Functional MRI: Past, Present, Future

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&
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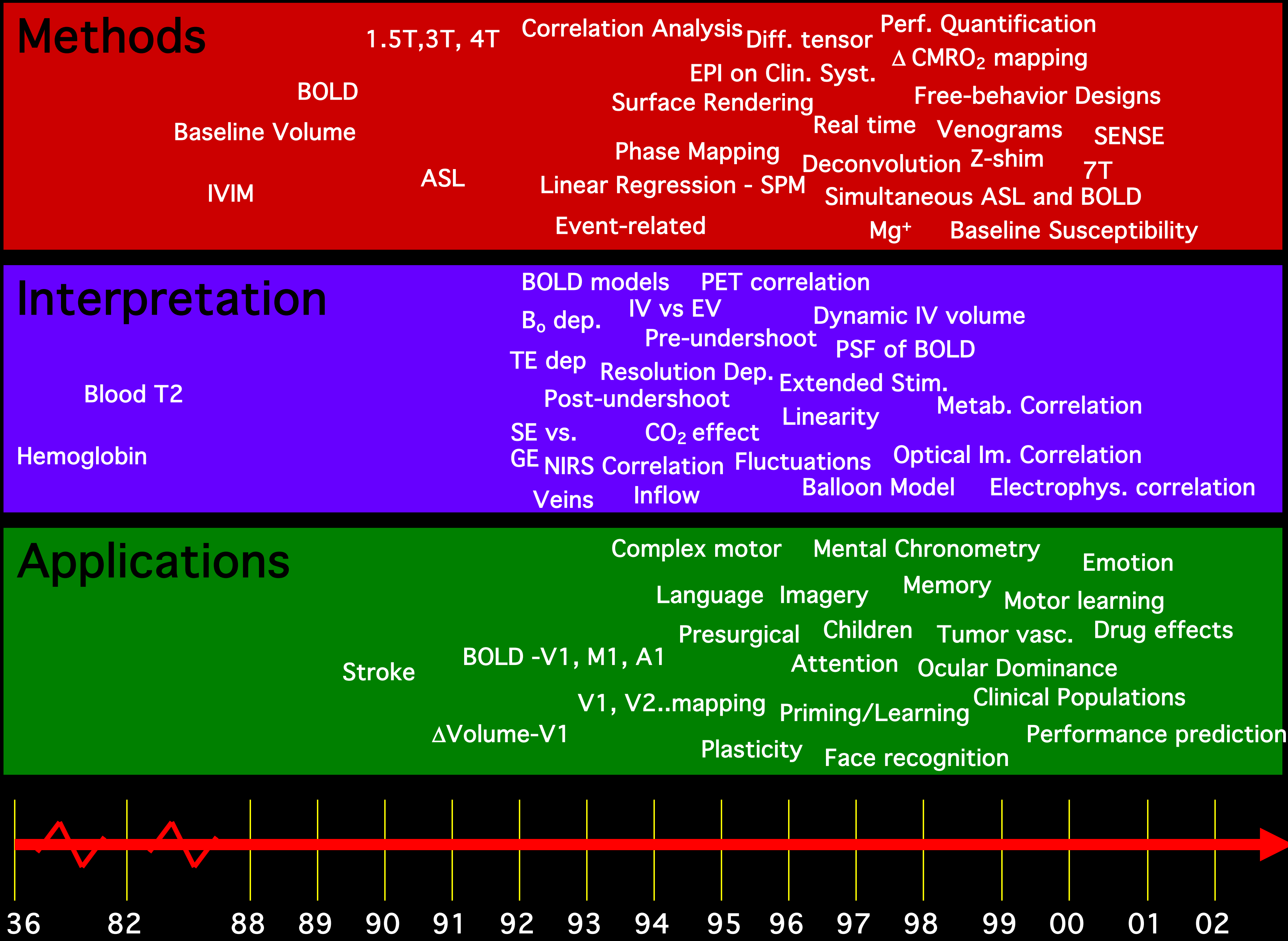
Laboratory of Brain and Cognition
National Institute of Mental Health

Past

Present

Future



Methods
1.5T,3T, 4T
Correlation Analysis
Diff. tensor
Perf. Quantification
Δ CMRO2 mapping
EPI on Clin. Syst.
BOLD
Surface Rendering
Free-behavior Designs
Baseline Volume
Real time
Venograms
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36
82
88
89
90
91
92
93
94
95
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97
98
99
00
01
02

Past

Present

Future

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.

