

New Frontiers in Functional Imaging

Peter A. Bandettini, Ph.D

bandettini@nih.gov

Unit on Functional Imaging Methods
Laboratory of Brain and Cognition
&
Functional MRI Core Facility

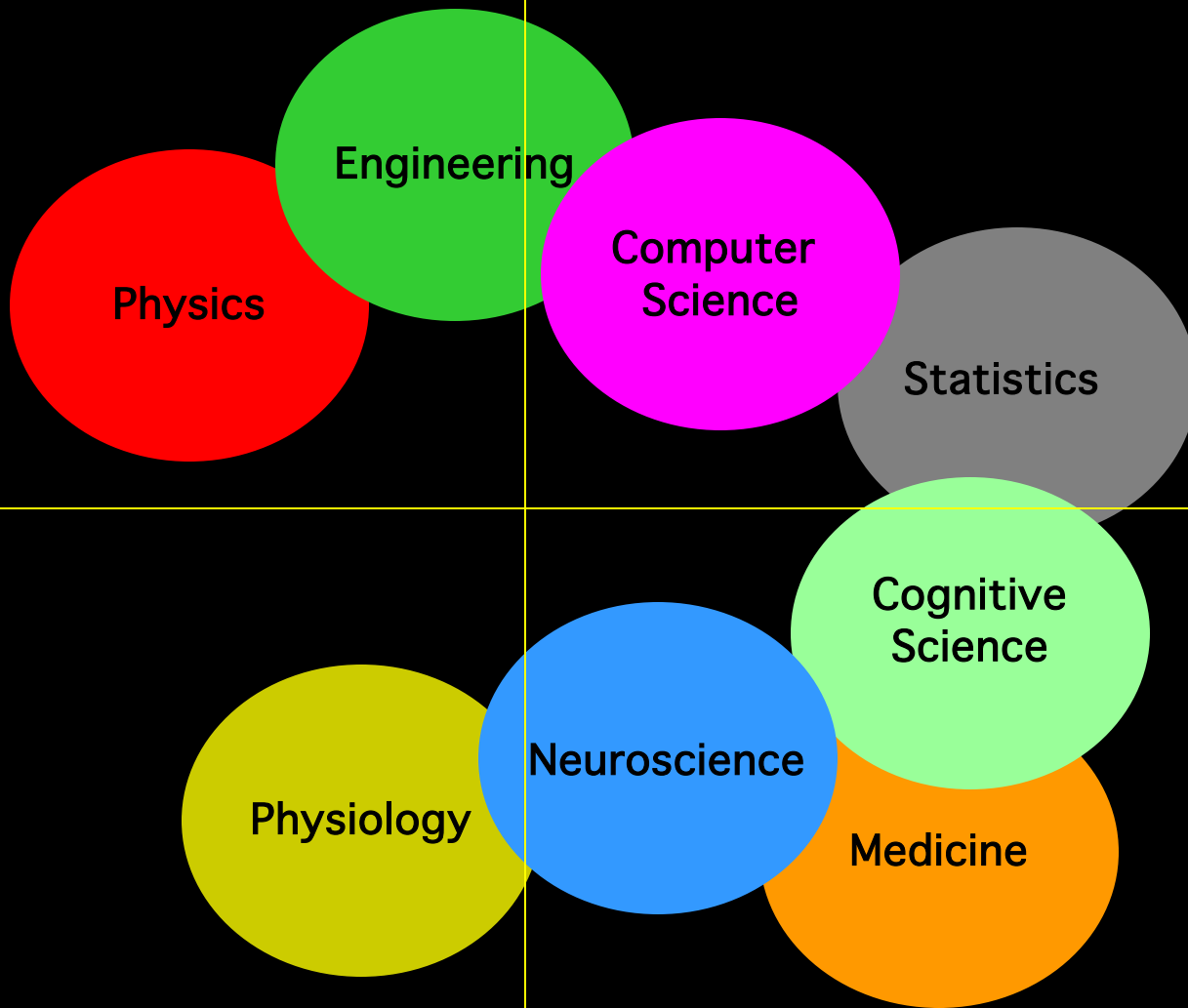


NIMH
National Institute
of Mental Health



Technology

Methodology



Interpretation

Applications

Focus of most of this talk is fMRI

...but the key to neuroimaging advances is in the integration of multiple techniques

-electrical, hemodynamic, metabolic changes with activation

Technology

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

Methodology

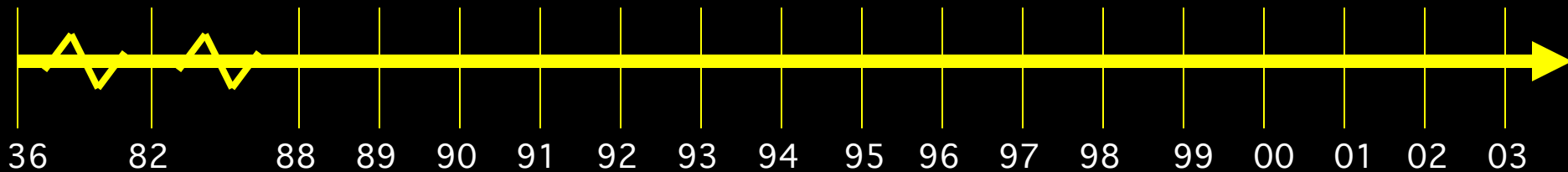
Baseline Volume
 IVIM
 Correlation Analysis
 Parametric Design
 Surface Mapping
 Phase Mapping
 Linear Regression
 Event-related
 Motion Correction
 Multi-Modal Mapping
 ICA
 Free-behavior Designs
 Mental Chronometry
 Deconvolution
 Fuzzy Clustering
 CO₂ Calibration
 Latency and Width Mod
 Multi-variate Mapping

Interpretation

Blood T2
 Hemoglobin
 BOLD models
 B₀ dep.
 TE dep
 SE vs. GE
 NIRS Correlation
 Veins
 PET correlation
 IV vs EV
 Pre-undershoot
 Resolution Dep.
 Post-undershoot
 CO₂ effect
 Inflow
 ASL vs. BOLD
 PSF of BOLD
 Extended Stim.
 Linearity
 Fluctuations
 Balloon Model
 Layer spec. latency
 Excite and Inhibit
 Metab. Correlation
 Optical Im. Correlation
 Electrophys. correlation

Applications

Complex motor Language Imagery Memory Emotion
 Motor learning Children Tumor vasc. Drug effects
 BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons
 Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations
 Δ Volume-V1 Plasticity Face recognition Performance prediction



- Functional contrast
- Signal interpretation
- Hardware and pulse sequences
- Paradigm design and processing

- Overview
- Current Limits
- Future Prospects

- **Functional contrast**
- Signal interpretation
- Hardware and pulse sequences
- Paradigm design and processing

- Overview
- Current Limits
- Future Prospects

Technology

MRI
EPI
Local Human Head Gradient Coils
ASL
Spiral EPI
Multi-shot fMRI
1.5T,3T, 4T
EPI on Clin. Syst.
Nav. pulses
Diff. tensor
Real time fMRI
Quant. ASL
Dynamic IV volume
Simultaneous ASL and BOLD
Mg⁺
Venography
Z-shim
Baseline Susceptibility
7T
SENSE
"vaso"
>8 channels
Current Imaging?

BOLD

Methodology

Baseline Volume

IVIM

Correlation Analysis
Parametric Design
Surface Mapping
Phase Mapping
Linear Regression
Event-related
Motion Correction
Multi-Modal Mapping
ICA
Free-behavior Designs
Mental Chronometry
Deconvolution
Fuzzy Clustering
CO₂ Calibration
Latency and Width Mod
Multi-variate Mapping

Interpretation

Blood T2

Hemoglobin

BOLD models
B₀ dep.
TE dep
SE vs. GE
NIRS Correlation
Veins
PET correlation
IV vs EV
Pre-undershoot
Resolution Dep.
Post-undershoot
CO₂ effect
Inflow
ASL vs. BOLD
PSF of BOLD
Extended Stim.
Linearity
Fluctuations
Balloon Model
Optical Im. Correlation
Electrophys. correlation
Layer spec. latency
Excite and Inhibit
Metab. Correlation

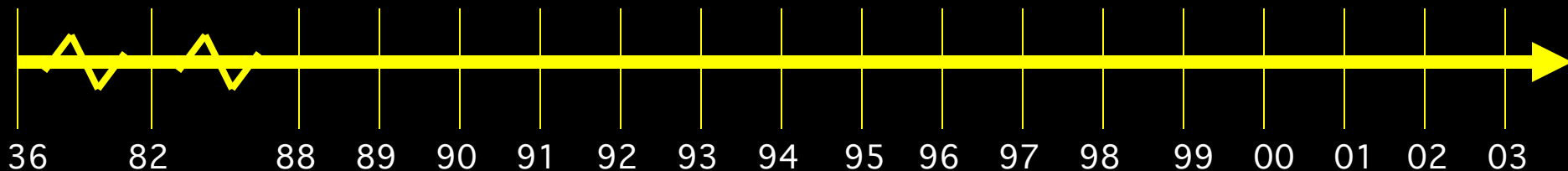
Applications

Volume - Stroke

Δ Volume-V1

BOLD -V1, M1, A1

Complex motor
Language
Imagery
Memory
Emotion
Motor learning
Children
Tumor vasc.
Drug effects
Presurgical
Attention
Ocular Dominance
Mirror neurons
V1, V2..mapping
Priming/Learning
Clinical Populations
Performance prediction
Plasticity
Face recognition

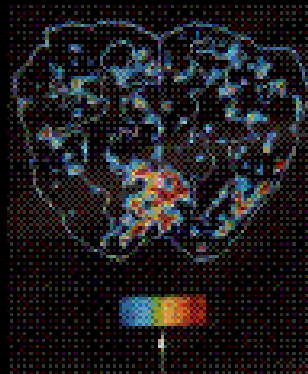
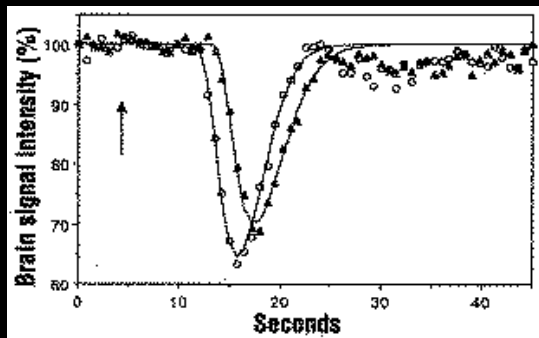
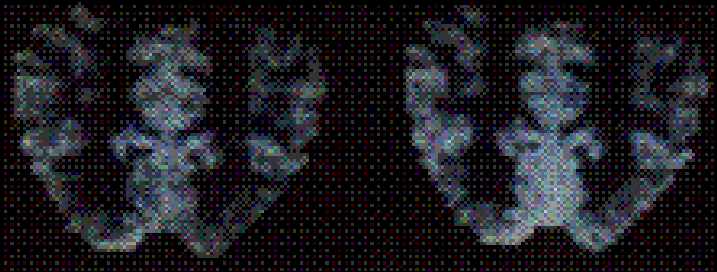


Blood Volume Imaging

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

Resting

Active

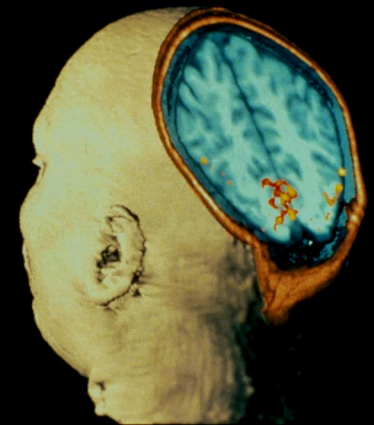


Photic Stimulation

MRI image showing activation of the Visual Cortex

From Belliveau, et al. Science Nov 1991

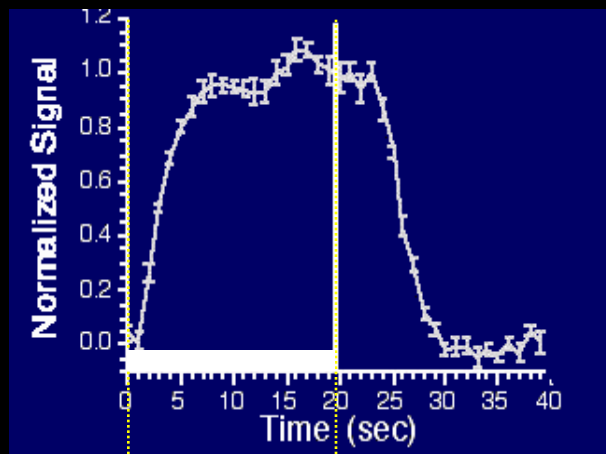
MBC - perfusion



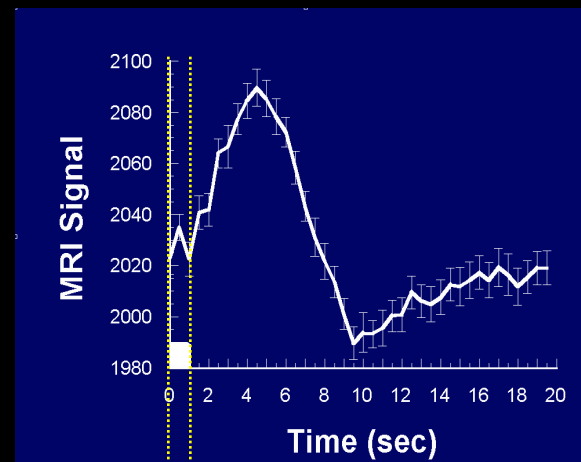
Blood Oxygenation Imaging



- 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.



task



task

Technology

MRI, EPI, 1.5T,3T, 4T, Local Human Head Gradient Coils, ASL, BOLD, Spiral EPI, Multi-shot fMRI, Diff. tensor, Real time fMRI, Quant. ASL, Dynamic IV volume, Simultaneous ASL and BOLD, Mg⁺, Venography, Z-shim, Baseline Susceptibility, 7T, SENSE, "vaso", >8 channels

Methodology

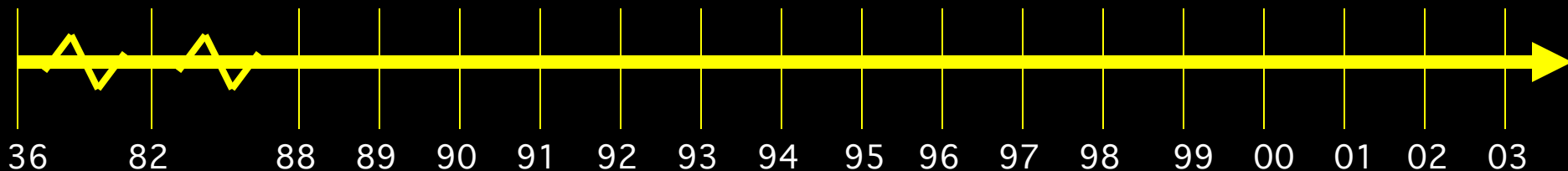
Baseline Volume, IVIM, Correlation Analysis, Parametric Design, Surface Mapping, Phase Mapping, Linear Regression, Event-related, Motion Correction, Multi-Modal Mapping, ICA, Free-behavior Designs, Mental Chronometry, Multi-variate Mapping, Deconvolution, Fuzzy Clustering, CO₂ Calibration, Latency and Width Mod

Interpretation

Blood T2, Hemoglobin, BOLD models, B₀ dep., TE dep, SE vs. GE, NIRS Correlation, Veins, PET correlation, IV vs EV, Pre-undershoot, Resolution Dep., CO₂ effect, Inflow, ASL vs. BOLD, PSF of BOLD, Extended Stim., Linearity, Fluctuations, Balloon Model, Optical Im. Correlation, Electrophys. correlation, Layer spec. latency, Excite and Inhibit, Metab. Correlation

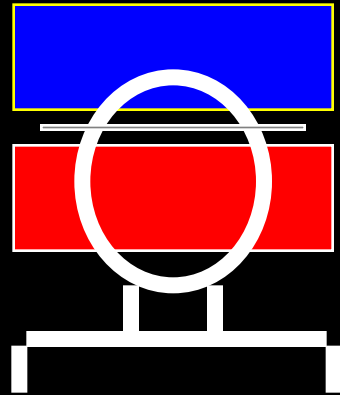
Applications

Complex motor Language, Imagery, Memory, Emotion, Motor learning, Children, Tumor vasc., Drug effects, Mirror neurons, Presurgical, Attention, Ocular Dominance, Clinical Populations, Performance prediction, Volume - Stroke, V1, V2..mapping, Priming/Learning, Plasticity, Face recognition

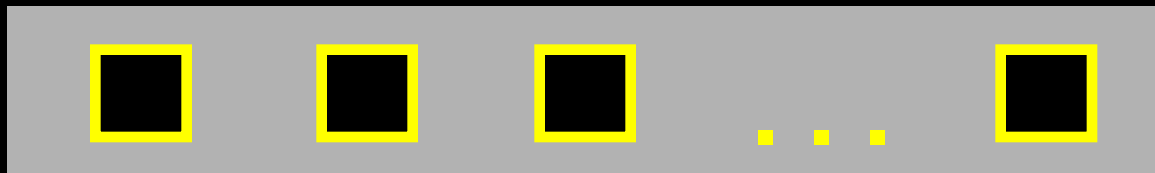
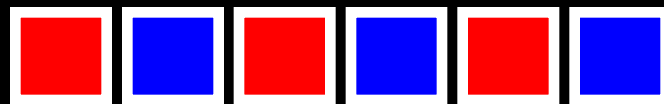
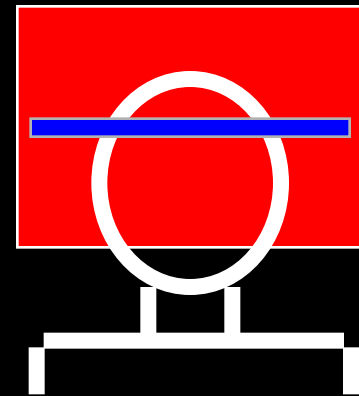


Blood Perfusion Imaging

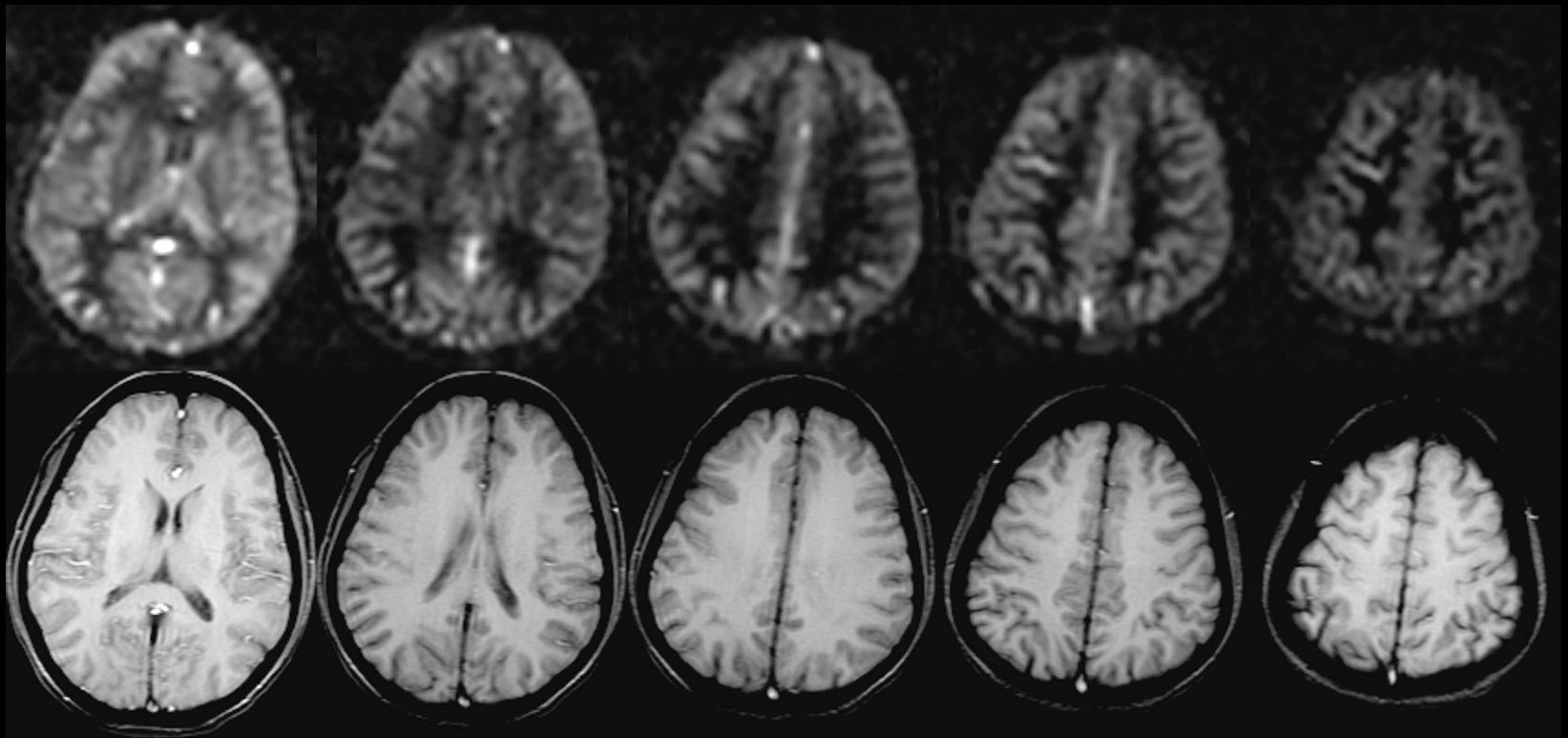
EPISTAR



FAIR



**Perfusion
Time Series**



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 and 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.

Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL Spiral EPI Multi-shot fMRI Diff. tensor Real time fMRI Quant. ASL Dynamic IV volume Simultaneous ASL and BOLD Venography Z-shim Baseline Susceptibility SENSE "vaso" 7T >8 channels

Methodology

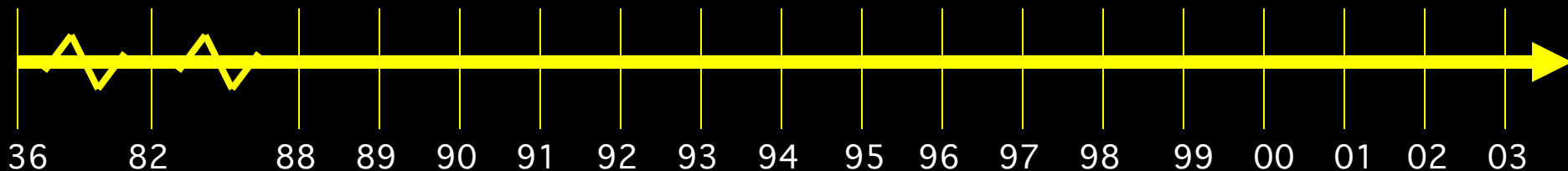
Baseline Volume IVIM Correlation Analysis Parametric Design Surface Mapping Phase Mapping Linear Regression Event-related Motion Correction Multi-Modal Mapping ICA Free-behavior Designs Mental Chronometry Multi-variate Mapping Deconvolution Fuzzy Clustering CO₂ Calibration Latency and Width Mod

Interpretation

Blood T2 Hemoglobin BOLD models B₀ dep. TE dep SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. CO₂ effect Inflow ASL vs. BOLD BOLD vs. PET Fluctuations Balloon Model Optical Im. Correlation Electrophys. correlation Layer spec. latency Excite and Inhibit Metab. Correlation

Applications

Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Presurgical Attention Ocular Dominance Mirror neurons Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations Performance prediction BOLD -V1, M1, A1 Δ Volume-V1 Plasticity Face recognition



Simultaneous BOLD and Perfusion



BOLD



Perfusion



Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL BOLD Spiral EPI Multi-shot fMRI Diff. tensor Real time fMRI Quant. ASL Dynamic IV volume Simultaneous ASL and BOLD Venography Z-shim Baseline Susceptibility SENSE "vaso" 7T >8 channels Current Imaging?

Methodology

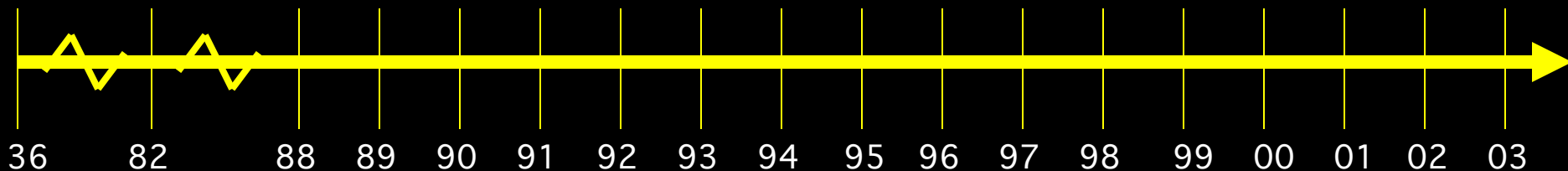
Baseline Volume IVIM Correlation Analysis Motion Correction CO₂ Calibration Parametric Design Multi-Modal Mapping Latency and Width Mod Surface Mapping ICA Free-behavior Designs Phase Mapping Mental Chronometry Multi-variate Mapping Linear Regression Deconvolution Fuzzy Clustering Event-related

Interpretation

Blood T2 Hemoglobin BOLD models PET correlation IV vs EV ASL vs. BOLD Layer spec. latency B₀ dep. Pre-undershoot PSE of BOLD Excite and Inhibit TE dep. Resolution Dep. Extended Stim. Metab. Correlation Post-undershoot Linearity SE vs. GE CO₂ effect NIRS Correlation Fluctuations Optical Im. Correlation Veins Inflow Balloon Model Electrophys. correlation

Applications

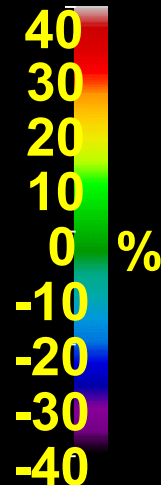
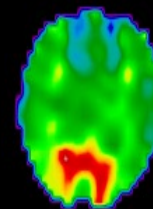
Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Presurgical Attention Ocular Dominance Mirror neurons BOLD -V1, M1, A1 Priming/Learning Clinical Populations Volume - Stroke V1, V2..mapping Plasticity Face recognition Performance prediction Δ Volume-V1



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

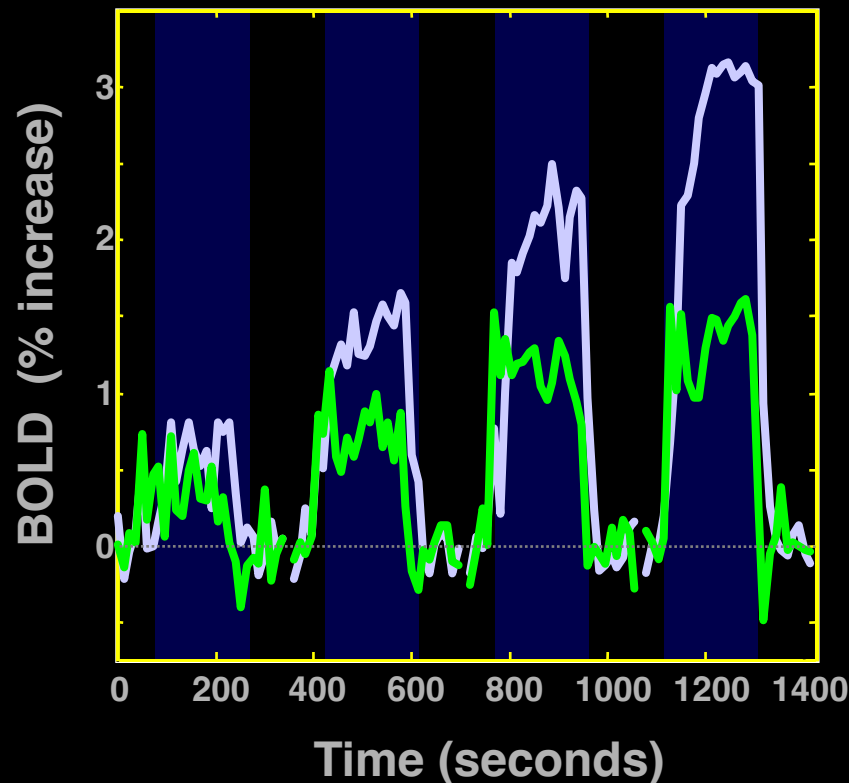
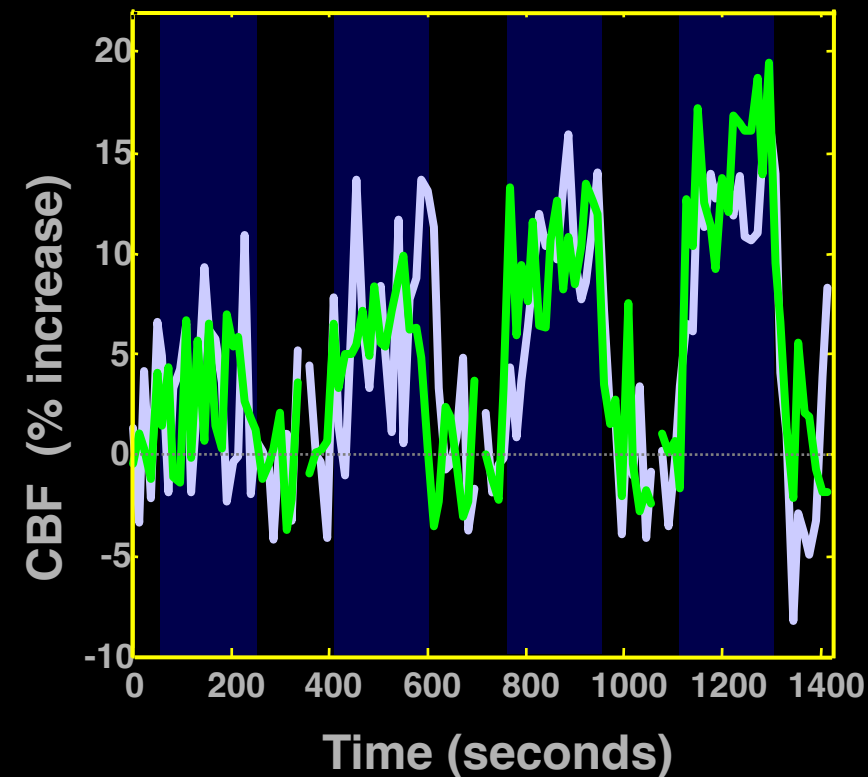
RICHARD D. HOGE^{*†}, JEFF ATKINSON^{*}, BRAD GILL^{*}, GÉRARD R. CRELIER^{*}, SEAN MARRETT[‡], AND G. BRUCE PIKE^{*}

^{*}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

Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL BOLD Spiral EPI Multi-shot fMRI Diff. tensor Real time fMRI Quant. ASL Dynamic IV volume Simultaneous ASL and BOLD Venography Z-shim Baseline Susceptibility SENSE "vaso" >8 channels Current Imaging?

