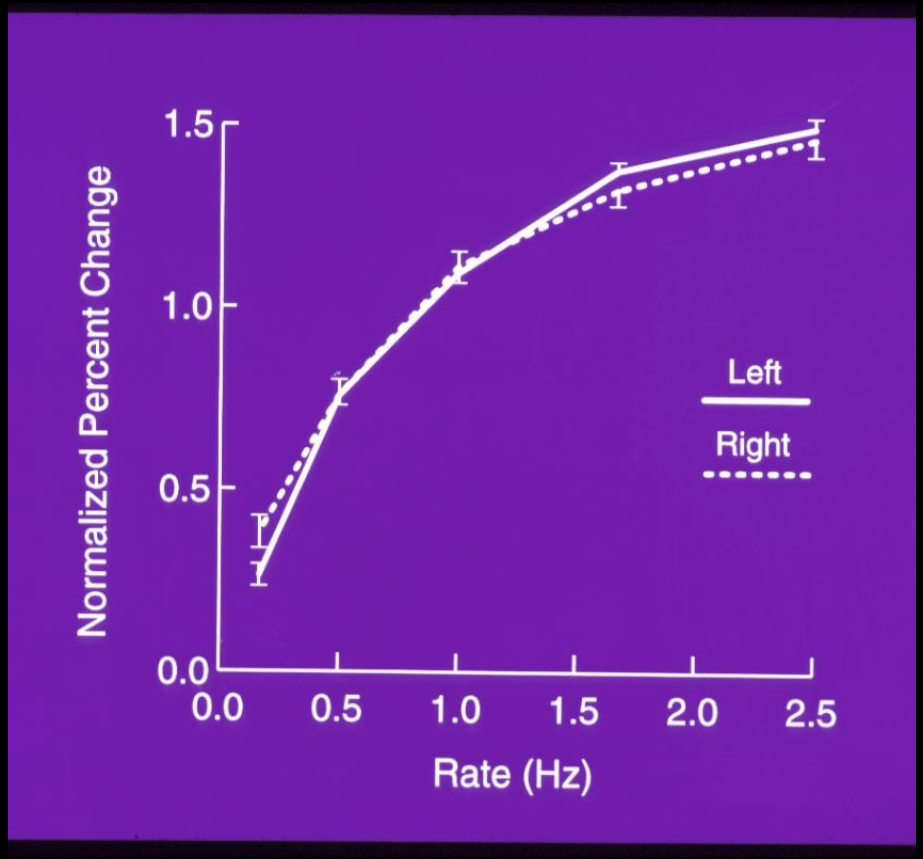
Motor Cortex

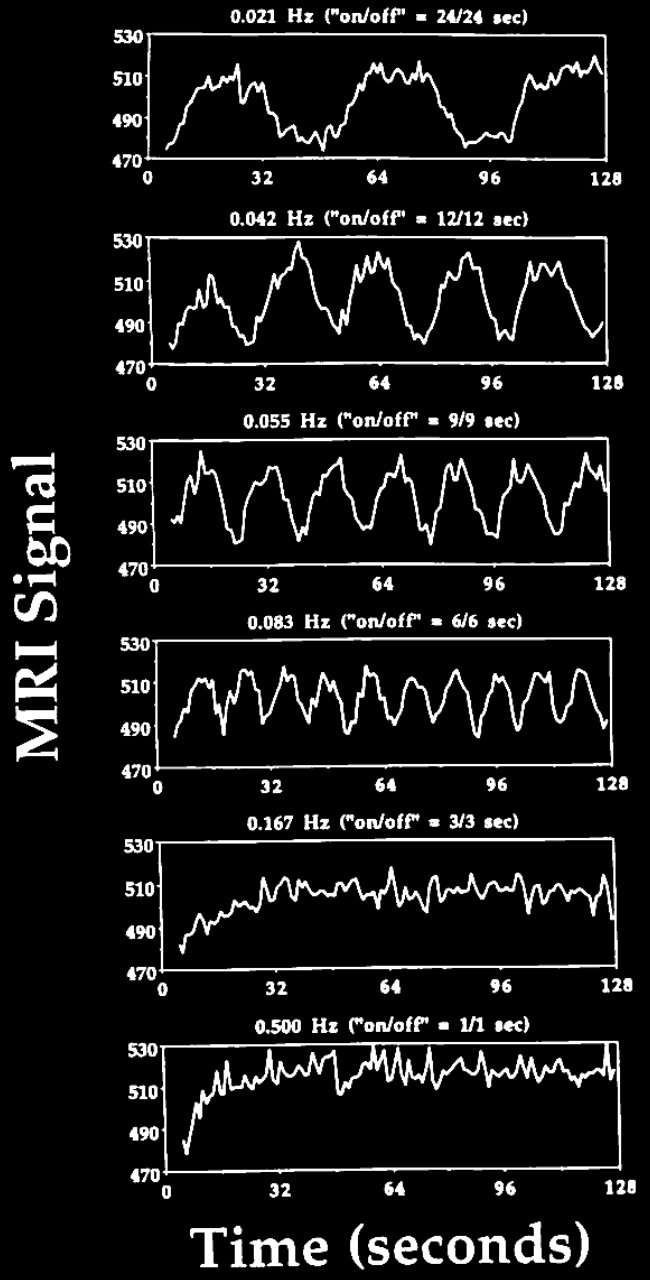


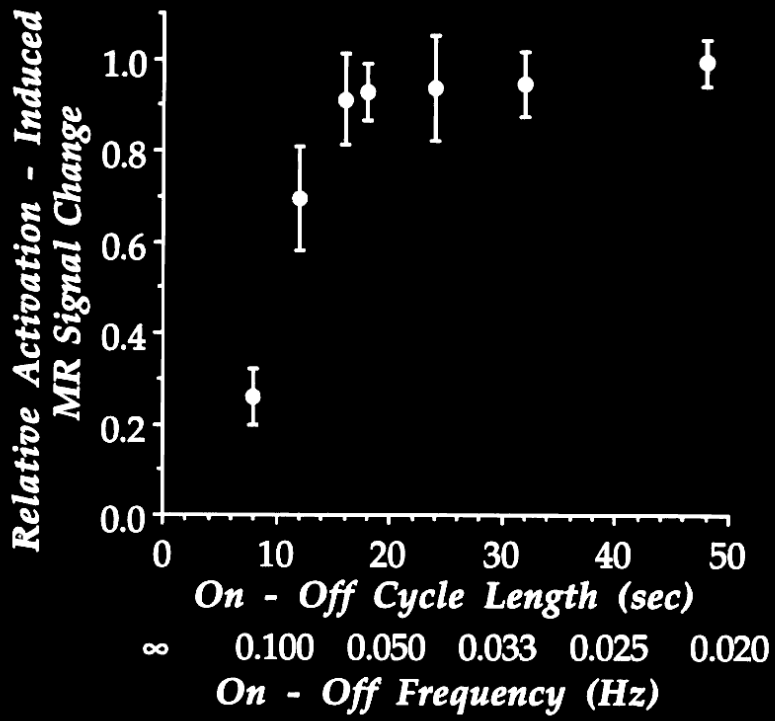
S. M. Rao et al, (1996) "Relationship between finger movement rate and functional magnetic resonance signal change in human primary motor cortex." *J. Cereb. Blood Flow and Met.* 16, 1250-1254.

Auditory Cortex



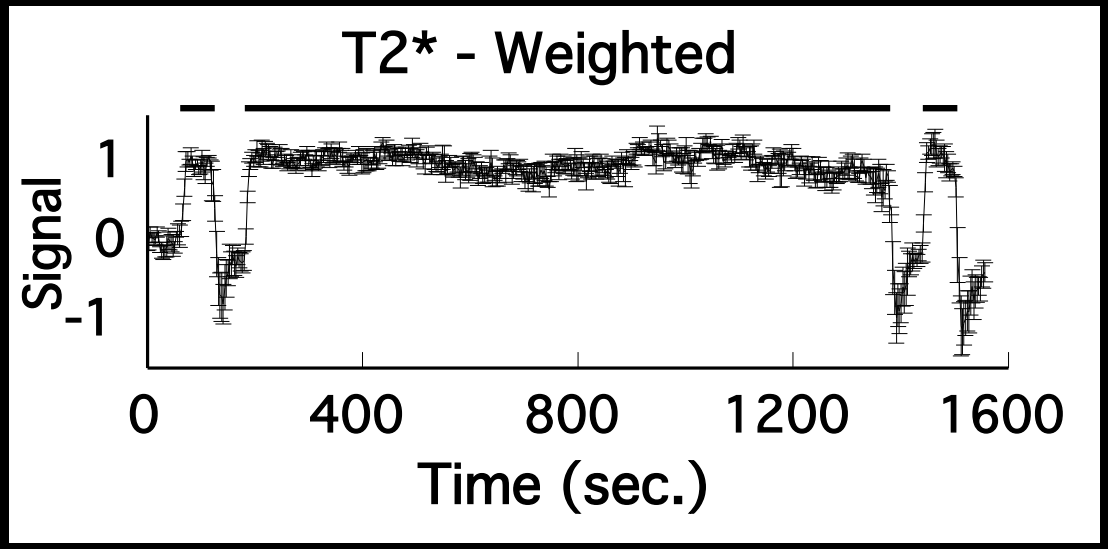
J. R. Binder, et al, (1994). "Effects of stimulus rate on signal response during functional magnetic resonance imaging of auditory cortex." *Cogn. Brain Res.* 2, 31-38



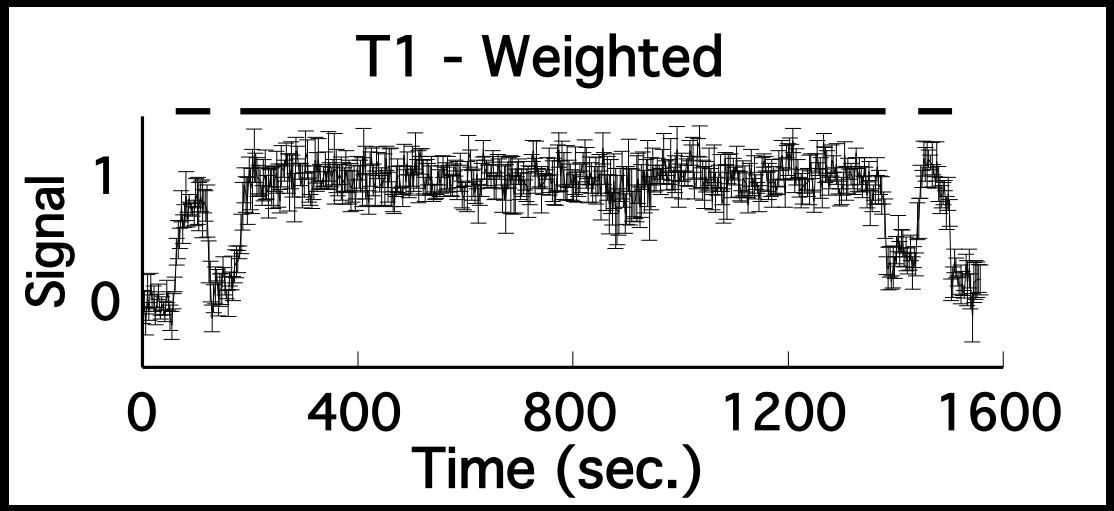


P. A. Bandettini, Functional MRI temporal resolution *in* "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

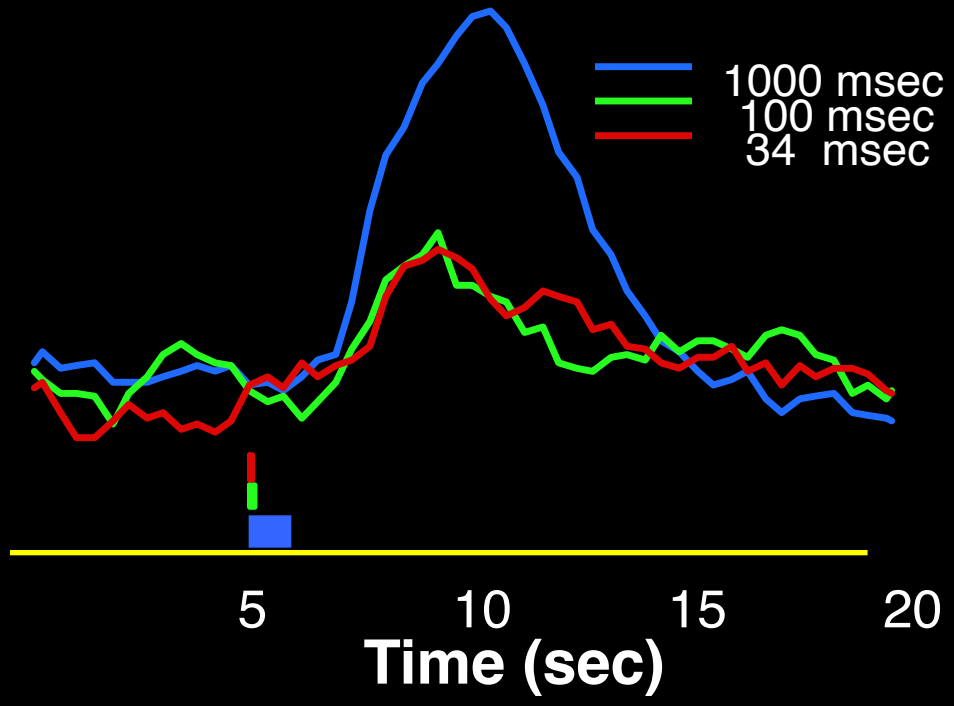
BOLD



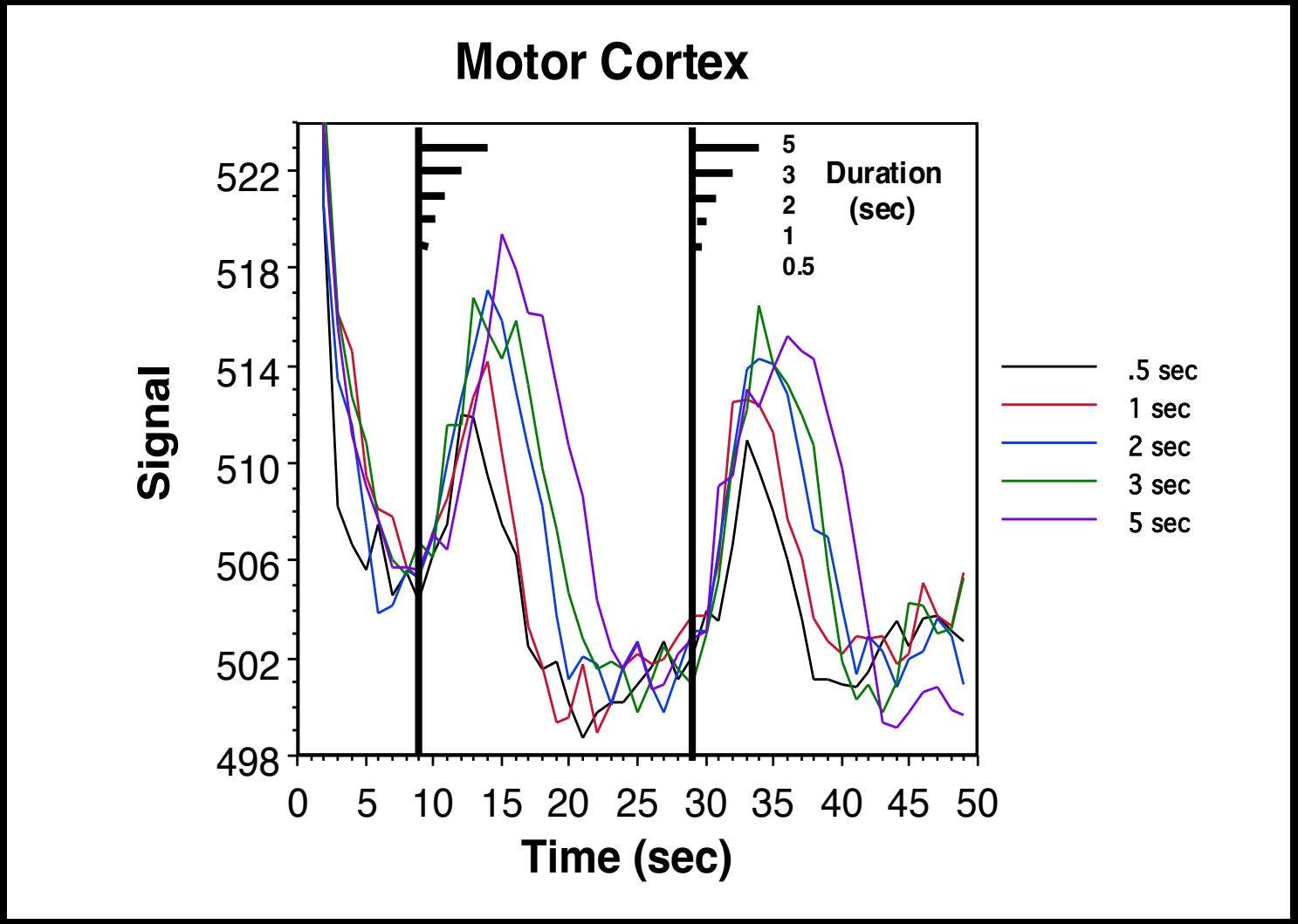
Flow



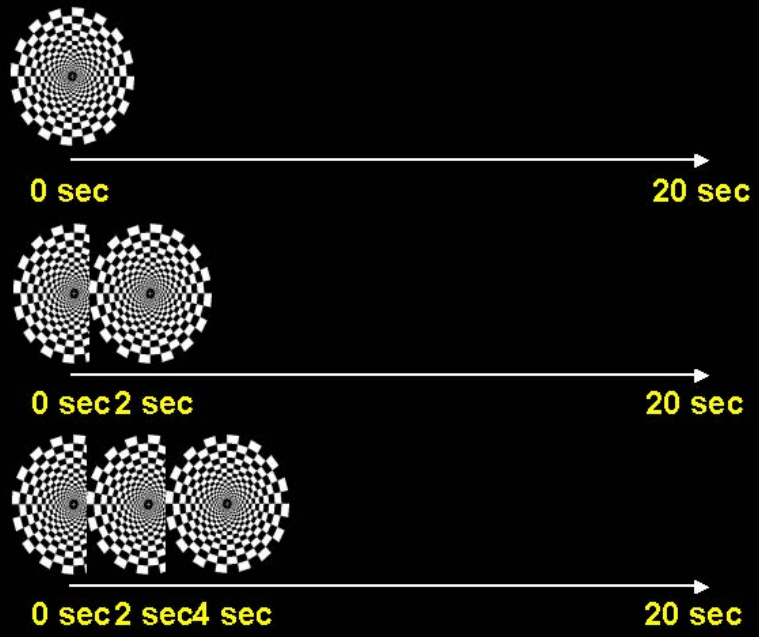
P. A. Bandettini, K. K. Kwong, T. L. Davis, R. B. H. Tootell, E. C. Wong, P. T. Fox, J. W. Belliveau, R. M. Weisskoff, B. R. Rosen, (1997). "Characterization of cerebral blood oxygenation and flow changes during prolonged brain activation." *Human Brain Mapping* 5, 93-109.