The Techniques

Blood Volume Imaging

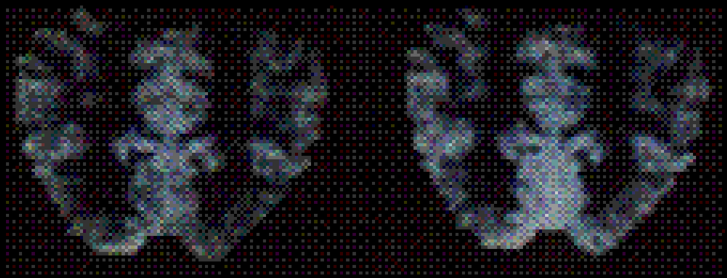
BOLD Contrast

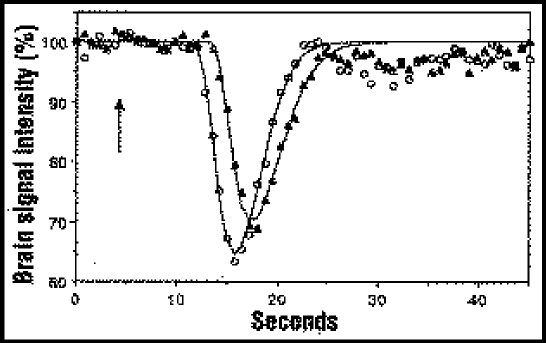
Arterial Spin Labeling

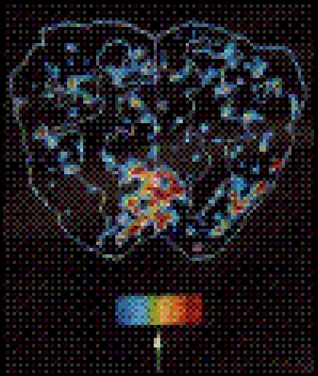
Blood Volume Imaging

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

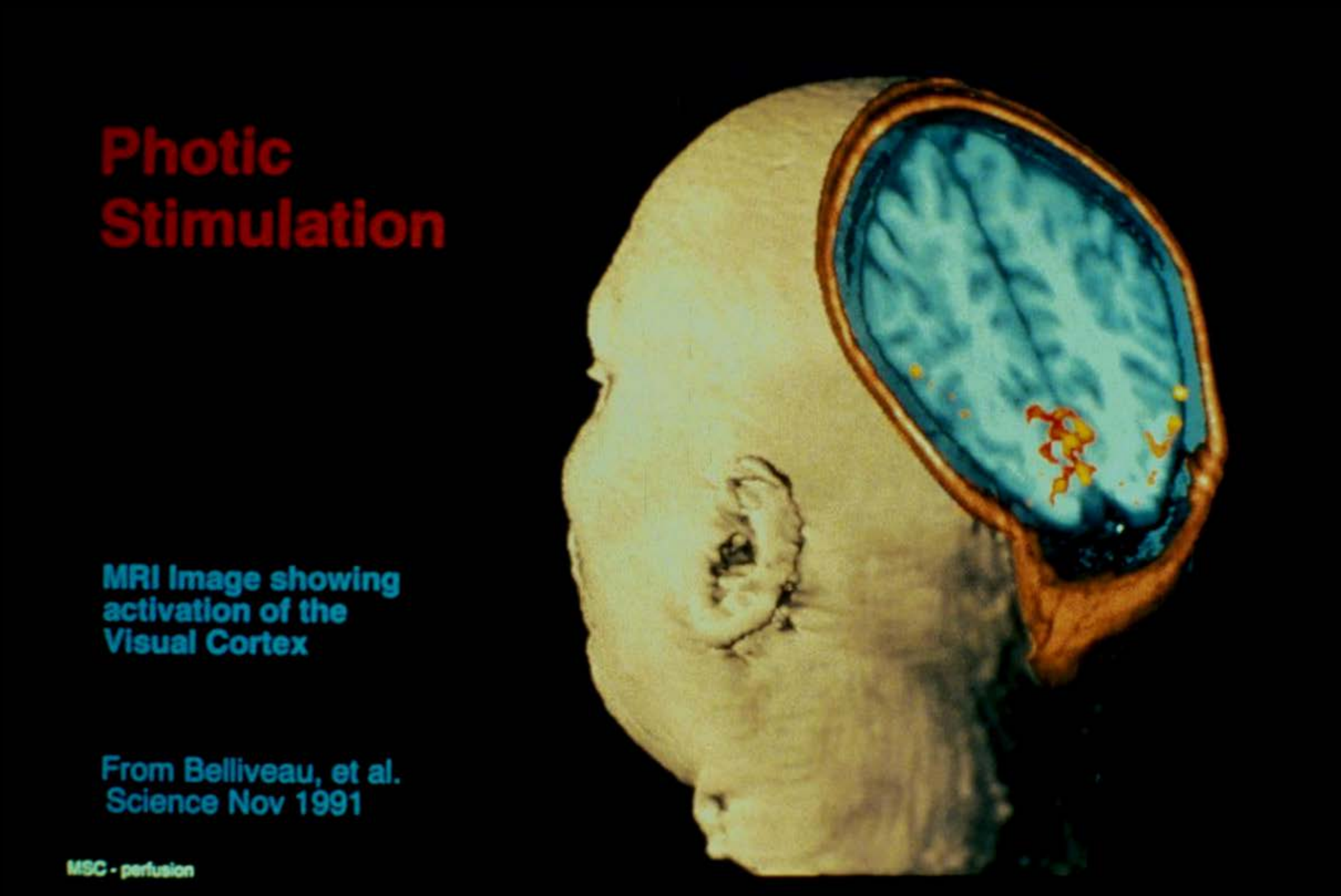
Resting **Active**





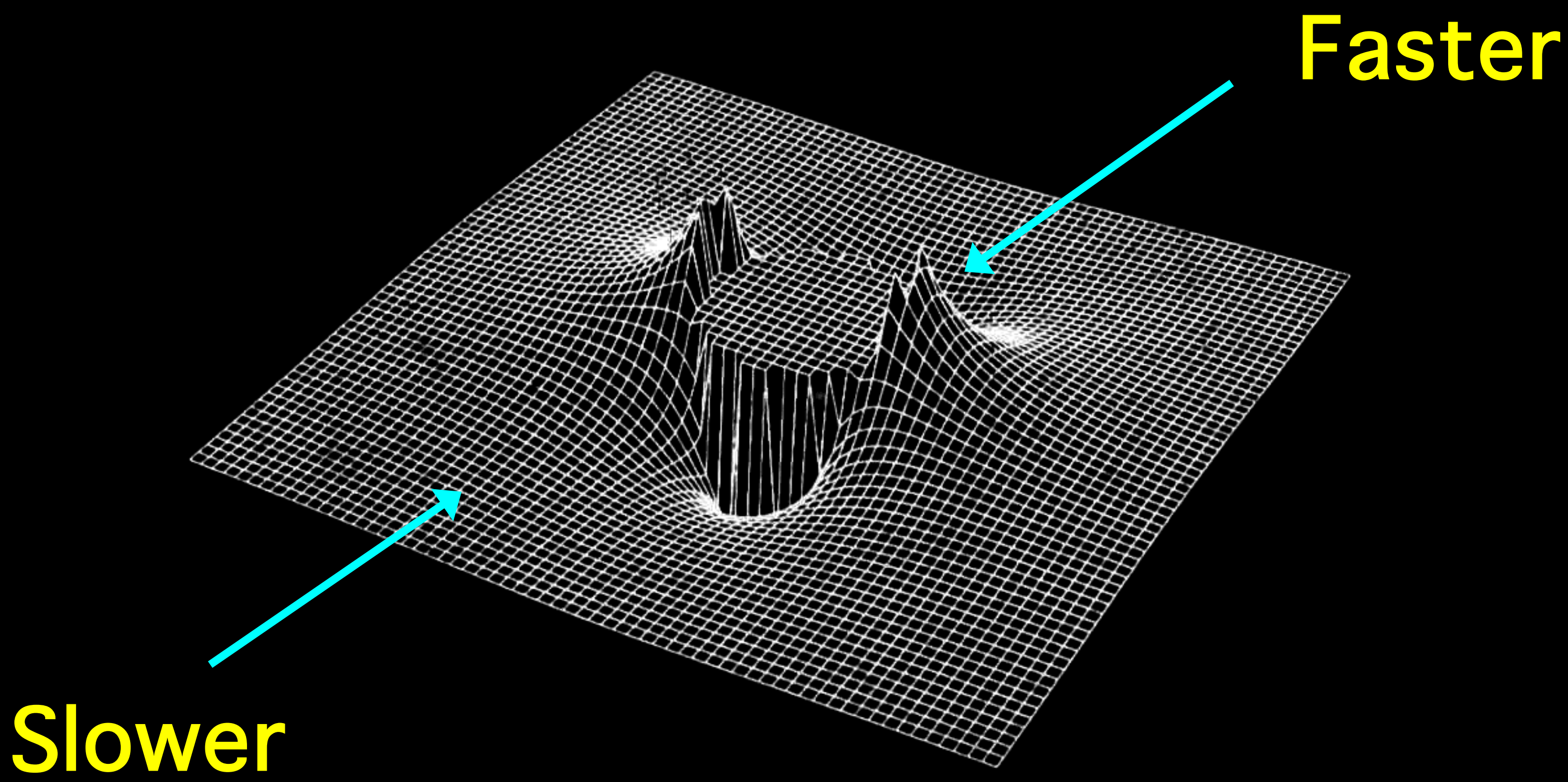


Blood Volume



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, J. W. Belliveau, D. A. Chesler, I. E. Goldberg, R. M.Weisskoff, B. P. Poncelet, D. N. Kennedy, B. E. Hoppel, M. S. Cohen, R.Turner, H. M. Cheng, T. J. Brady, B. R. Rosen, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.

S. Ogawa, D. W. Tank, R. Menon, J. M. Ellermann, S.-G. Kim, H. Merkle, K. Ugurbil, (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, E. C. Wong, R. S. Hinks, R. S. Tikofsky, J. S. Hyde, (1992) "Time course EPI of human brain function during task activation." Magn. Reson. Med 25, 390-397.

BOLD Contrast in the Detection of Neuronal Activity

Cerebral Tissue Activation

↓

Local Vasodilation

↓

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

↓

Increase in Capillary and Venous Blood Oxygenation

↓

Decrease in Deoxy-hemoglobin

Deoxy-hemoglobin: paramagnetic
Oxy-hemoglobin: diamagnetic

↓

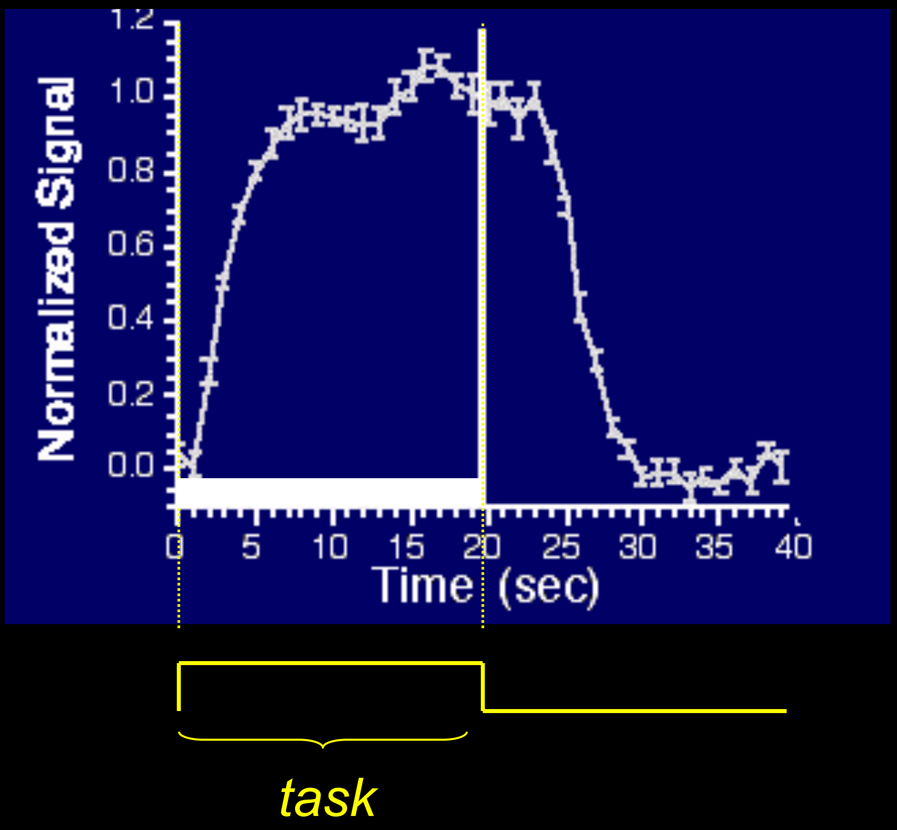
Decrease in susceptibility-related intravoxel dephasing → Increase in T2 and T2*