Methodology

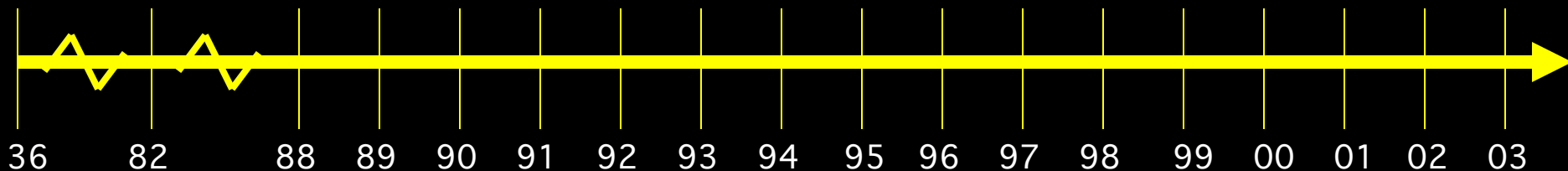
Baseline Volume IVIM Correlation Analysis Parametric Design Surface Mapping Phase Mapping Linear Regression Event-related Motion Correction Deconvolution Fuzzy Clustering CO₂ Calibration Multi-Modal Mapping Latency and Width Mod ICA Free-behavior Designs Mental Chronometry Multi-variate Mapping

Interpretation

Blood T2 Hemoglobin BOLD models B₀ dep. TE dep SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. CO₂ effect Inflow ASL vs. BOLD BSE of BOLD Extended Stim. Linearity Fluctuations Balloon Model Optical Im. Correlation Electrophys. correlation Layer spec. latency Excite and Inhibit Metab. Correlation

Applications

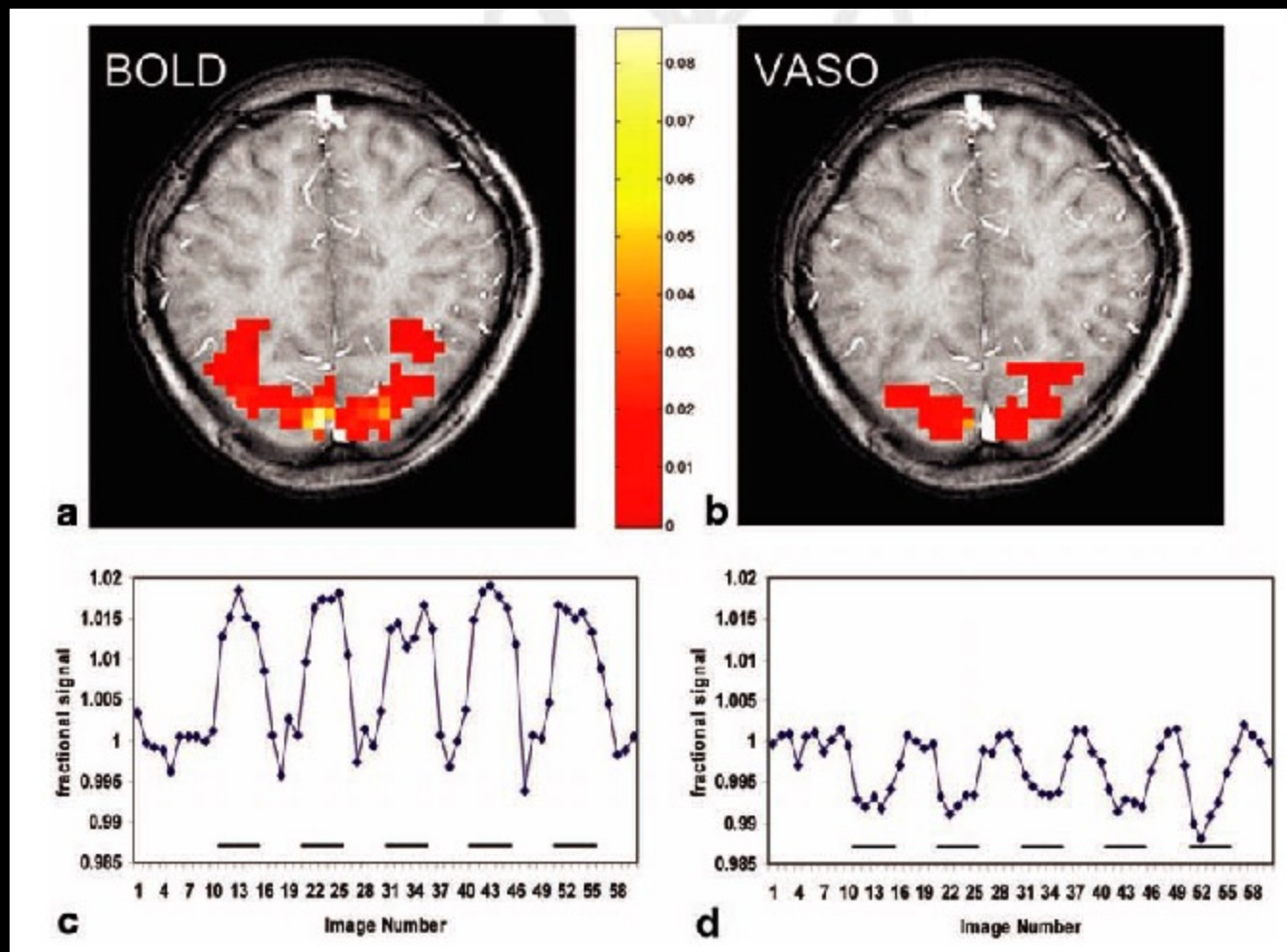
Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Mirror neurons Presurgical Attention Ocular Dominance BOLD -V1, M1, A1 Priming/Learning Clinical Populations V1, V2..mapping Plasticity Face recognition Performance prediction Δ Volume-V1



Functional Magnetic Resonance Imaging Based on Changes in Vascular Space Occupancy

Hanzhang Lu,¹⁻³ Xavier Golay,^{1,3} James J. Pekar,^{1,3} and Peter C.M. van Zijl^{1,3*}

MAGNET RESON MED 50 (2): 263-274 AUG 2003



Technology

MRI, EPI, 1.5T,3T, 4T, Local Human Head Gradient Coils, EPI on Clin. Syst., Nav. pulses, Diff. tensor, Mg⁺, Venography, 7T, >8 channels, SENSE, "vaso", BOLD, ASL, Spiral EPI, Multi-shot fMRI, Quant. ASL, Dynamic IV volume, Z-shim, Baseline Susceptibility, Simultaneous ASL and BOLD, Current Imaging?

Methodology

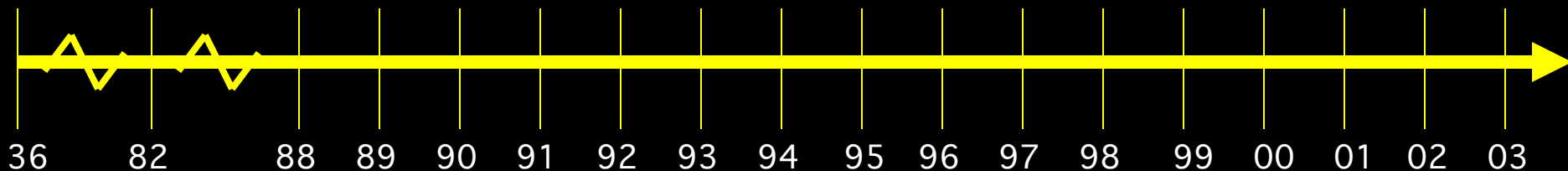
Baseline Volume, IVIM, Correlation Analysis, Motion Correction, CO₂ Calibration, Parametric Design, Multi-Modal Mapping, Latency and Width Mod, Surface Mapping, ICA, Free-behavior Designs, Phase Mapping, Mental Chronometry, Multi-variate Mapping, Linear Regression, Deconvolution, Fuzzy Clustering, Event-related

Interpretation

Blood T2, Hemoglobin, BOLD models, PET correlation, IV vs EV, ASL vs. BOLD, Layer spec. latency, B₀ dep., Pre-undershoot, TE dep., Resolution Dep., Extended Stim., Excite and Inhibit, Post-undershoot, Linearity, Metab. Correlation, SE vs. GE, CO₂ effect, NIRS Correlation, Fluctuations, Optical Im. Correlation, Veins, Inflow, Balloon Model, Electrophys. correlation

Applications

Complex motor Language, Imagery, Memory, Emotion, Motor learning, Children, Tumor vasc., Drug effects, BOLD -V1, M1, A1, Presurgical, Attention, Ocular Dominance, Mirror neurons, Volume - Stroke, V1, V2..mapping, Priming/Learning, Clinical Populations, Δ Volume-V1, Plasticity, Face recognition, Performance prediction



Neuronal Current Imaging

- Neuronal activity is directly associated with ionic currents.
- These bio-currents induce **spatially distributed and transient** magnetic flux density changes and magnetic field gradients.
- In the context of MRI, these currents therefore alter **the magnetic phase** of surrounding water protons.

Derivation of B field generated in an MRI

voxel by a current dipole

Single dendritic tree having a diameter d , and length L behaves like a conductor with conductivity σ . Resistance is $R=V/I$, where $R=4L/(\pi d^2 \sigma)$. From Biot-Savart:

$$\mathbf{B} = \frac{\mu_0}{4\pi} \frac{\mathbf{Q}}{r^2} = \frac{\mu_0}{16} \frac{d^2 \sigma V}{r^2}$$

by substituting $d = 4\mu\text{m}$, $\sigma \approx 0.25 \Omega^{-1} \text{m}^{-1}$, $V = 10\text{mV}$ and

$r = 4\text{cm}$ (measurement distance when using MEG) the resulting value is: **$B \approx 0.002 \text{ fT}$**

Because **$B_{\text{MEG}} = 100 \text{ fT}$** (or more) is measured by MEG on the scalp, a large number of neurons, ($0.002 \text{ fT} \times 50,000 = 100 \text{ fT}$), must coherently act to generate such field. These bundles of neurons produce, within a typical voxel, $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$, a field of order:

$$B_{\text{MRI}} = B_{\text{MEG}} \left(\frac{r_{\text{MEG}}}{r_{\text{MRI}}} \right)^2 = B_{\text{MEG}} \left(\frac{4 \text{ cm}}{0.1 \text{ cm}} \right)^2 = 1600 B_{\text{MEG}}$$

$$\mathbf{B}_{\text{MRI}} \approx 0.2 \text{ nT}$$

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).

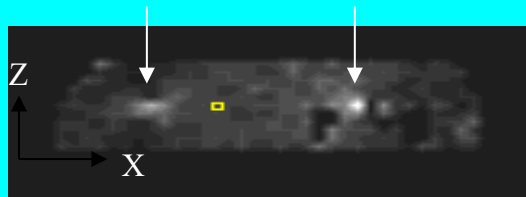
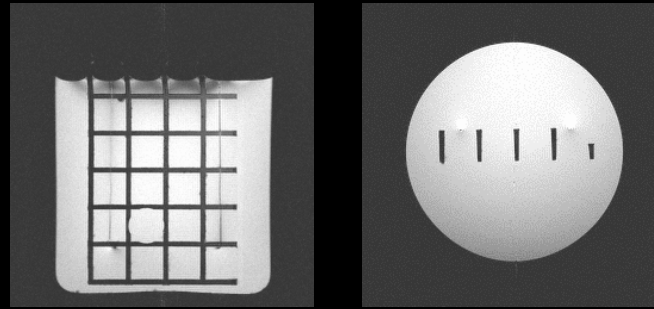
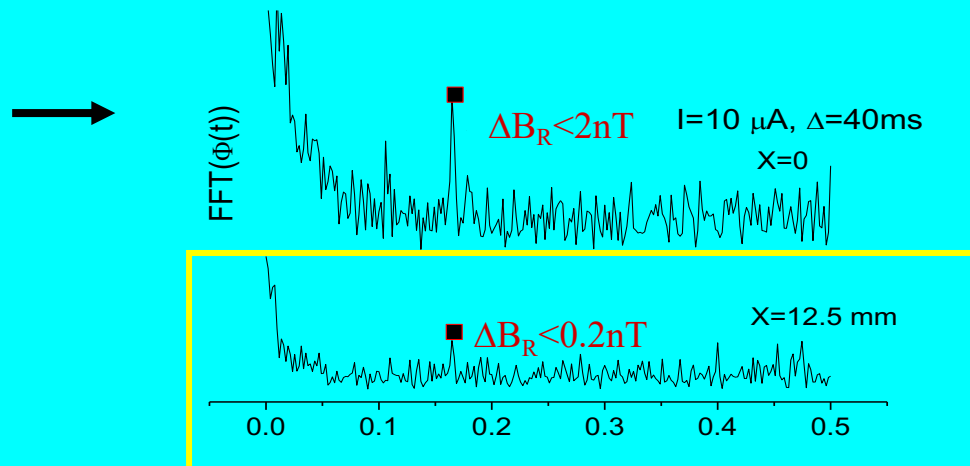
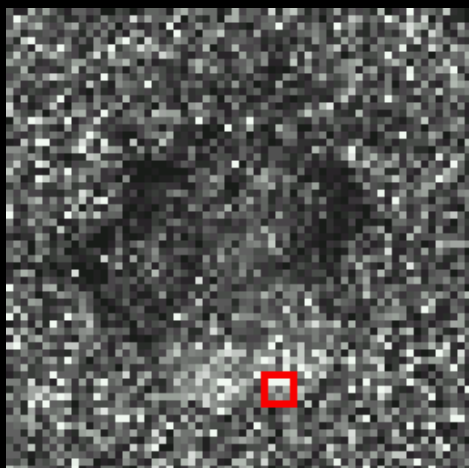


Figure 1

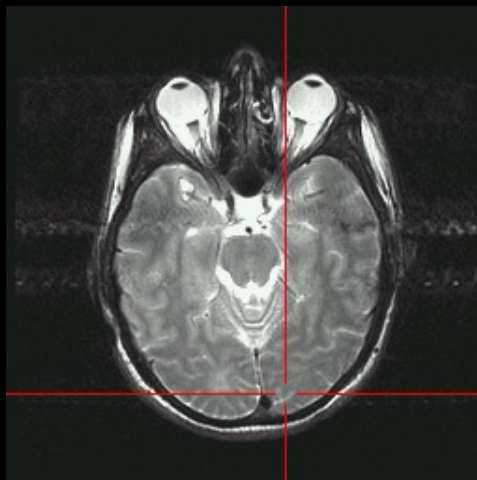


J. Bodurka, P. A. Bandettini. Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes, *Magn. Reson. Med.* 47: 1052-1058, (2002).

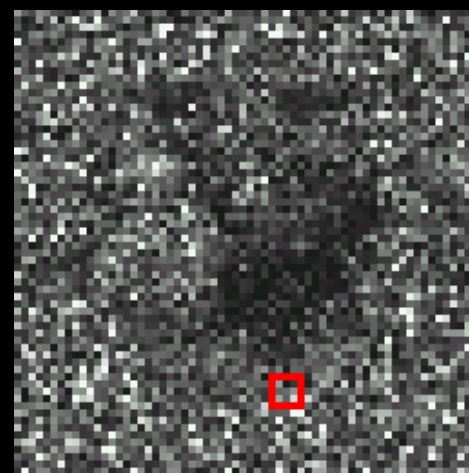
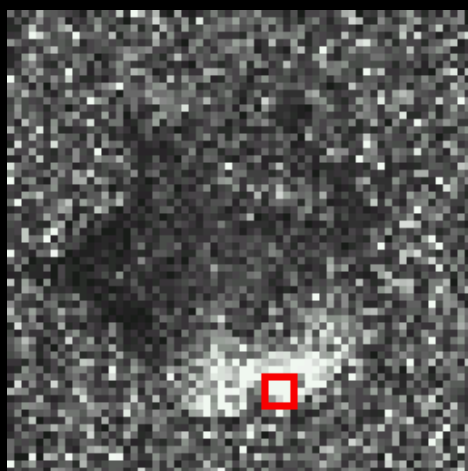
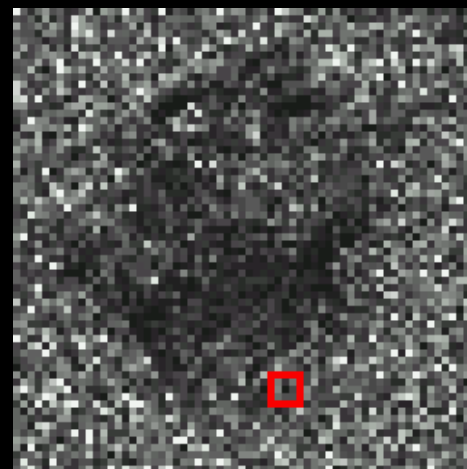
Closed



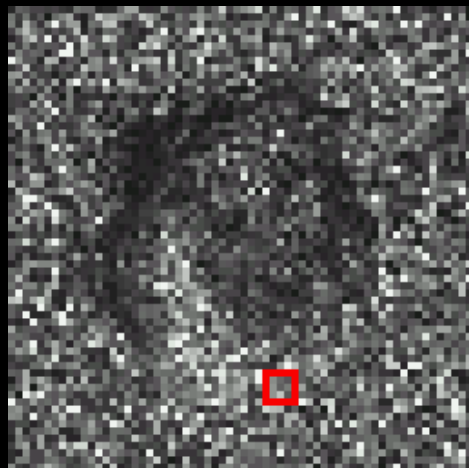
Phase $\nu=0.12\text{Hz}$



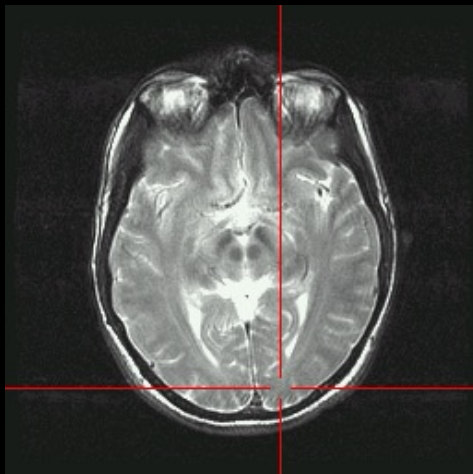
Open



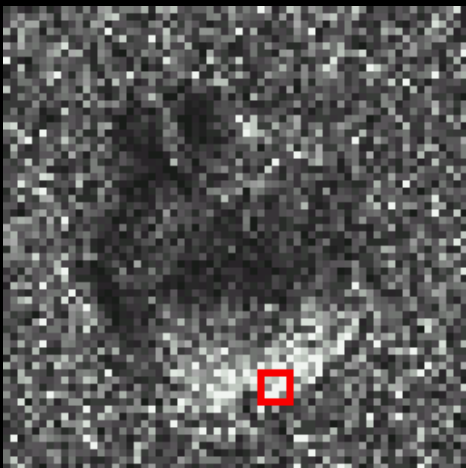
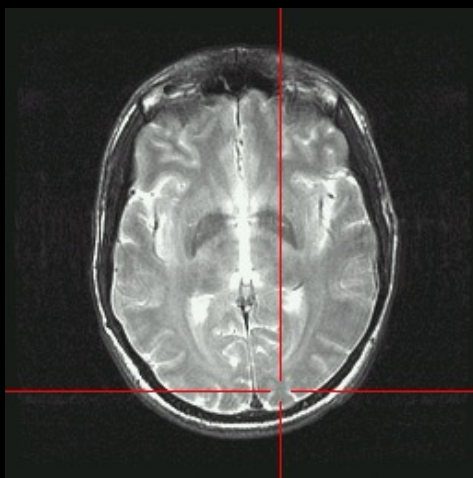
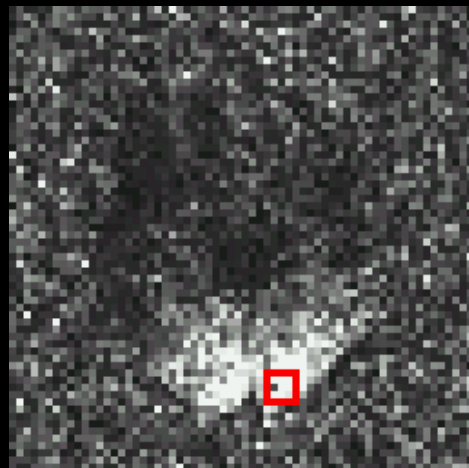
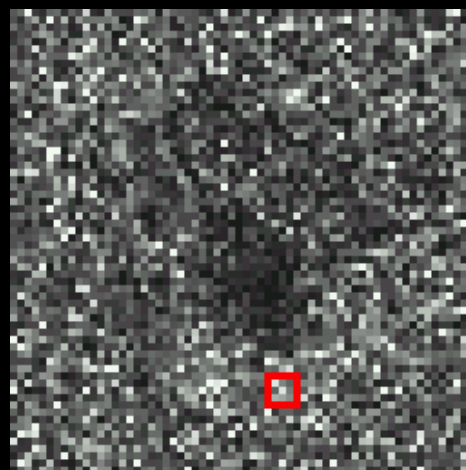
Closed



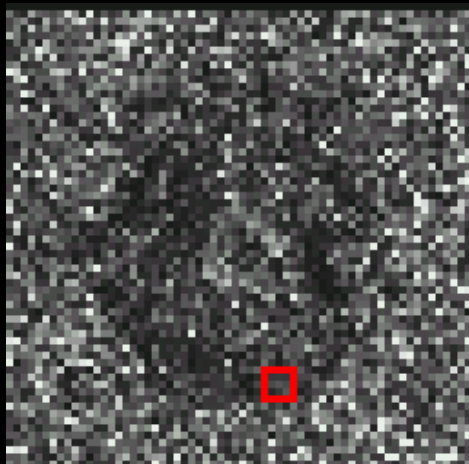
Phase $\nu=0.12\text{Hz}$



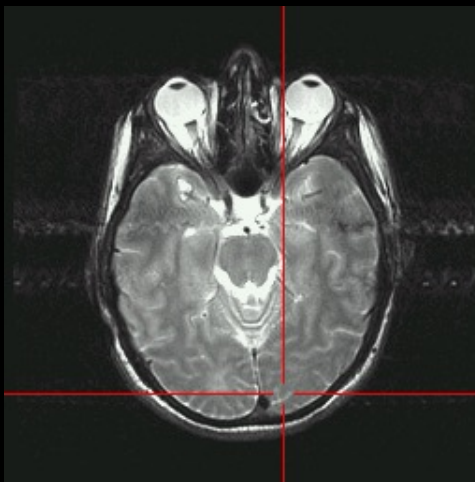
Open



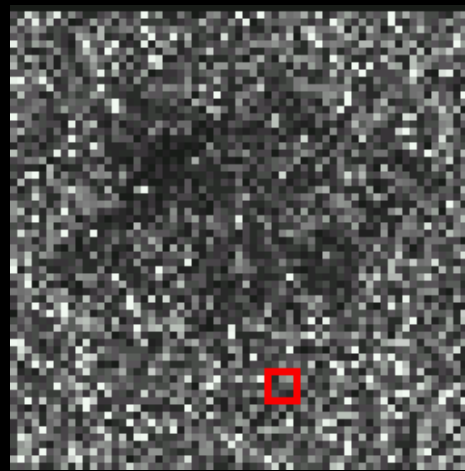
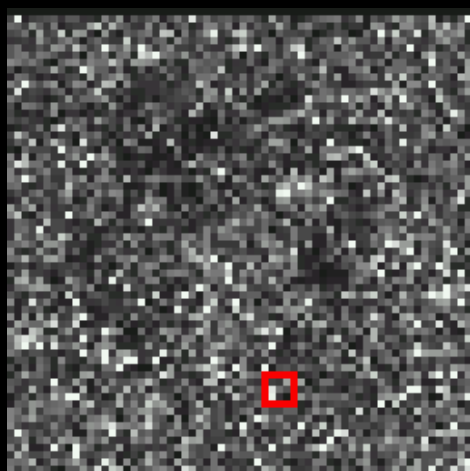
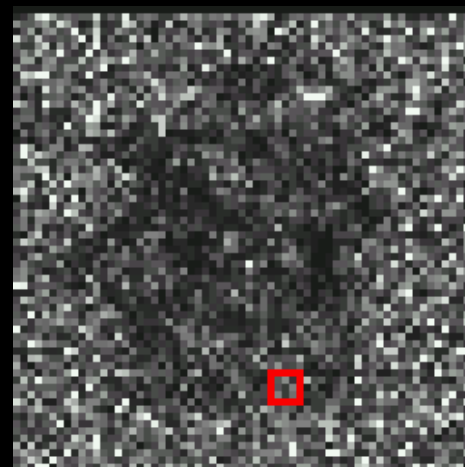
Closed