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).



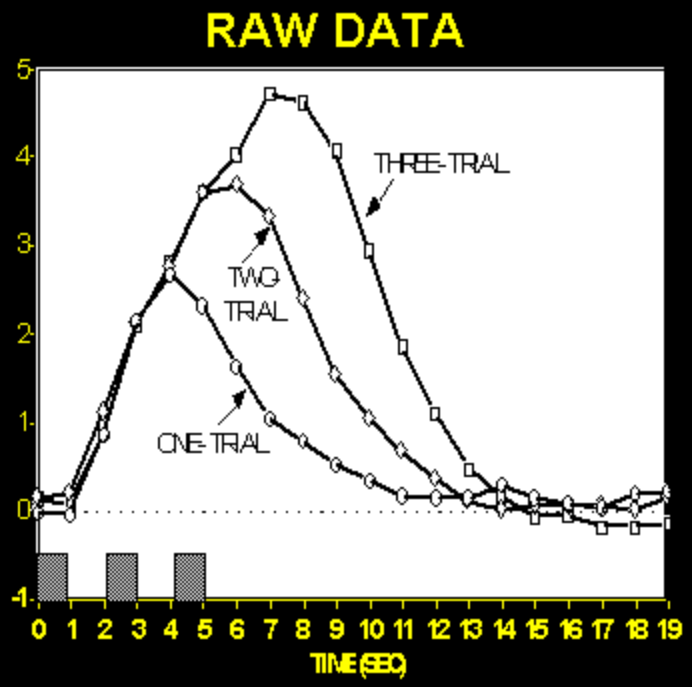
Bandettini, et al., The functional dynamics of blood oxygenation level contrast in the motor cortex, 12'th Proc. Soc. Magn. Reson. Med., New York, p. 1382. (1993).

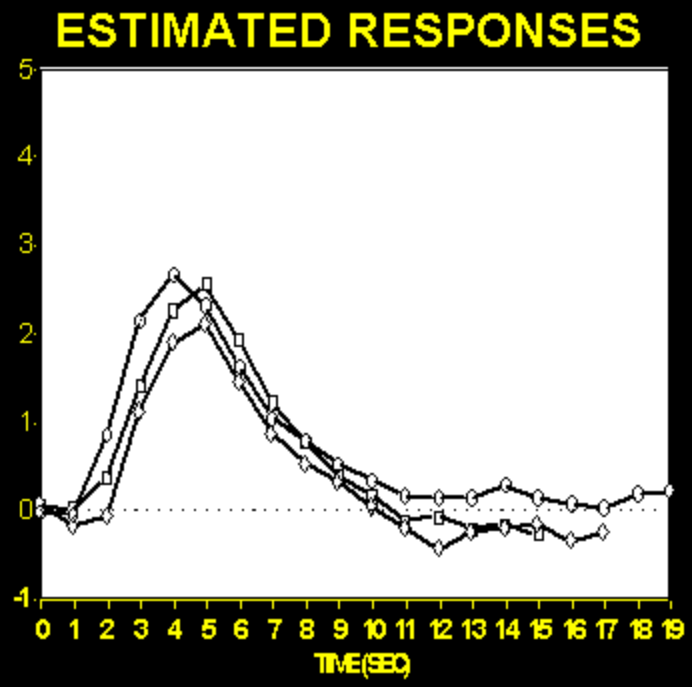


◆ Human Brain Mapping 5:329–340(1997) ◆

Selective Averaging of Rapidly Presented Individual Trials Using fMRI

Anders M. Dale* and Randy L. Buckner





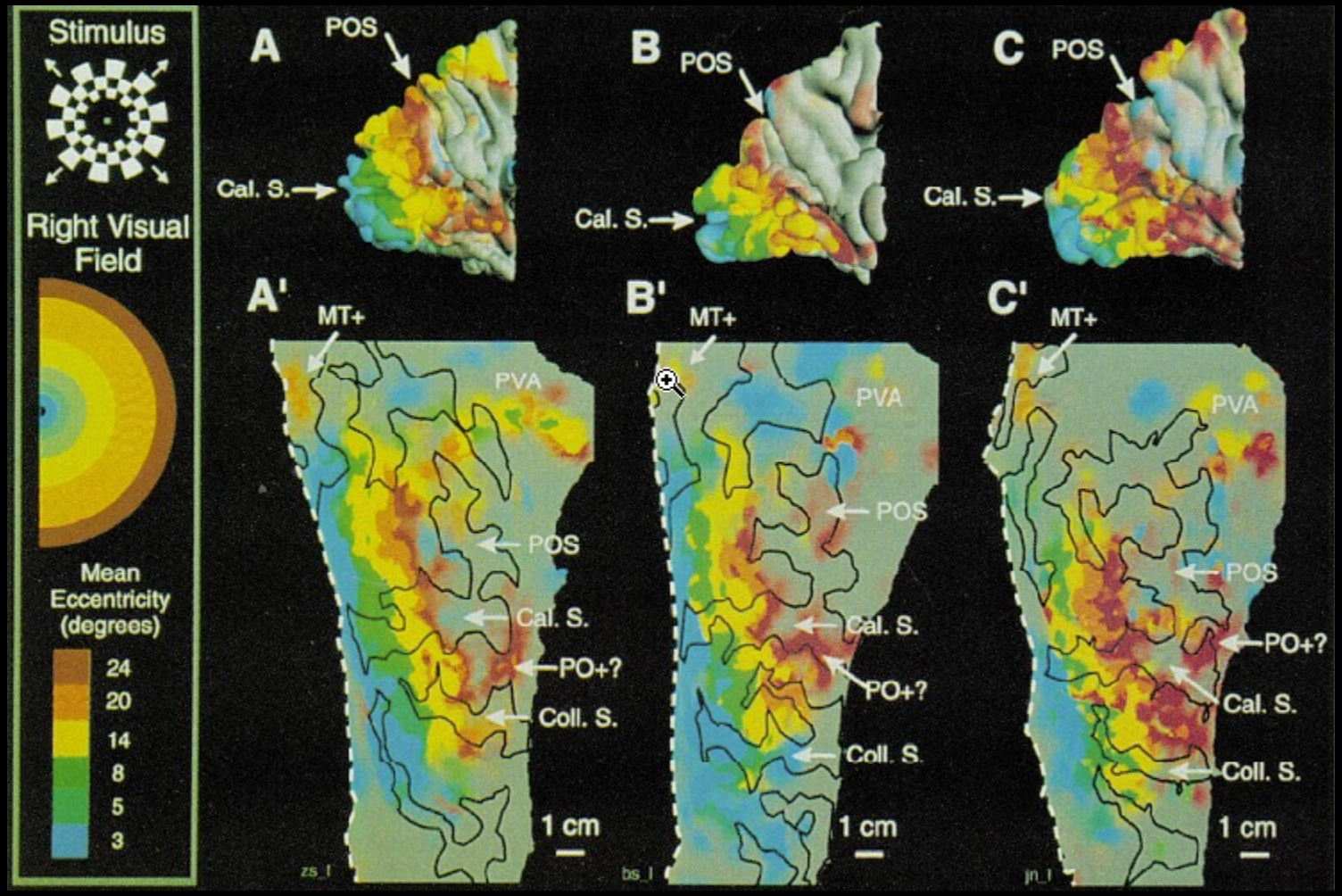
Neuronal Activation Input Strategies

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

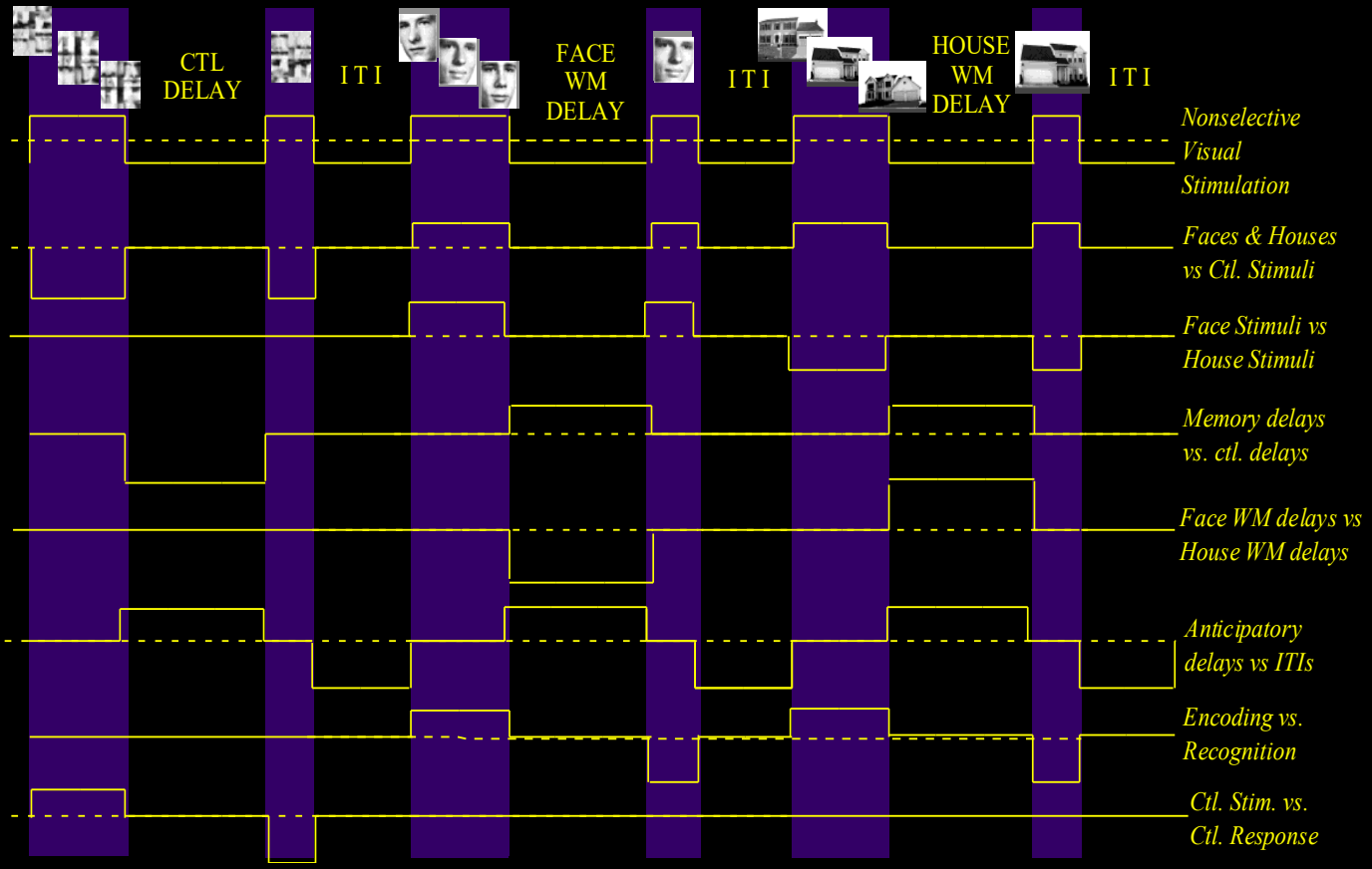
Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 2382–2386, March 1996
Neurobiology

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*



Example of a Set of Orthogonal Contrasts for Multiple Regression



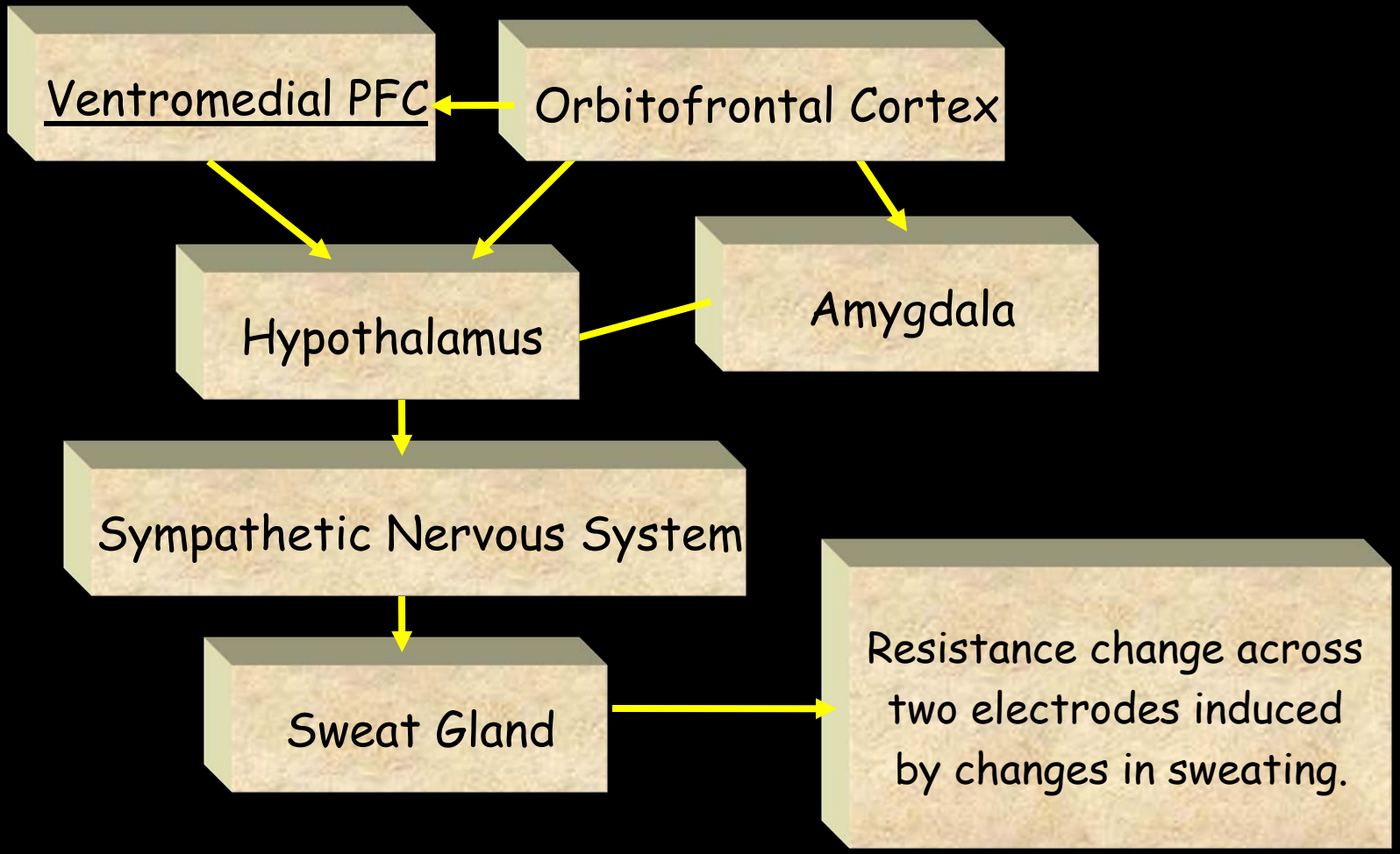
Courtney, S. M., L. G. Ungerleider, et al. (1997). "Transient and sustained activity in a distributed neural system for human working memory." Nature 386(6625): 608-11.