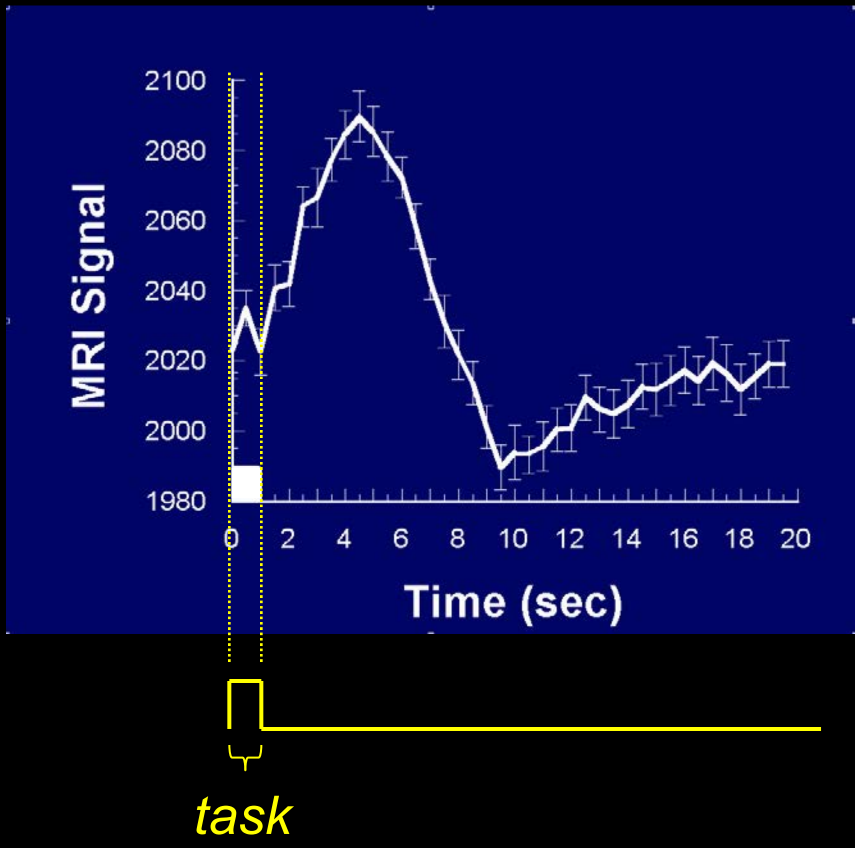
↓

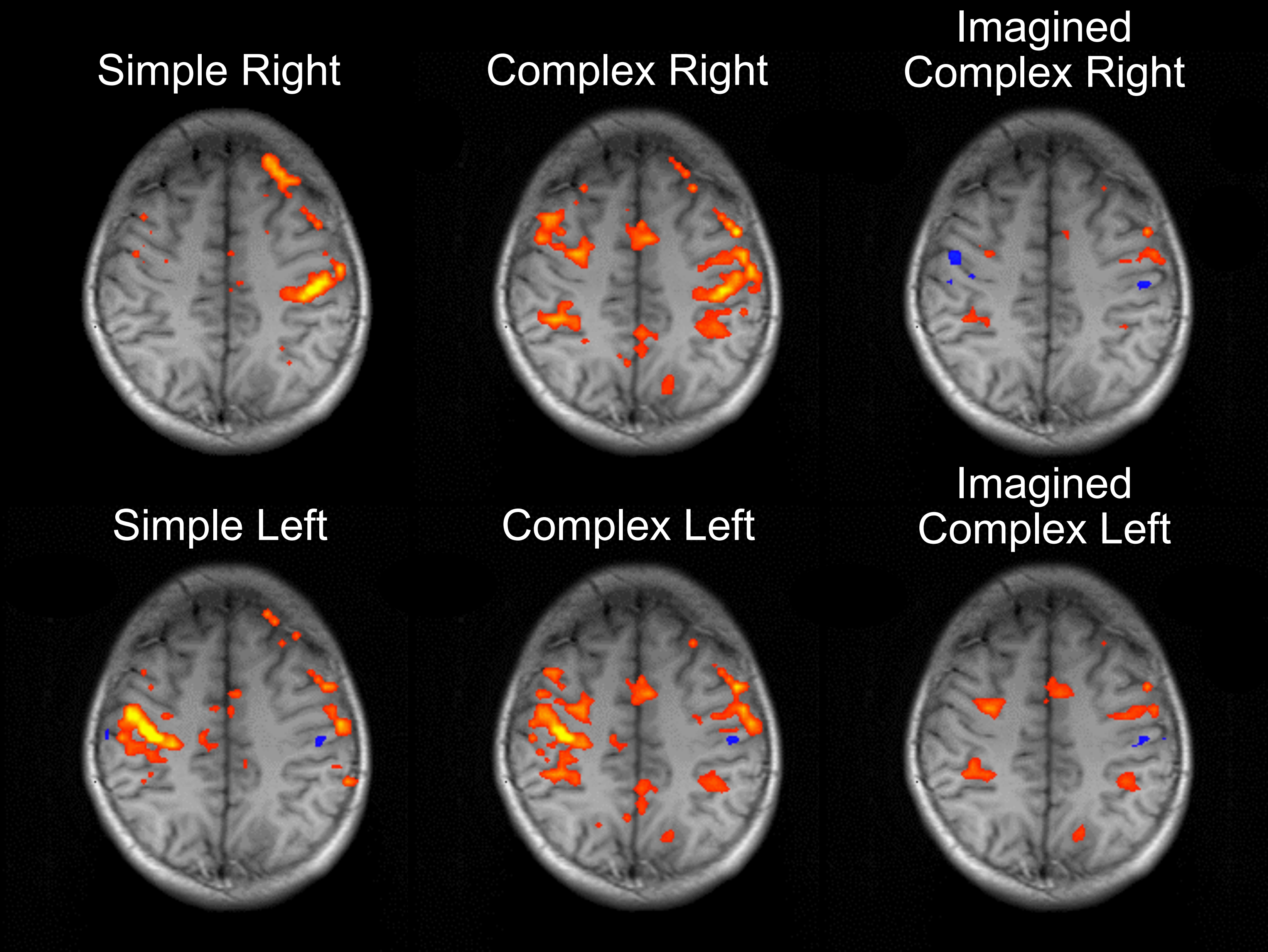
Local Signal Increase in T2 and T2* - weighted sequences