Magnitude $v=0.12\text{Hz}$



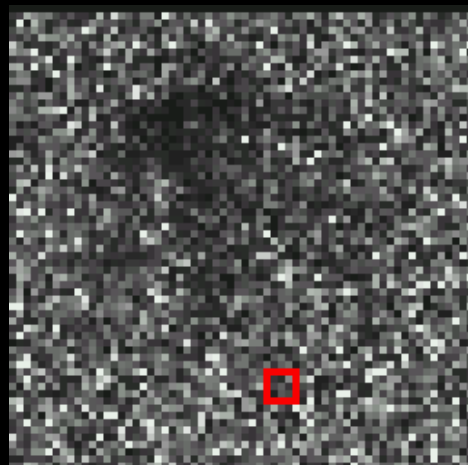
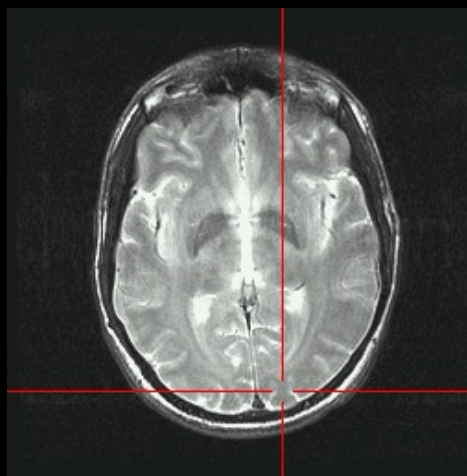
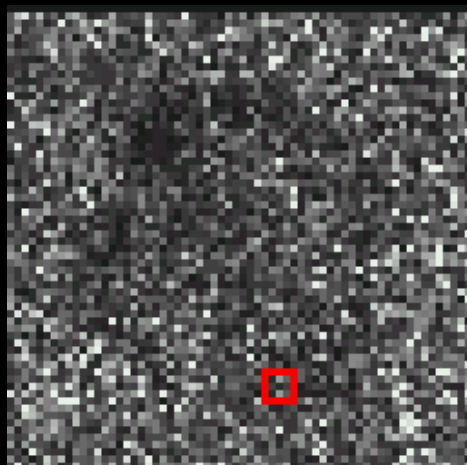
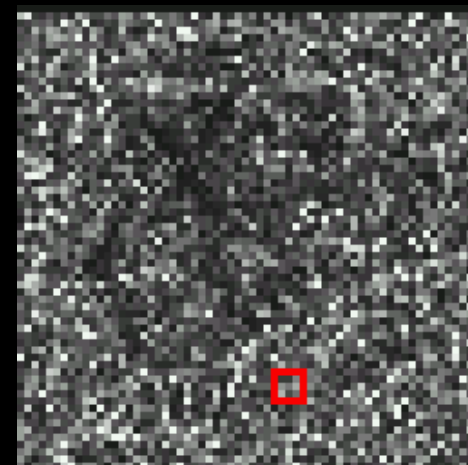
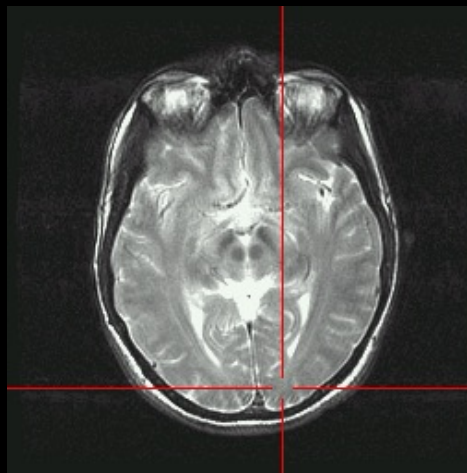
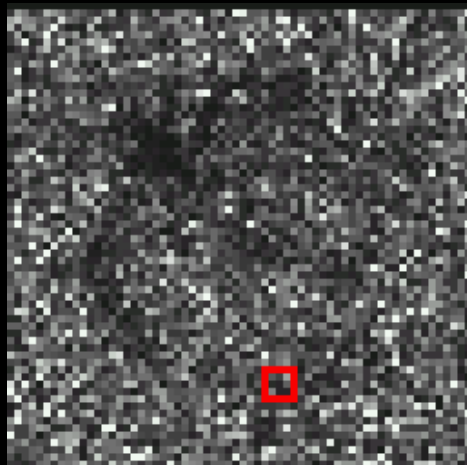
Open



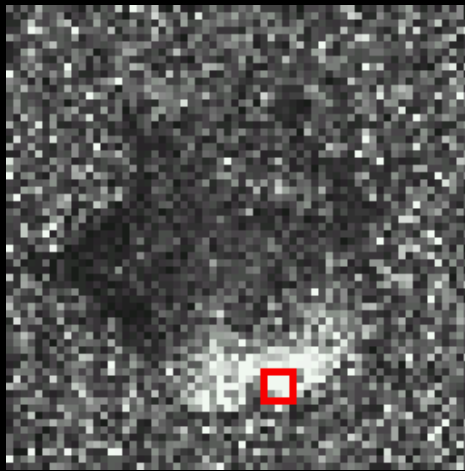
Closed

Magnitude $\nu=0.12$ Hz

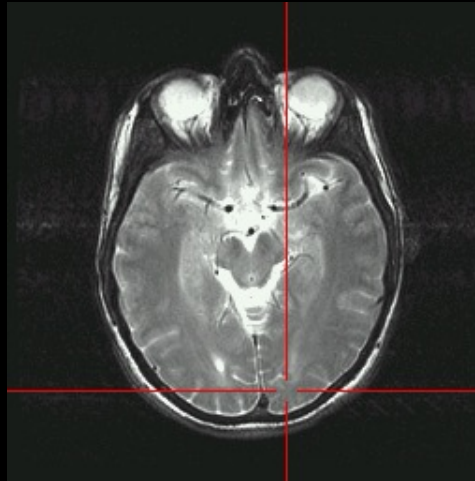
Open



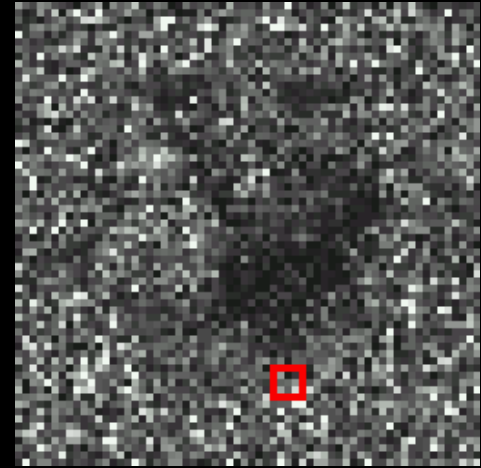
Closed



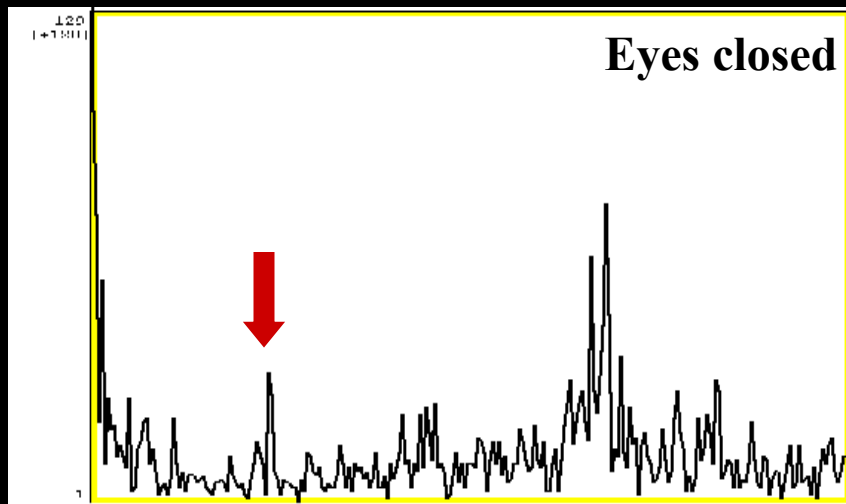
Phase $\nu=0.12\text{Hz}$



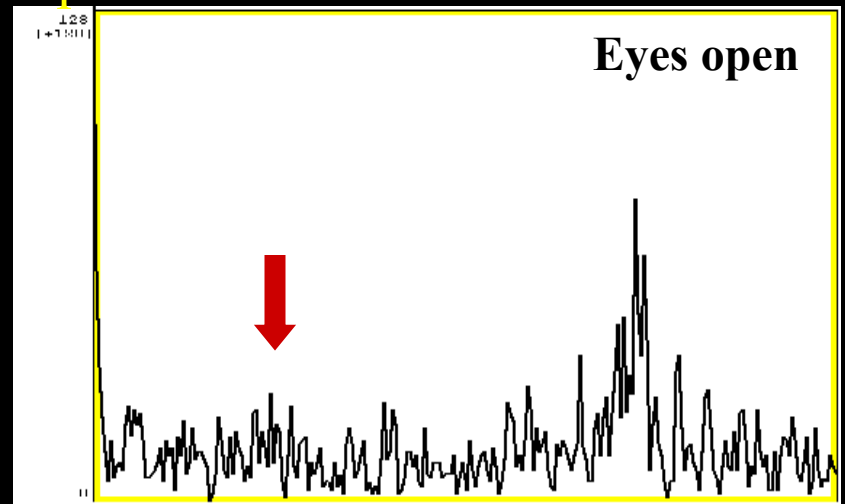
Open



Power spectra



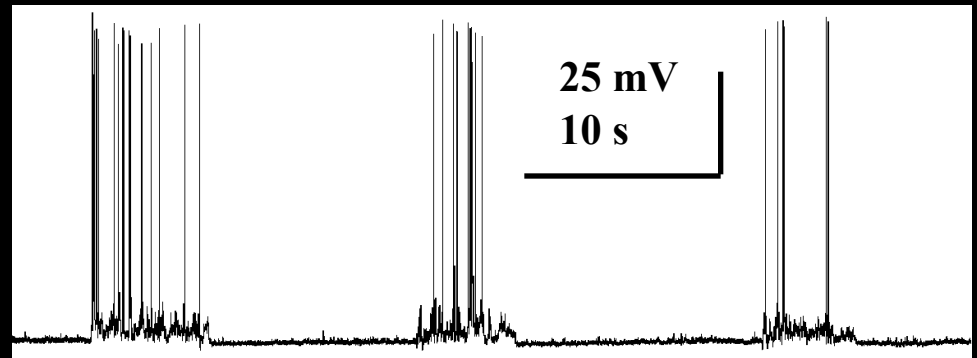
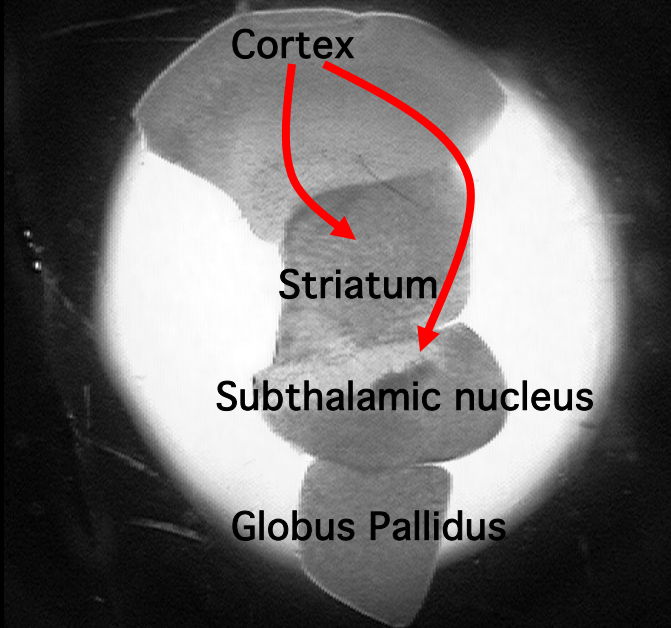
0.5 Hz

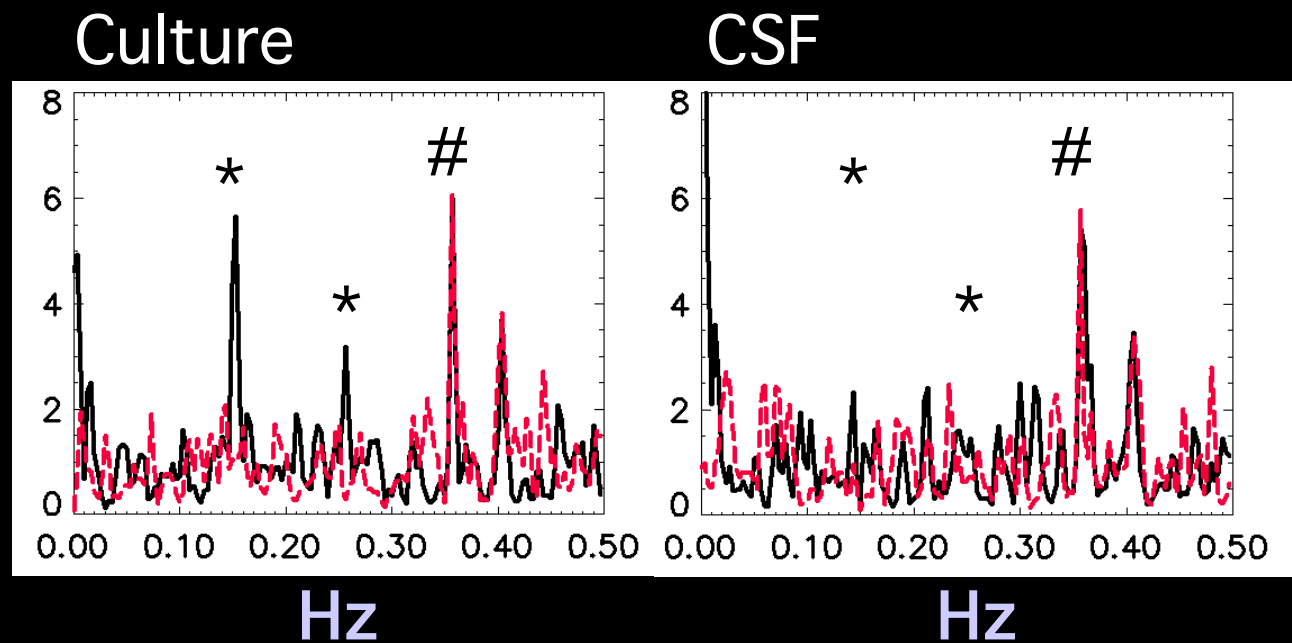
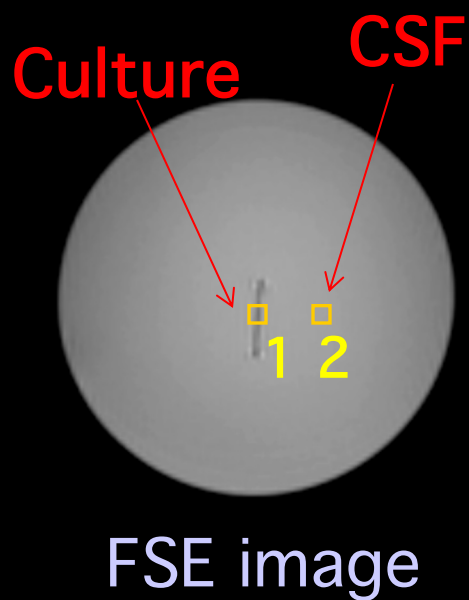


0.5 Hz

In Vitro Results

Newborn rat brains have been found to exhibit spontaneous and synchronous firing at specific frequencies





Active state: 10 min, Inactive state: 10 min after TTX admin.

*: activity

#: scanner pump frequency

Petridou et al.

- Functional contrast
- **Signal interpretation**
- Hardware and pulse sequences
- Paradigm design and processing

- Overview
- Current Limits
- Future Prospects

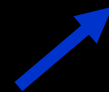
Neuronal Activation

Measured Signal

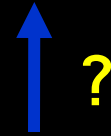


?

Hemodynamics

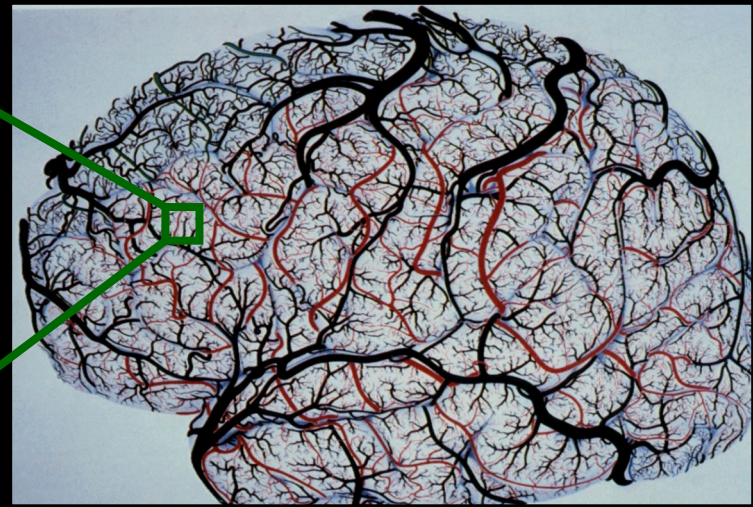
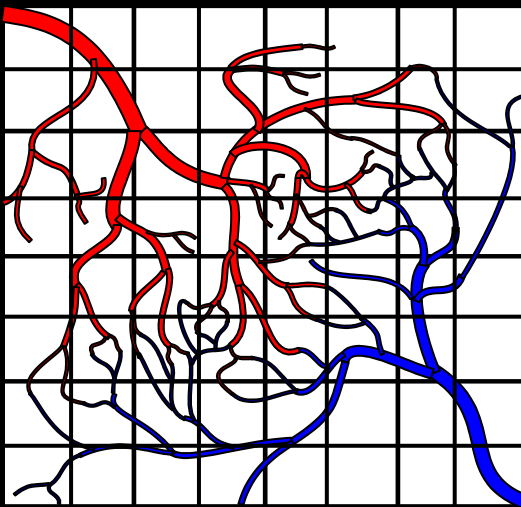


?



?

Noise



Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL Spiral EPI Multi-shot fMRI BOLD Simultaneous ASL and BOLD Current Imaging? "vaso" SENSE 7T >8 channels Diff. tensor Mg+ Venography Real time fMRI Nav. pulses Quant. ASL Dynamic IV volume Z-shim Baseline Susceptibility

Methodology

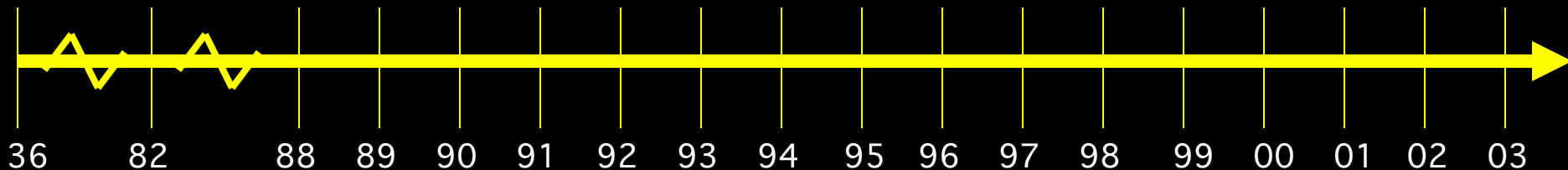
Baseline Volume IVIM Correlation Analysis Parametric Design Surface Mapping Phase Mapping Linear Regression Event-related Deconvolution Fuzzy Clustering Motion Correction CO₂ Calibration Multi-Modal Mapping Latency and Width Mod ICA Free-behavior Designs Mental Chronometry Multi-variate Mapping

Interpretation

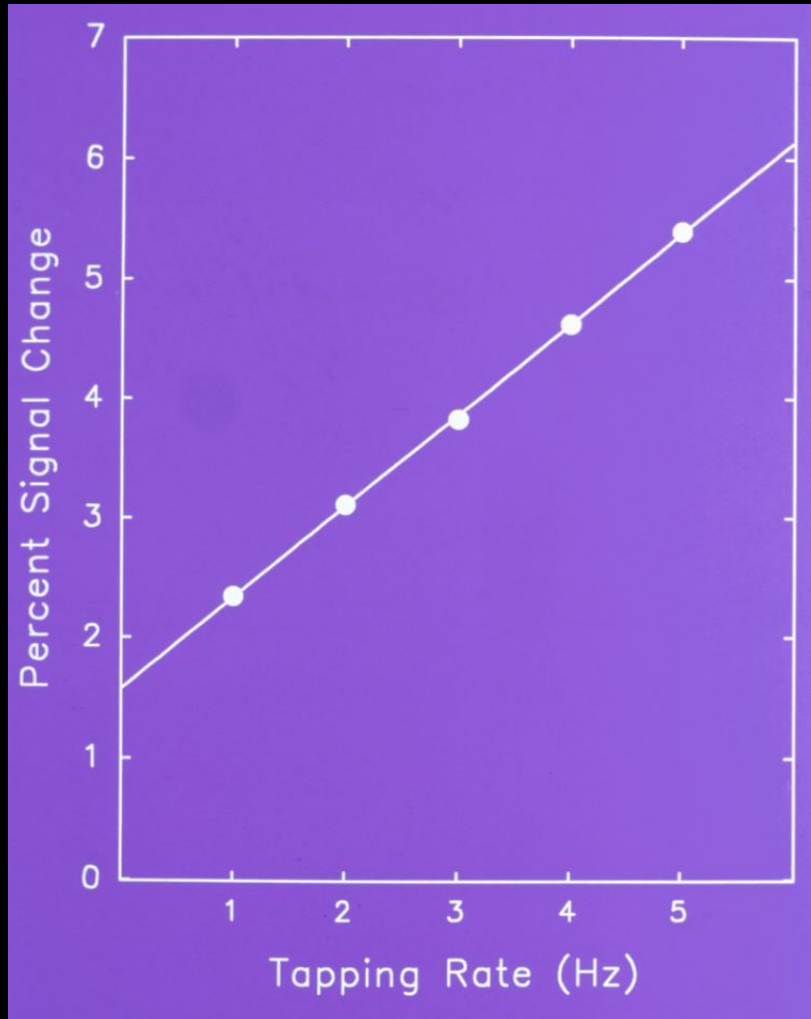
Blood T2 Hemoglobin BOLD models B₀ dep. TE dep SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. CO₂ effect Inflow ASL vs. BOLD BSE of BOLD Layer spec. latency Excite and Inhibit Extended Stim. Linearity Metab. Correlation Optical Im. Correlation Electrophys. correlation

Applications

Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Mirror neurons Presurgical Attention Ocular Dominance BOLD -V1, M1, A1 Priming/Learning Clinical Populations Volume - Stroke V1, V2..mapping Plasticity Face recognition Δ Volume-V1 Performance prediction

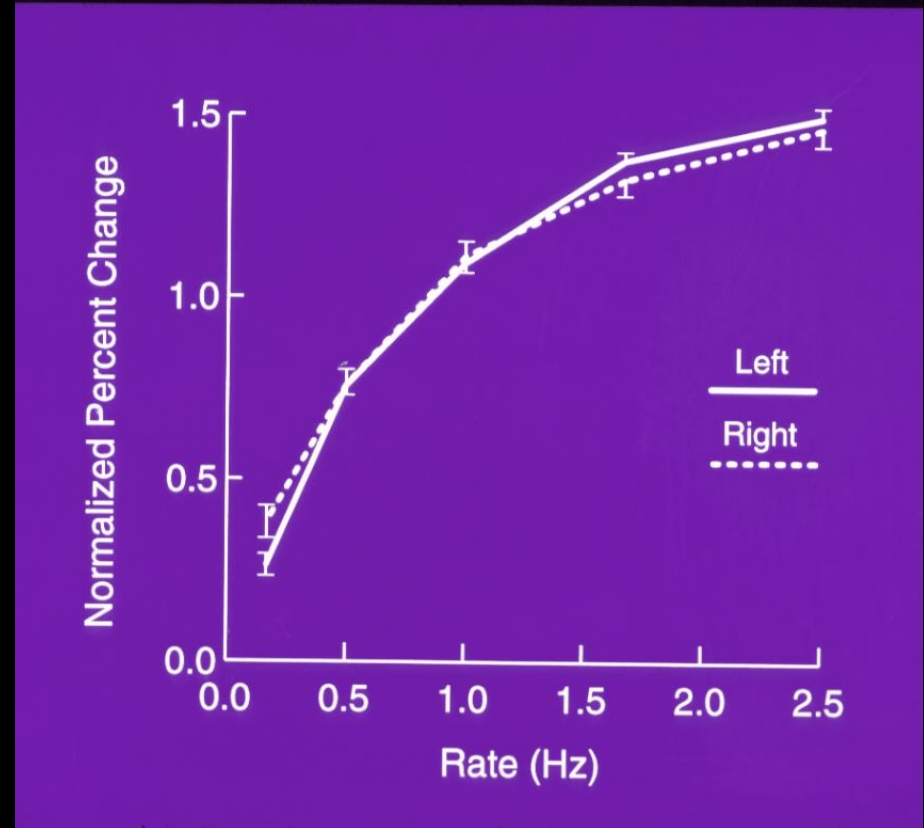


Motor Cortex



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

Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL BOLD Multi-shot fMRI Spiral EPI Dynamic IV volume Simultaneous ASL and BOLD Current Imaging? Diff. tensor Real time fMRI Quant. ASL Venography Z-shim Baseline Susceptibility SENSE "vaso" >8 channels

Methodology

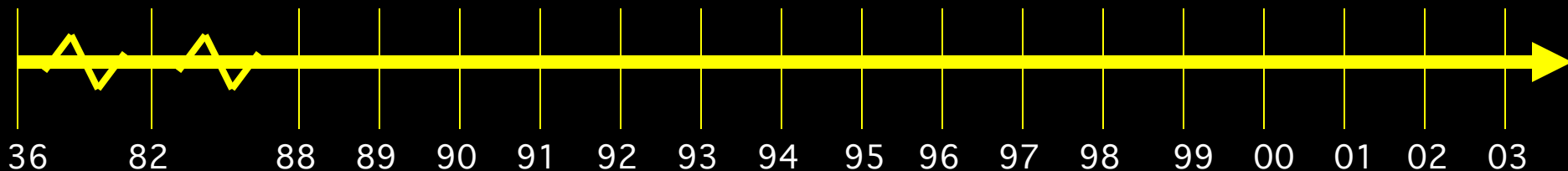
Baseline Volume IVIM Correlation Analysis Parametric Design Motion Correction CO₂ Calibration Multi-Modal Mapping Latency and Width Mod Surface Mapping ICA Free-behavior Designs Phase Mapping Linear Regression Mental Chronometry Multi-variate Mapping Event-related Deconvolution Fuzzy Clustering

Interpretation

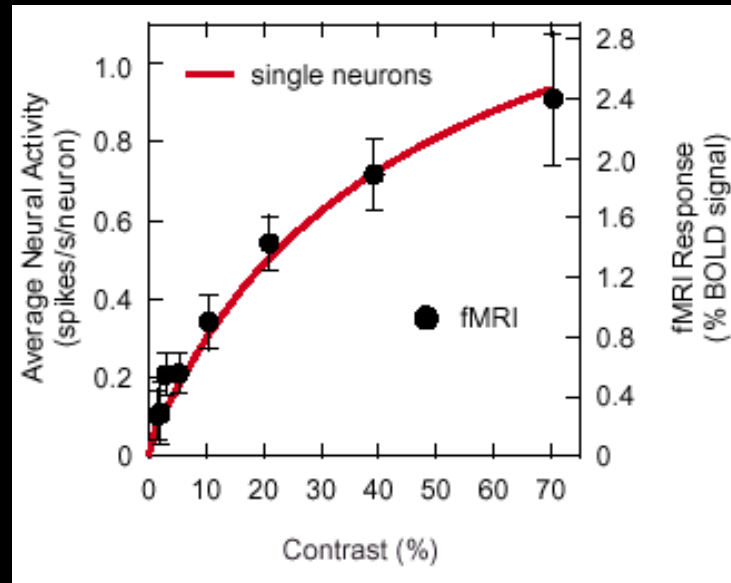
Blood T2 Hemoglobin BOLD models B₀ dep. TE dep SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. CO₂ effect Inflow ASL vs. BOLD BSE of BOLD Extended Stim. Linearity Fluctuations Balloon Model Optical Im. Correlation Electrophys. correlation Layer spec. latency Excite and Inhibit Metab. Correlation

Applications

Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Presurgical Attention Ocular Dominance Mirror neurons V1, V2..mapping Priming/Learning Clinical Populations Performance prediction BOLD -V1, M1, A1 Δ Volume-V1 Plasticity Face recognition



fMRI responses in human V1 are proportional to average firing rates in monkey V1



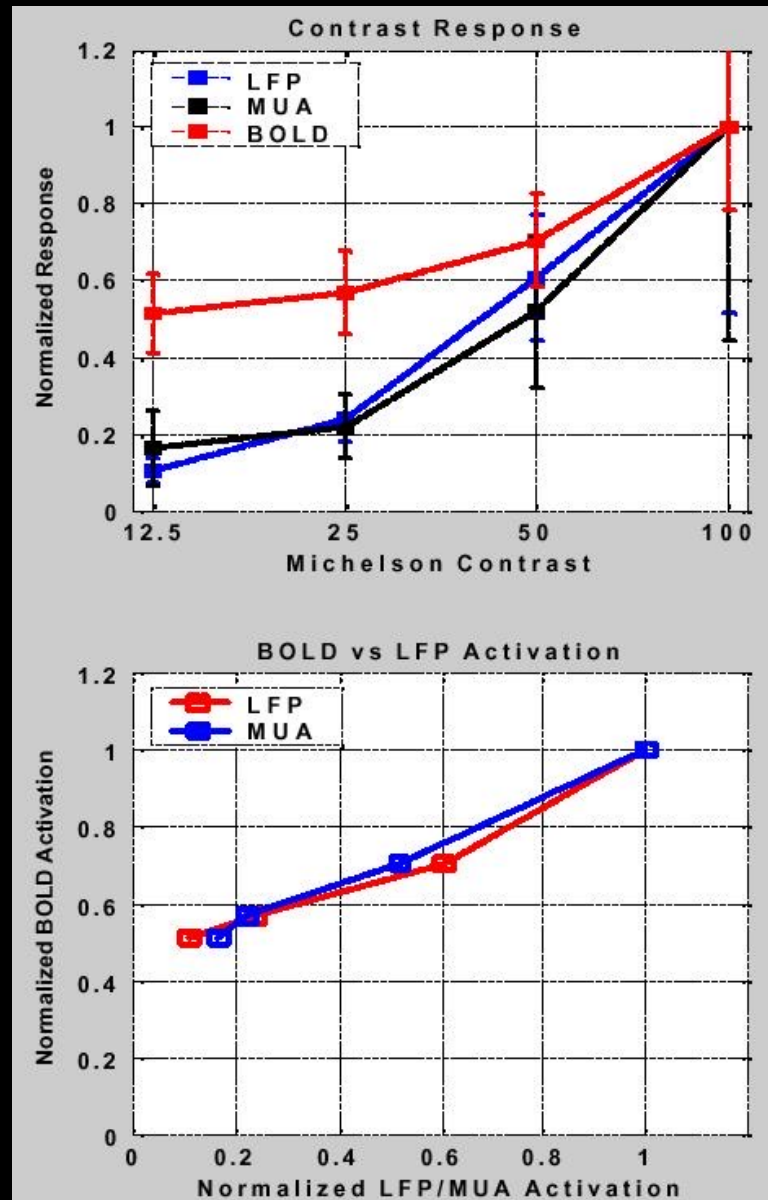
Heeger, D. J., Huk, A. C., Geisler, W. S., and Albrecht, D. G. 2000. Spikes versus BOLD: What does neuroimaging tell us about neuronal activity? *Nat. Neurosci.* 3: 631–633.