Free Behavior Design

Use a continuous measure as a reference function:

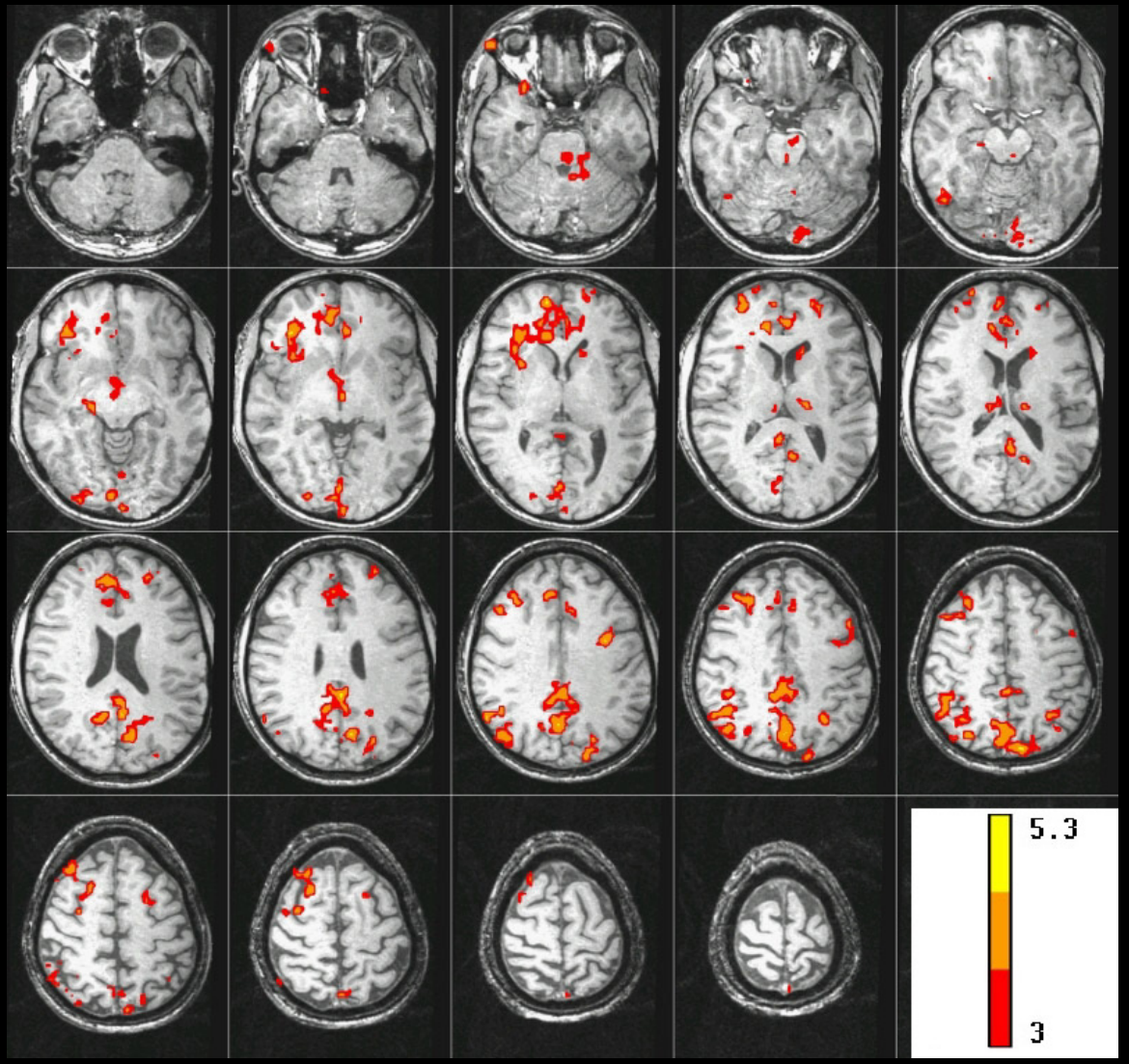
- Task performance
- Skin Conductance
- Heart, respiration rate..
- Eye position
- EEG

The Skin Conductance Response (SCR)



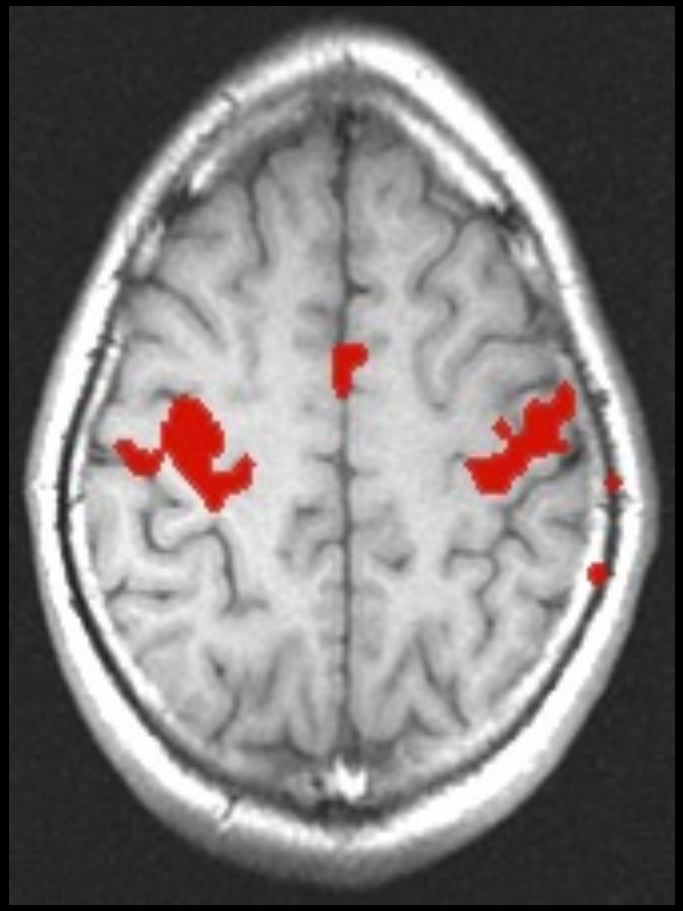
Patterson et al. (submitted)

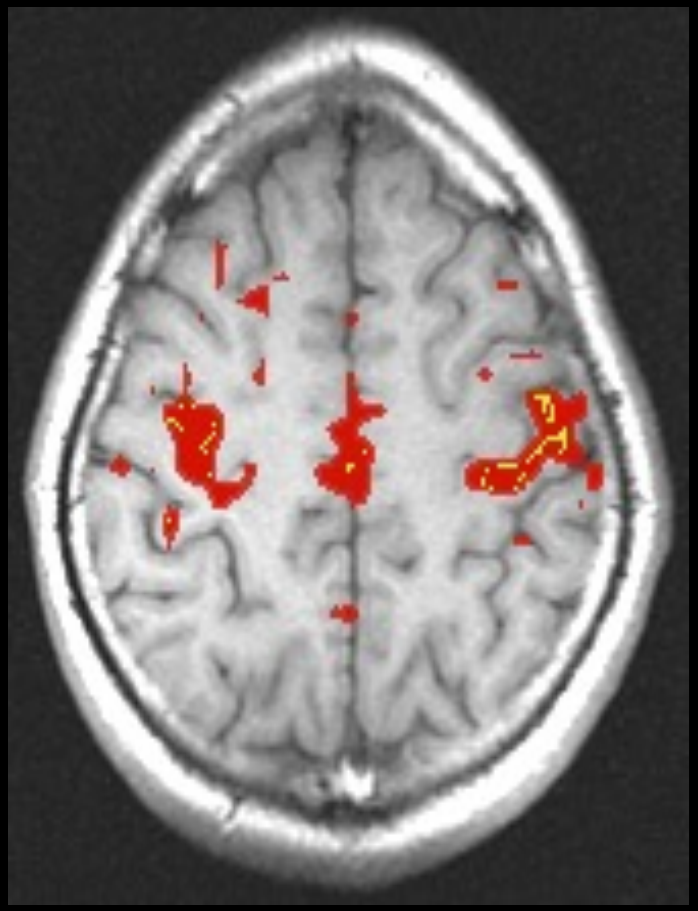
Brain activity correlated with SCR during "Rest"



Patterson et al. (submitted)

Resting Hemodynamic Autocorrelations





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

Refinements

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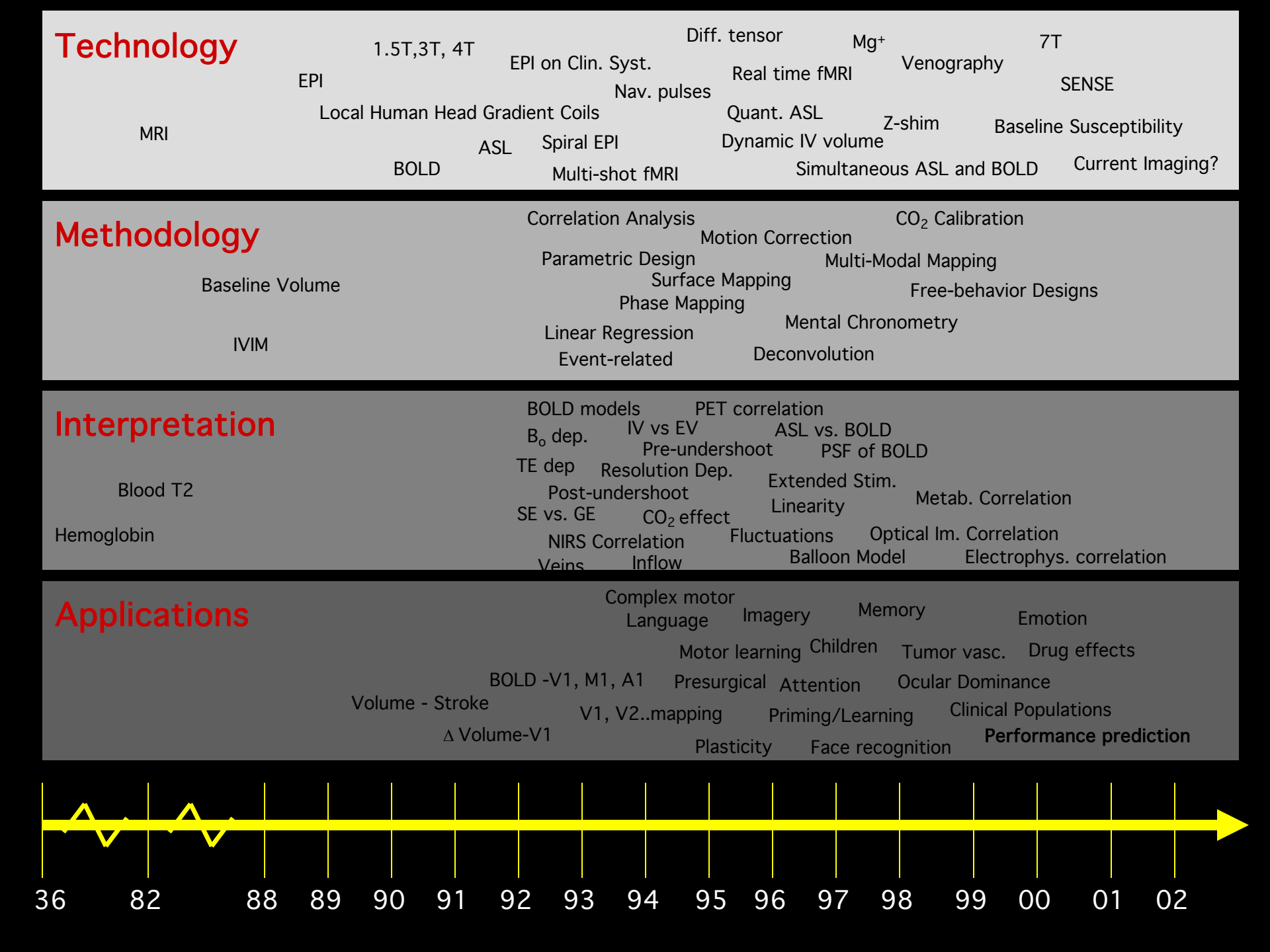
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V1, V2..mapping
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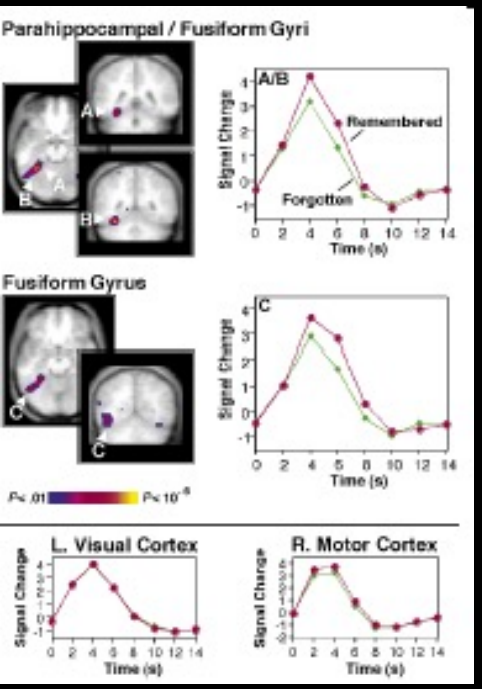
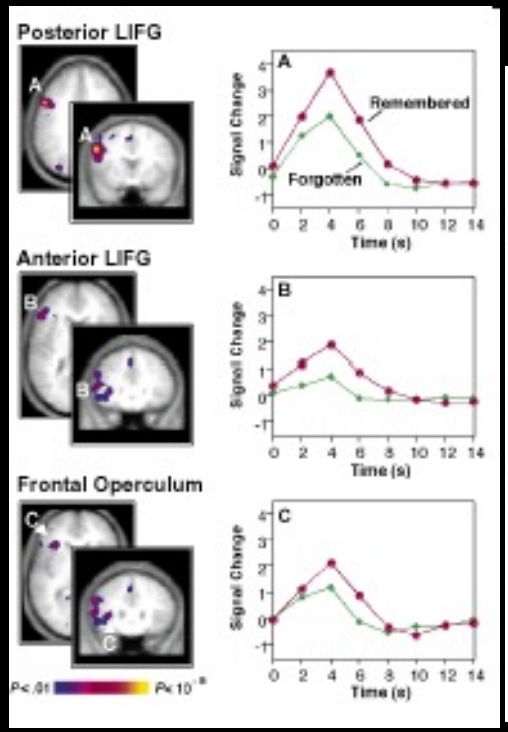
Building Memories: Remembering and Forgetting of Verbal Experiences as Predicted by Brain Activity

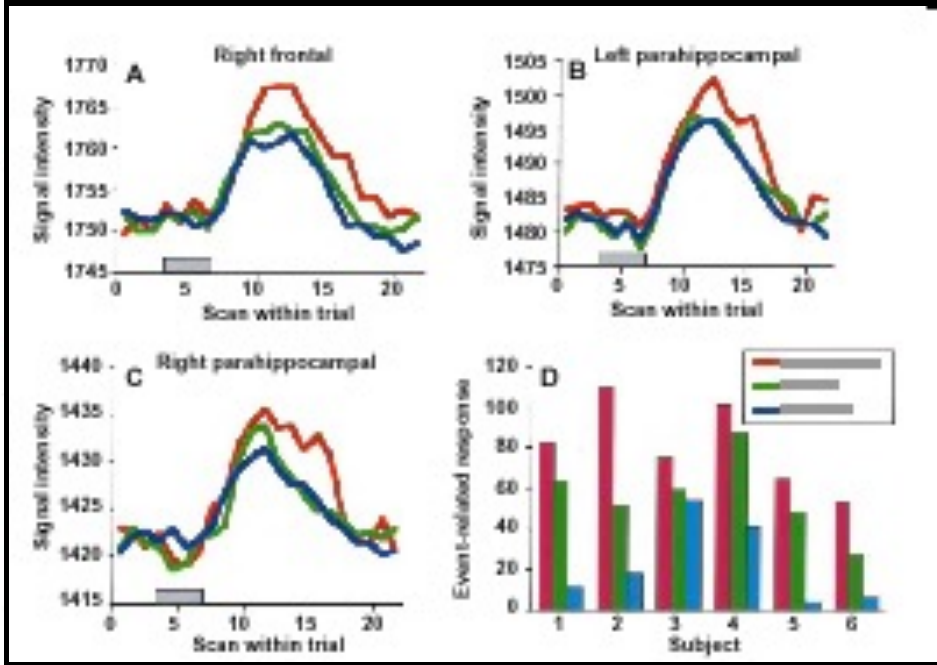
Anthony D. Wagner,* Daniel L. Schacter, Michael Rotte,† Wilma Koutstaal, Anat Maril, Anders M. Dale, Bruce R. Rosen, Randy L. Buckner