The BOLD Signal

Blood Oxygenation Level Dependent (BOLD) signal changes







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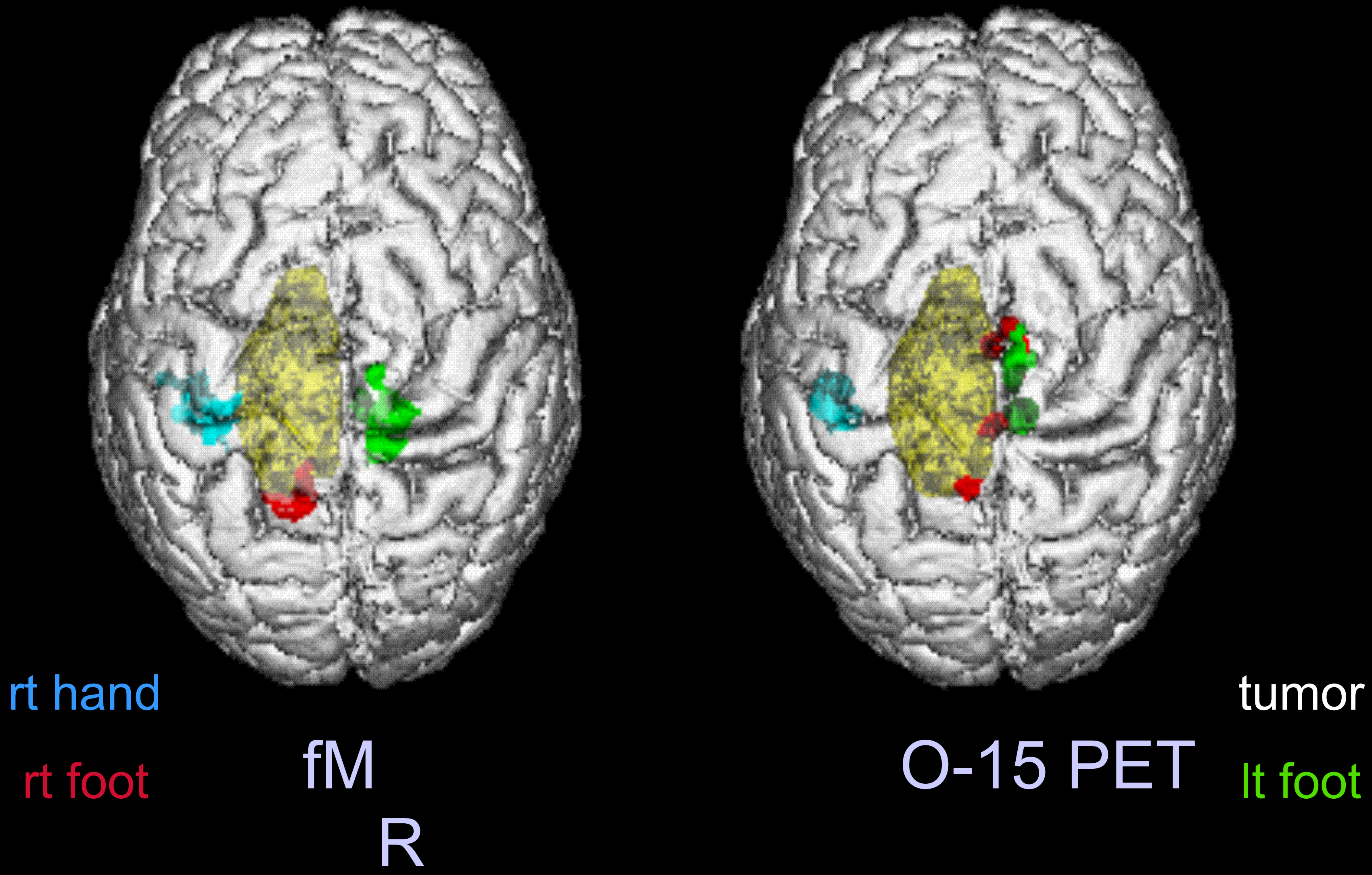
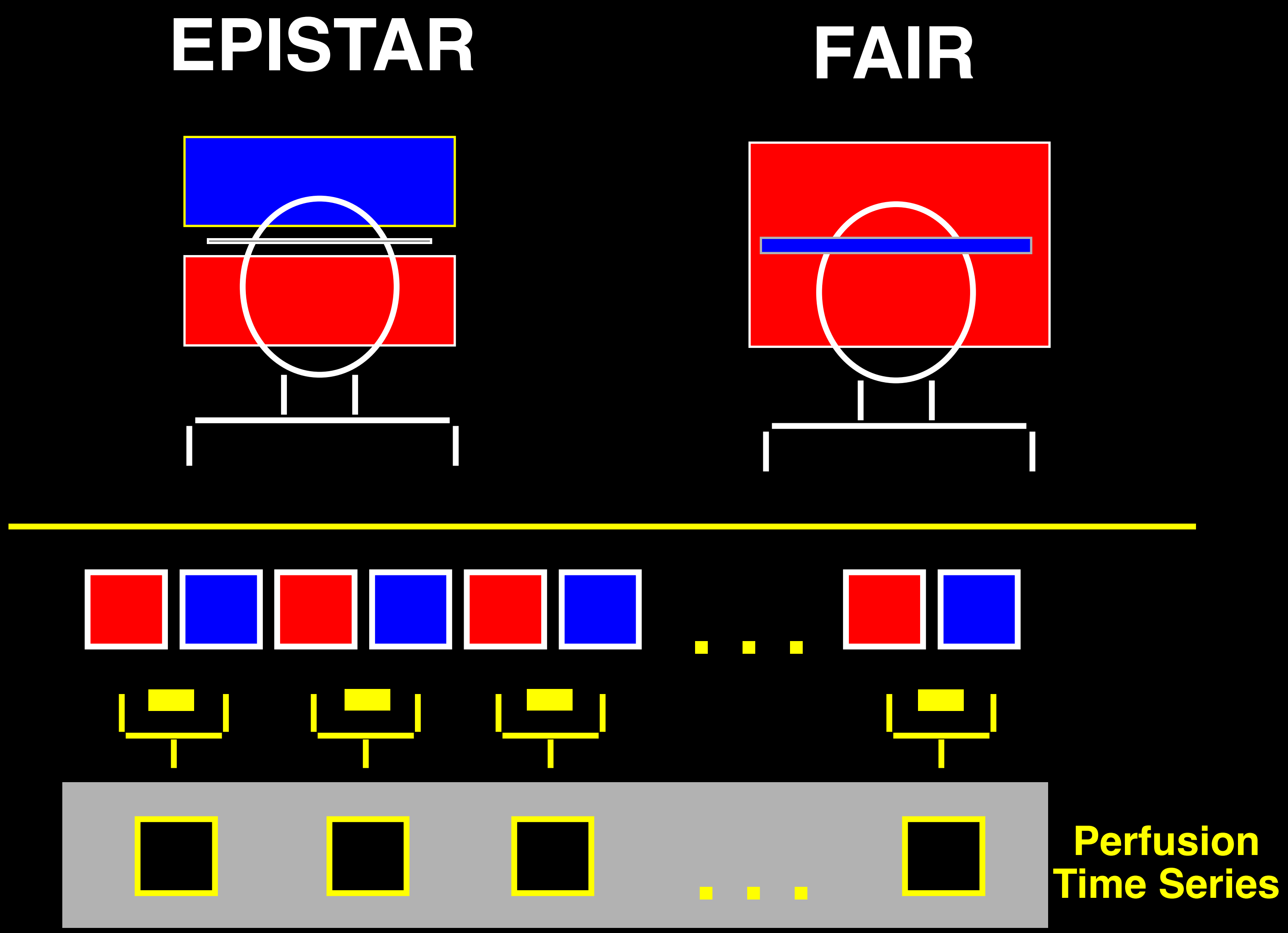
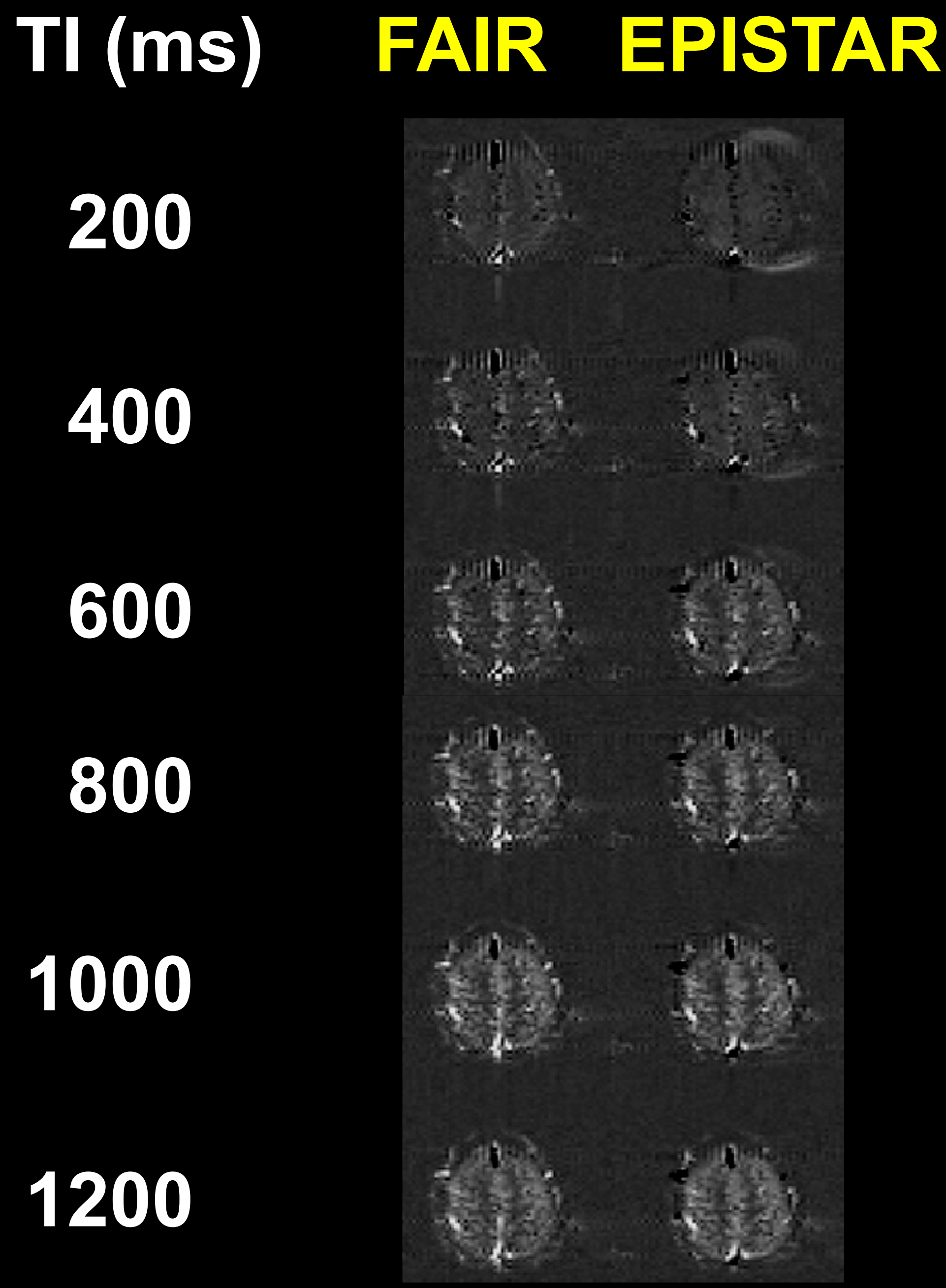
Sensorimotor Mapping