0.4 spikes/sec -> 1% BOLD

Rees, G., Friston, K., and Koch, C. 2000. A direct quantitative relationship between the functional properties of human and macaque V5. *Nat. Neurosci.* 3: 716–723.

9 spikes/sec -> 1% BOLD

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

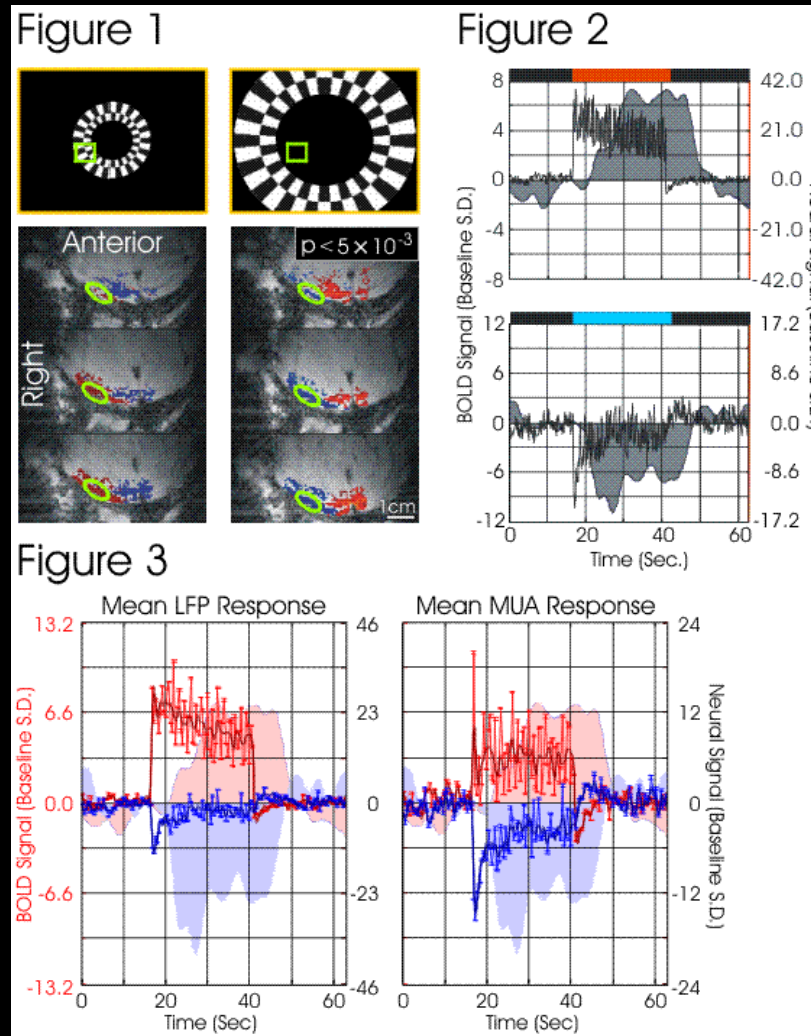


HBM 2003

Poster number: 308

The Negative BOLD Response in Monkey V1 Is Associated with Decreases in Neuronal Activity

Amir Shmuel*†, Mark Augath, Axel Oeltermann, Jon Pauls, Yusuke Murayama, Nikos K. Logothetis



Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL Spiral EPI Multi-shot fMRI BOLD Simultaneous ASL and BOLD Current Imaging? "vaso" SENSE >8 channels Diff. tensor Mg+ Venography 7T Real time fMRI Nav. pulses Quant. ASL Dynamic IV volume Z-shim Baseline Susceptibility

Methodology

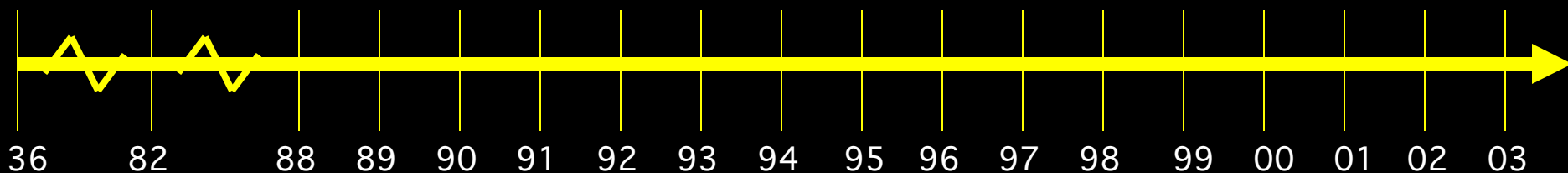
Baseline Volume IVIM Correlation Analysis Parametric Design Motion Correction CO₂ Calibration Multi-Modal Mapping Latency and Width Mod Surface Mapping ICA Free-behavior Designs Phase Mapping Linear Regression Mental Chronometry Multi-variate Mapping Event-related Deconvolution Fuzzy Clustering

Interpretation

Blood T2 Hemoglobin BOLD models B₀ dep. TE dep. SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. CO₂ effect Inflow ASL vs. BOLD Extended Stim. Linearity Fluctuations Balloon Model Electrophys. correlation Layer spec. latency Excite and Inhibit Metab. Correlation Optical Im. Correlation

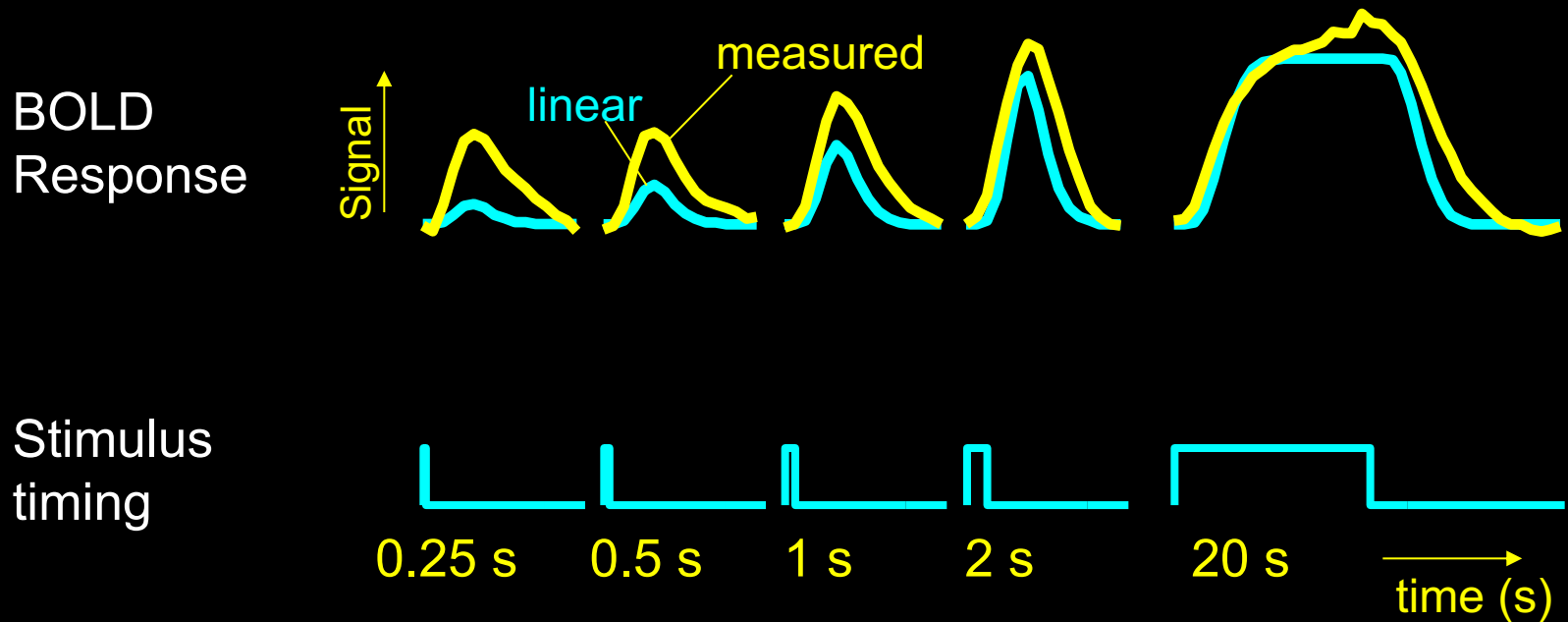
Applications

Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Presurgical Attention Ocular Dominance Mirror neurons V1, V2..mapping Priming/Learning Clinical Populations Performance prediction BOLD -V1, M1, A1 Δ Volume-V1 Plasticity Face recognition



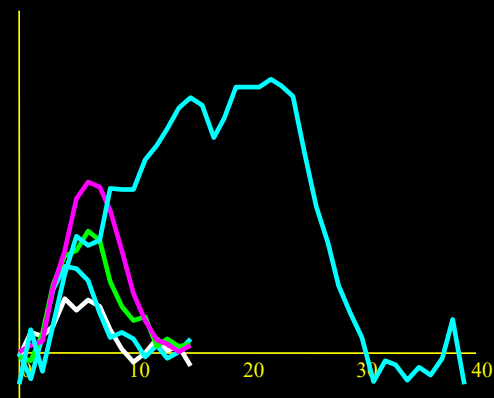
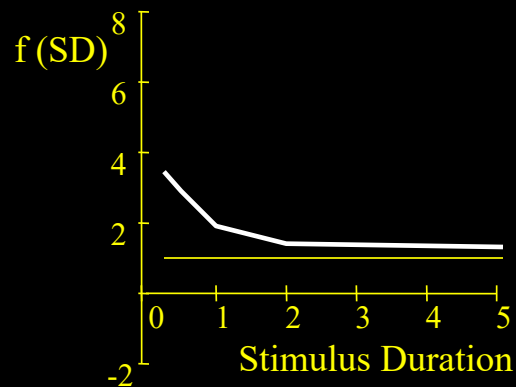
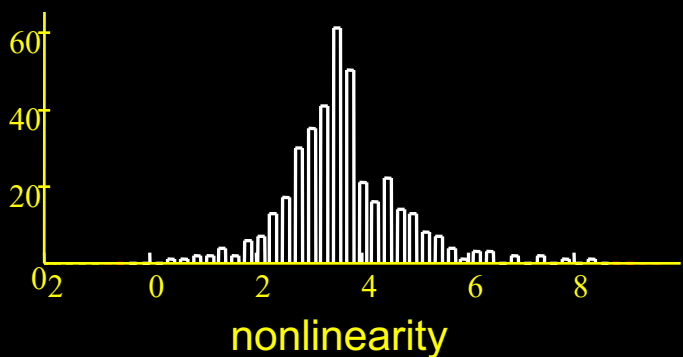
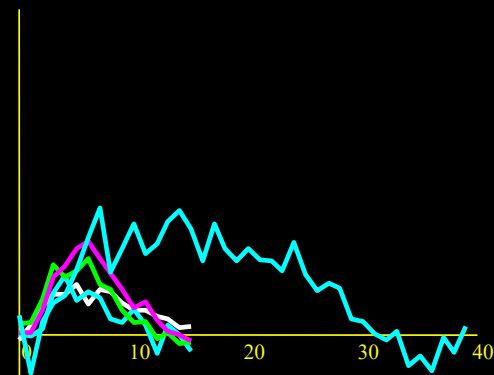
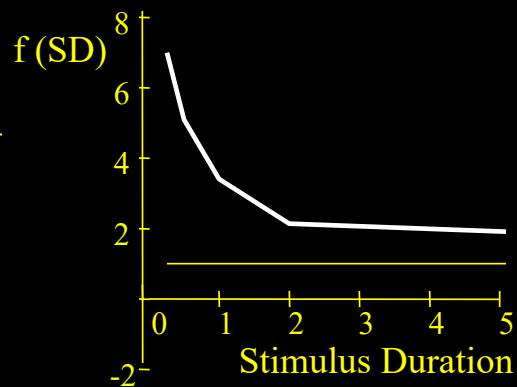
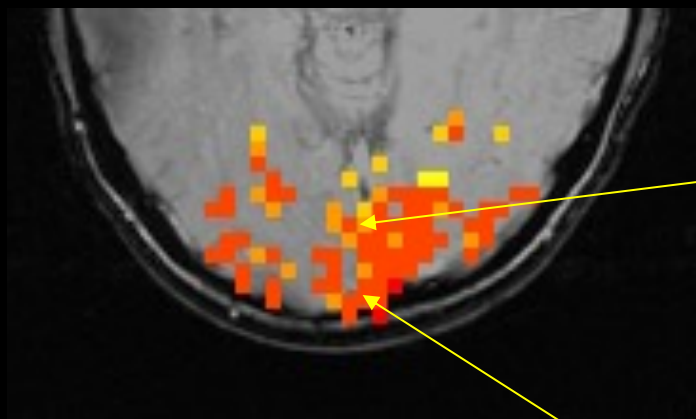
Dynamic Nonlinearity Assessment

Different stimulus “ON” periods



Brief stimuli produce larger responses than expected

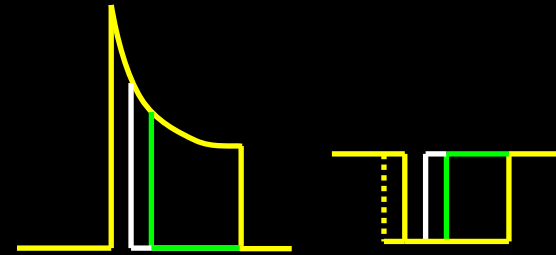
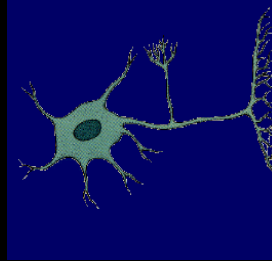
Spatial Heterogeneity of BOLD Nonlinearity



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

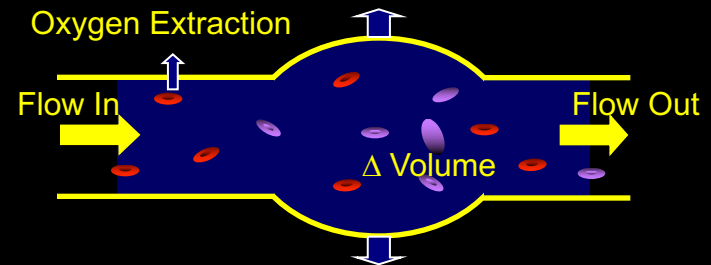
Sources of this Nonlinearity

- Neuronal



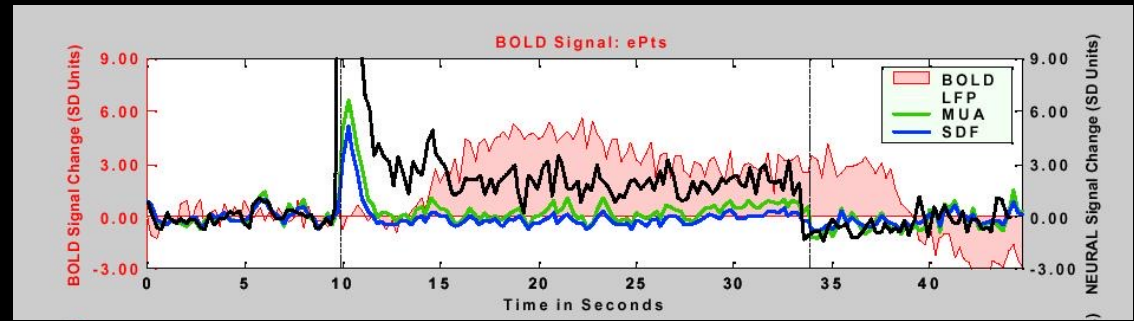
- Hemodynamic

- Oxygen extraction
- Blood volume dynamics

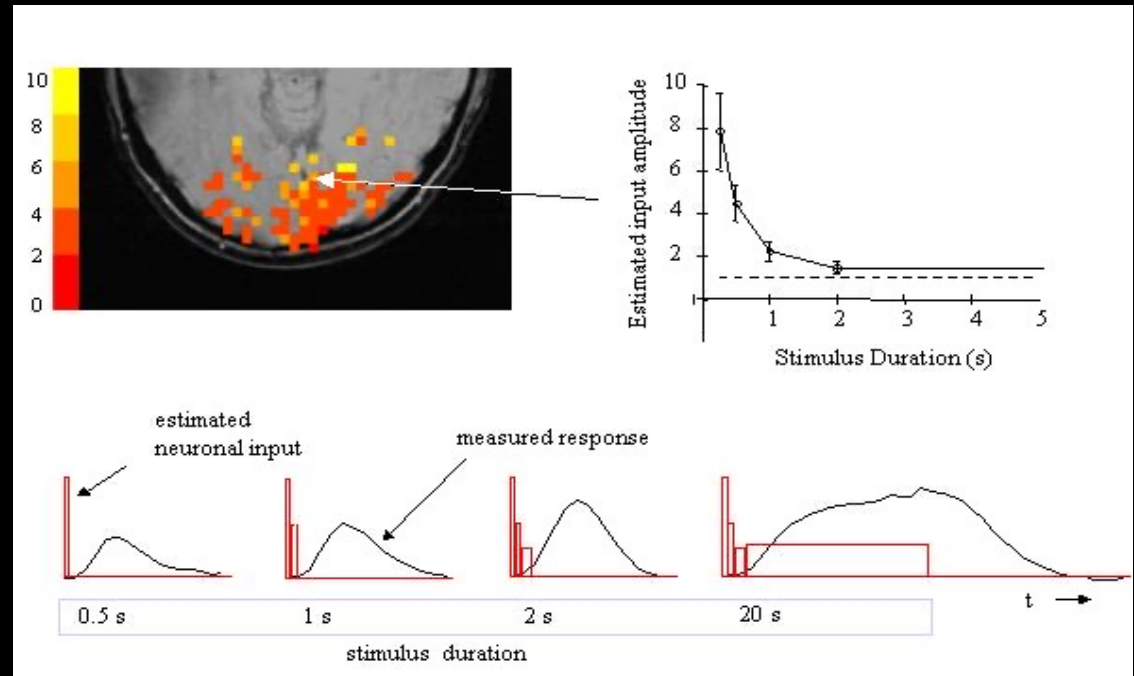


BOLD Correlation with Neuronal Activity

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

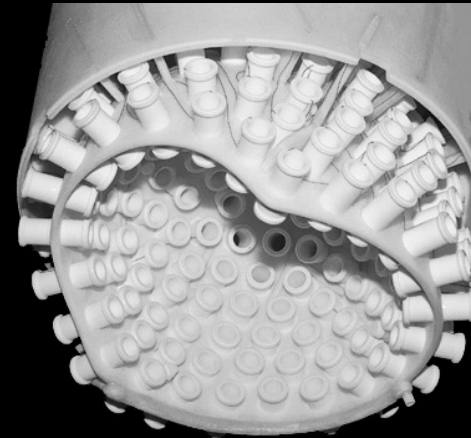
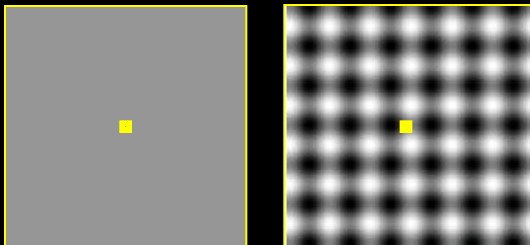


P. A. Bandettini and L. G. Ungerleider, (2001) “From neuron
to BOLD: new connections.”
Nature Neuroscience, 4: 864-866.

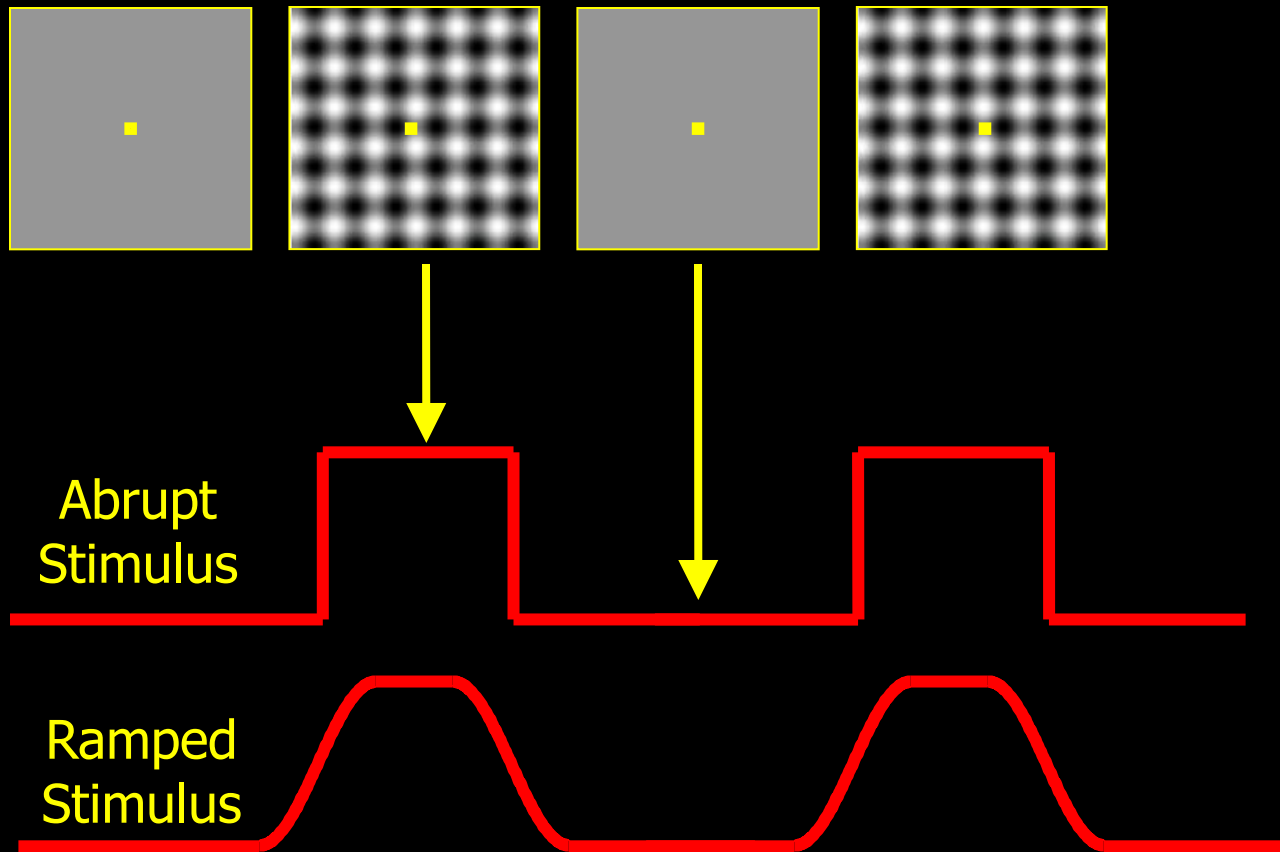


MEG and Ramped Stimulus

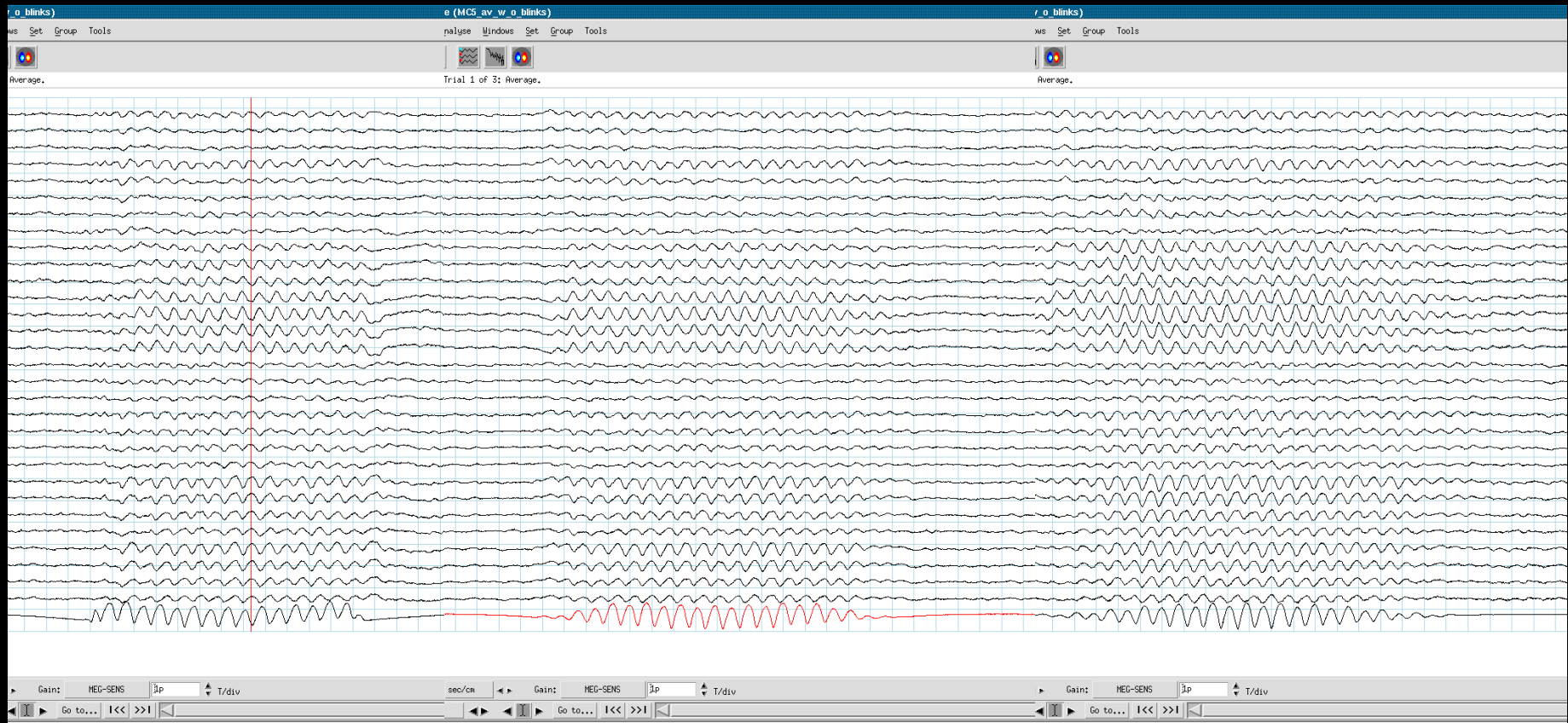
- 6 subjects
- SD: 1 or 2 seconds
- Ramp: 0, 0.5, 1 second
- 8 Hz Counterphase-modulated checkerboards
- Fixation without task
 - No blinking point
- 45 repeats
- 3 sec ISI
- 275 channels
- 600 Hz



MEG – Ramped stimuli



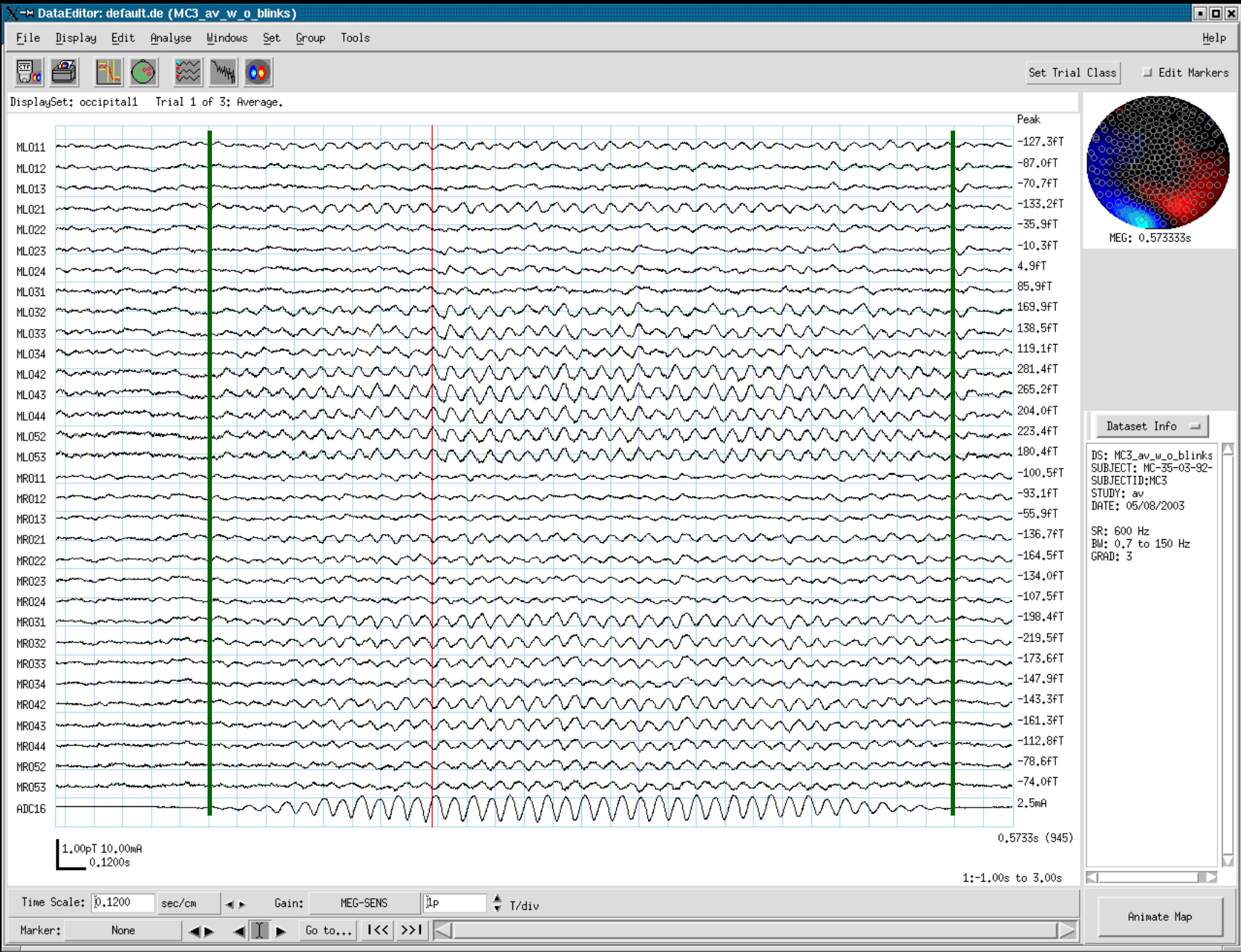
Composite – 1 second Stimulus Duration



No Ramp

0.5 second Ramp

1 second Ramp



Technology

MRI 1.5T,3T, 4T EPI Local Human Head Gradient Coils ASL BOLD Multi-shot fMRI Spiral EPI EPI on Clin. Syst. Nav. pulses Diff. tensor Real time fMRI Quant. ASL Dynamic IV volume Simultaneous ASL and BOLD Mg⁺ Venography Z-shim Baseline Susceptibility SENSE "vaso" 7T >8 channels Current Imaging?