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





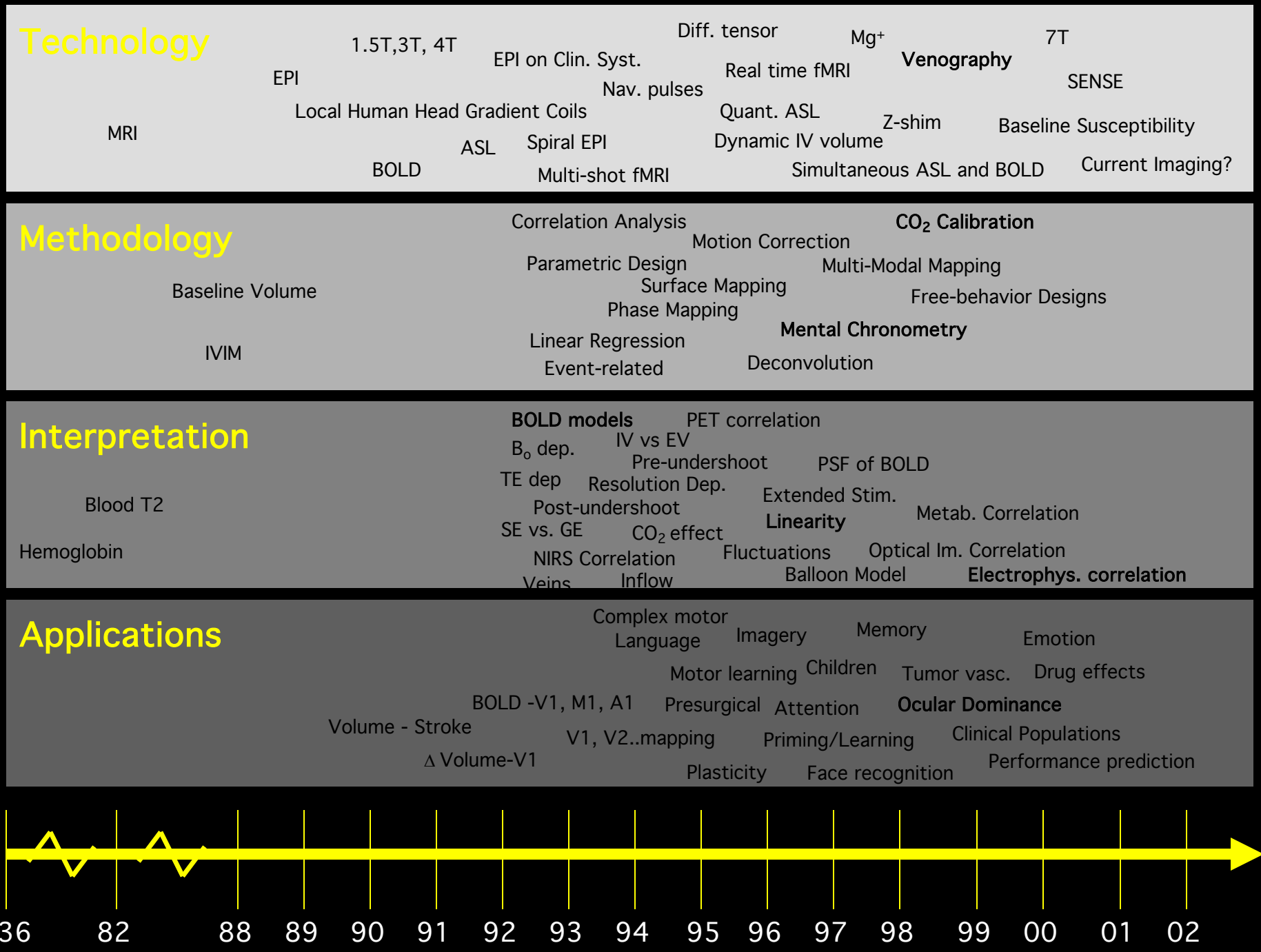


Science, Vol 281, August 1998

Past

Present

Future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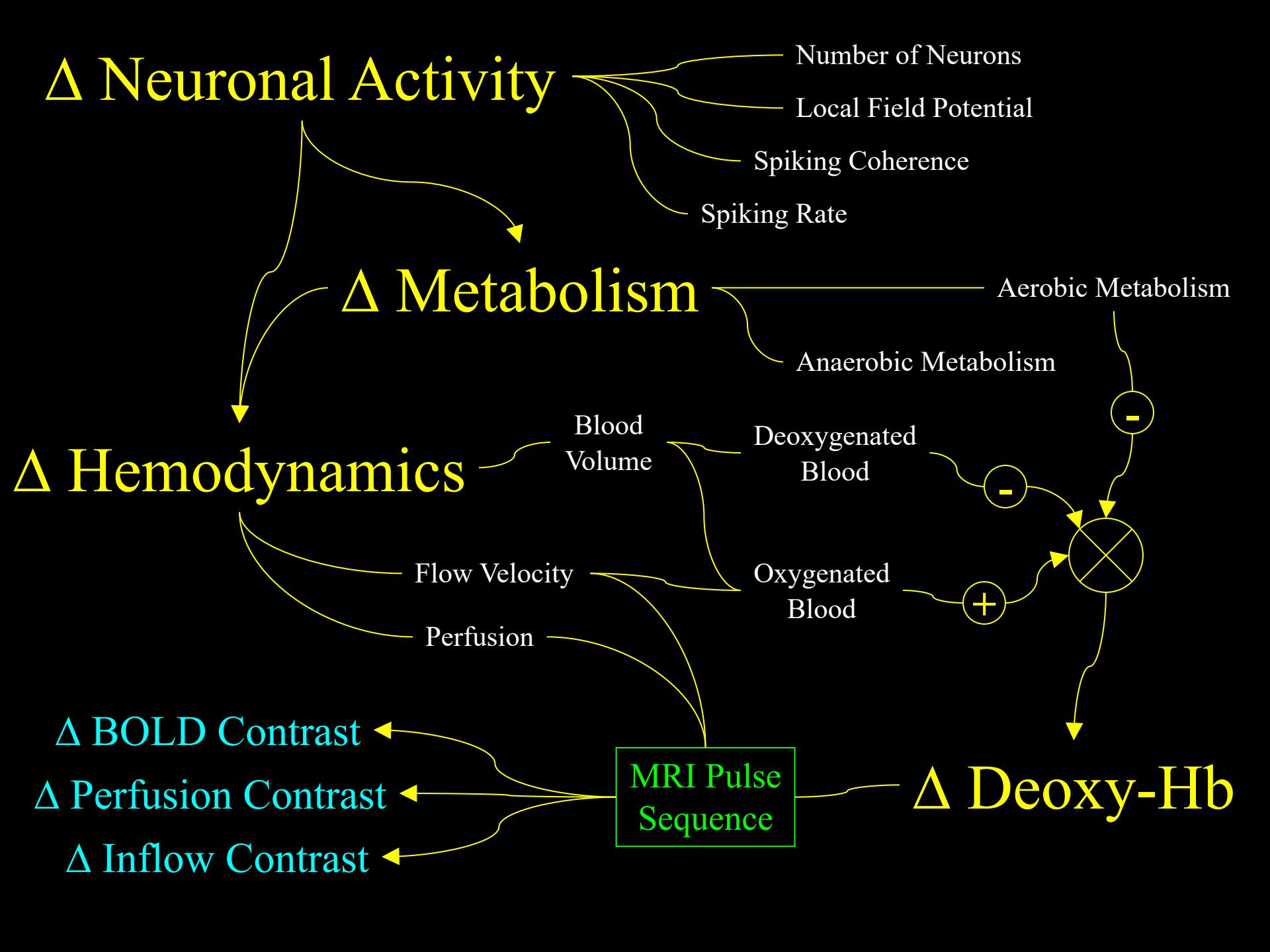
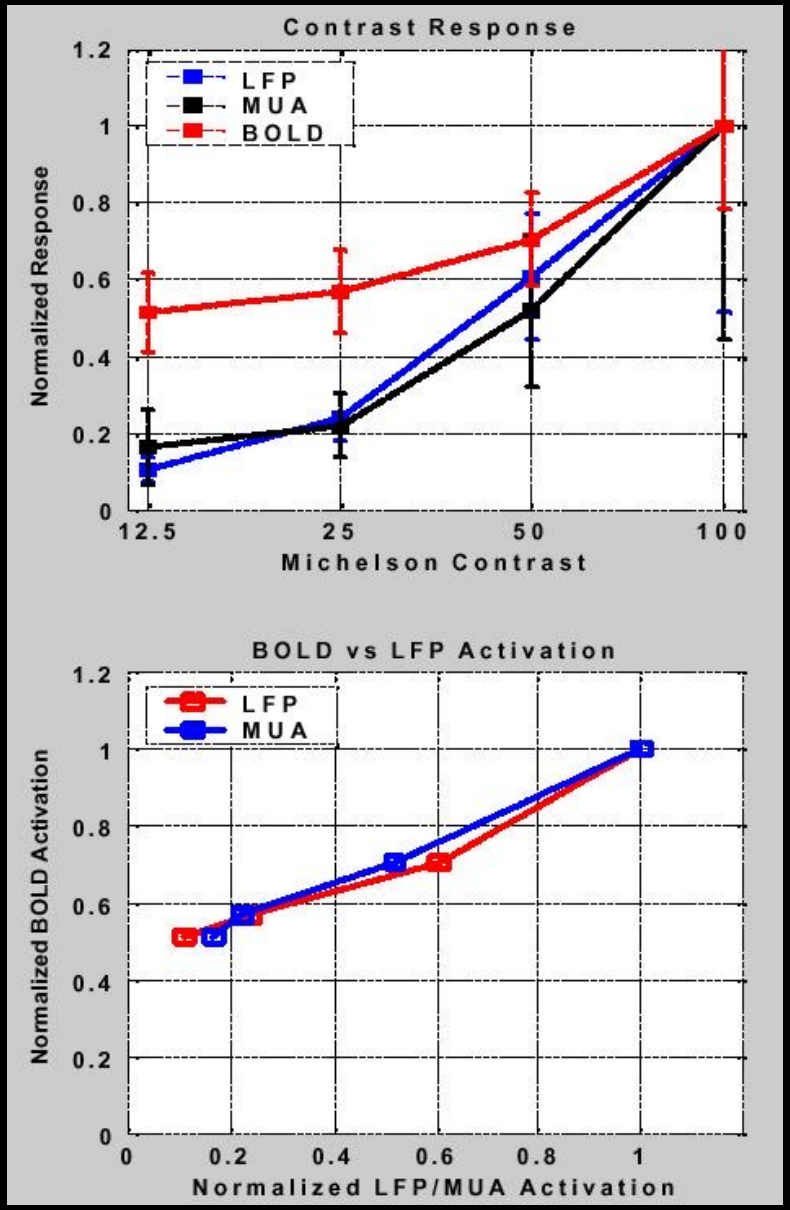
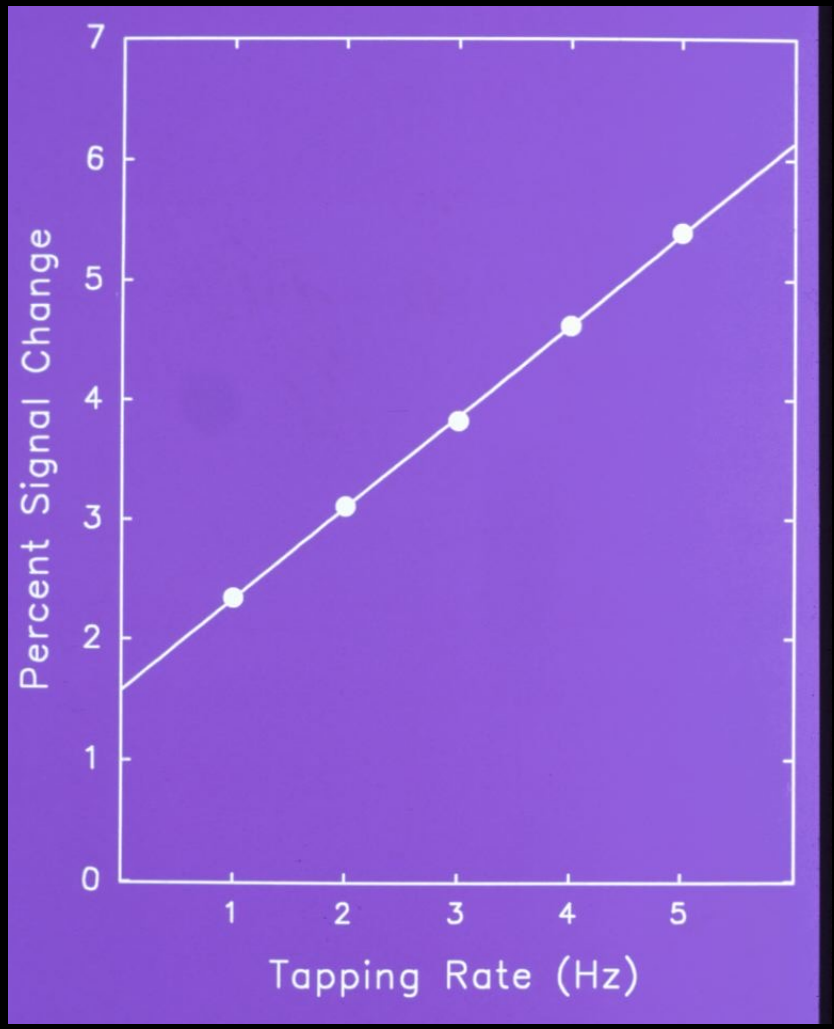

Δ Neuronal Activity
Number of Neurons
Local Field Potential
Spiking Coherence
Spiking Rate
Δ Metabolism
Aerobic Metabolism
Anaerobic Metabolism
Δ Hemodynamics
Blood Volume
Deoxygenated Blood
Flow Velocity
Oxygenated Blood
Perfusion
-
-
+
Δ BOLD Contrast
Δ Perfusion Contrast
Δ Inflow Contrast
MRI Pulse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



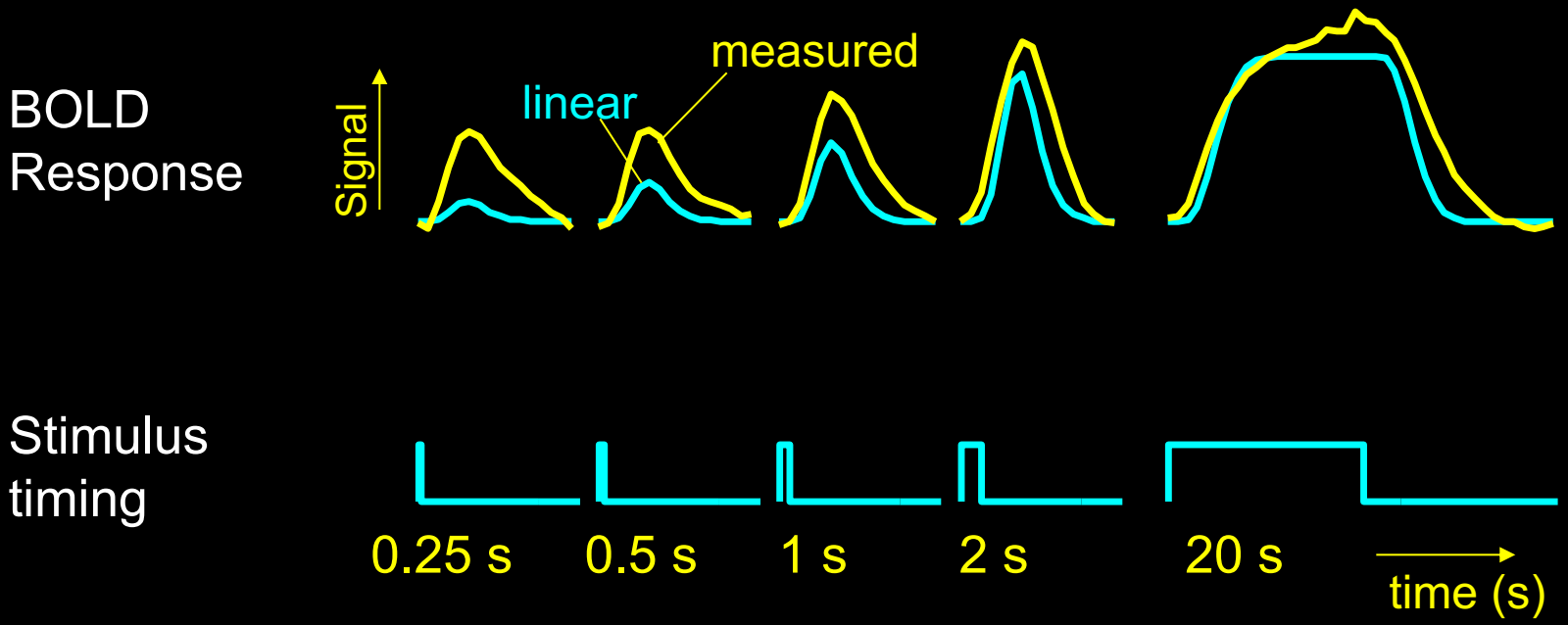
Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157