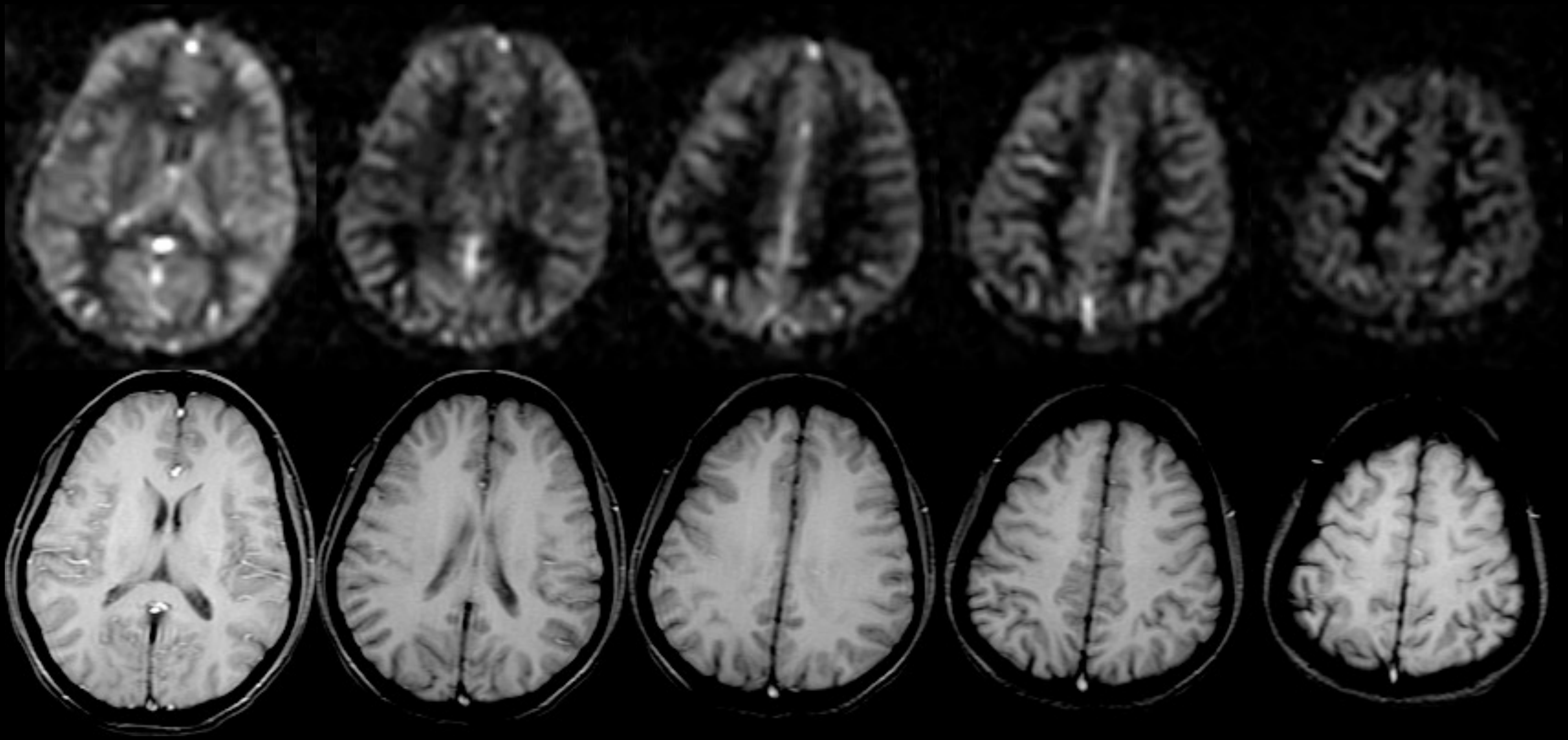


Blood Perfusion

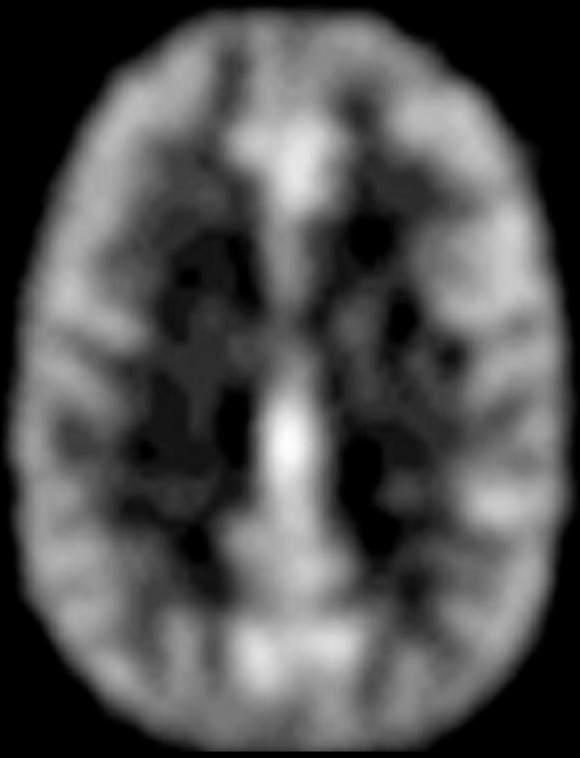



TI (ms)
FAIR
EPISTAR
200
400
600
800
1000
1200

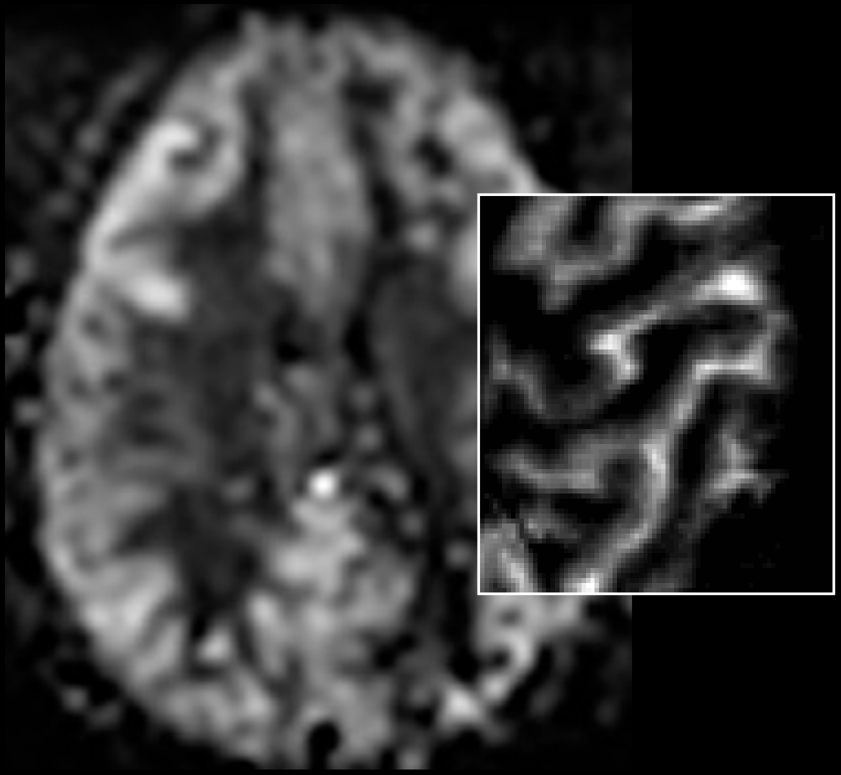
Resting ASL Signal



Comparison with Positron Emission Tomography



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



MRI: ASL

Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

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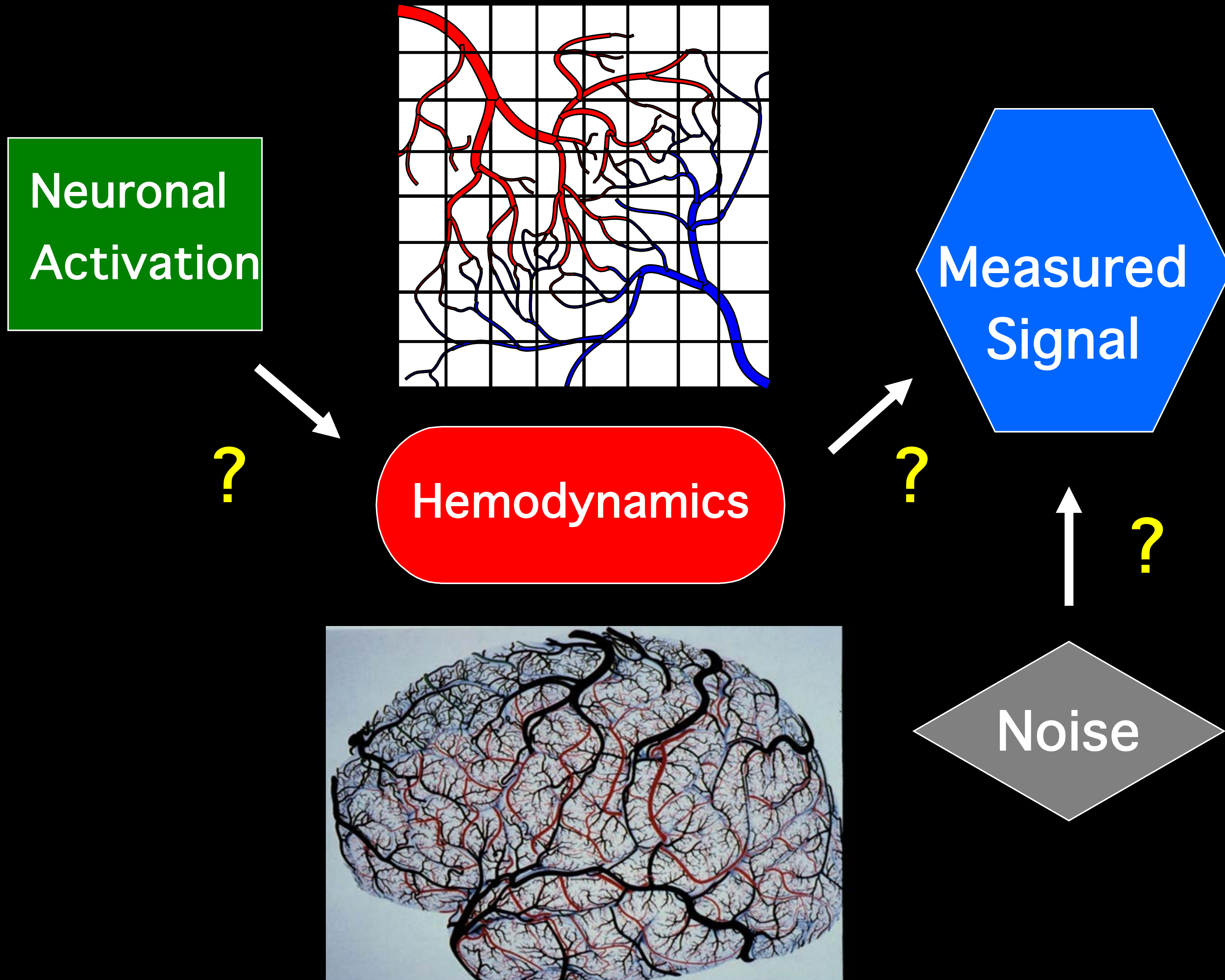
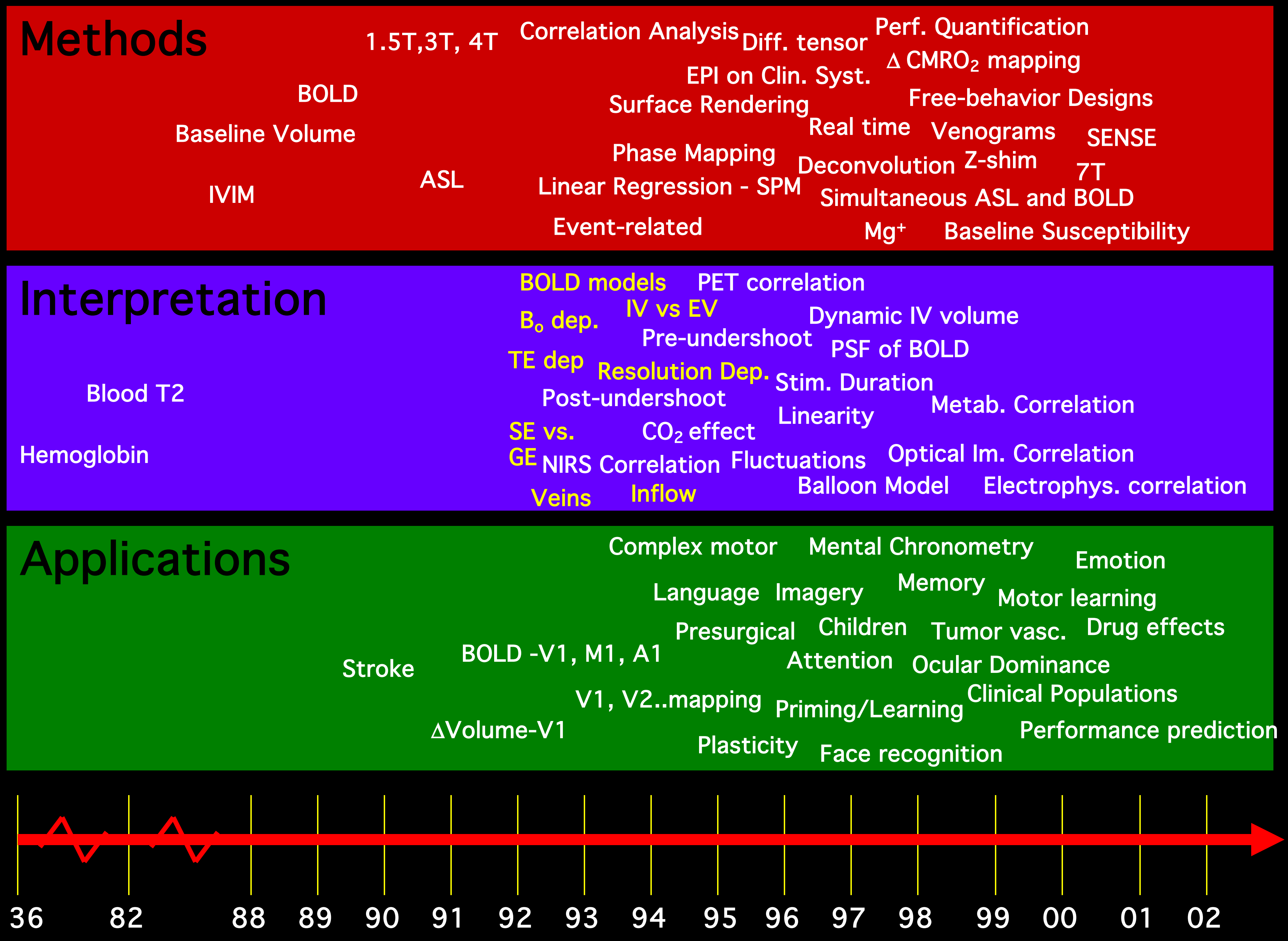