Methodology

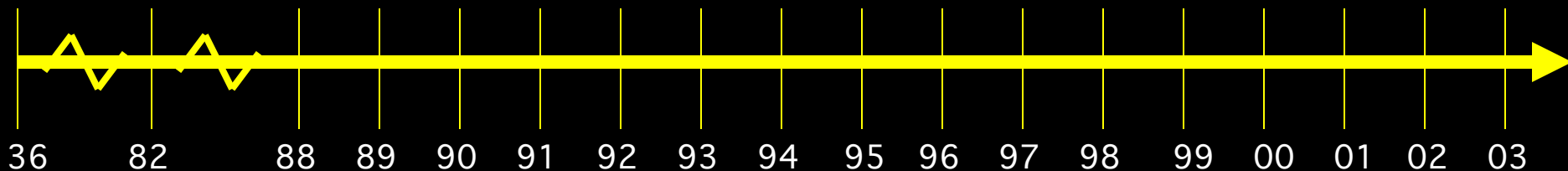
Baseline Volume IVIM Correlation Analysis Parametric Design Motion Correction CO₂ Calibration Multi-Modal Mapping Latency and Width Mod Surface Mapping ICA Free-behavior Designs Phase Mapping Linear Regression Mental Chronometry Multi-variate Mapping Event-related Deconvolution Fuzzy Clustering

Interpretation

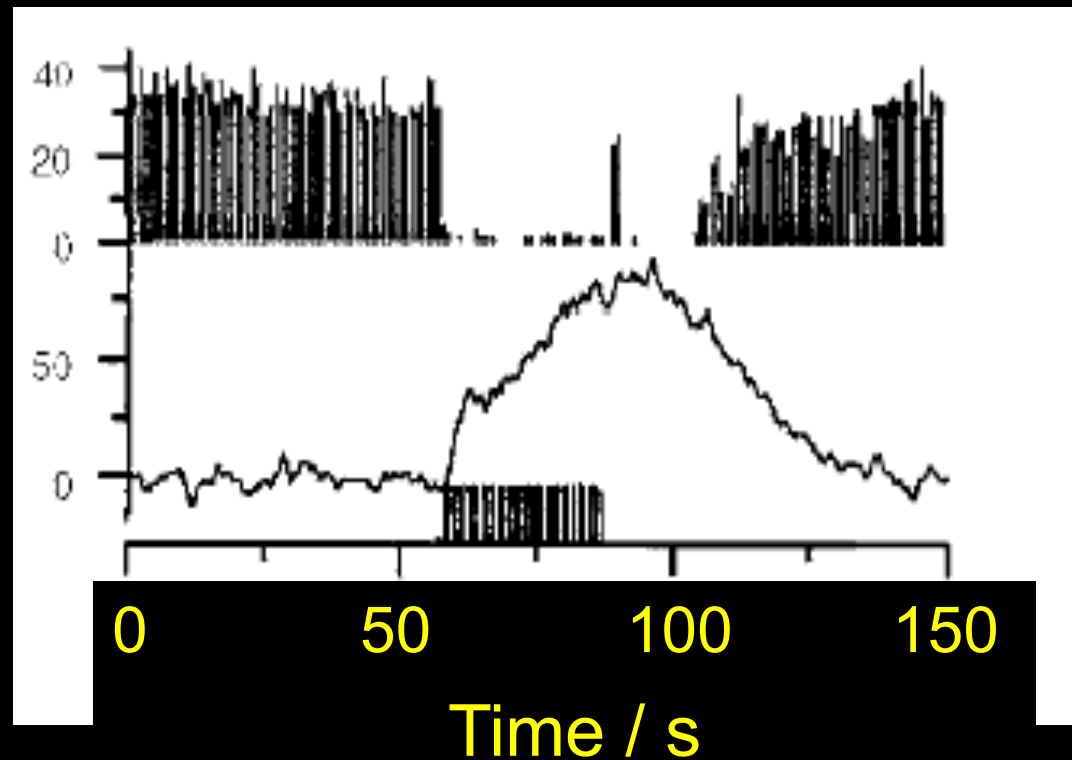
Blood T2 Hemoglobin BOLD models B₀ dep. TE dep. SE vs. GE NIRS Correlation Veins PET correlation IV vs EV Pre-undershoot Resolution Dep. Post-undershoot CO₂ effect Inflow ASL vs. BOLD Extended Stim. Linearity Fluctuations Balloon Model Optical Im. Correlation Electrophys. correlation Layer spec. latency Excite and Inhibit Metab. Correlation

Applications

Complex motor Language Imagery Memory Emotion Motor learning Children Tumor vasc. Drug effects Presurgical Attention Ocular Dominance Mirror neurons Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations Performance prediction Δ Volume-V1 Plasticity Face recognition



Divergence of spike rate and blood flow during parallel fiber stimulation



Mathiesen, Caesar, Akgören, Lauritzen (1998), J Physiol 512.2:555-566

- Functional contrast
- Signal interpretation
- **Hardware and pulse sequences**
- Paradigm design and processing
- Spatial and temporal resolution

- Overview
- Current Limits
- Future Prospects

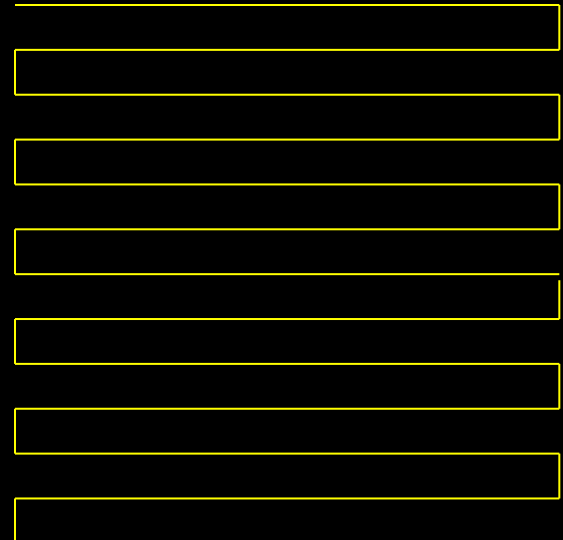
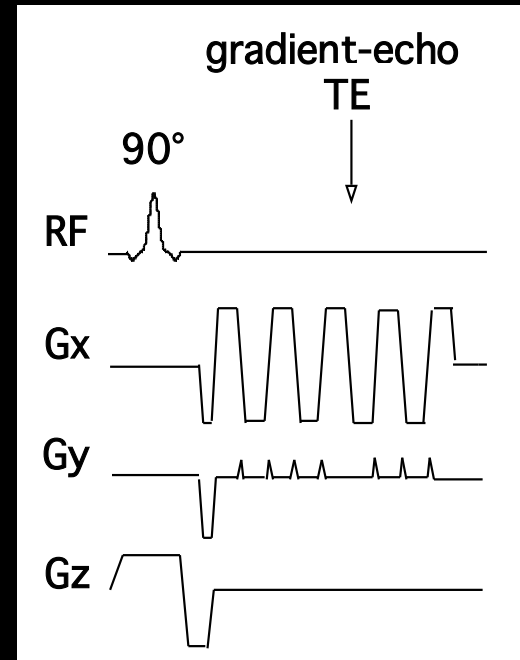
Single Shot EPI

T2* decay



EPI Readout Window

≈ 20 to 40 ms



Technology

MRI, 1.5T,3T, 4T, EPI, Local Human Head Gradient Coils, BOLD, ASL, Spiral EPI, Multi-shot fMRI, EPI on Clin. Syst., Nav. pulses, Diff. tensor, Real time fMRI, Quant. ASL, Dynamic IV volume, Simultaneous ASL and BOLD, Current Imaging?, Mg⁺, Venography, Z-shim, Baseline Susceptibility, SENSE, "vaso", 7T, >8 channels

Methodology

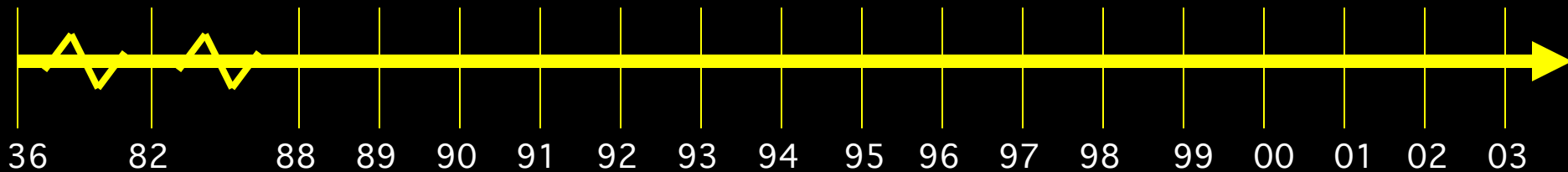
Baseline Volume, IVIM, Correlation Analysis, Parametric Design, Motion Correction, CO₂ Calibration, Multi-Modal Mapping, Latency and Width Mod, Surface Mapping, ICA, Free-behavior Designs, Phase Mapping, Linear Regression, Event-related, Deconvolution, Fuzzy Clustering, Mental Chronometry, Multi-variate Mapping

Interpretation

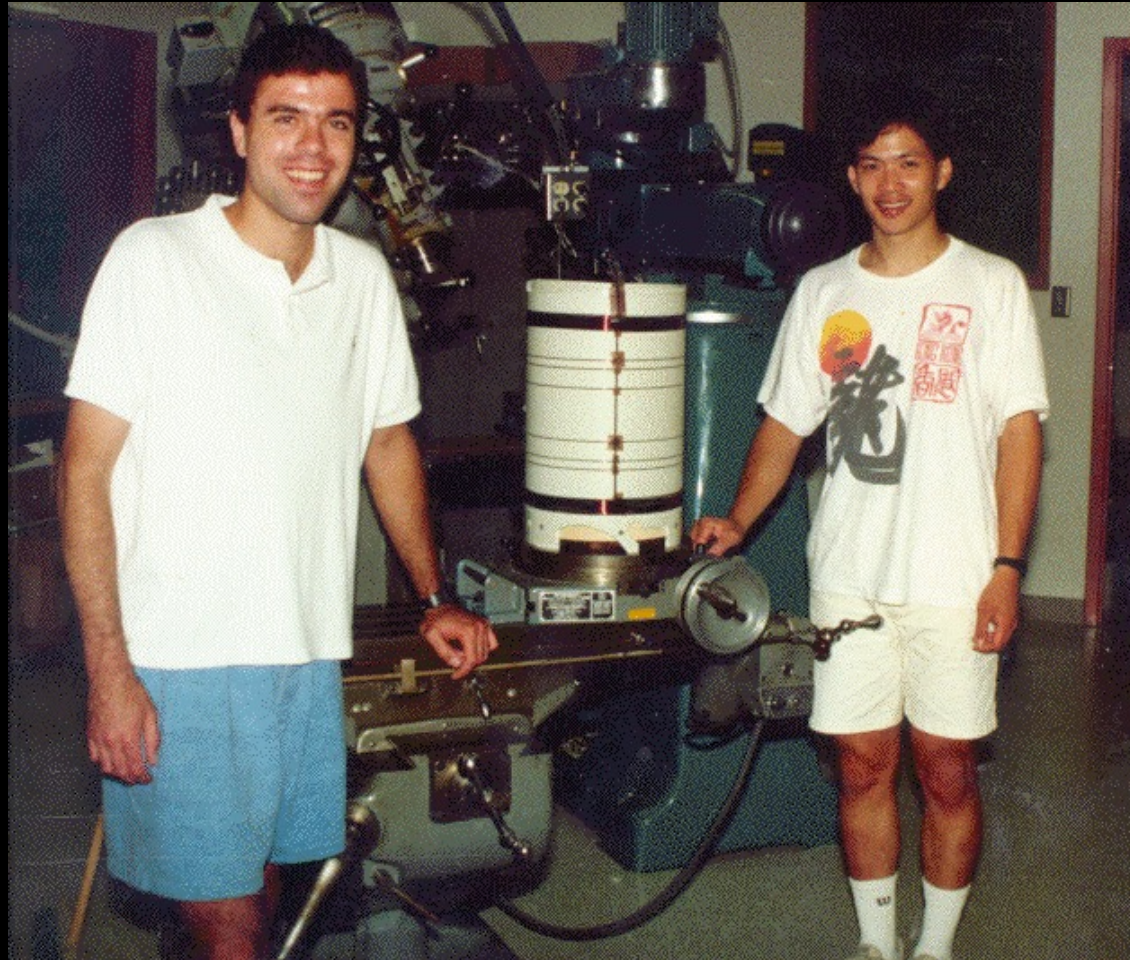
Blood T2, Hemoglobin, BOLD models, B₀ dep., TE dep., SE vs. GE, NIRS Correlation, Veins, PET correlation, IV vs EV, Pre-undershoot, Resolution Dep., Post-undershoot, CO₂ effect, Inflow, ASL vs. BOLD, Extended Stim., Linearity, Fluctuations, Balloon Model, Electrophys. correlation, Layer spec. latency, Excite and Inhibit, Metab. Correlation, Optical Im. Correlation

Applications

Complex motor Language Imagery Memory Emotion, Motor learning Children Tumor vasc. Drug effects, Presurgical Attention Ocular Dominance Mirror neurons, Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations Performance prediction, Δ Volume-V1, Plasticity Face recognition



Local gradients solved the problem

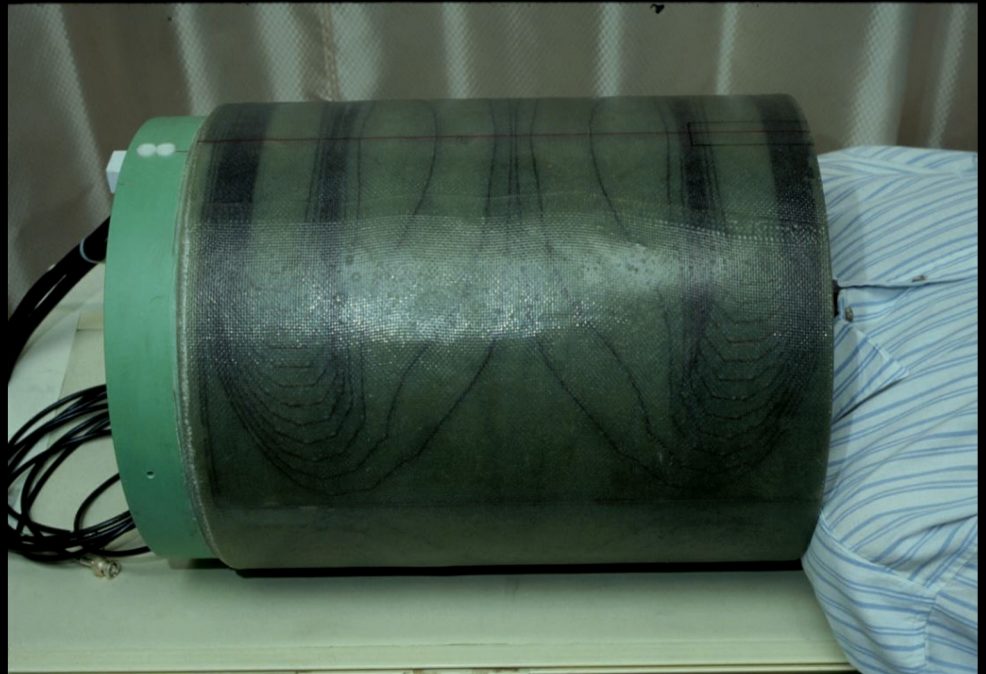


August, 1991

1991-1992



1992-1999



General Electric 3 Tesla Scanner



Technology

MRI 1.5T,3T, 4T EPI EPI on Clin. Syst. Diff. tensor Mg⁺ 7T >8 channels
Local Human Head Gradient Coils Nav. pulses Real time fMRI Venography SENSE "vaso"
ASL Spiral EPI Quant. ASL Z-shim Baseline Susceptibility
BOLD Multi-shot fMRI Dynamic IV volume Simultaneous ASL and BOLD Current Imaging?

Methodology

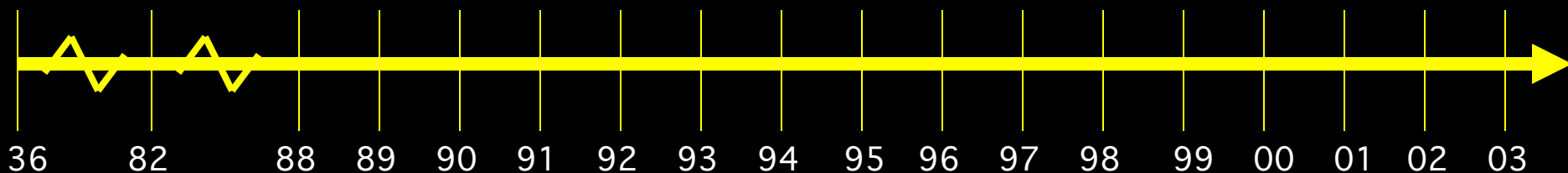
Baseline Volume Correlation Analysis CO₂ Calibration
Parametric Design Motion Correction Multi-Modal Mapping Latency and Width Mod
Surface Mapping ICA Free-behavior Designs
Phase Mapping Mental Chronometry Multi-variate Mapping
IVIM Linear Regression Event-related Deconvolution Fuzzy Clustering

Interpretation

Blood T₂ Hemoglobin BOLD models PET correlation IV vs EV ASL vs. BOLD Layer spec. latency
B₀ dep. Pre-undershoot PSE of BOLD
TE dep Resolution Dep. Extended Stim. Excite and Inhibit
Post-undershoot Linearity Metab. Correlation
SE vs. GE CO₂ effect Fluctuations Optical Im. Correlation
Veins Inflow Balloon Model Electrophys. correlation

Applications

Complex motor Language Imagery Memory Emotion
Motor learning Children Tumor vasc. Drug effects
BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons
Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations
 Δ Volume-V1 Plasticity Face recognition Performance prediction



Single shot full k-space echo-planar-imaging with an eight-channel phase array coil at 3T.

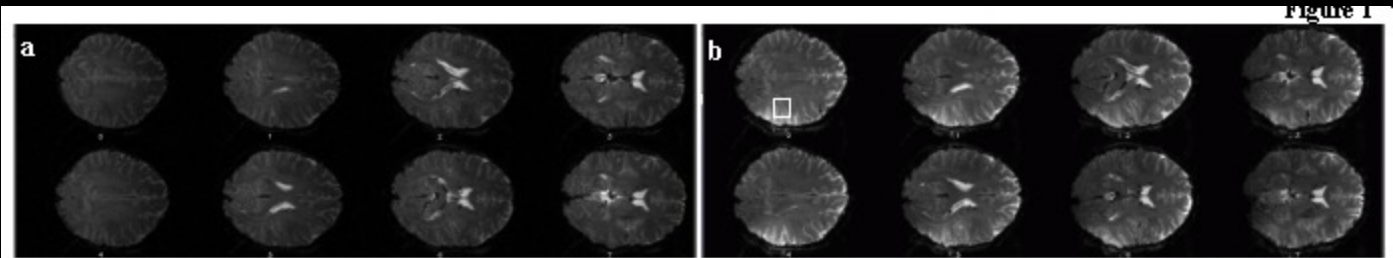
Jerzy Bodurka¹, Peter van Gelderen², Patrick Ledden³, Peter Bandettini¹, Jeff Duyn²

¹Functional MRI Facility NIMH/NIH, ²Advance MRI NINDS/NIH, ³Nova Medical Inc.

Quadrature Head Coil

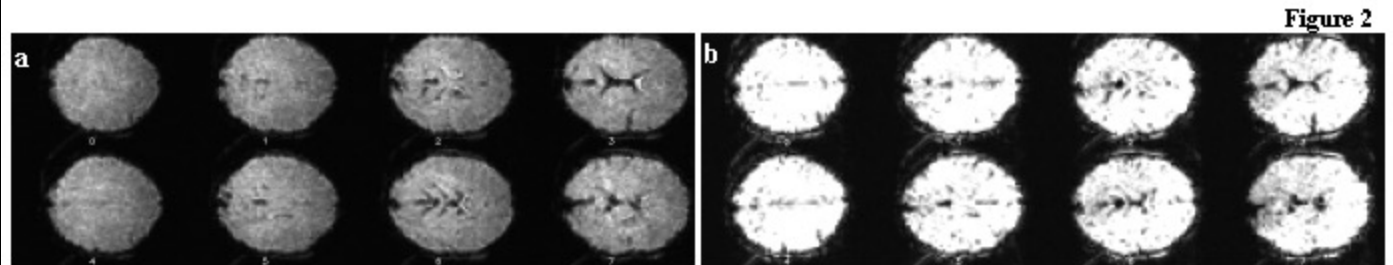
8 Channel Array

128 x 96



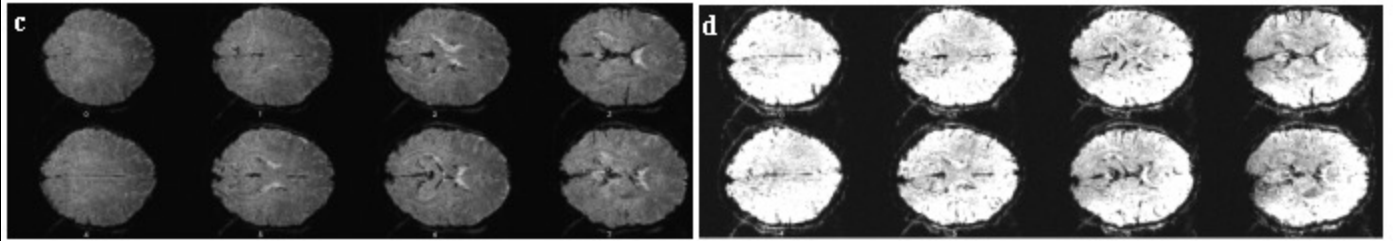
SNR

64 x 48



TSNR

128 x 96



Technology

MRI, 1.5T,3T, 4T, EPI, Local Human Head Gradient Coils, BOLD, ASL, Spiral EPI, Multi-shot fMRI, EPI on Clin. Syst., Nav. pulses, Diff. tensor, Real time fMRI, Quant. ASL, Dynamic IV volume, Simultaneous ASL and BOLD, Current Imaging?, Mg⁺, Venography, Z-shim, Baseline Susceptibility, SENSE, "vaso", >8 channels, 7T

Methodology

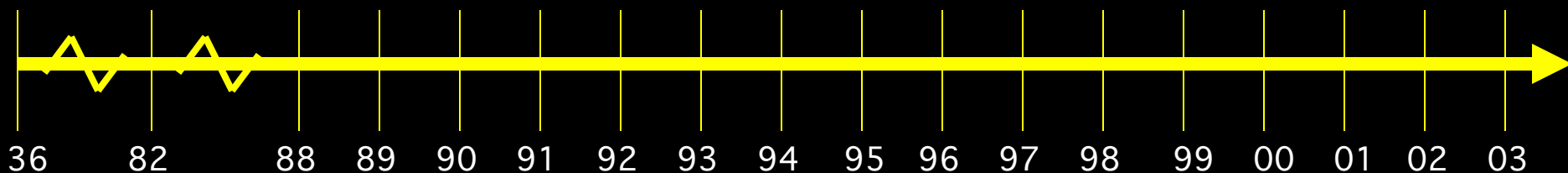
Baseline Volume, IVIM, Correlation Analysis, Parametric Design, Motion Correction, CO₂ Calibration, Multi-Modal Mapping, Latency and Width Mod, Surface Mapping, ICA, Free-behavior Designs, Phase Mapping, Linear Regression, Mental Chronometry, Multi-variate Mapping, Event-related, Deconvolution, Fuzzy Clustering