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

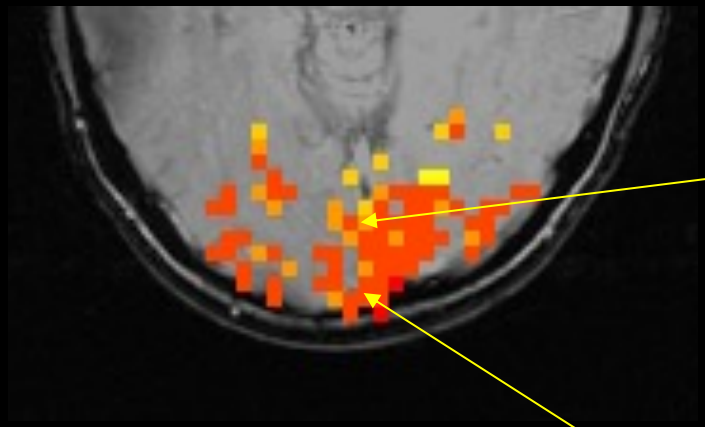
Different stimulus "ON" periods

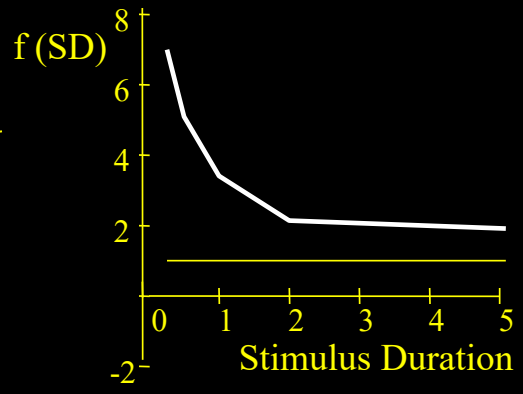


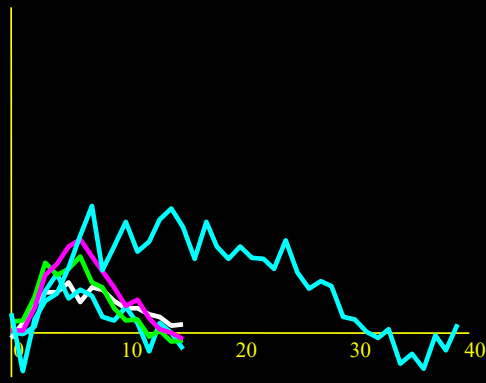
Brief stimuli produce larger responses than expected

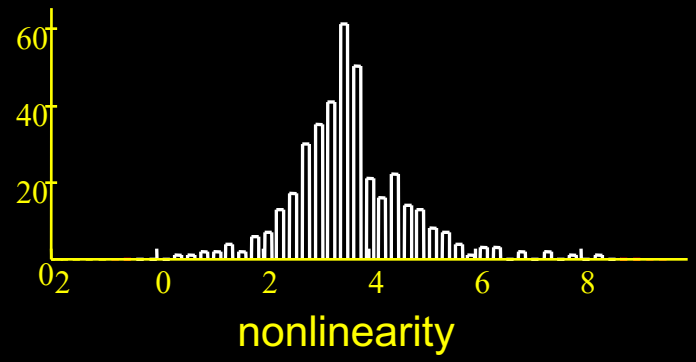
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

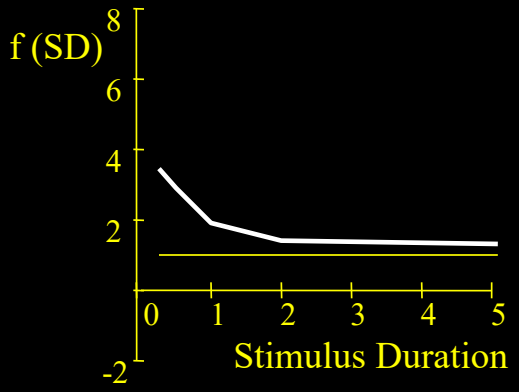
Spatial Heterogeneity of BOLD Nonlinearity

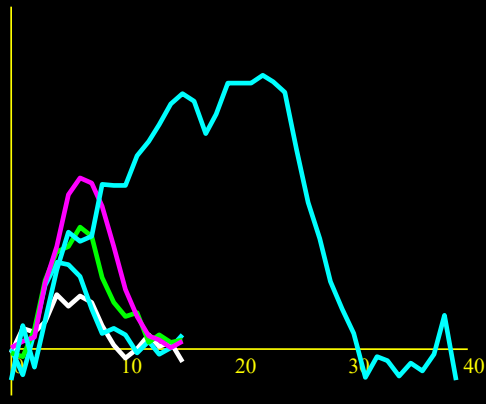








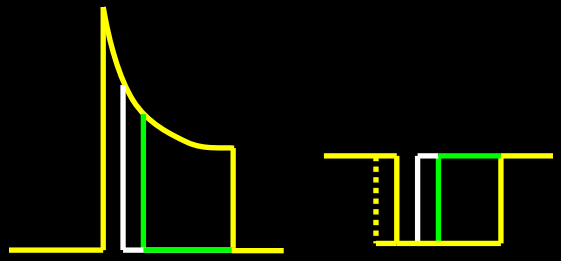




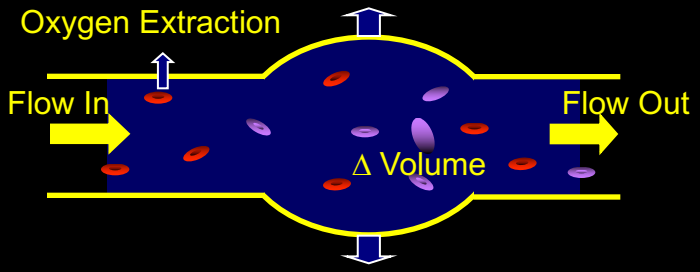
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

Sources of this Nonlinearity

- Neuronal

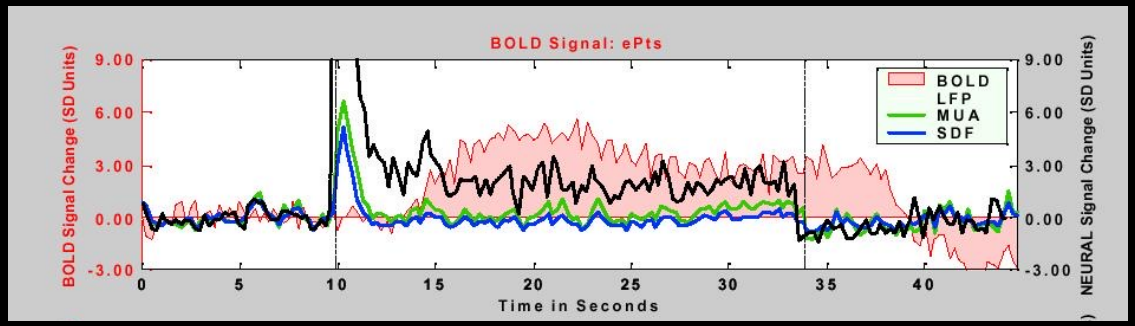


- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics

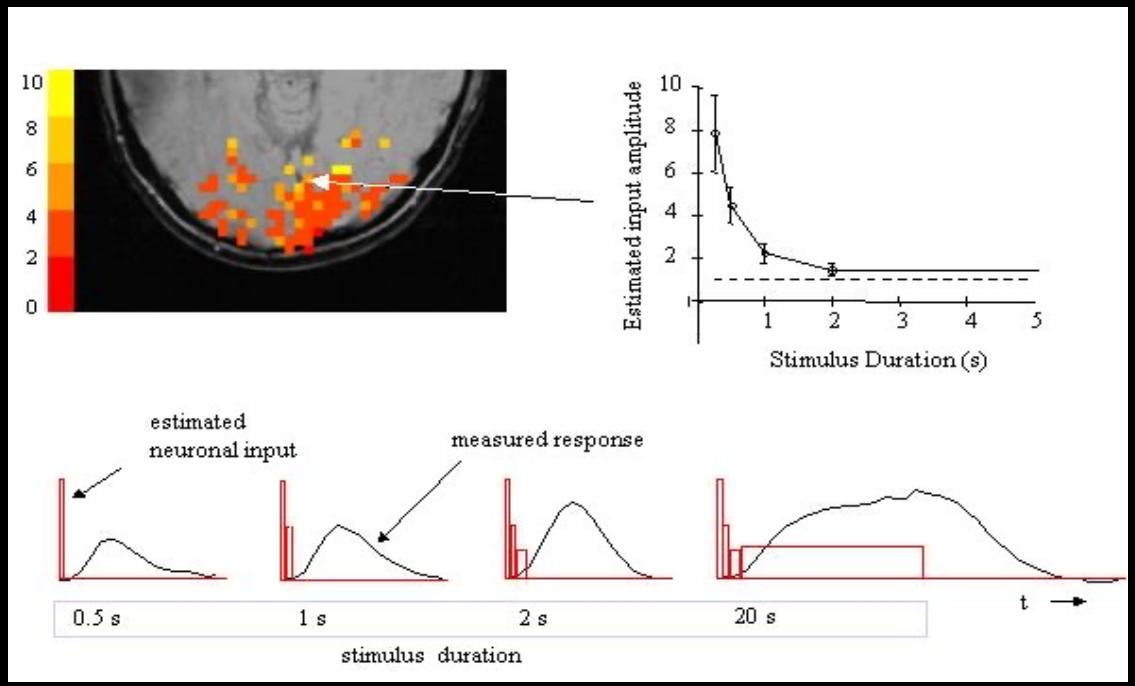


BOLD Correlation with Neuronal Activity

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

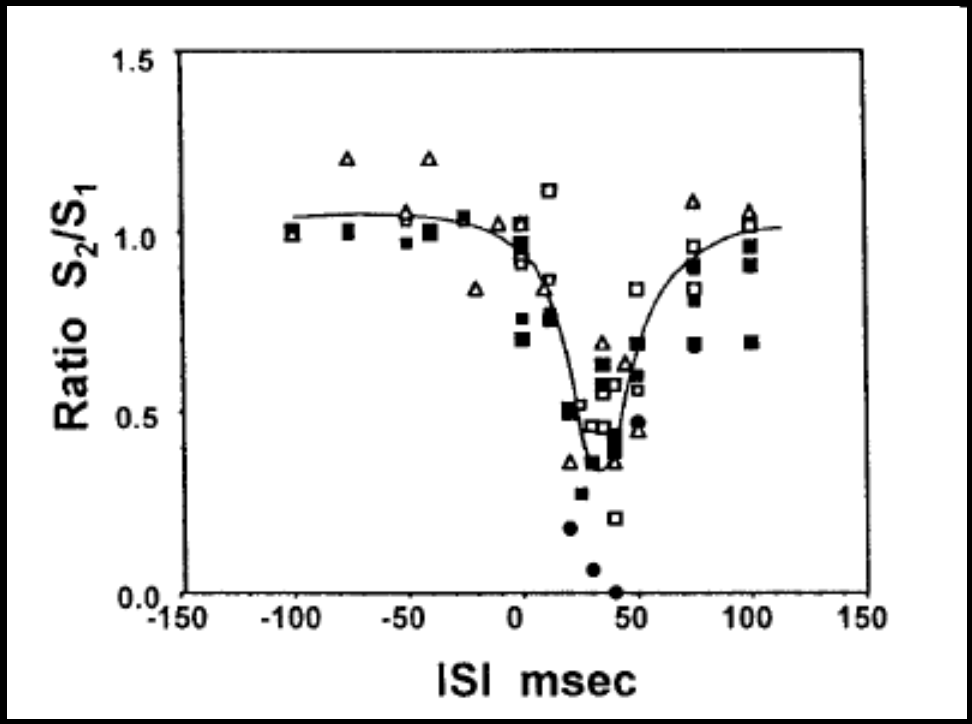


P. A. Bandettini and L. G. Ungerleider, (2001) "From neuron to BOLD: new connections." Nature Neuroscience, 4: 864-866.



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[§]



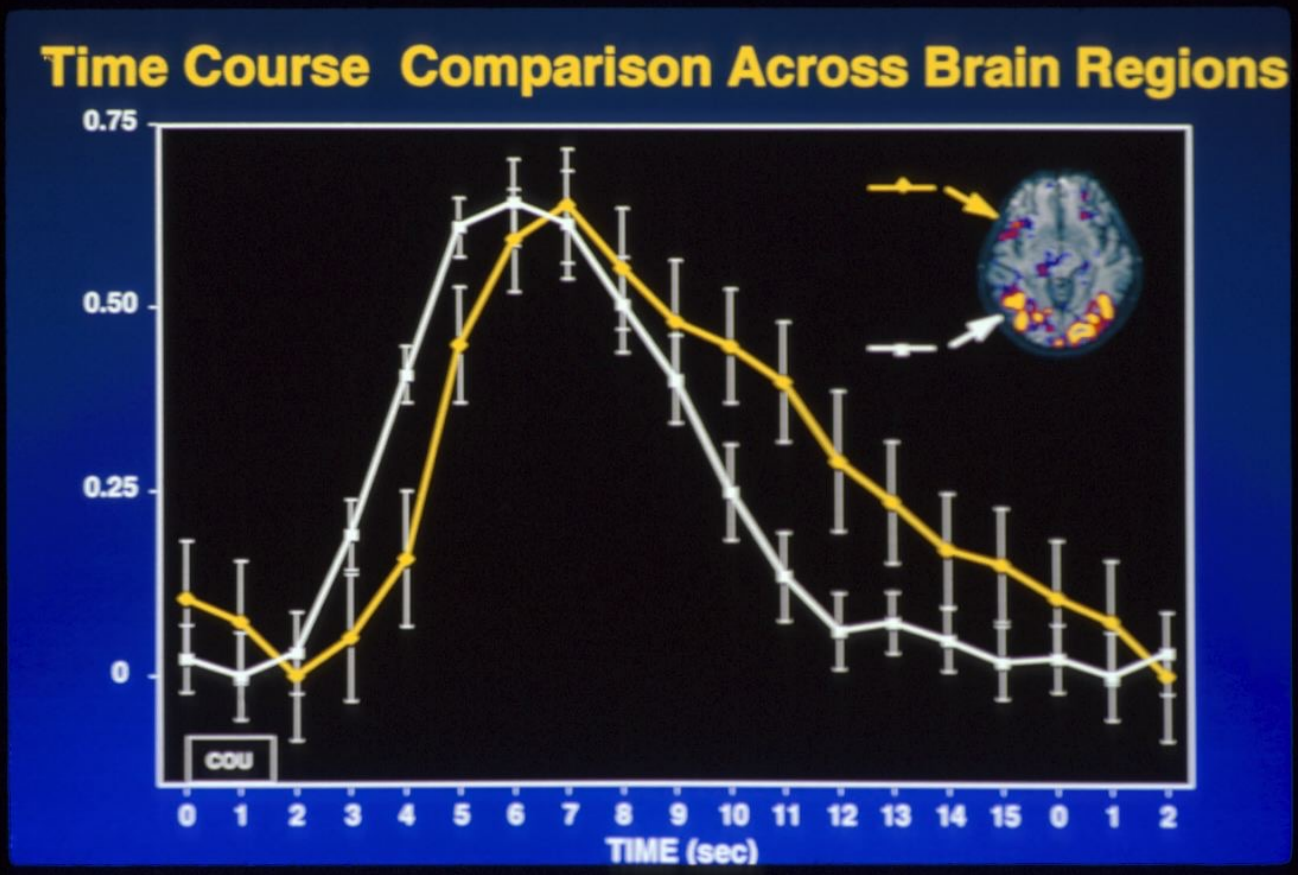
11026–11031 PNAS **September 26, 2000** vol. 97 no. 20