Neuronal
Activation
?
Hemodynamics
?
Measured
Signal
?
Noise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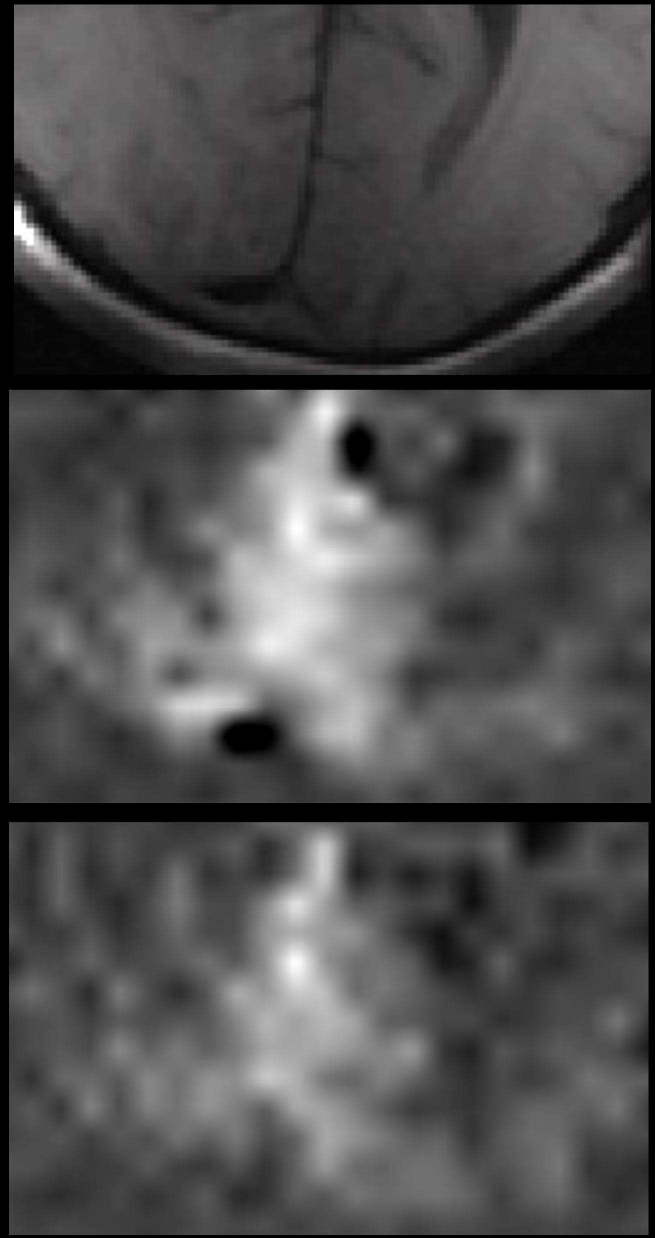
Gradient - Echo

Spin - Echo



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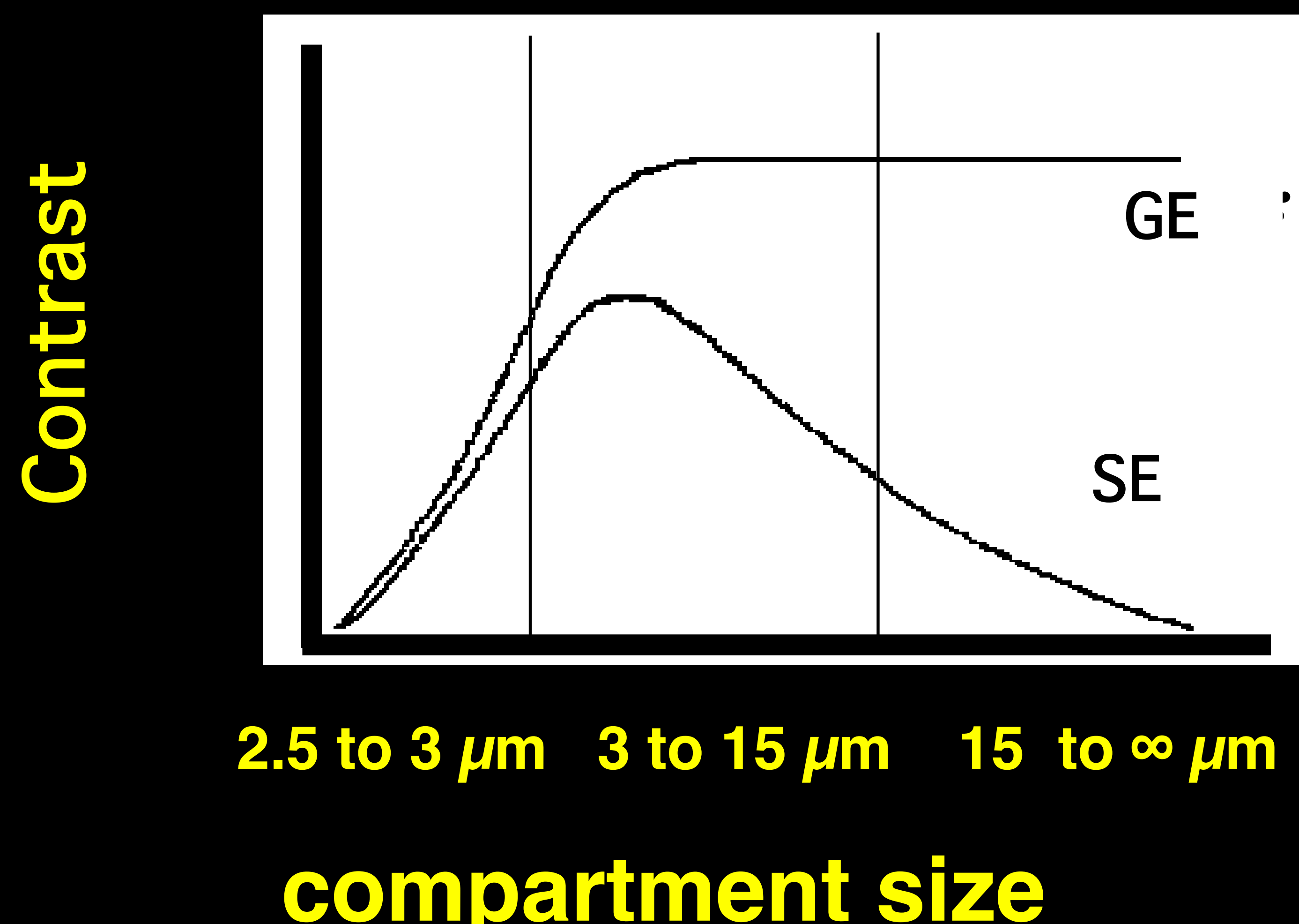