Interpretation

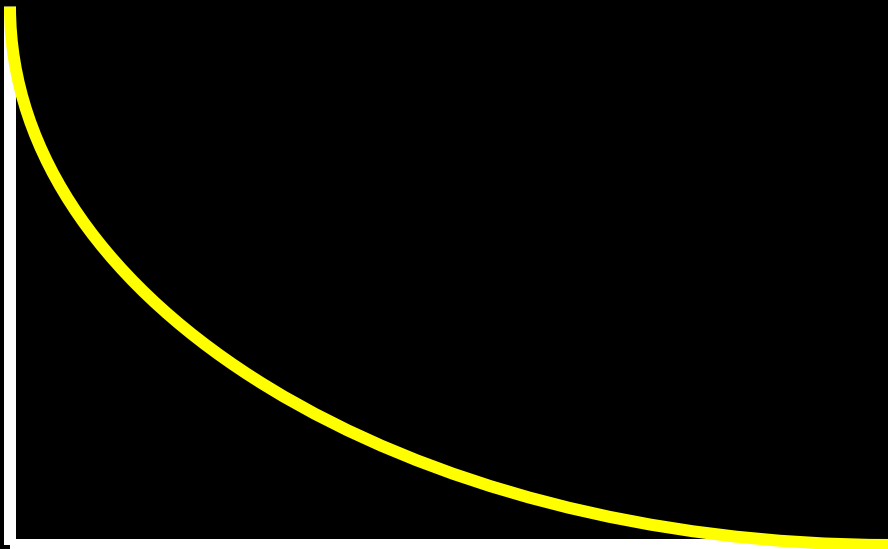
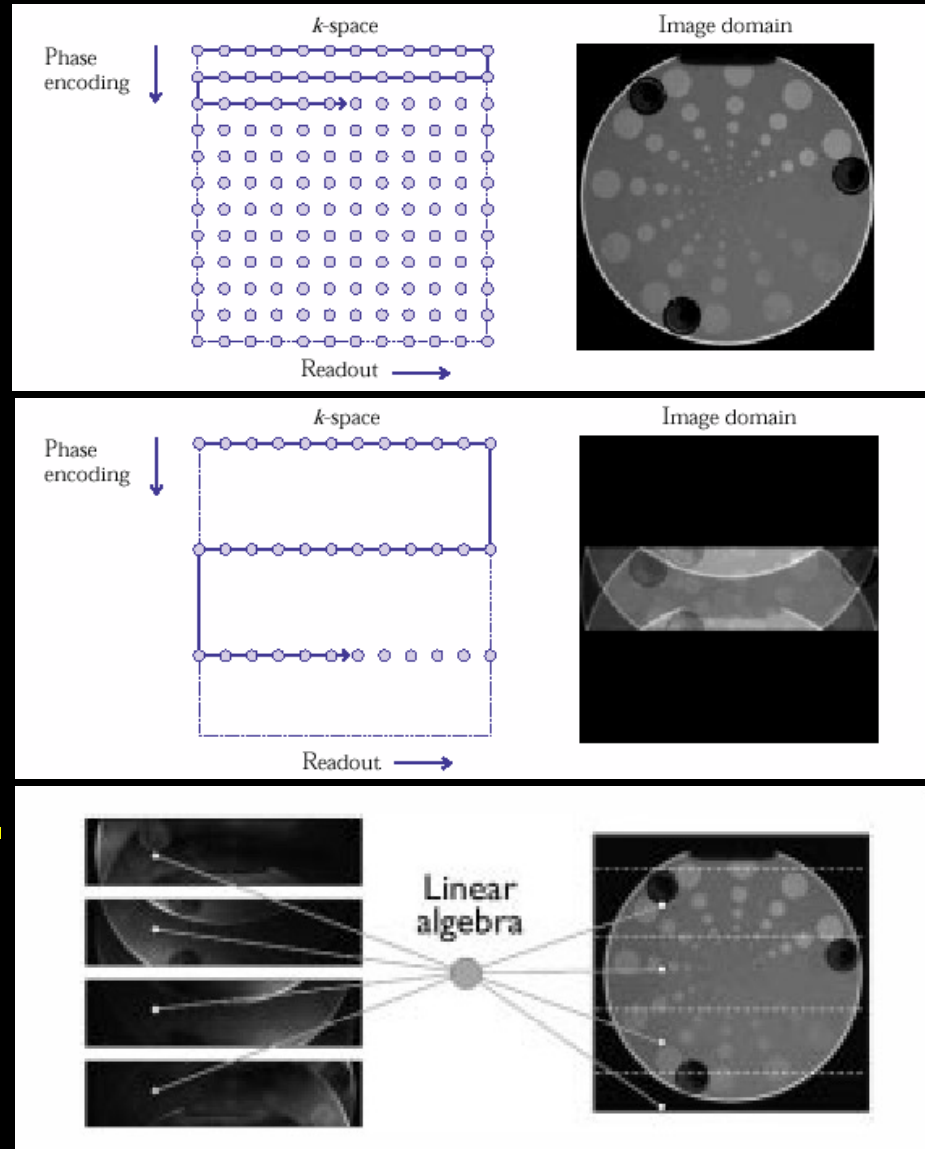
Blood T2, Hemoglobin, BOLD models, PET correlation, IV vs EV, ASL vs. BOLD, Layer spec. latency, Pre-undershoot, Post-undershoot, Extended Stim., Excite and Inhibit, SE vs. GE, CO₂ effect, Linearity, Metab. Correlation, NIRS Correlation, Veins, Inflow, Fluctuations, Balloon Model, Optical Im., Correlation, Electrophys. correlation

Applications

Complex motor Language, Imagery, Memory, Emotion, Motor learning, Children, Tumor vasc., Drug effects, BOLD -V1, M1, A1, Presurgical, Attention, Ocular Dominance, Mirror neurons, Volume - Stroke, V1, V2..mapping, Priming/Learning, Clinical Populations, Performance prediction, Δ Volume-V1, Plasticity, Face recognition



SENSE Imaging



≈ 5 to 30 ms

Pruessmann, et al.

- Functional contrast
- Signal interpretation
- Hardware and pulse sequences
- **Paradigm design and processing**

- Overview
- Current Limits
- Future Prospects

Neuronal Activation Input Strategies

1. Block Design

2. Parametric Design

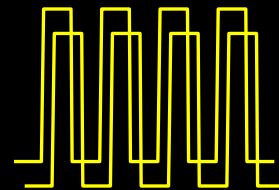
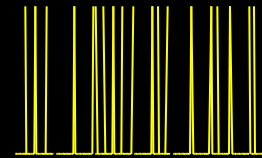
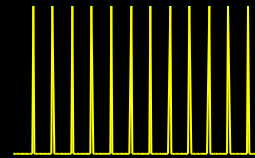
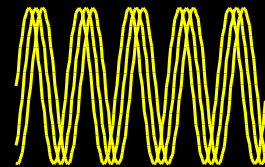
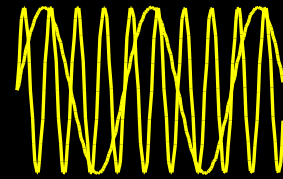
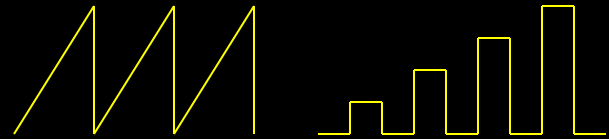
3. Frequency Encoding

4. Phase Encoding

5. Event Related

6. Orthogonal Design

7. Free Behavior Design



Technology

MRI

1.5T,3T, 4T

EPI

Local Human Head Gradient Coils

BOLD

ASL

Spiral EPI

Multi-shot fMRI

EPI on Clin. Syst.

Nav. pulses

Diff. tensor

Real time fMRI

Quant. ASL

Dynamic IV volume

Mg⁺

Venography

Z-shim

Baseline Susceptibility

7T

>8 channels

SENSE

"vaso"

Simultaneous ASL and BOLD

Current Imaging?

Methodology

Baseline Volume

IVIM

Correlation Analysis

Parametric Design

Phase Mapping

Surface Mapping

Linear Regression

Event-related

Motion Correction

CO₂ Calibration

Multi-Modal Mapping

ICA

Free-behavior Designs

Mental Chronometry

Deconvolution

Fuzzy Clustering

Latency and Width Mod

Multi-variate Mapping

Interpretation

Blood T2

Hemoglobin

BOLD models

B₀ dep.

TE dep

SE vs. GE

NIRS Correlation

Veins

IV vs EV

Pre-undershoot

Resolution Dep.

CO₂ effect

Inflow

PET correlation

ASL vs. BOLD

Extended Stim.

Linearity

Fluctuations

Balloon Model

Metab. Correlation

Optical Im. Correlation

Electrophys. correlation

Layer spec. latency

Excite and Inhibit

Applications

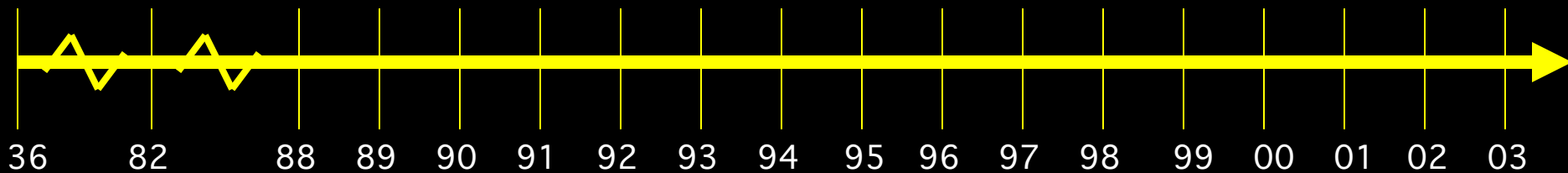
Complex motor Language Imagery Memory Emotion

Motor learning Children Tumor vasc. Drug effects

BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons

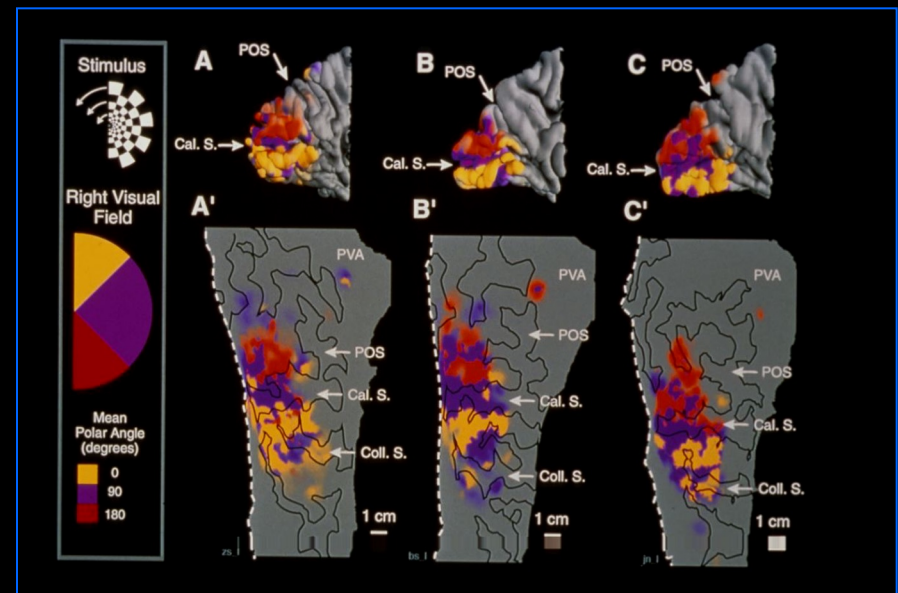
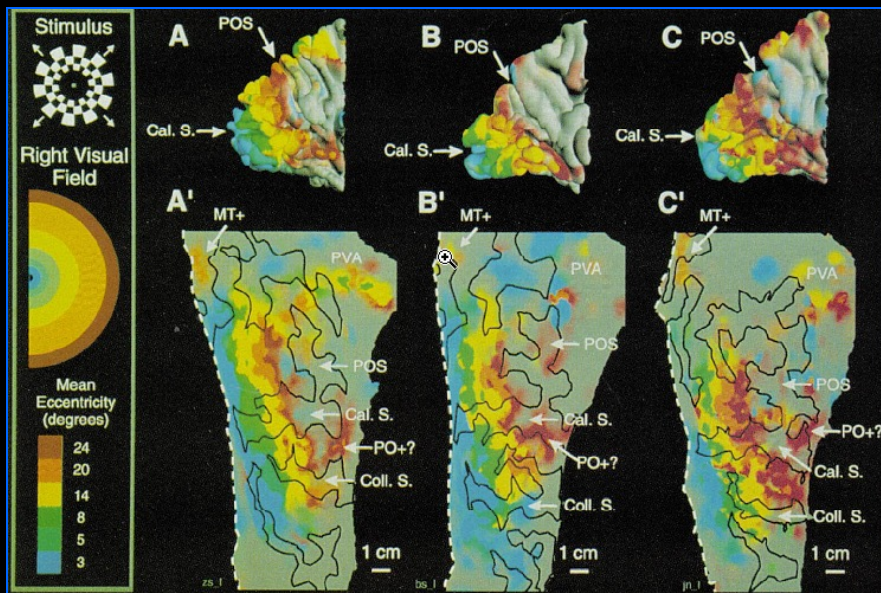
Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations

Δ Volume-V1 Plasticity Face recognition Performance prediction



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*



Technology

MRI 1.5T,3T, 4T EPI EPI on Clin. Syst. Diff. tensor Mg+ Venography 7T >8 channels
Local Human Head Gradient Coils Nav. pulses Real time fMRI SENSE "vaso"
ASL Spiral EPI Quant. ASL Z-shim Baseline Susceptibility
BOLD Multi-shot fMRI Dynamic IV volume Simultaneous ASL and BOLD Current Imaging?

Methodology

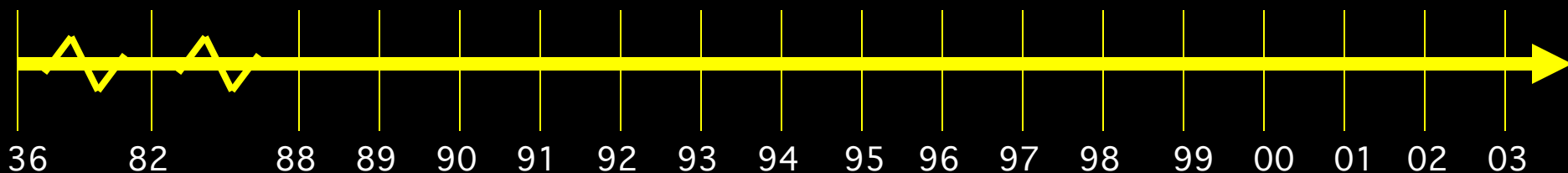
Baseline Volume IVIM Correlation Analysis Motion Correction CO₂ Calibration
Parametric Design Surface Mapping Multi-Modal Mapping Latency and Width Mod
Phase Mapping ICA Free-behavior Designs
Event-related Linear Regression Mental Chronometry Multi-variate Mapping
Deconvolution Fuzzy Clustering

Interpretation

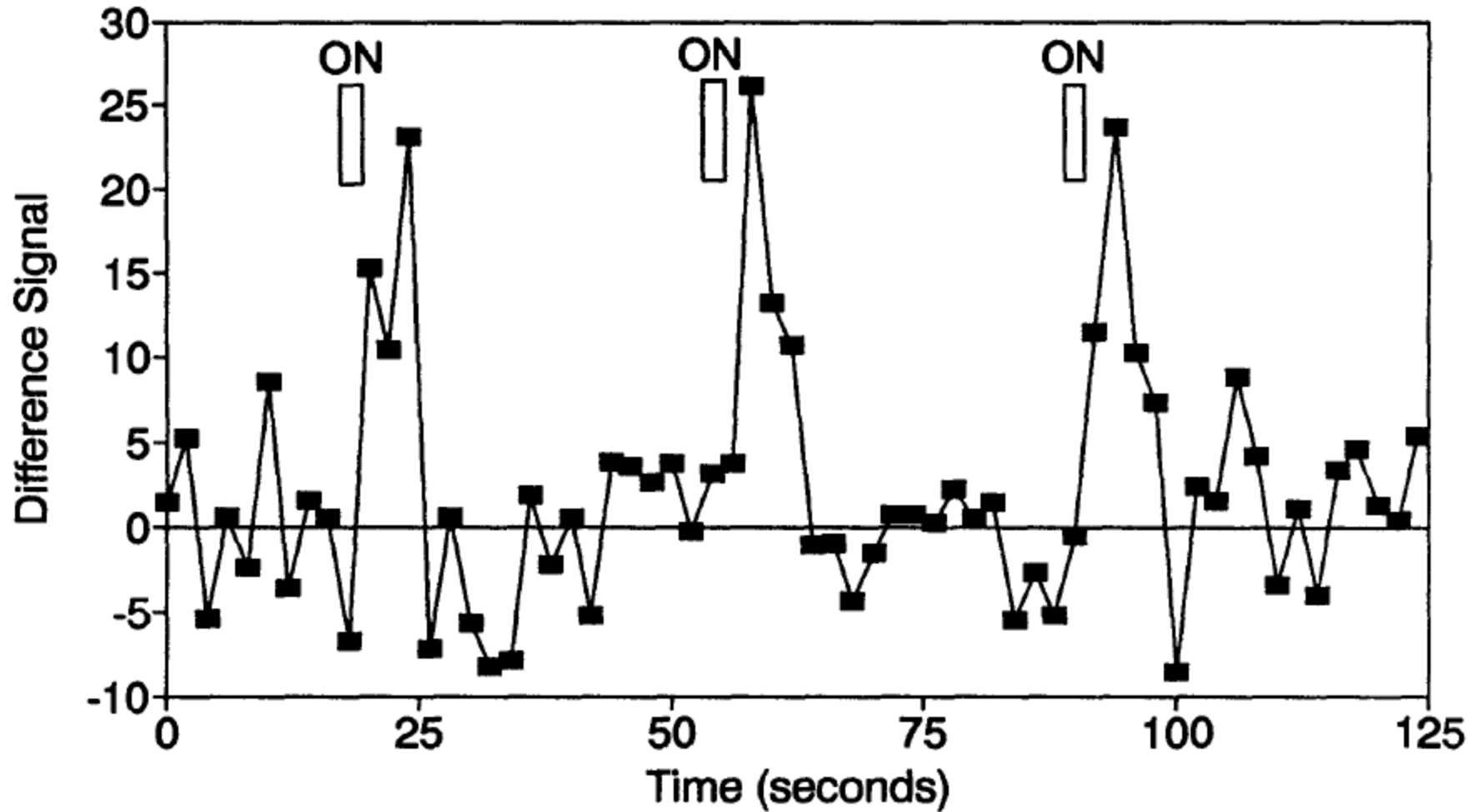
Blood T2 Hemoglobin BOLD models PET correlation ASL vs. BOLD Layer spec. latency
B₀ dep. IV vs EV Pre-undershoot PSE of BOLD
TE dep Resolution Dep. Extended Stim. Excite and Inhibit
Post-undershoot Linearity Metab. Correlation
SE vs. GE CO₂ effect Fluctuations Optical Im. Correlation
NIRS Correlation Veins Inflow Balloon Model Electrophys. correlation

Applications

Complex motor Language Imagery Memory Emotion
Motor learning Children Tumor vasc. Drug effects
BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons
Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations
 Δ Volume-V1 Plasticity Face recognition Performance prediction



First Event-related fMRI Results



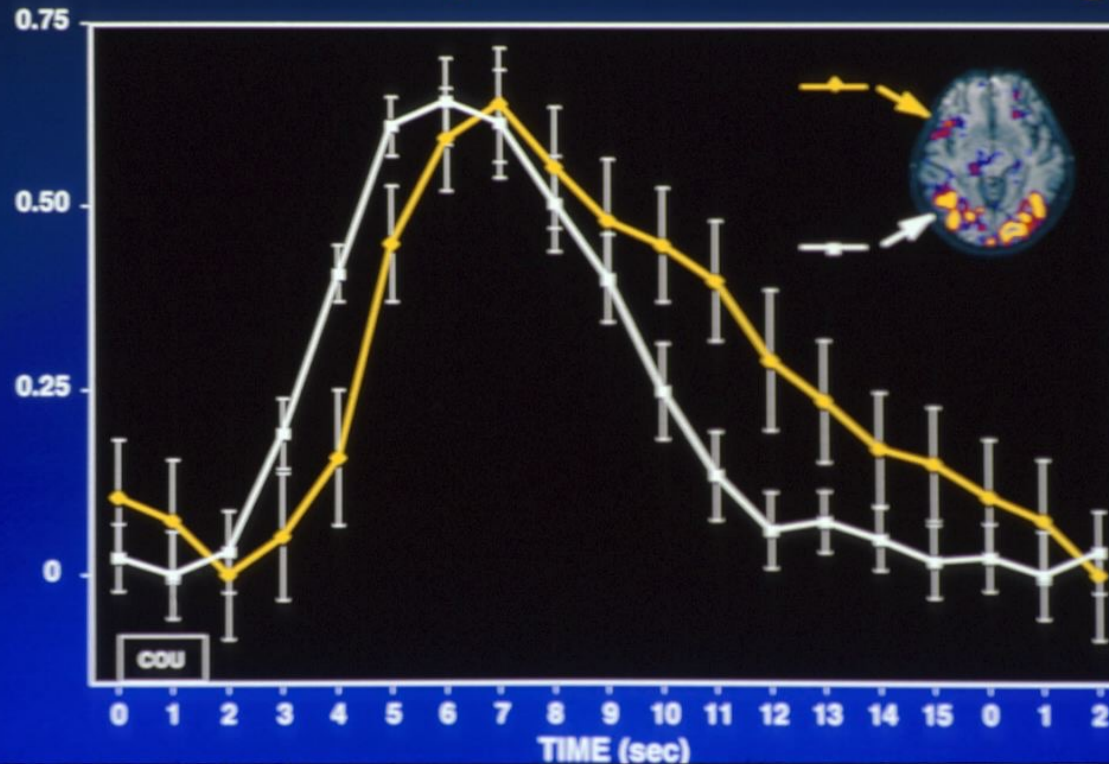
Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." *Proc. Natl. Acad. Sci. USA* 89: 11069-11073.

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. RAICHEL^{§**††}, AND BRUCE R. ROSEN^{†‡}

Time Course Comparison Across Brain Regions



Technology

MRI 1.5T,3T, 4T EPI EPI on Clin. Syst. Diff. tensor Mg+ Venography 7T >8 channels
Local Human Head Gradient Coils Nav. pulses Real time fMRI SENSE "vaso"
ASL Spiral EPI Quant. ASL Z-shim Baseline Susceptibility
BOLD Multi-shot fMRI Dynamic IV volume Simultaneous ASL and BOLD Current Imaging?

Methodology

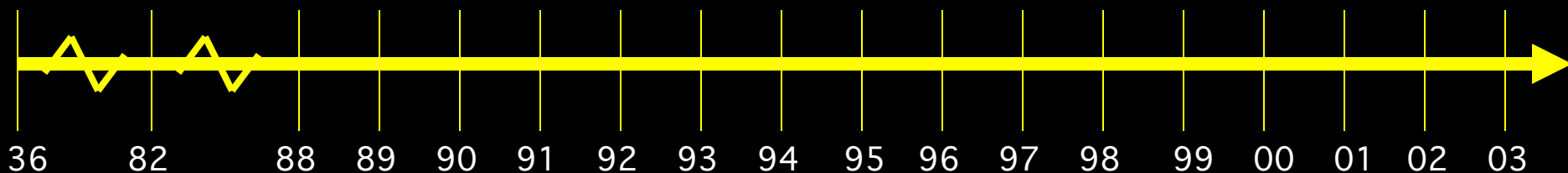
Baseline Volume Correlation Analysis Motion Correction CO₂ Calibration
Parametric Design Multi-Modal Mapping Latency and Width Mod
Phase Mapping Surface Mapping ICA Free-behavior Designs
Event-related Linear Regression Mental Chronometry Multi-variate Mapping
Deconvolution Fuzzy Clustering

Interpretation

Blood T₂ BOLD models PET correlation ASL vs. BOLD Layer spec. latency
Hemoglobin B₀ dep. IV vs EV Pre-undershoot PSE of BOLD Excite and Inhibit
TE dep Resolution Dep. Extended Stim. Metab. Correlation
SE vs. GE CO₂ effect Linearity
NIRS Correlation Fluctuations Optical Im. Correlation
Veins Inflow Balloon Model Electrophys. correlation

Applications

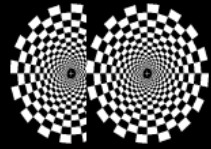
Complex motor Language Imagery Memory Emotion
Motor learning Children Tumor vasc. Drug effects
BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons
Volume - Stroke V1, V2..mapping Priming/Learning Clinical Populations
 Δ Volume-V1 Plasticity Face recognition Performance prediction





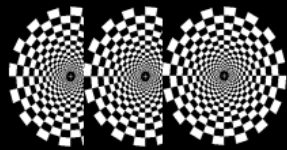
0 sec

20 sec



0 sec 2 sec

20 sec



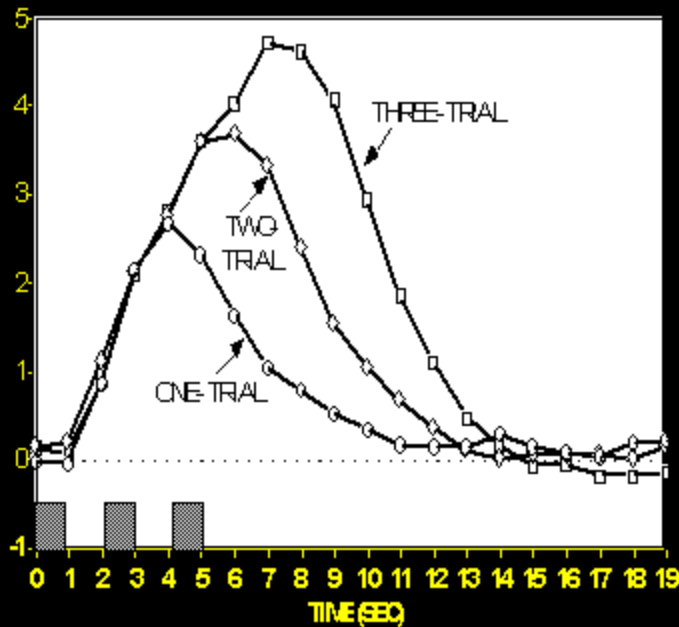
0 sec 2 sec 4 sec

20 sec

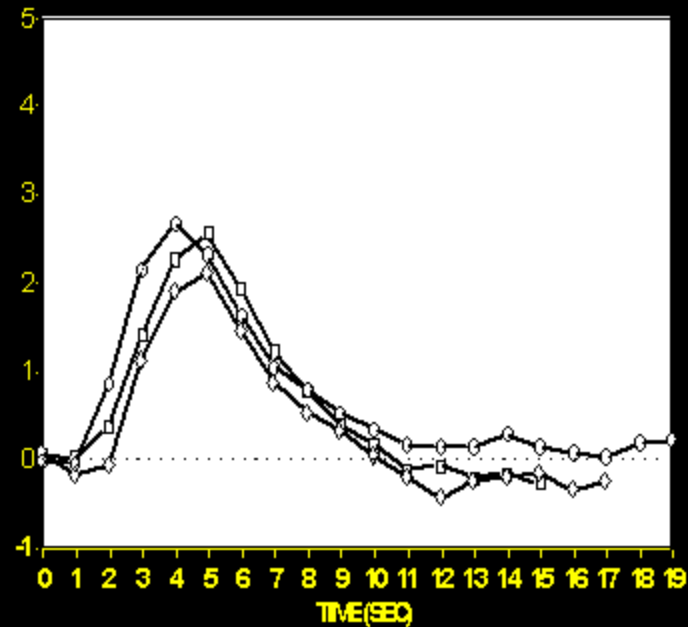
Selective Averaging of Rapidly Presented Individual Trials Using fMRI

Anders M. Dale* and Randy L. Buckner

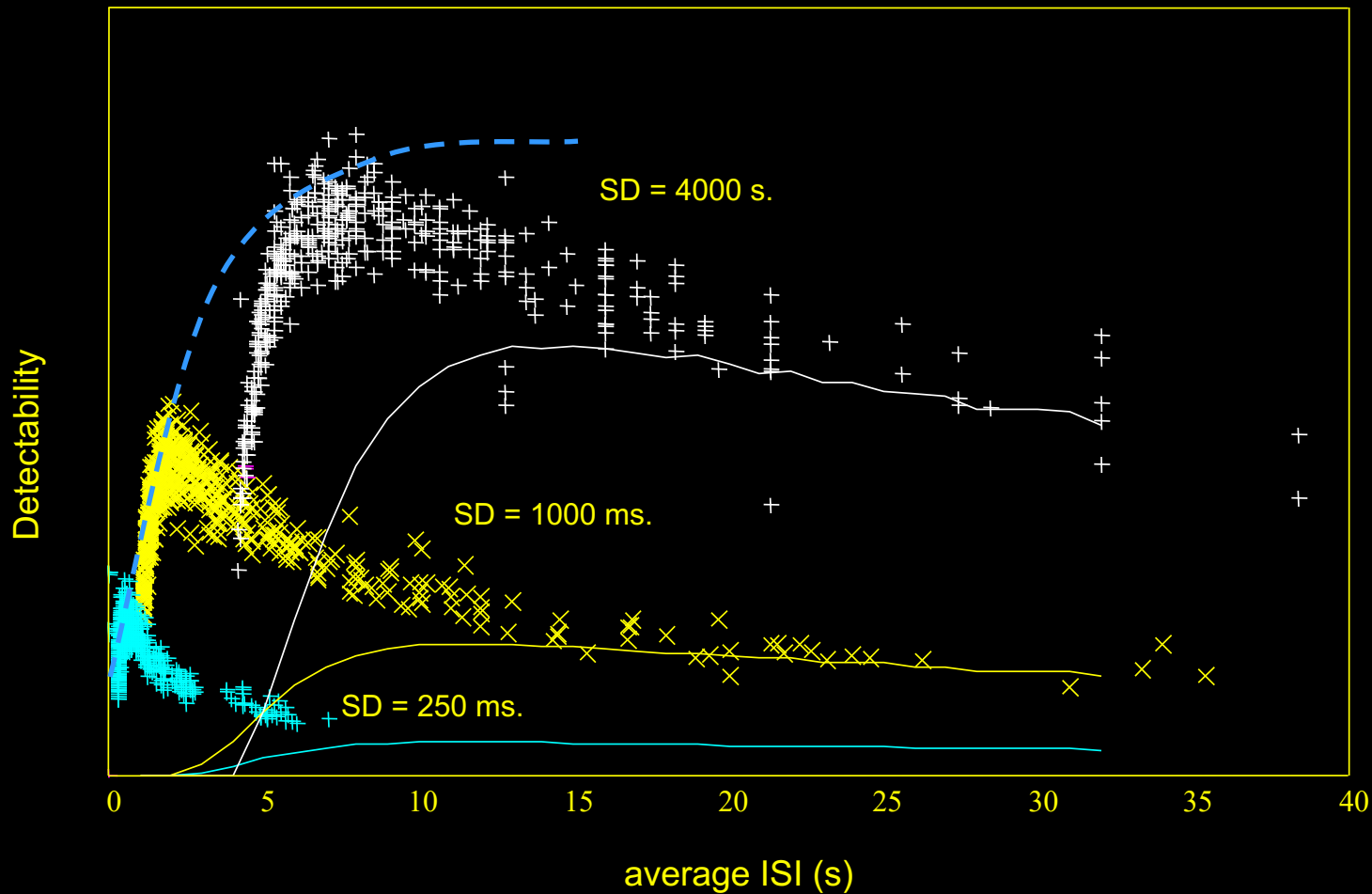
RAW DATA



ESTIMATED RESPONSES



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).