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

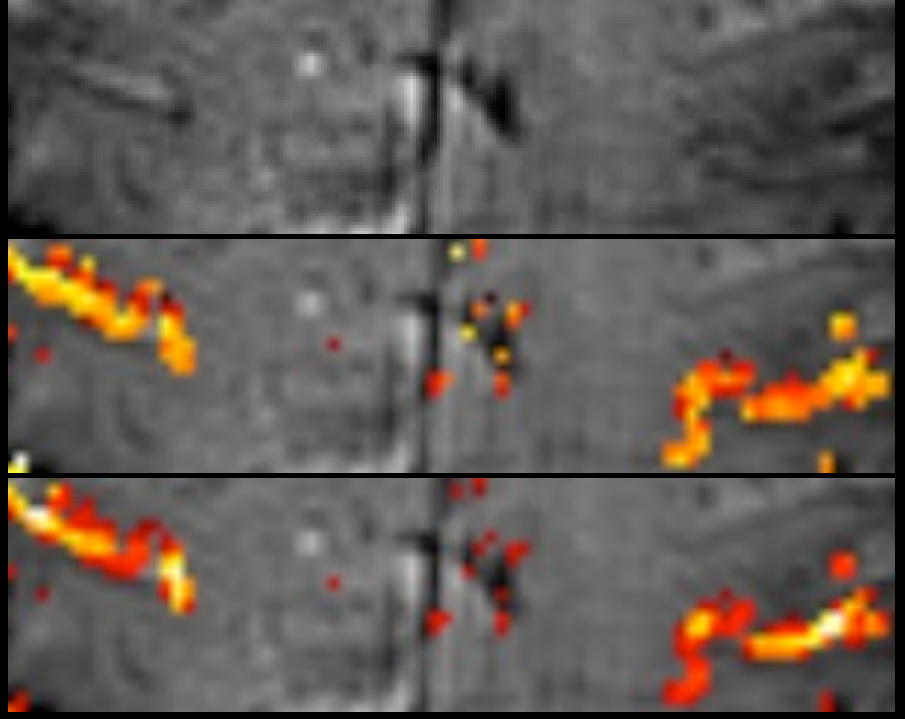
(neuroimaging/single trial/language/prefrontal)

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



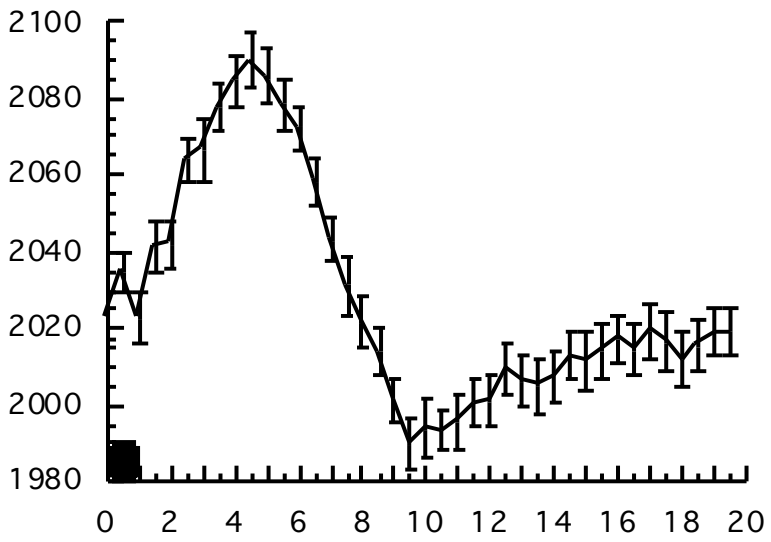
Latency

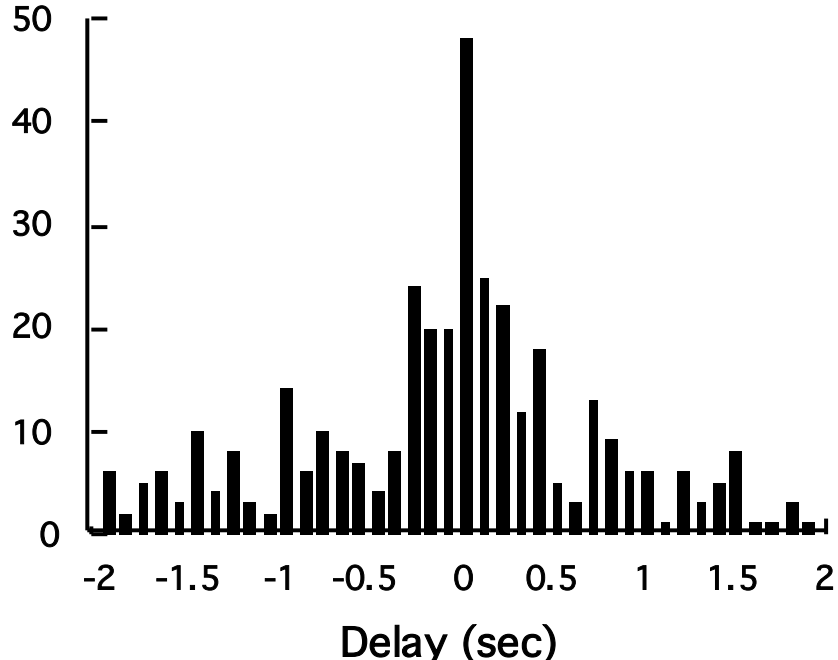
Magnitude



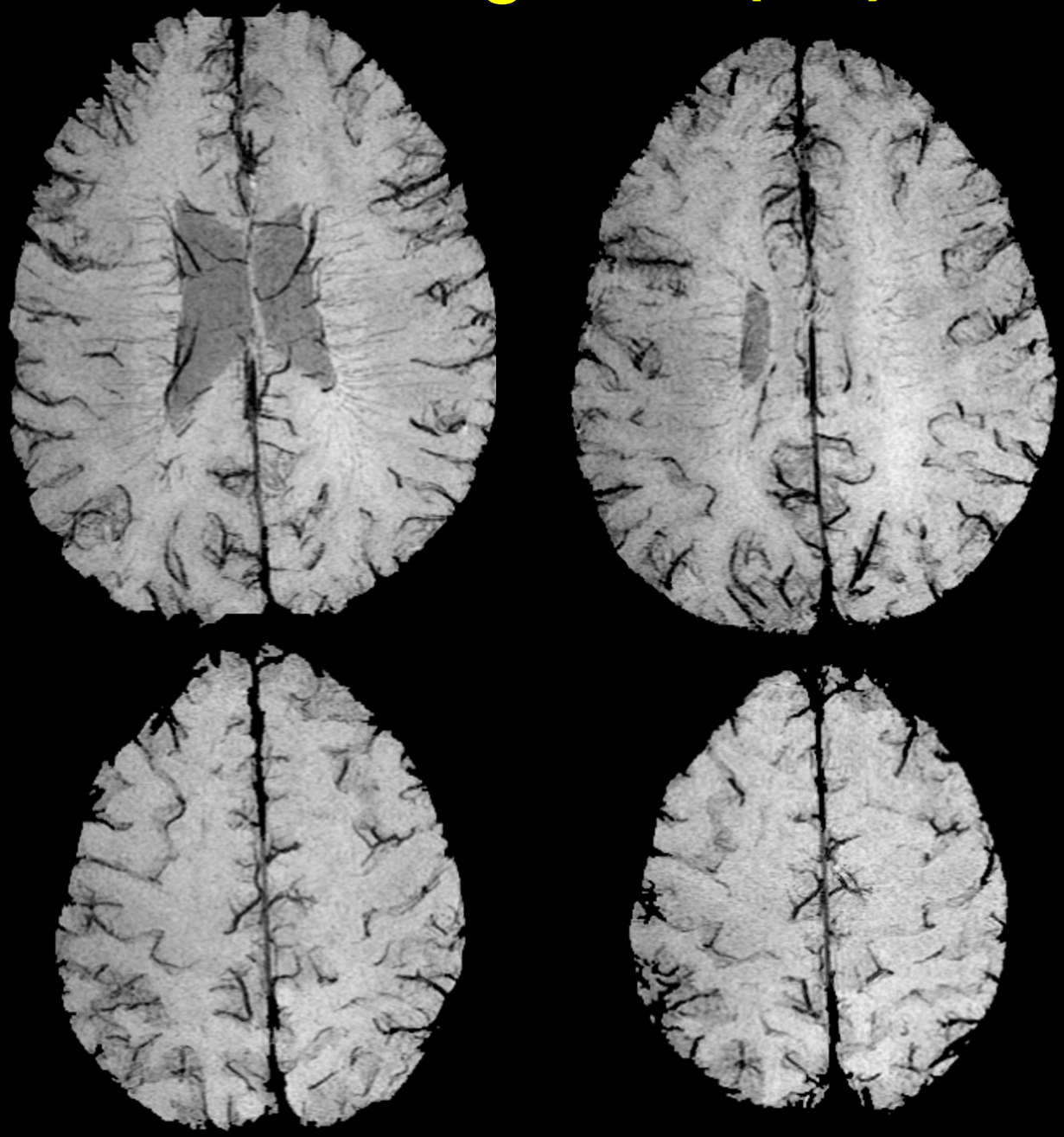
+ 2 sec

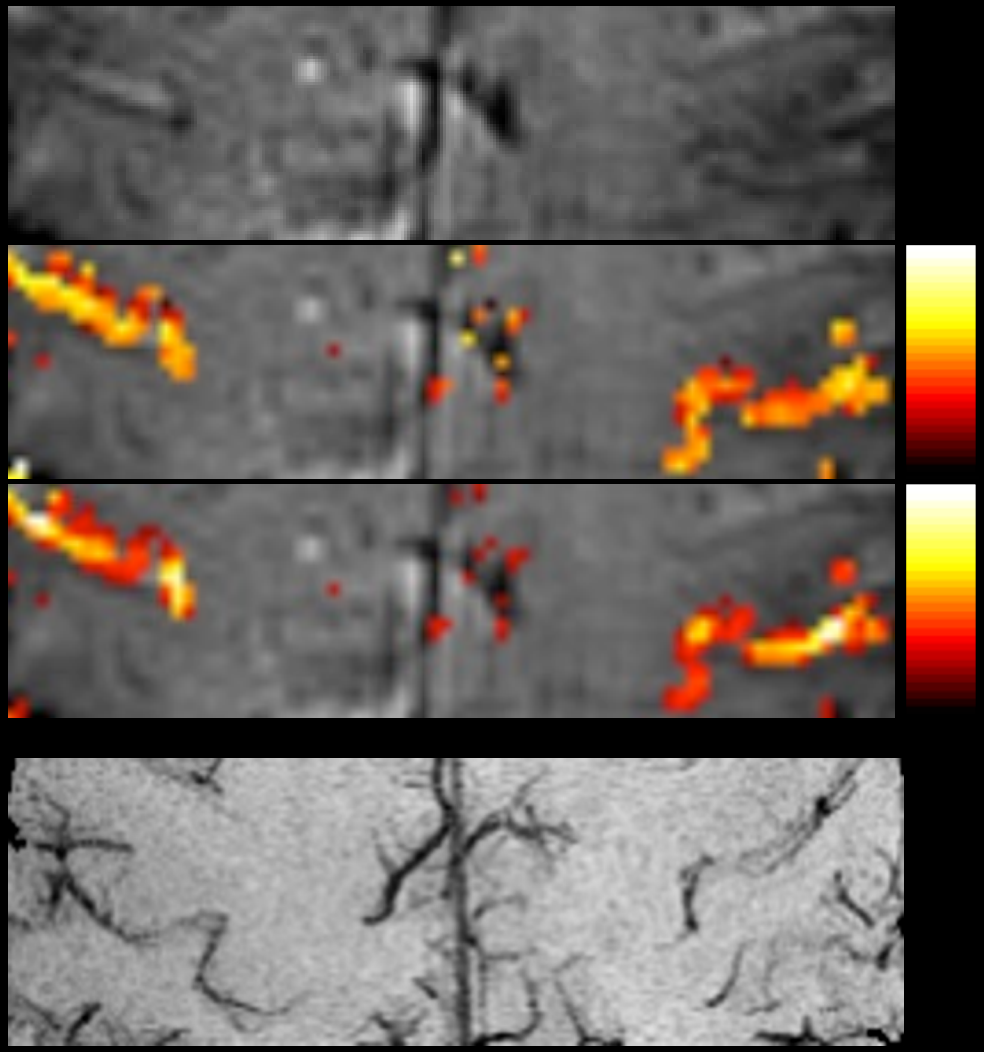
- 2 sec





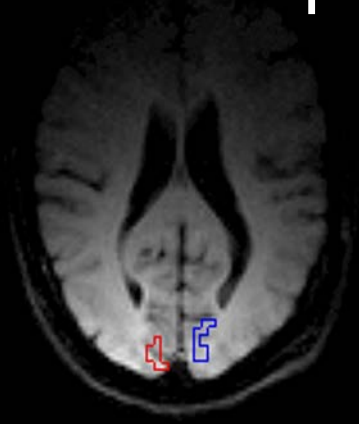
Venograms (3T)



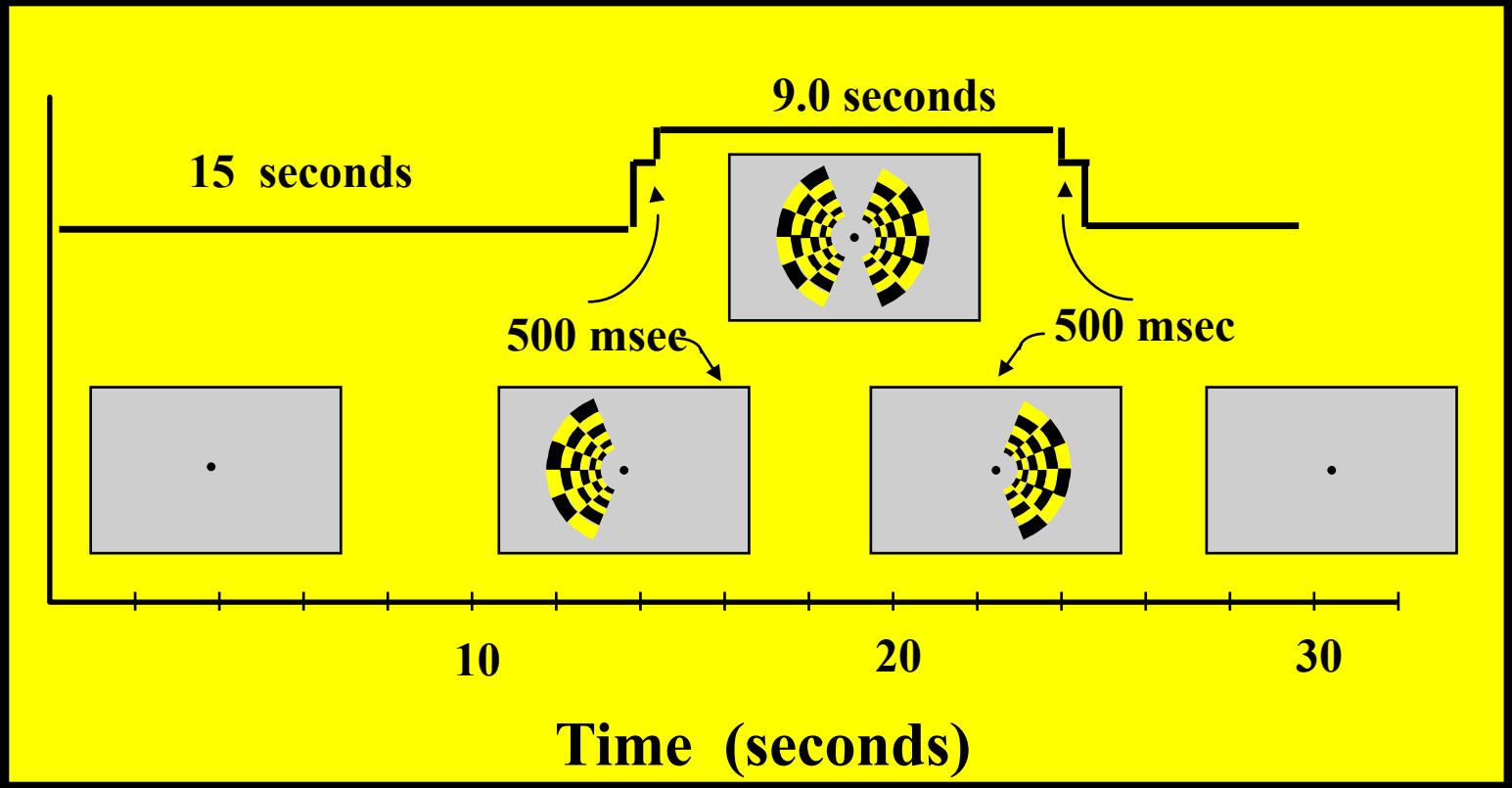


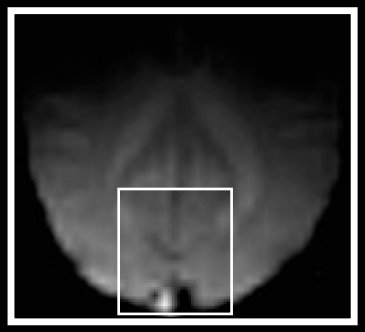
Hemi-Field Experiment

Left Hemisphere



Right Hemisphere



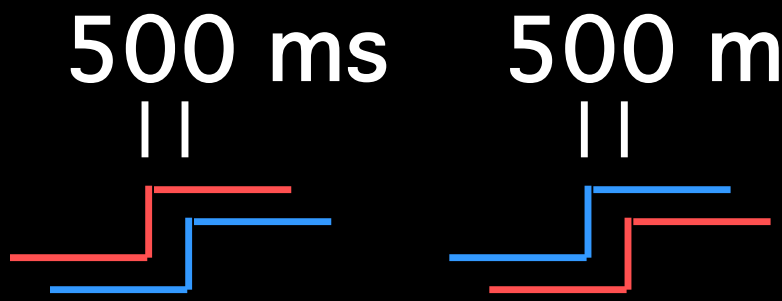


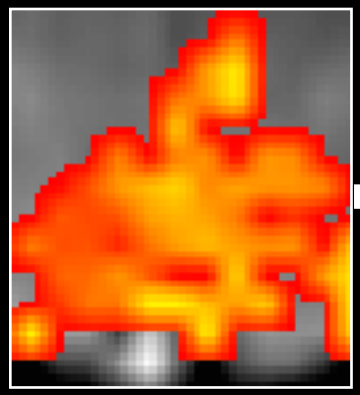
Calibration Techniques.....