GE
SE
Contrast
2.5 to 3 μm
3 to 15 μm
15 to ∞ μm
compartment size

T1 - weighted

T2* weighted

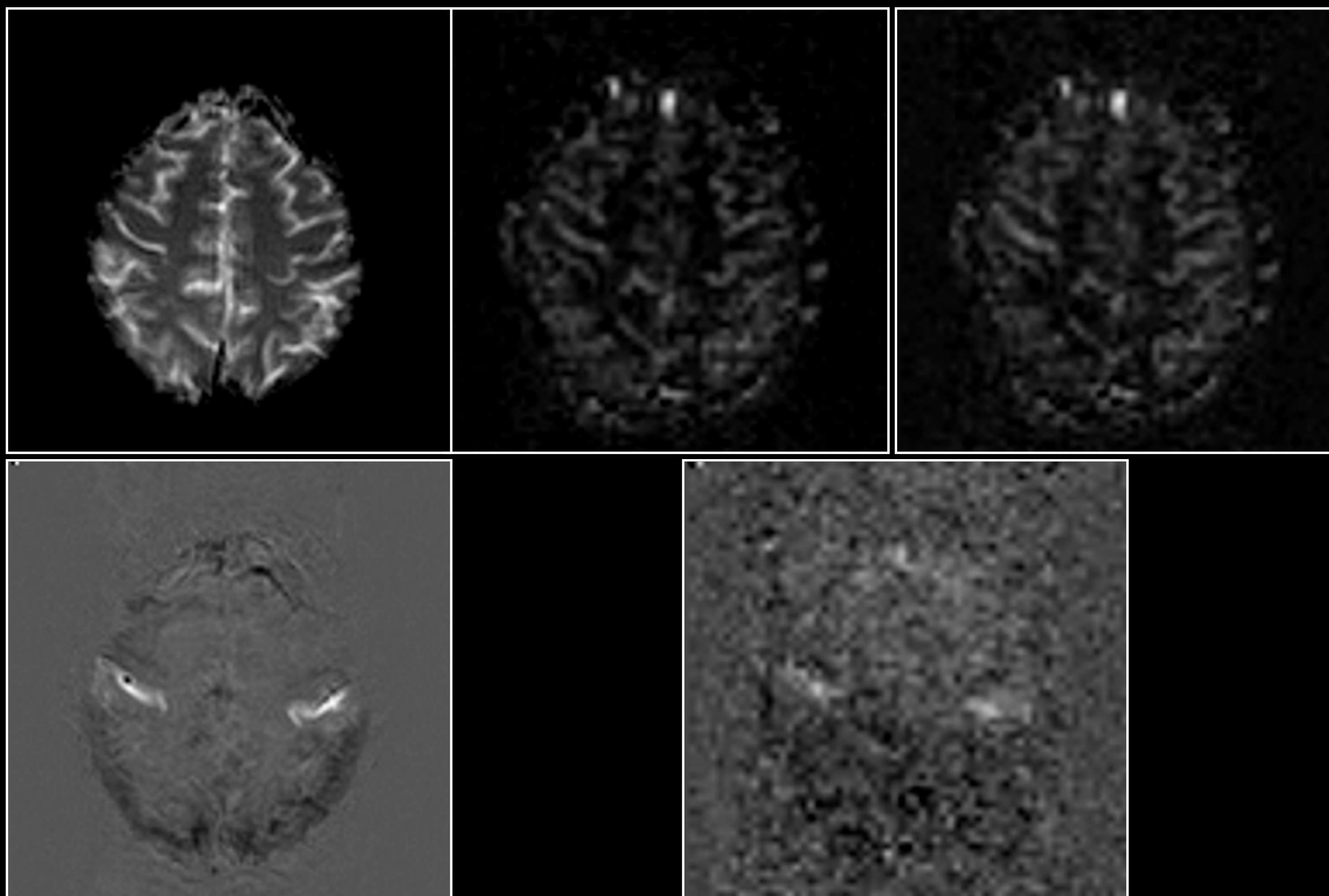
T1 and T2* weighted

Perfusion

BOLD

Rest

Activation

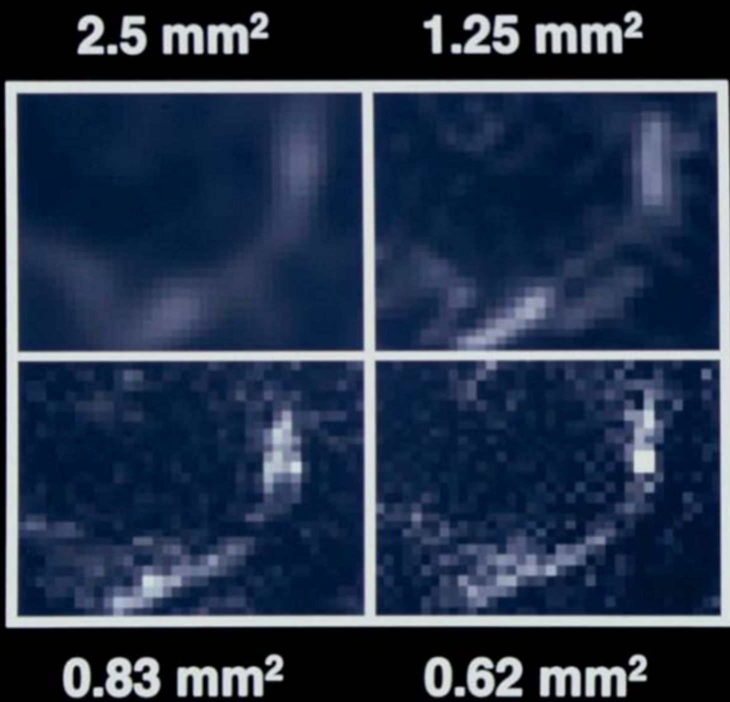


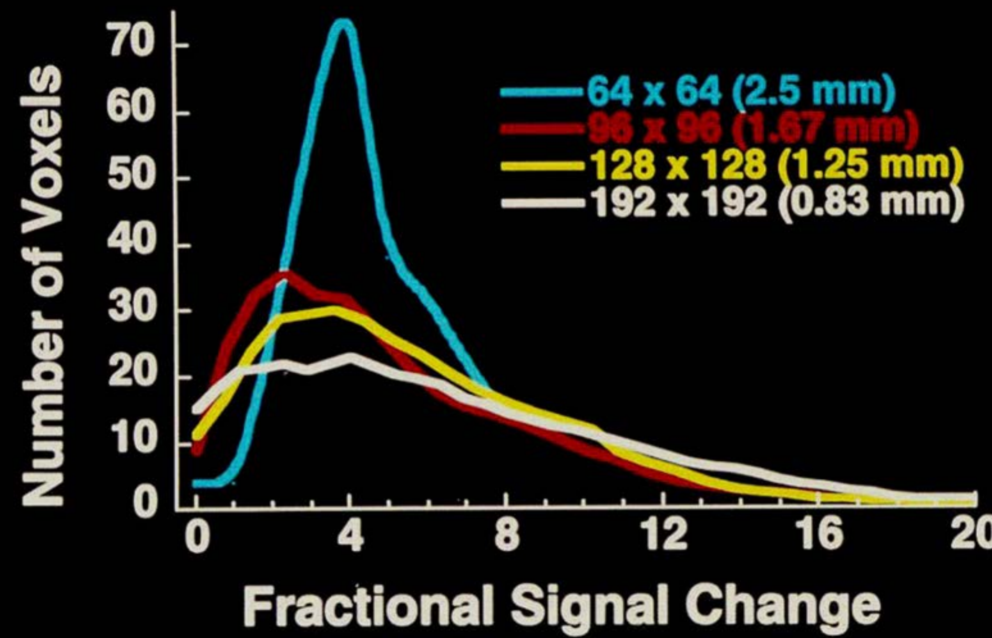
Anatomy

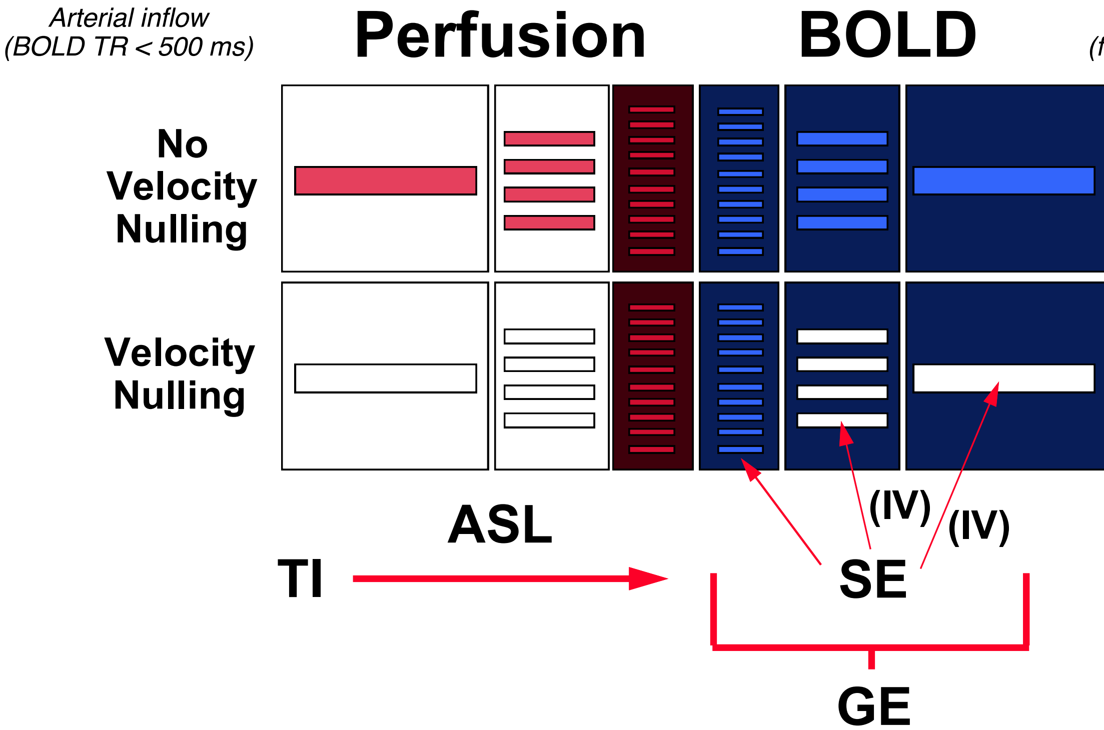
BOLD

Perfusion

Fractional Signal Change