Technology

MRI 1.5T,3T, 4T EPI EPI on Clin. Syst. Diff. tensor Mg⁺ Venography 7T >8 channels
Local Human Head Gradient Coils Nav. pulses Real time fMRI SENSE "vaso"
BOLD ASL Spiral EPI Quant. ASL Dynamic IV volume Z-shim Baseline Susceptibility
Multi-shot fMRI Simultaneous ASL and BOLD Current Imaging?

Methodology

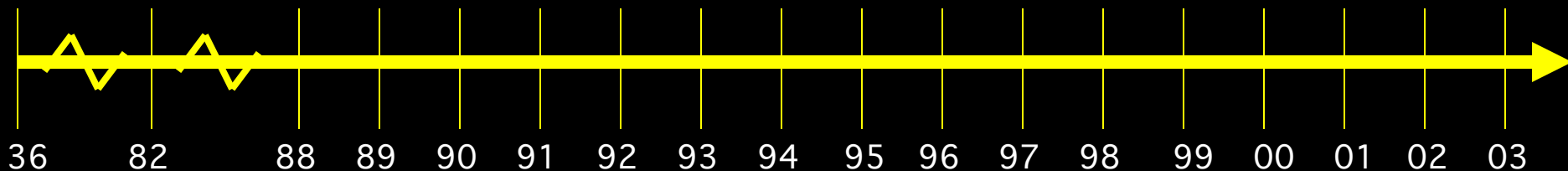
Baseline Volume Correlation Analysis Motion Correction CO₂ Calibration
Parametric Design Multi-Modal Mapping Latency and Width Mod
Phase Mapping Surface Mapping ICA Free-behavior Designs
Event-related Linear Regression Mental Chronometry Multi-variate Mapping
Deconvolution Fuzzy Clustering

Interpretation

Blood T2 BOLD models PET correlation ASL vs. BOLD Layer spec. latency
Hemoglobin B₀ dep. IV vs EV Pre-undershoot PSE of BOLD Excite and Inhibit
TE dep Resolution Dep. Extended Stim. Linearity Metab. Correlation
SE vs. GE CO₂ effect Fluctuations Optical Im. Correlation
Veins Inflow Balloon Model Electrophys. correlation

Applications

Complex motor Language Imagery Memory Emotion
Motor learning Children Tumor vasc. Drug effects
Volume - Stroke BOLD -V1, M1, A1 Presurgical Attention Ocular Dominance Mirror neurons
 Δ Volume-V1 V1, V2..mapping Priming/Learning Clinical Populations
Plasticity Face recognition Performance prediction

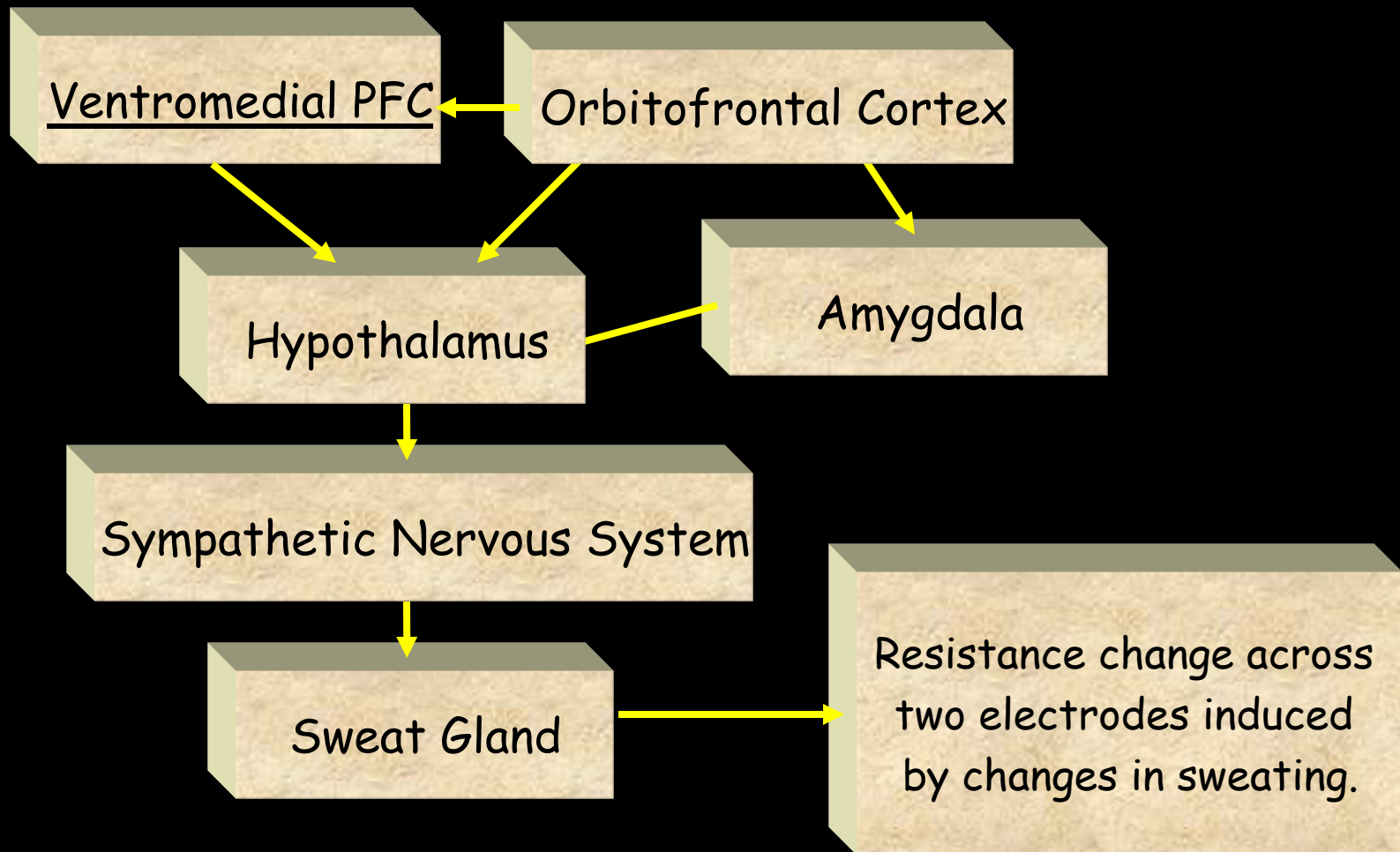


Free Behavior Design

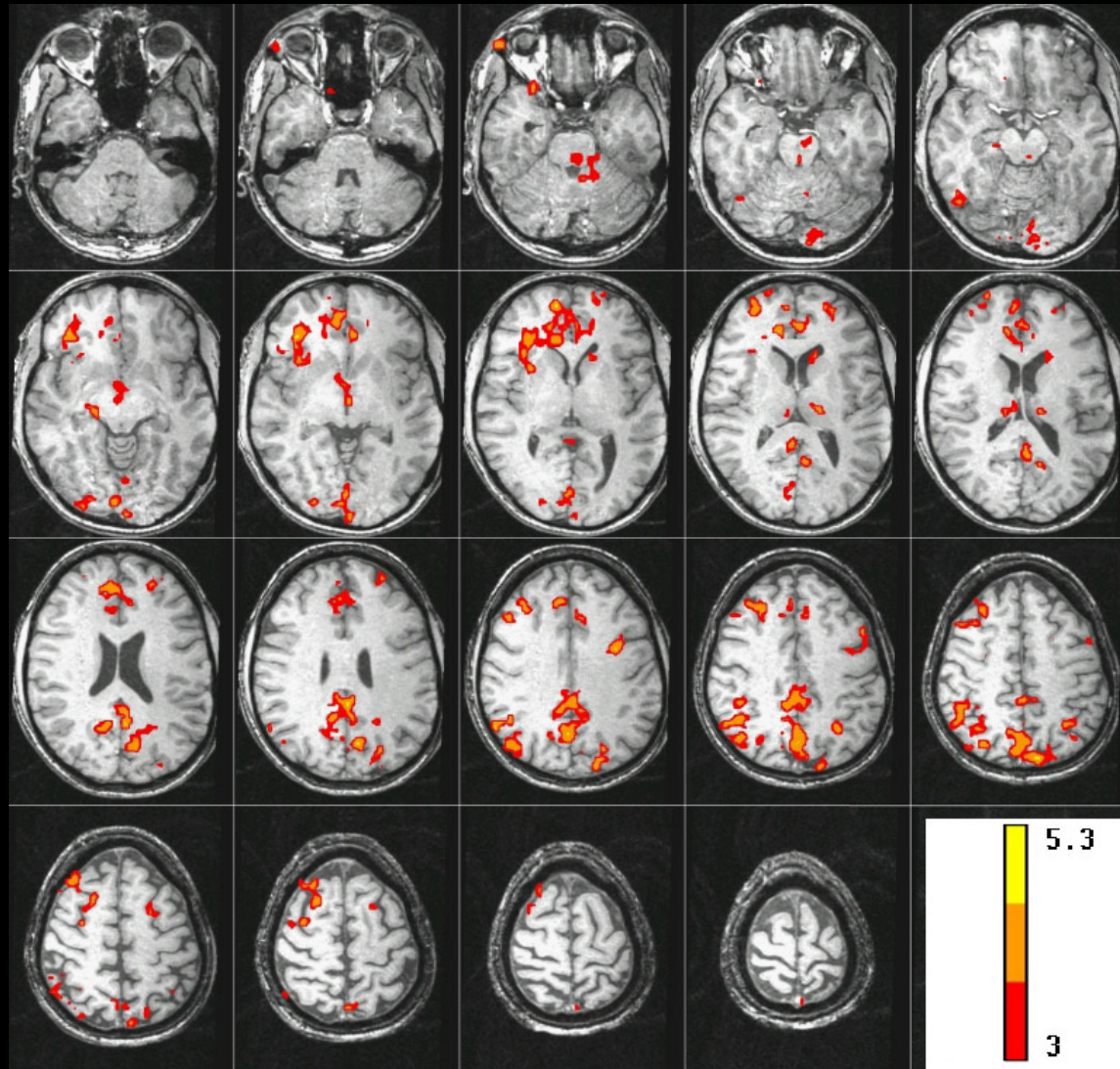
Use a continuous measure as a reference function:

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

The Skin Conductance Response (SCR)



Brain activity correlated with SCR during “Rest”



J. C. Patterson II, L. G. Ungerleider, and P. A. Bandettini, Task - independent functional brain activity correlation with skin conductance changes: an fMRI study. *NeuroImage* 17: 1787-1806, (2002).

Simultaneous EEG and fMRI of the alpha rhythm

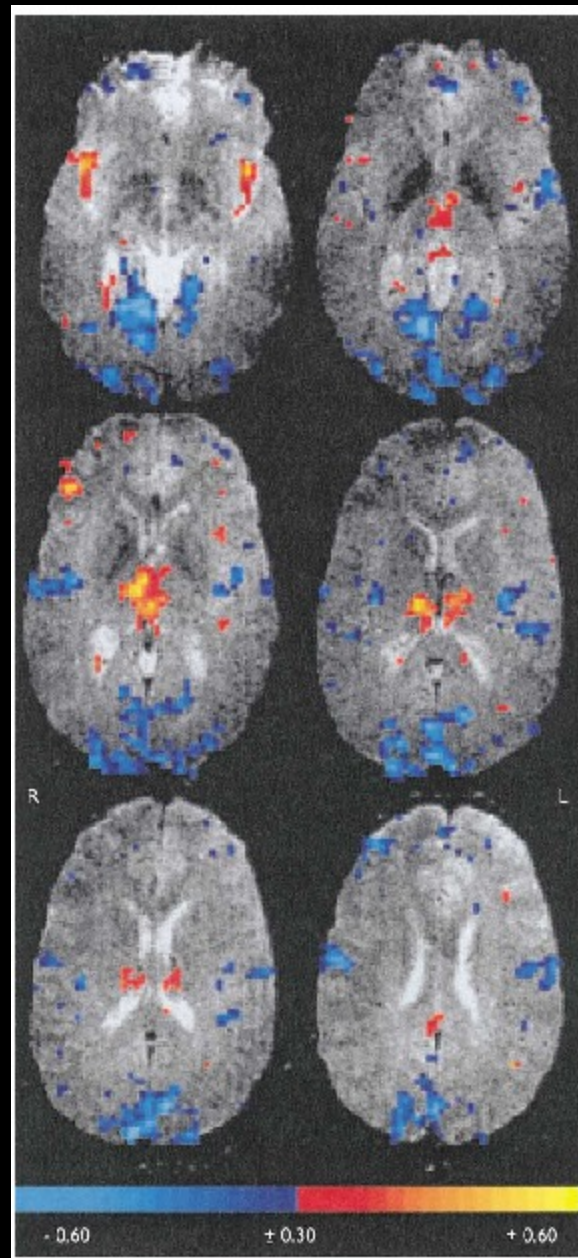
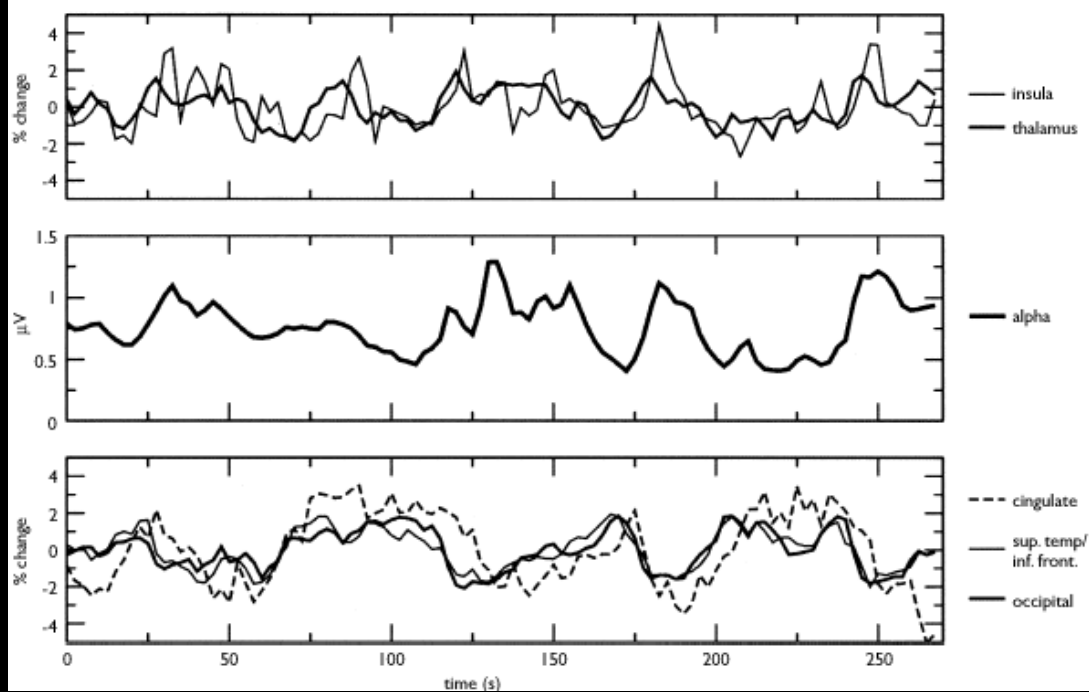
Robin I. Goldman,^{2,CA} John M. Stern,¹ Jerome Engel Jr¹ and Mark S. Cohen

Ahmanson-Lovelace Brain Mapping Center, UCLA, 660 Charles Young Drive South, Los Angeles, CA 90095; ¹Department of Neurology, UCLA School of Medicine, Los Angeles, CA; ²Hatch Center for MR Research, Columbia University, HSD, 710 W. 168th St., NIB-1, Mailbox 48, NY, NY 10032, USA

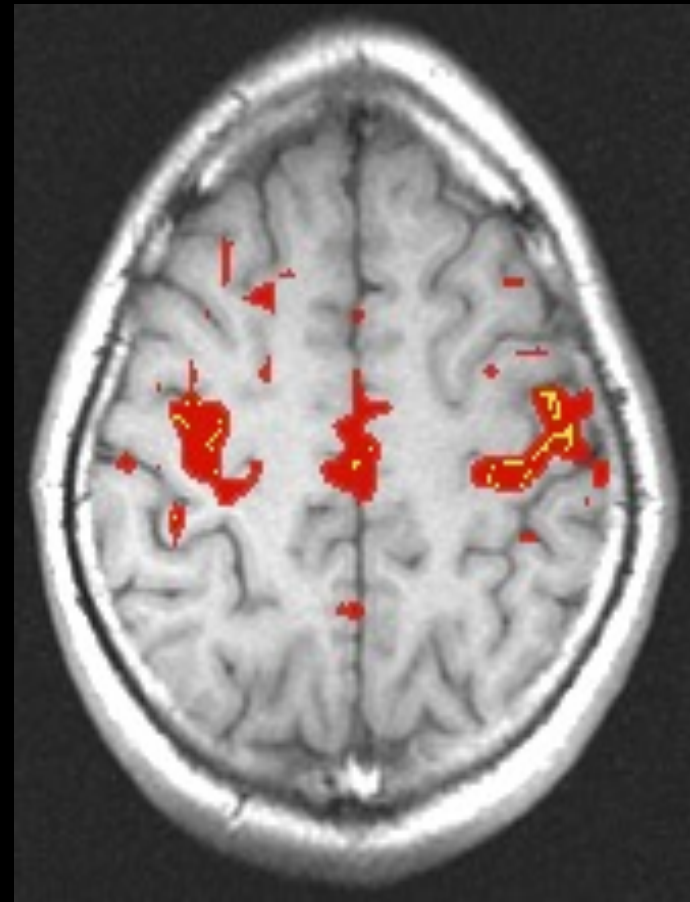
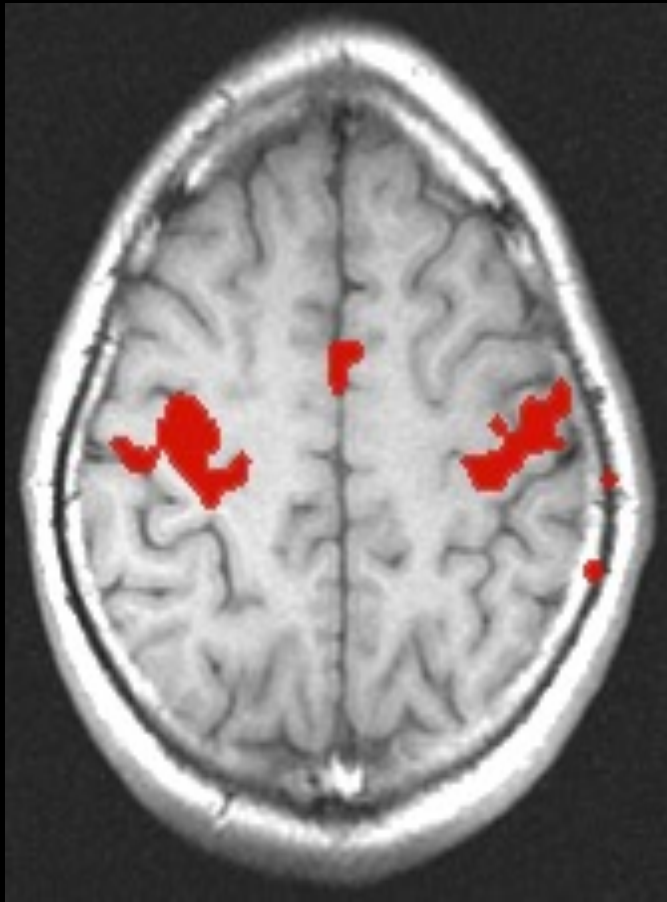
^{CA,2}Corresponding Author and Address: rg2146@columbia.edu

Received 28 October 2002; accepted 30 October 2002

DOI: 10.1097/01.wnr.0000047685.08940.d0

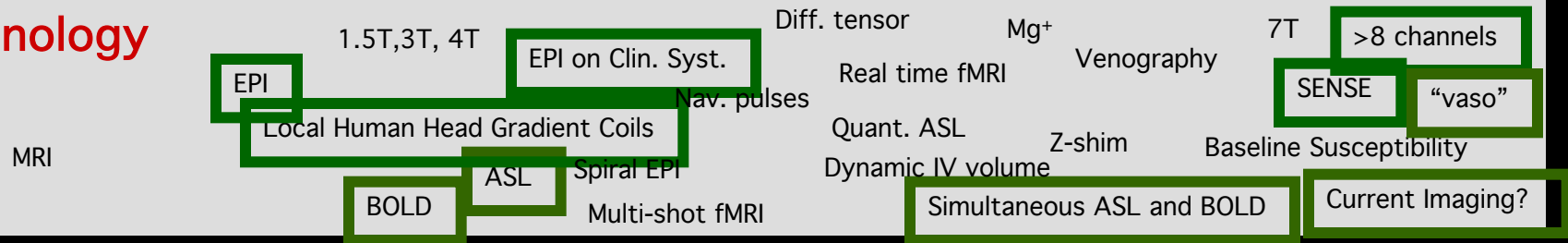


Resting State Fluctuations

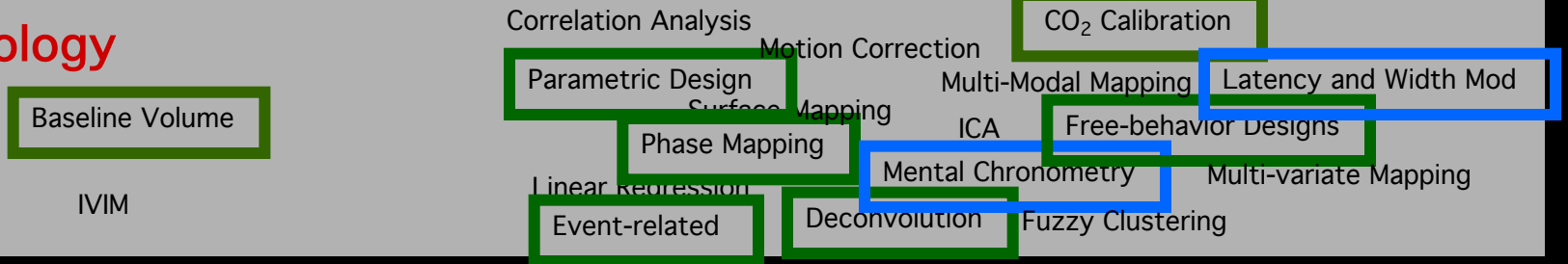


B. Biswal *et al.*, MRM, 34:537 (1995)

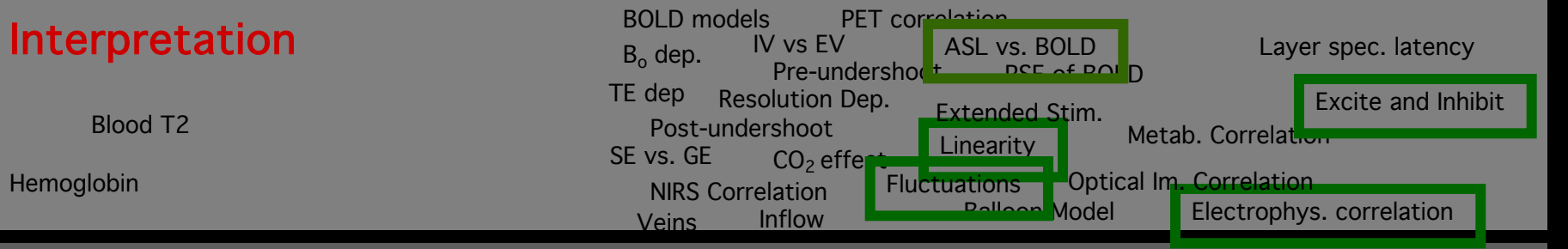
Technology



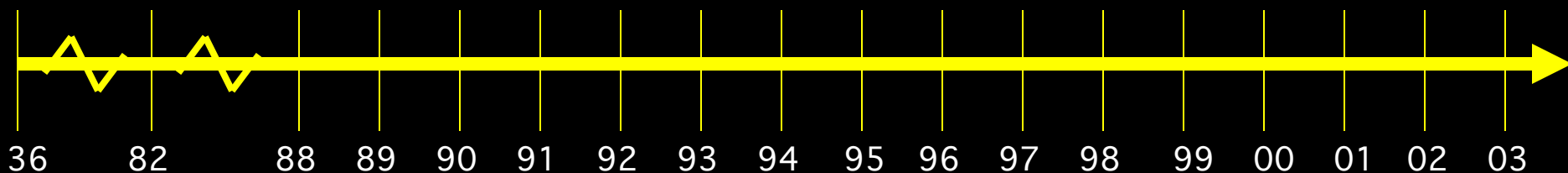
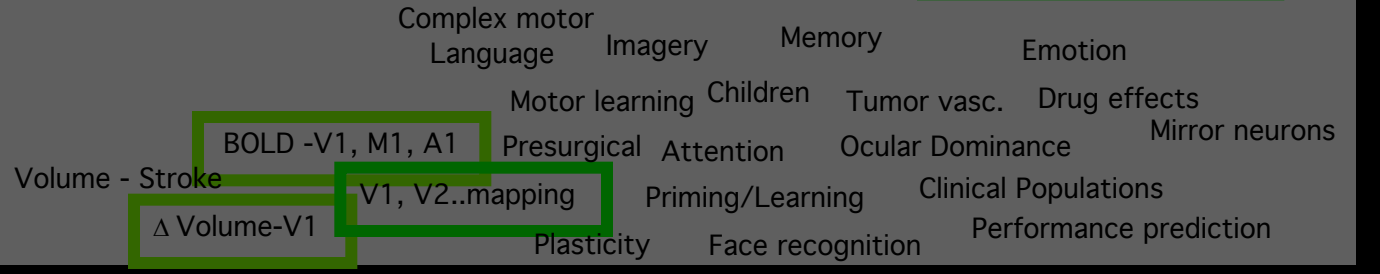
Methodology