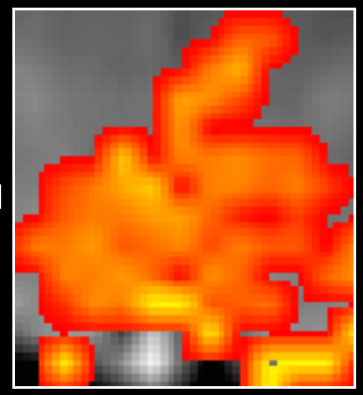
500 ms 500 ms

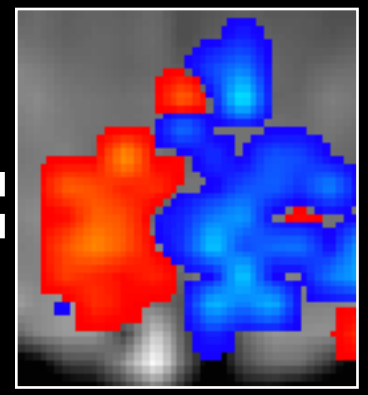
Right Hemifield

Left Hemifield





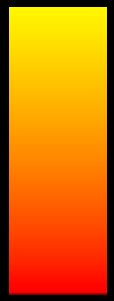




+ 2.5 s

0 s

- 2.5 s



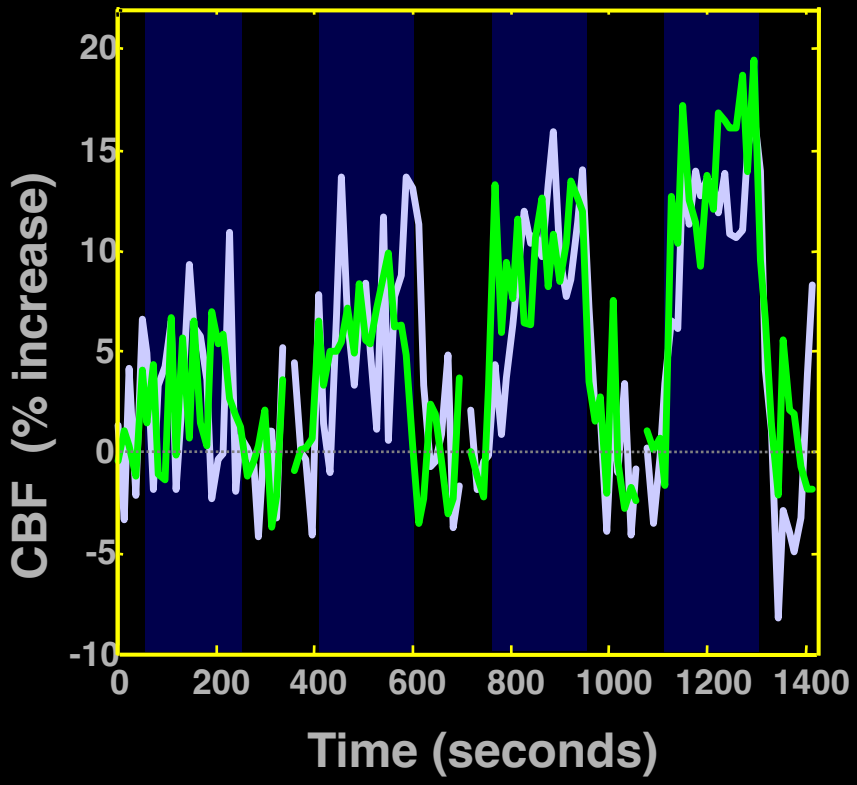
Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 9403–9408, August 1999
Neurobiology

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

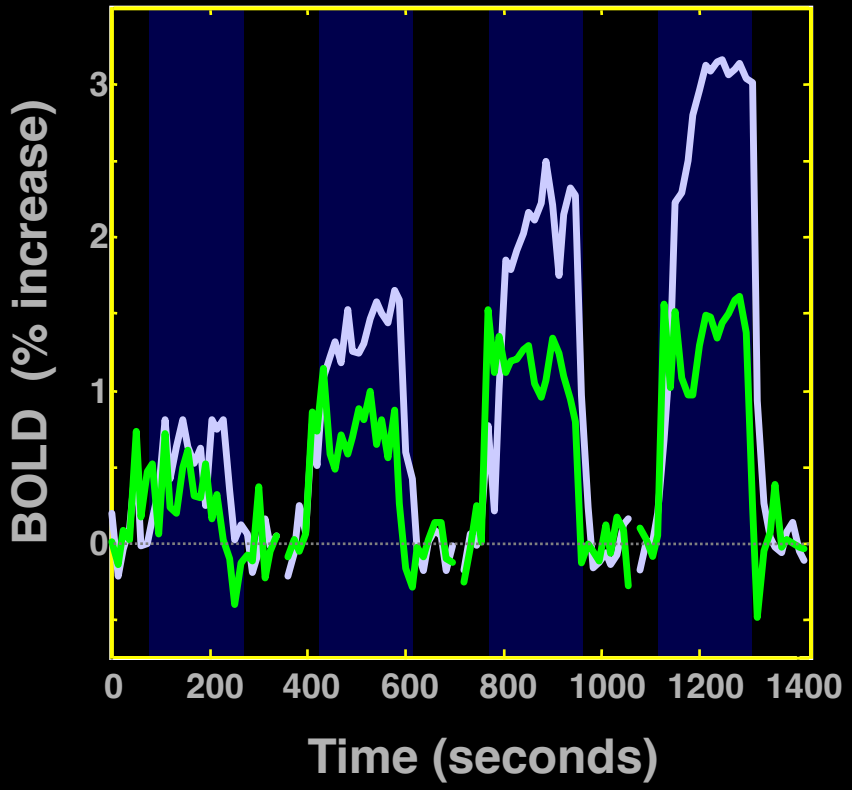
RICHARD D. HOGE*†, JEFF ATKINSON*, BRAD GILL*, GÉRARD R. CRELIER*, SEAN MARRETT‡, AND G. BRUCE PIKE*

*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



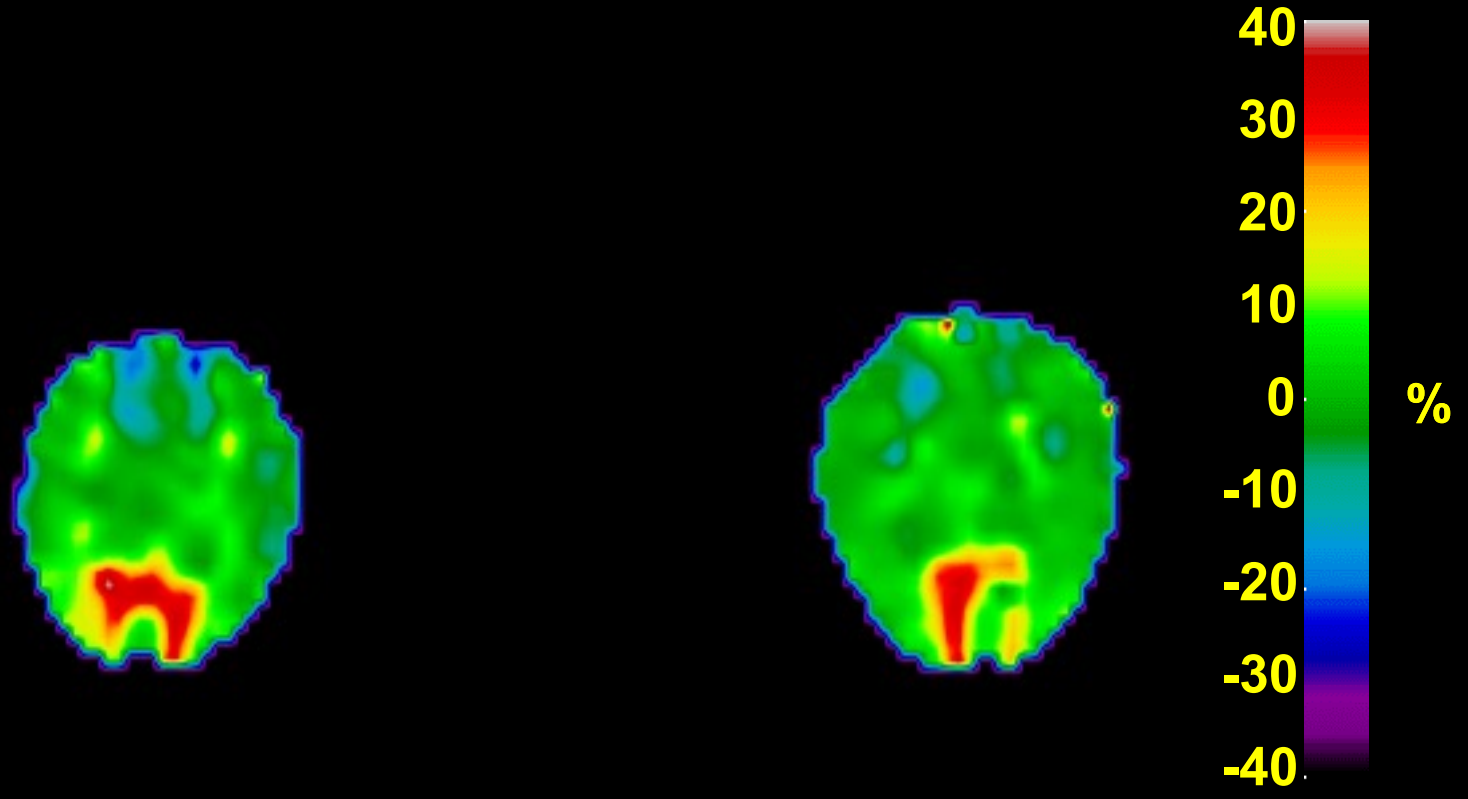
BOLD



Simultaneous Perfusion and BOLD imaging during graded visual activation and hypercapnia

N=12

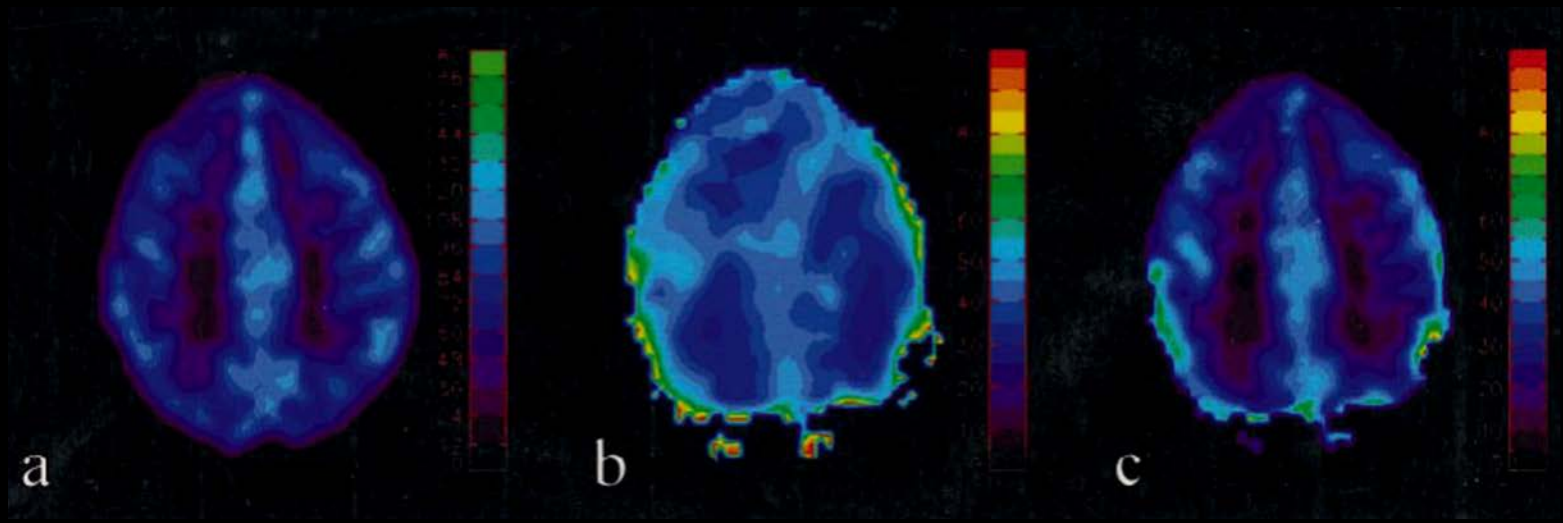
Computed $CMRO_2$ Changes



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

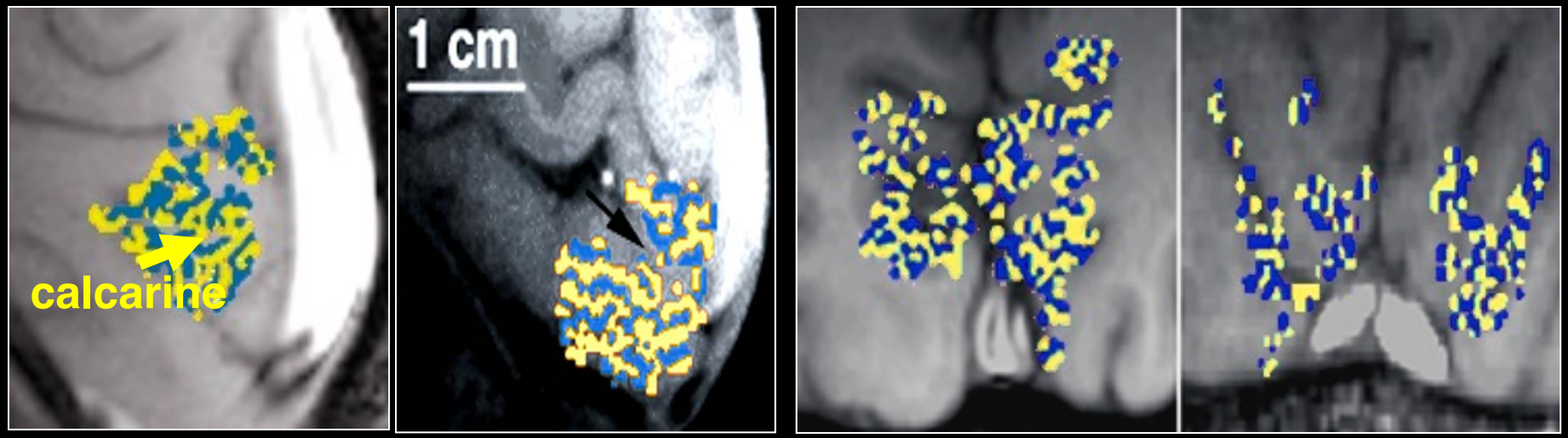
Quantitative measurements of cerebral metabolic rate of oxygen utilization using MRI: a volunteer study

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

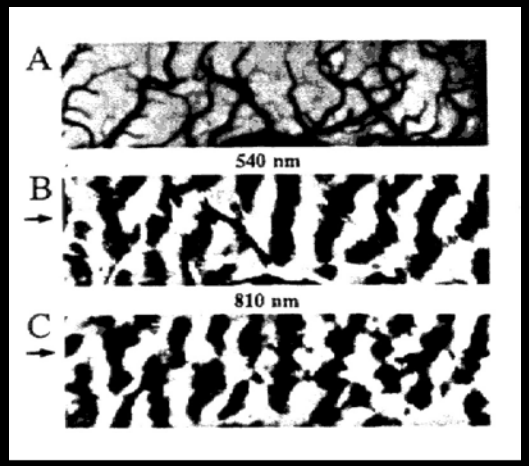


CBF OEF $CMRO_2$

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).

Past

Present

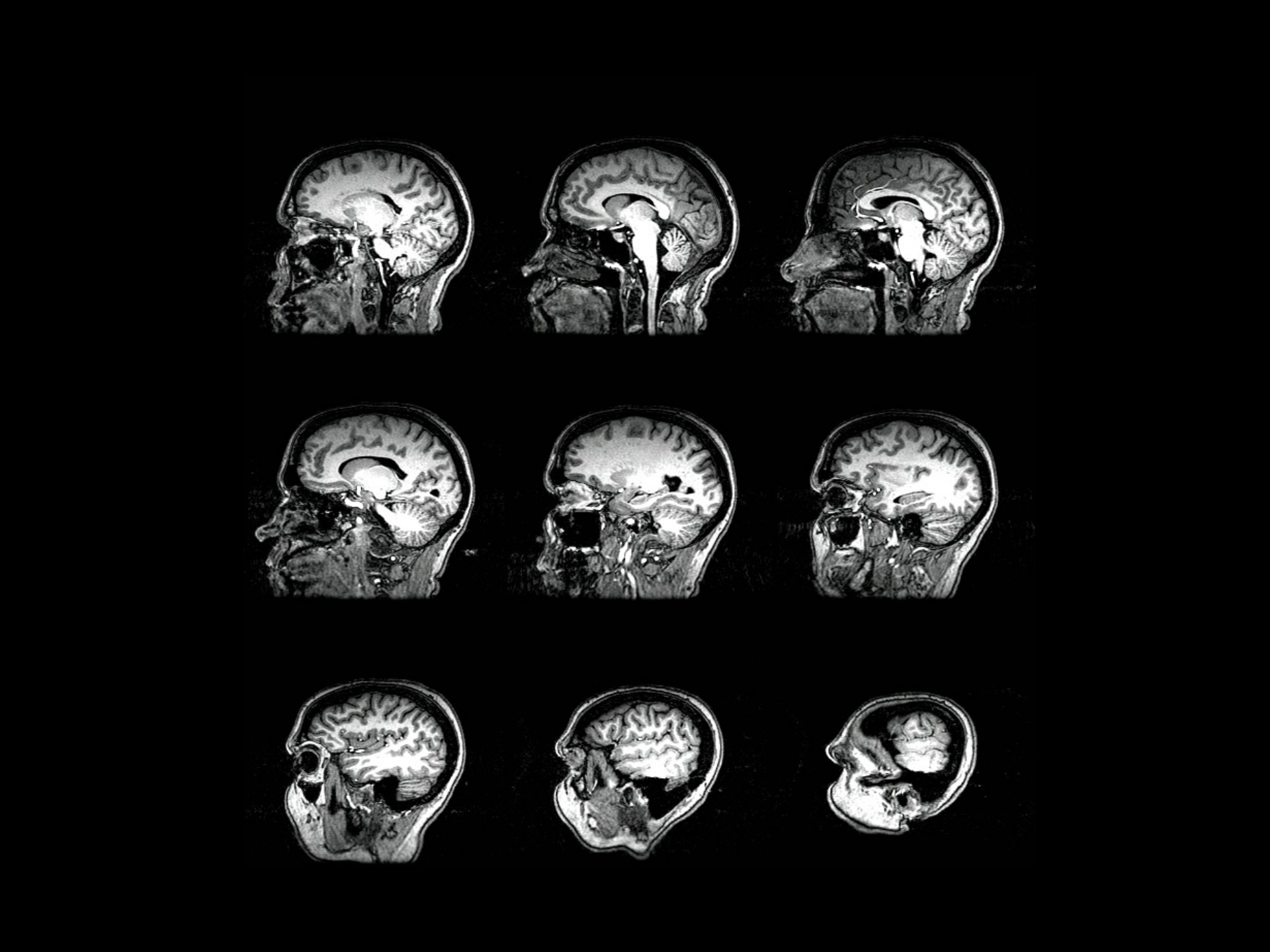
Future

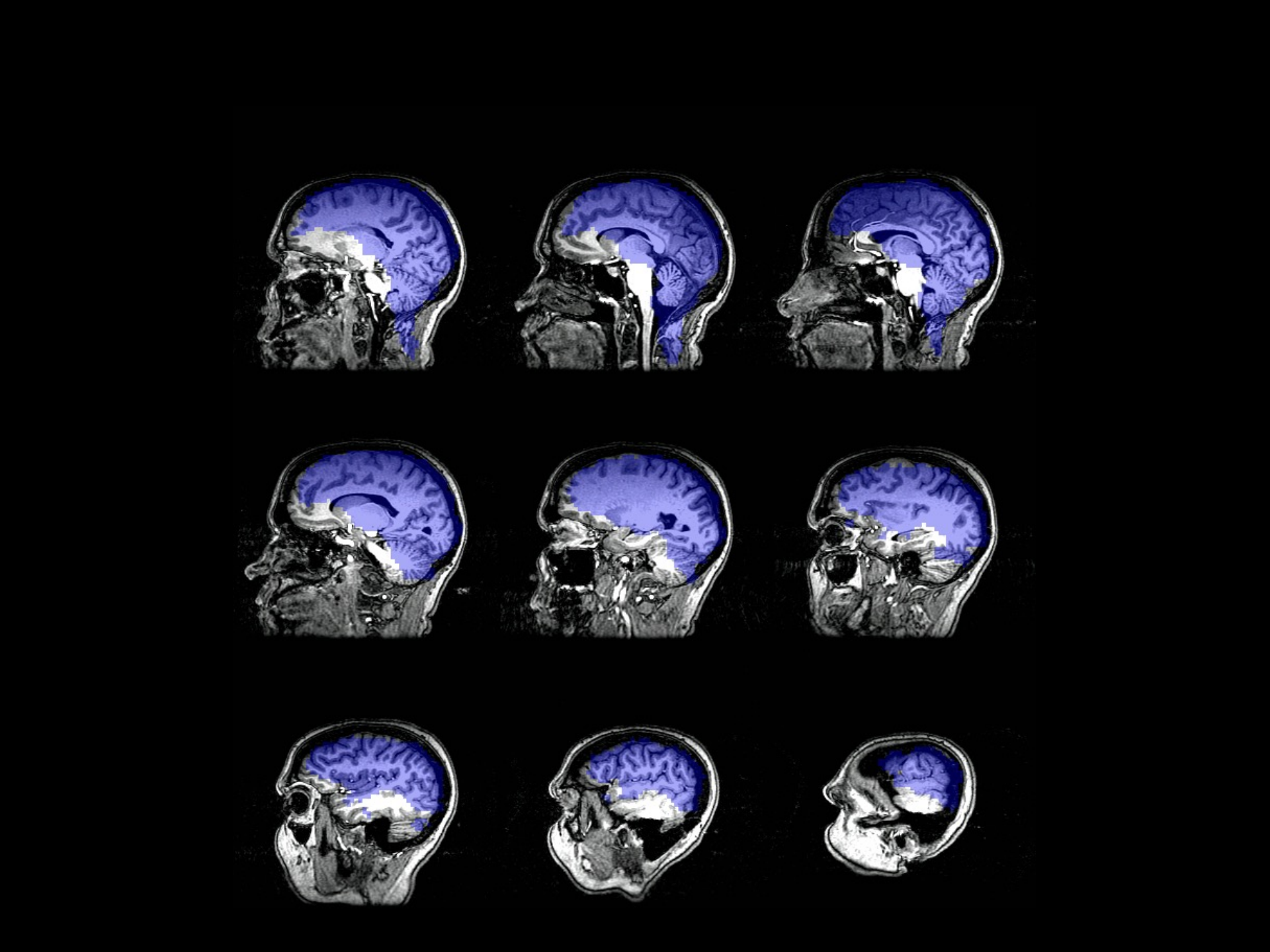
Future

Imaging Methods

Implementation

- 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

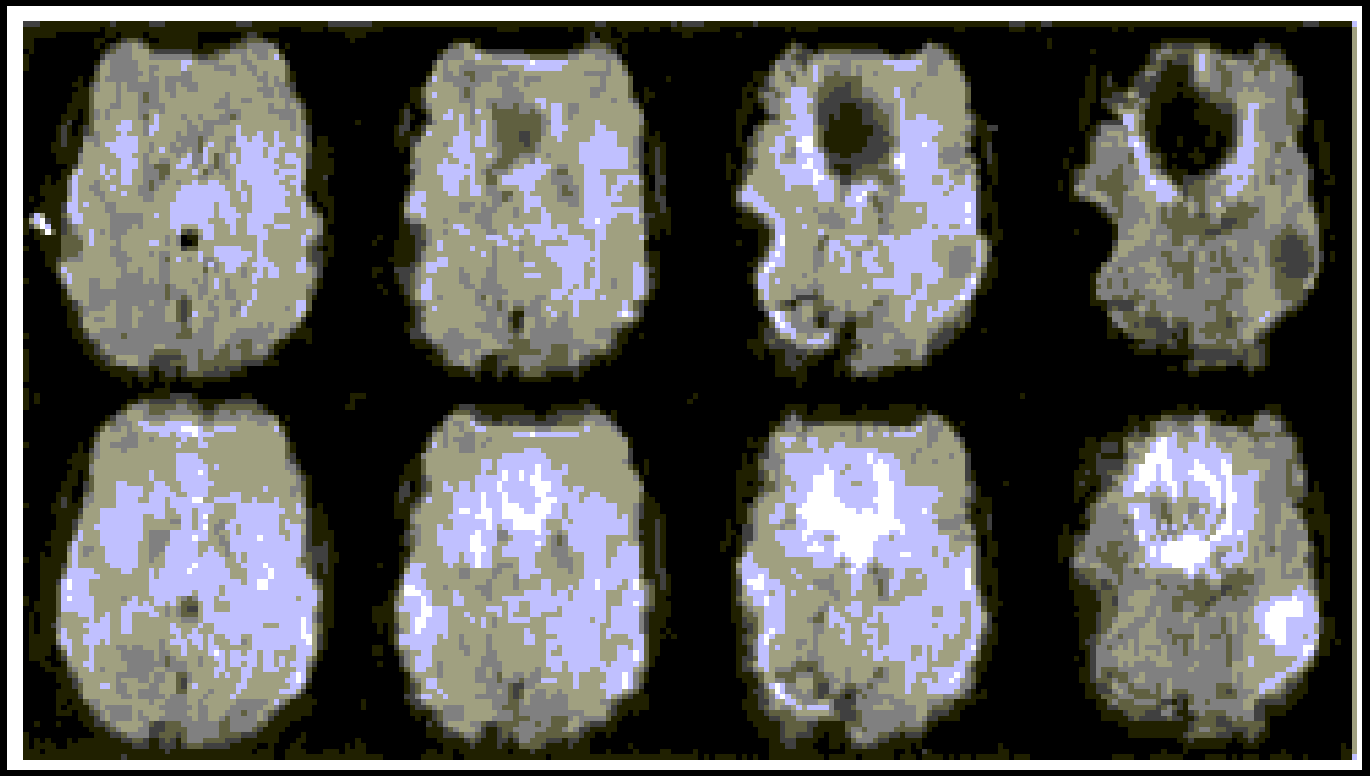




Magnetic Resonance in Medicine 42:290–299 (1999)

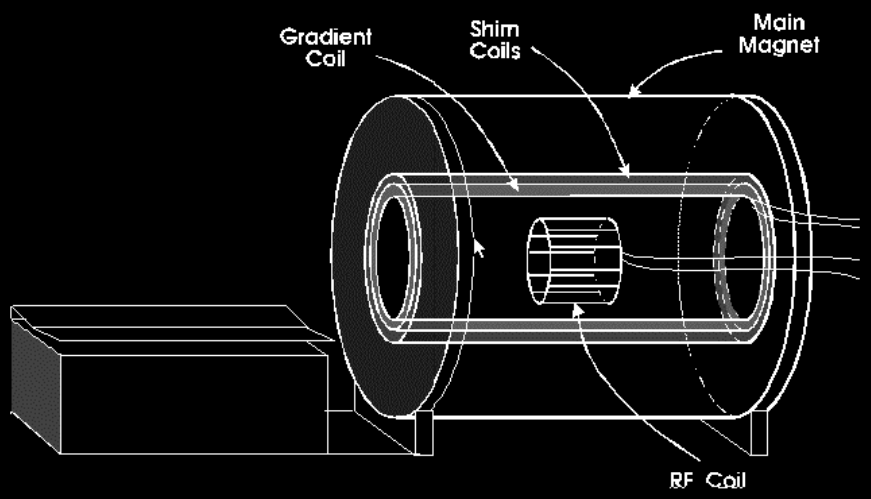
3D z-Shim Method for Reduction of Susceptibility Effects in BOLD fMRI

Gary H. Glover*



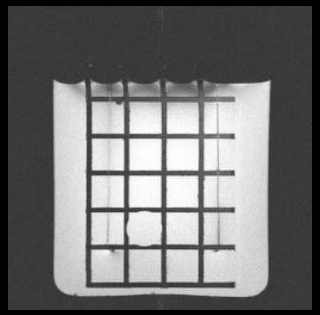
2 G/cm, 350 T/m/s

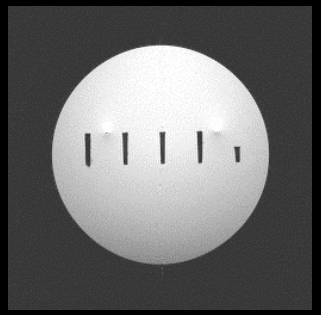
4 G/cm, 150 T/m/s



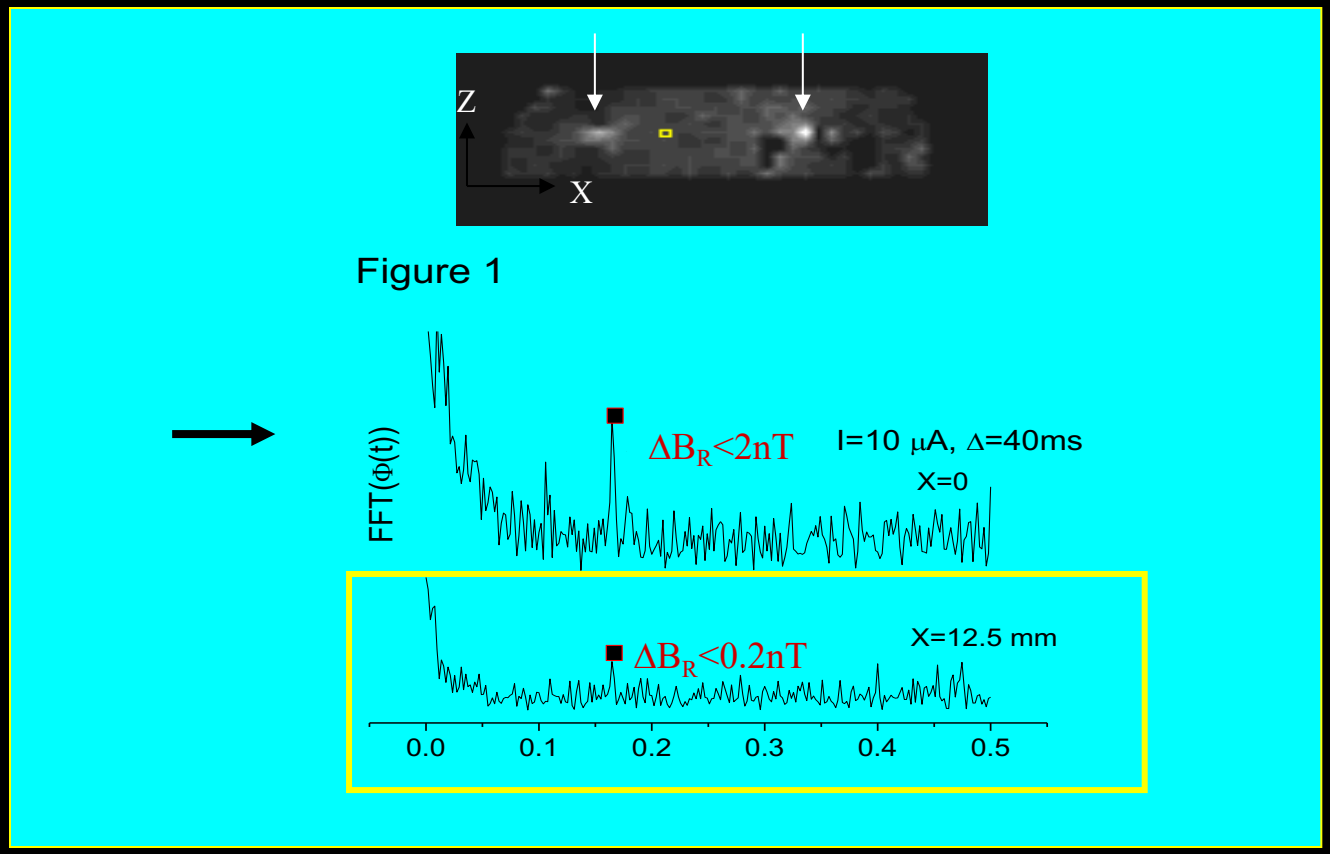
10 G/cm, 1000 T/m/s

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. (in press).

Functional Imaging Methods / 3T Group

Director:

Peter Bandettini

Staff Scientists:

Sean Marrett

Jerzy Bodurka

Frank Ye

Wen-Ming Luh

Post Docs:

Rasmus Birn

Hauke Heekeren

David Knight

Patrick Bellgowan

Ziad Saad

Graduate Student:

Natalia Petridou

Summer Students:

Dan Kelley

Hannah Chang

Program Assistant:

Kay Kuhns

Scanning Technologists:

Karen Bove-Bettis

Paula Rowser