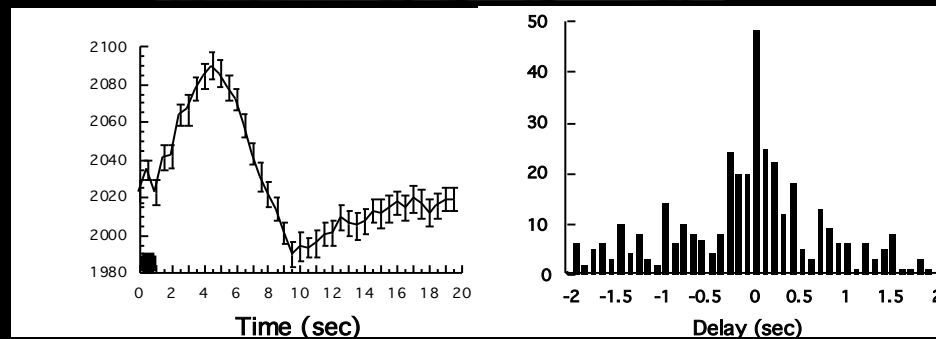
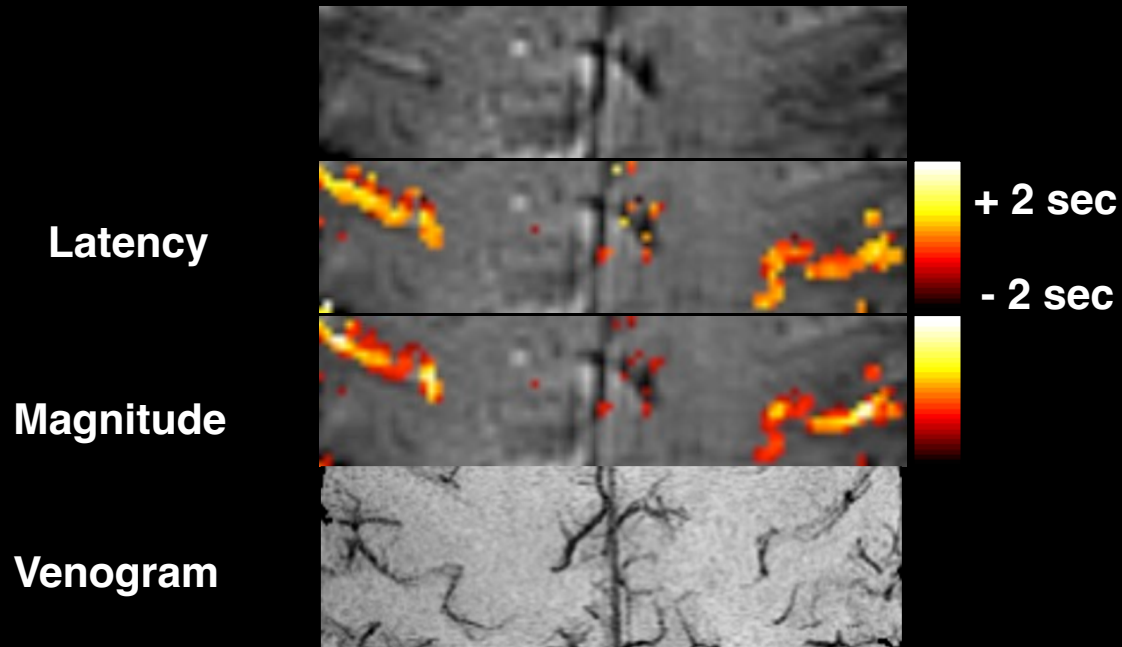
Interpretation



Applications

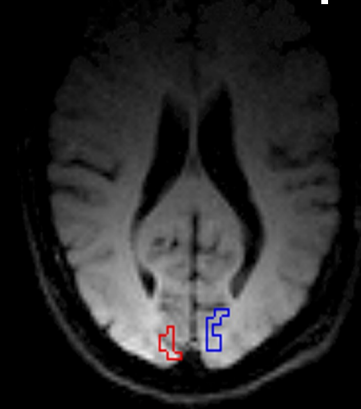


Latency and Width

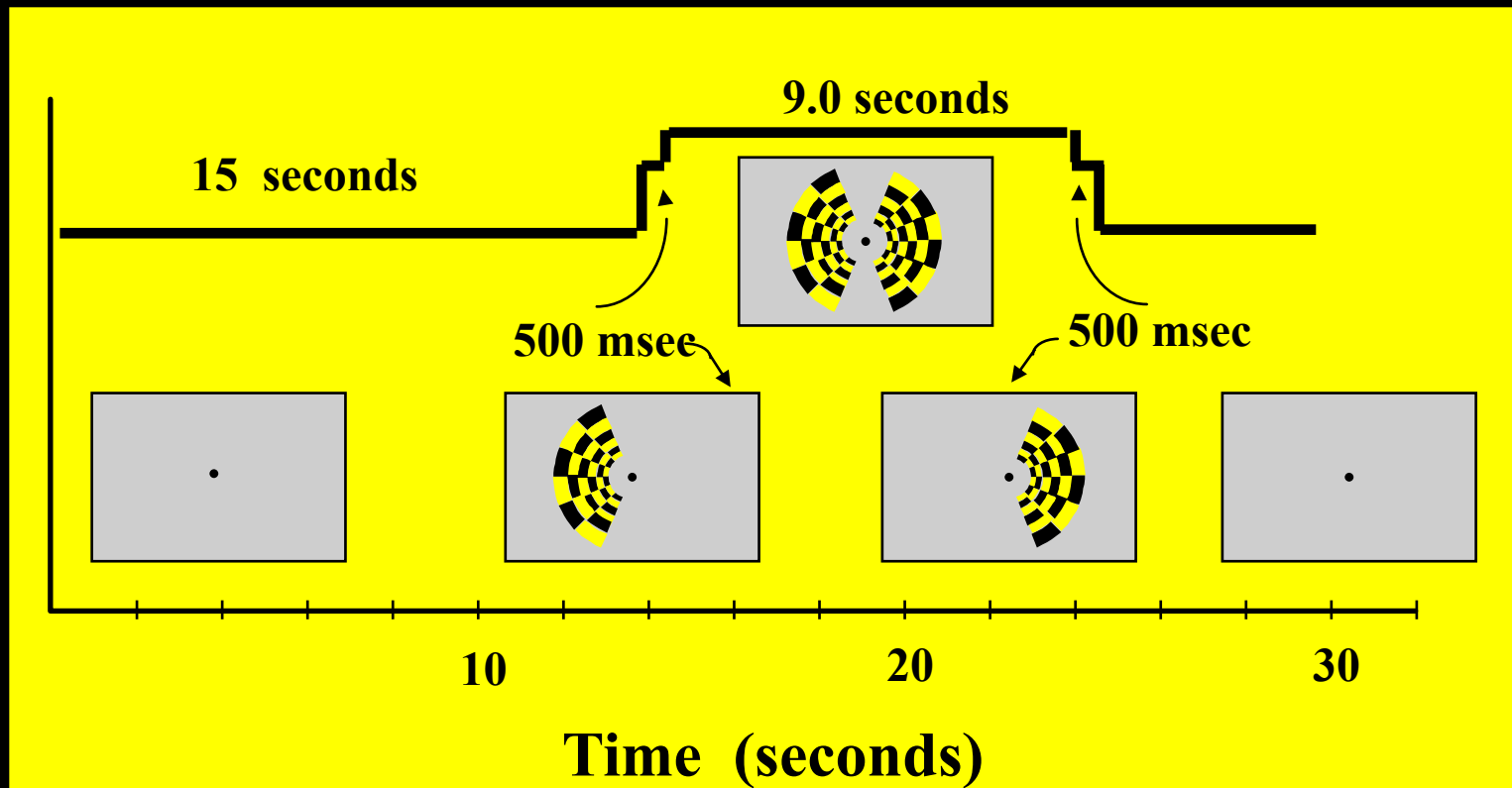


Hemi-Field Experiment

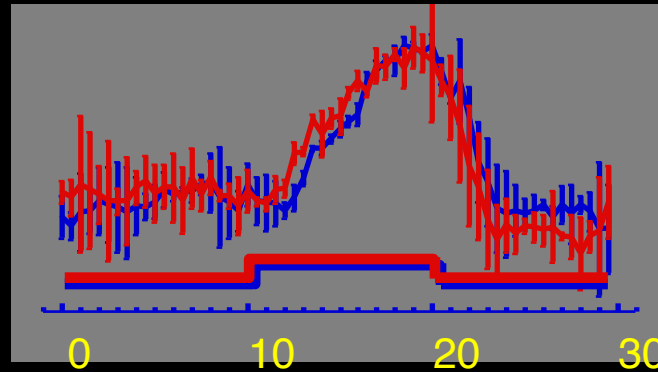
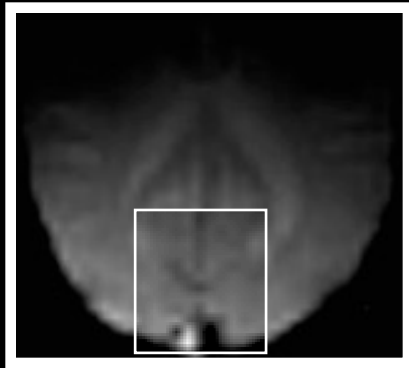
Left Hemisphere



Right Hemisphere



Timing Modulation (calibration)



500 ms



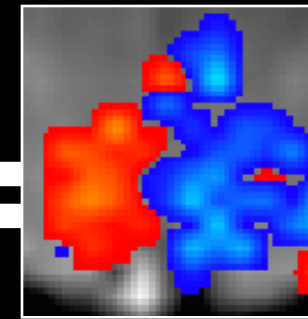
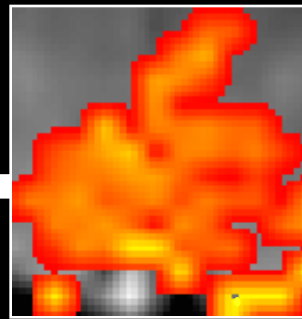
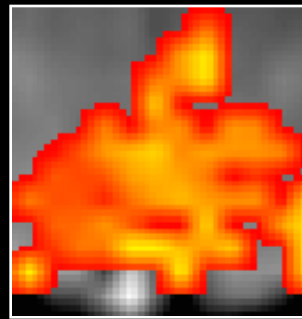
500 ms



Right Hemifield

Left Hemifield

+ 2.5 s
0 s
- 2.5 s



Understanding neural system dynamics through task modulation and measurement of functional MRI amplitude, latency, and width

P. S. F. Bellgowan^{*†}, Z. S. Saad[‡], and P. A. Bandettini^{*}

^{*}Laboratory of Brain and Cognition and [‡]Scientific and Statistical Computing Core, National Institute of Mental Health, Bethesda, MD 20892

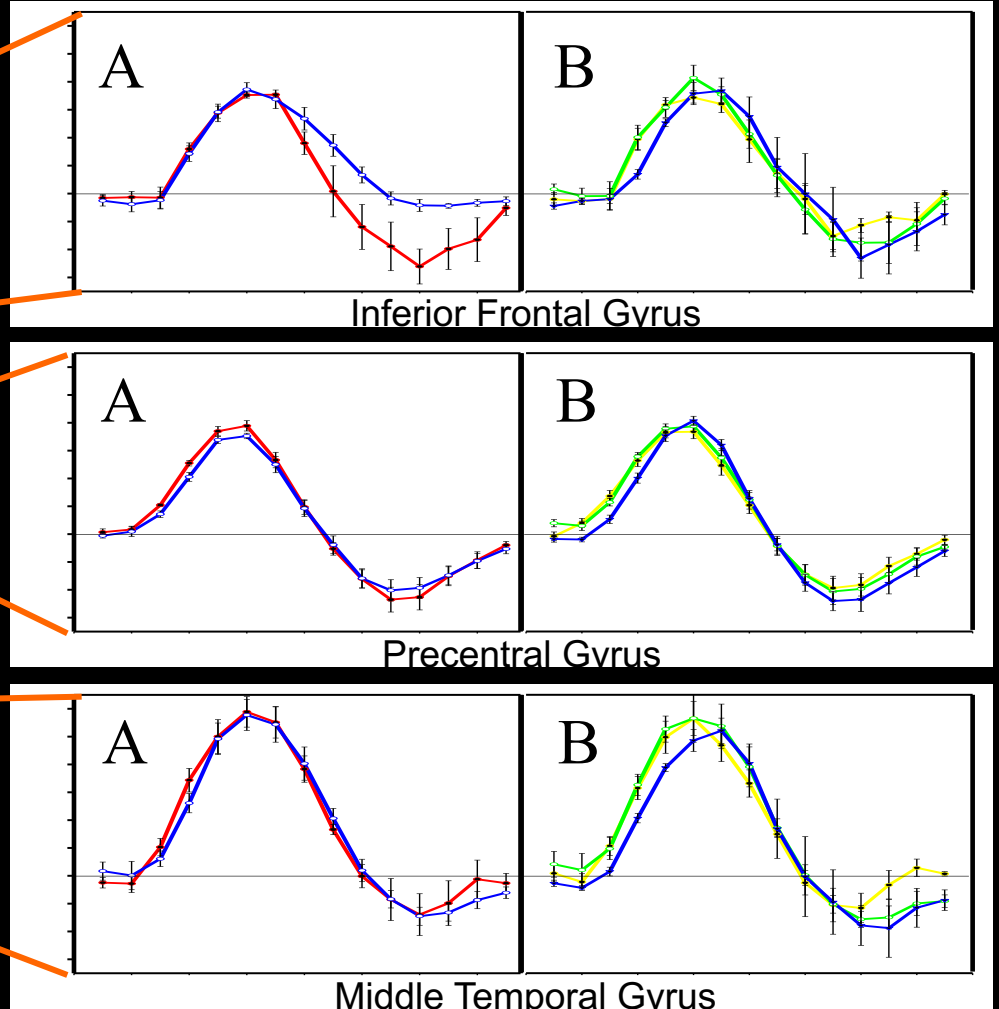
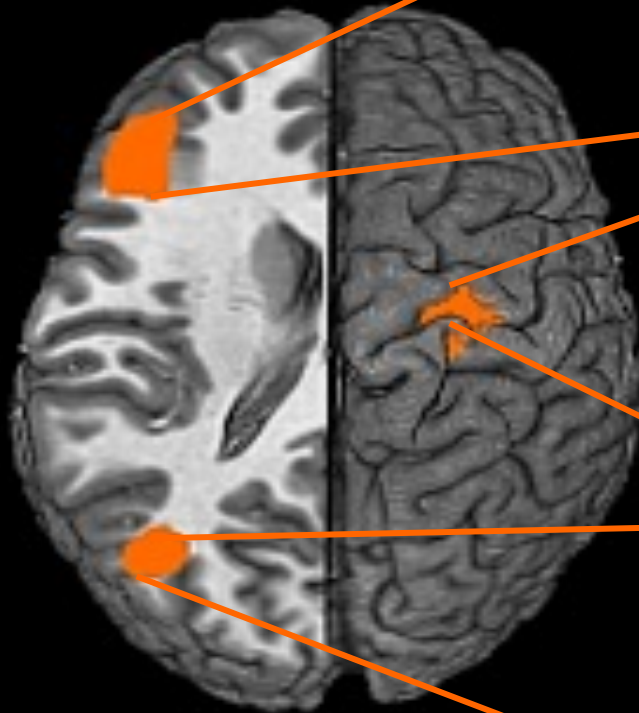
Communicated by Leslie G. Ungerleider, National Institutes of Health, Bethesda, MD, December 19, 2002 (received for review October 31, 2002)

Proc. Nat'l. Acad. Sci. USA **100**, 1415-1419 (2003).

		Lexical Delay		
		Words	Non-Words	Mean Reaction Time
Rotational Delay	0°	smudge	dierts	823 ms
	60°	frollic	cuhlos	891 ms
	120°	sloch	gednus	1446 ms
Mean Reaction Time		986 ms	1219 ms	

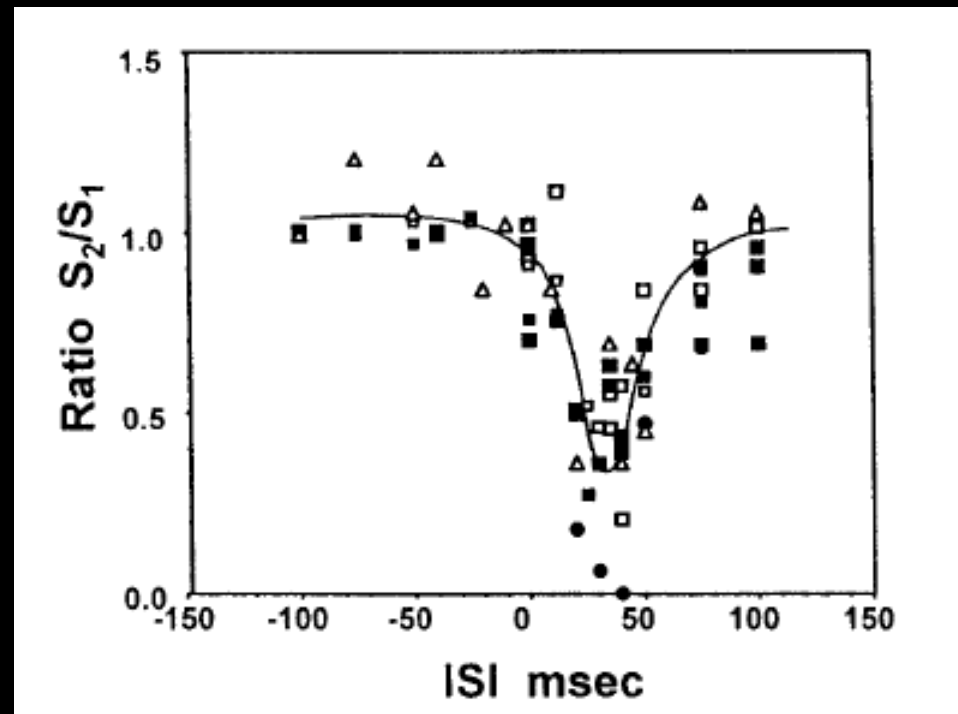
Word vs. Non-word **0°, 60°, 120° Rotation**

Regions of Interest

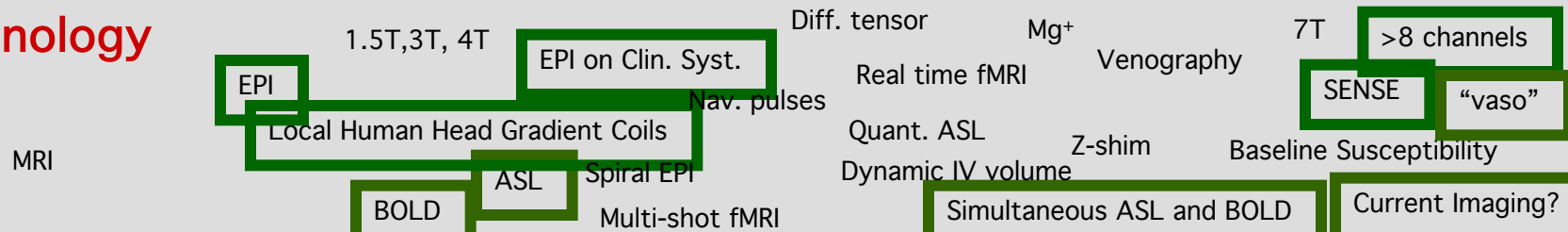


An approach to probe some neural systems interaction by functional MRI at neural time scale down to milliseconds

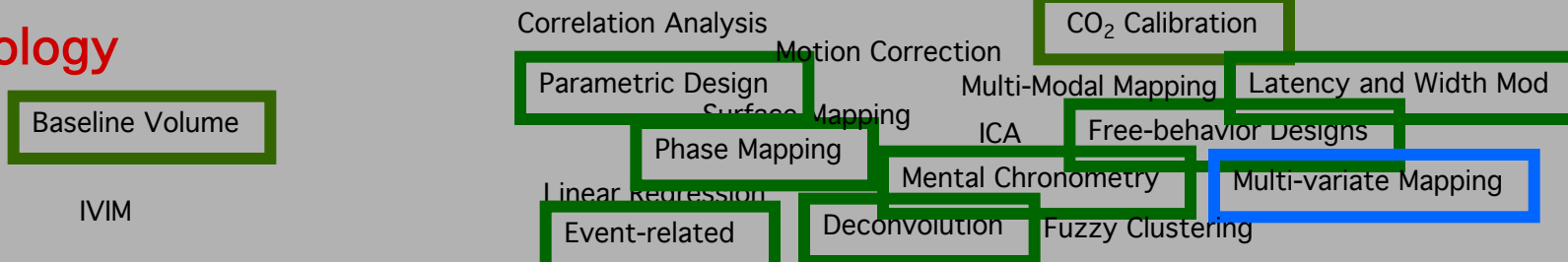
Seiji Ogawa^{††}, Tso-Ming Lee[†], Ray Stepnoski[†], Wei Chen[§], Xiao-Hong Zhu[§], and Kamil Ugurbil[§]



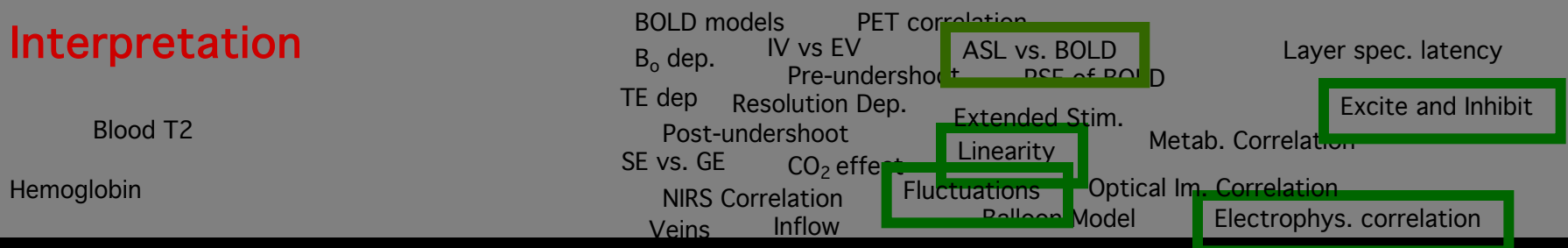
Technology



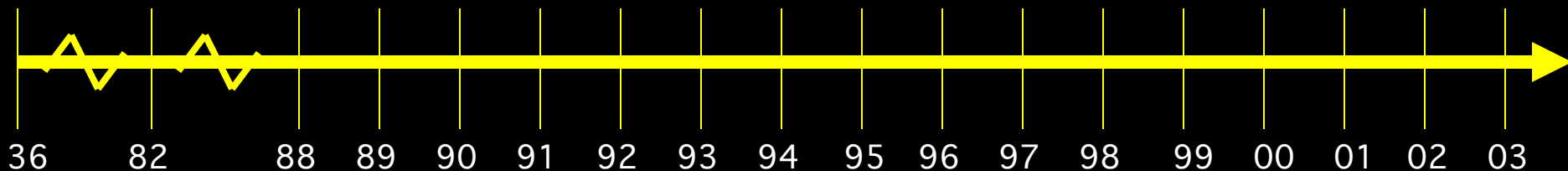
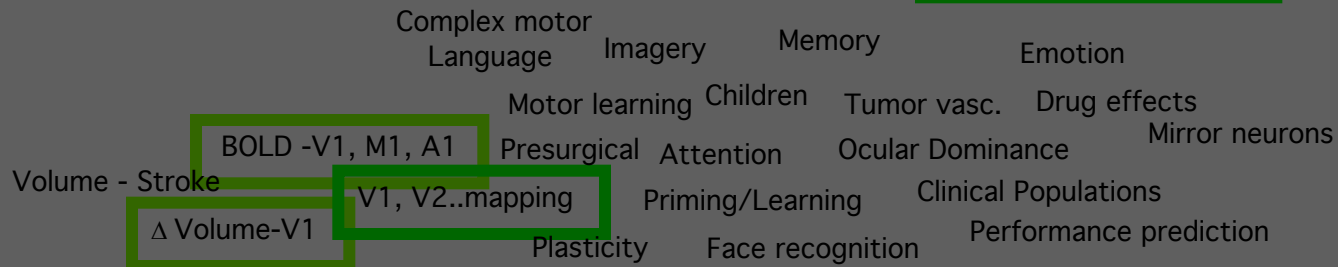
Methodology



Interpretation



Applications



Functional magnetic resonance imaging (fMRI) “brain reading”: detecting and classifying distributed patterns of fMRI activity in human visual cortex

David D. Cox^{a,b,*} and Robert L. Savoy^{a,b,c}

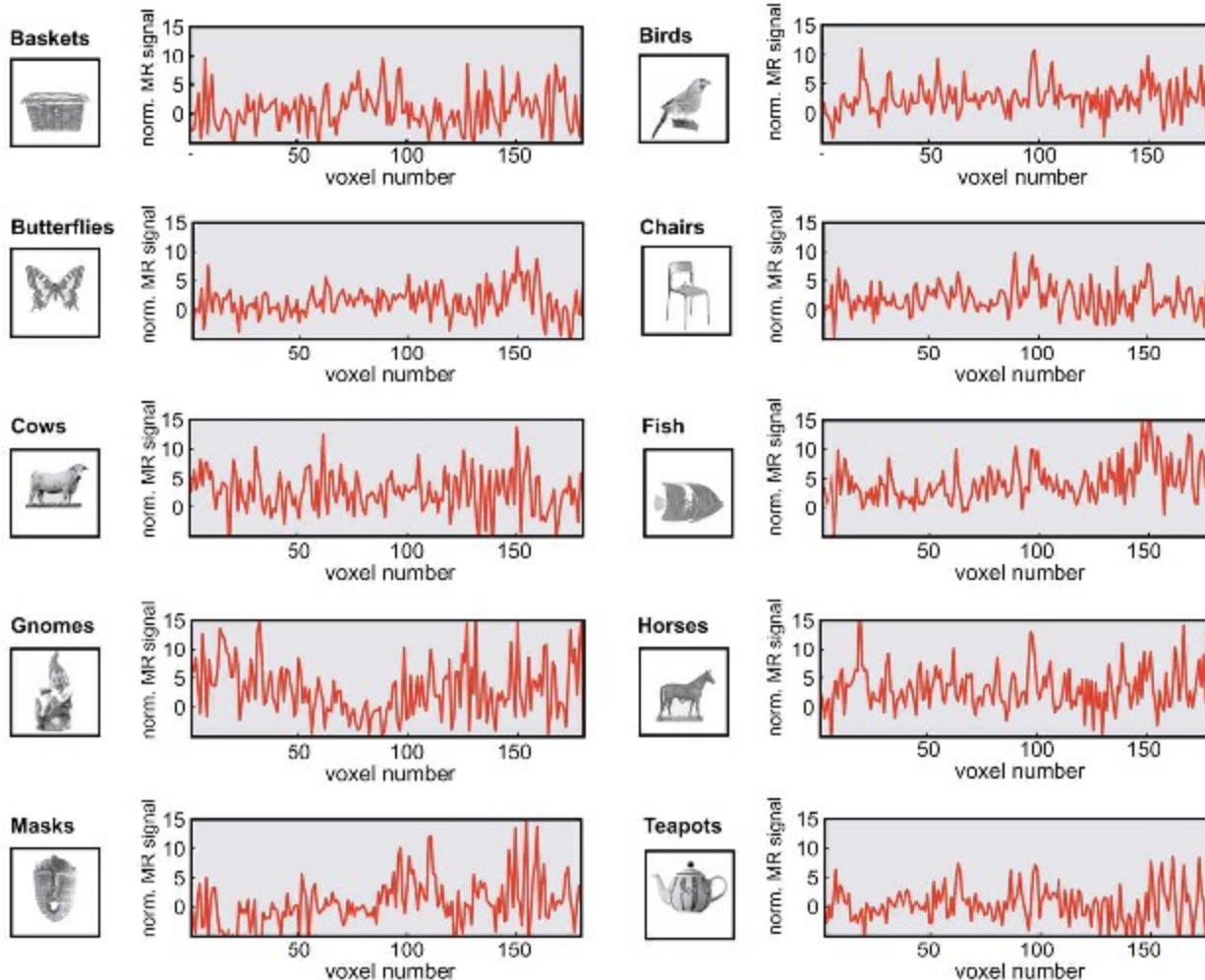
^a Rowland Institute for Science, Cambridge, MA 02142, USA

^b Athinoula A. Martinos Center for Structural and Functional Biomedical Imaging, Charlestown, MA 02129, USA

^c HyperVision, Inc., P.O. Box 158, Lexington, MA 02420, USA

Received 15 July 2002; accepted 10 December 2002

NEUROIMAGE 19 (2): 261-270 Part 1 JUN 2003



The Future

Sensitivity
Resolution
Calibration
Integration
Correlation

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

Anthony Boemio

Patrick Bellgowan

Ziad Saad

Graduate Student:

Natalia Petridou

Post-Back. IRTA Students:

Hanh Ngyun

Ilana Levy

Elisa Kapler

August Tuan

Dan Kelley

Visiting Fellows:

Sergio Casciaro

Marta Maieron

Guosheng Ding

Clinical Fellow:

James Patterson

Psychologist:

Julie Frost

Summer Students:

Allison Sanders

Julia Choi

Thomas Gallo

Jenna Gelfand

Hannah Chang

Courtney Kemps

Douglass Ruff

Carla Wettig

Kang-Xing Jin

Program Assistant:

Kay Kuhns

Scanning Technologists:

Karen Bove-Bettis

Paula Rowser

Alda Ottley