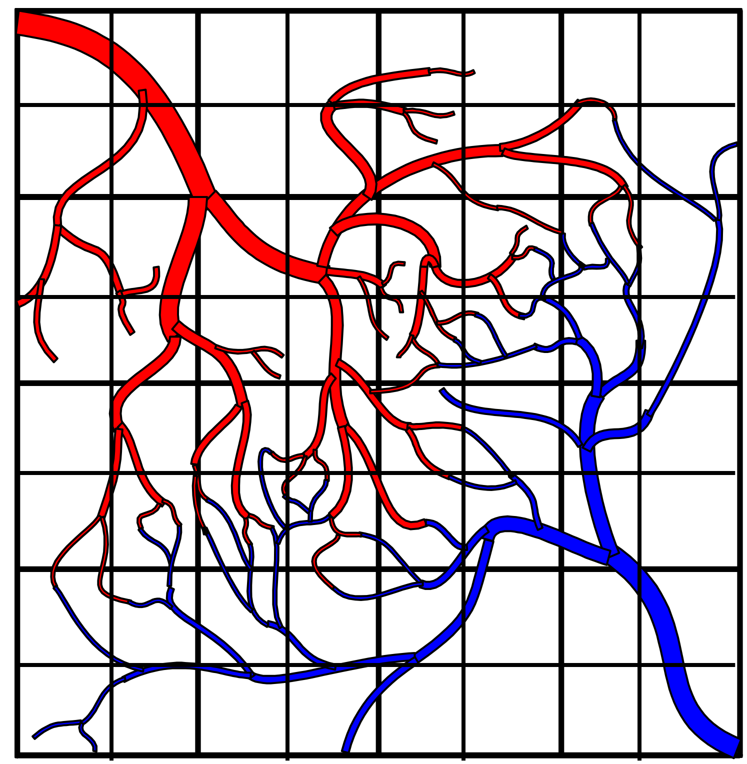






Pulse Sequence Sensitivity

Spatial Heterogeneity



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Dynamics, Paradigm Design and Processing

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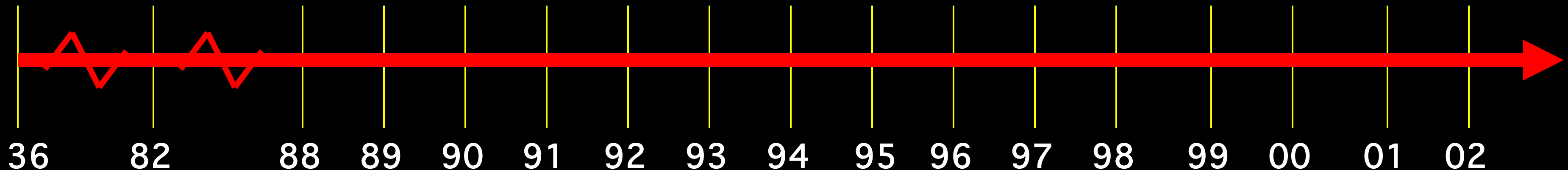
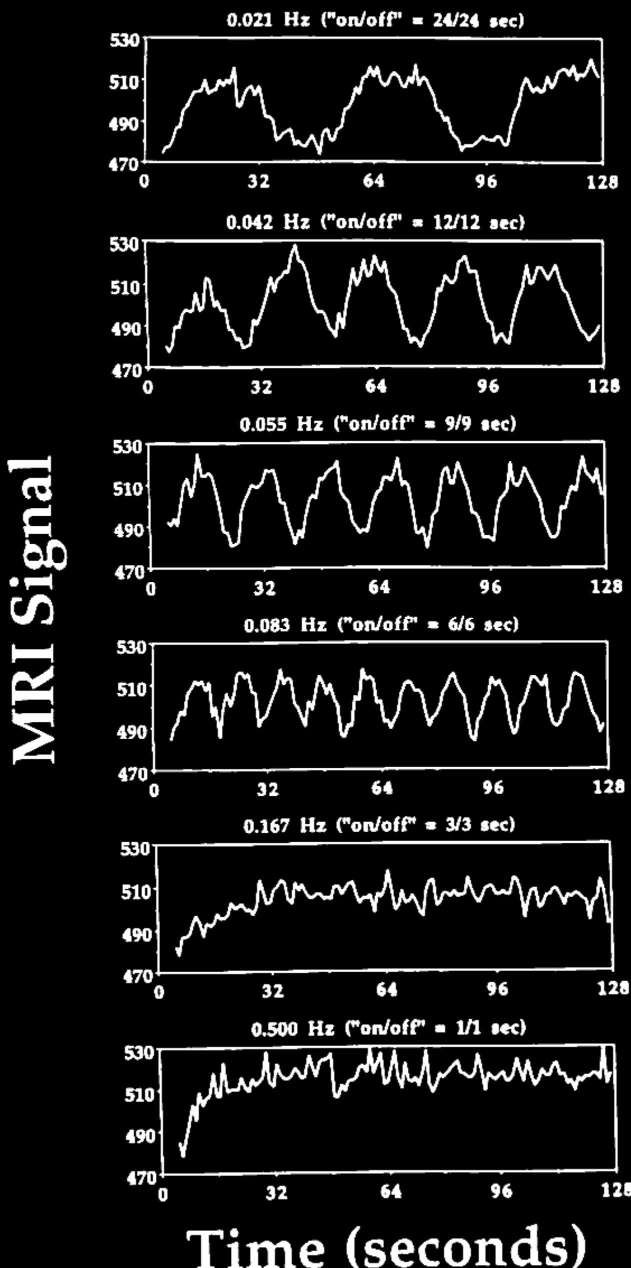
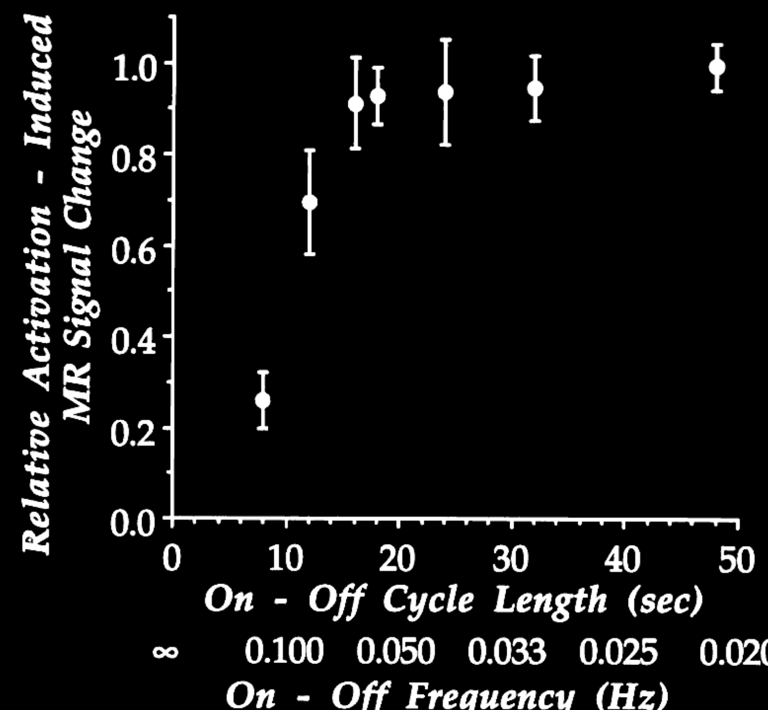
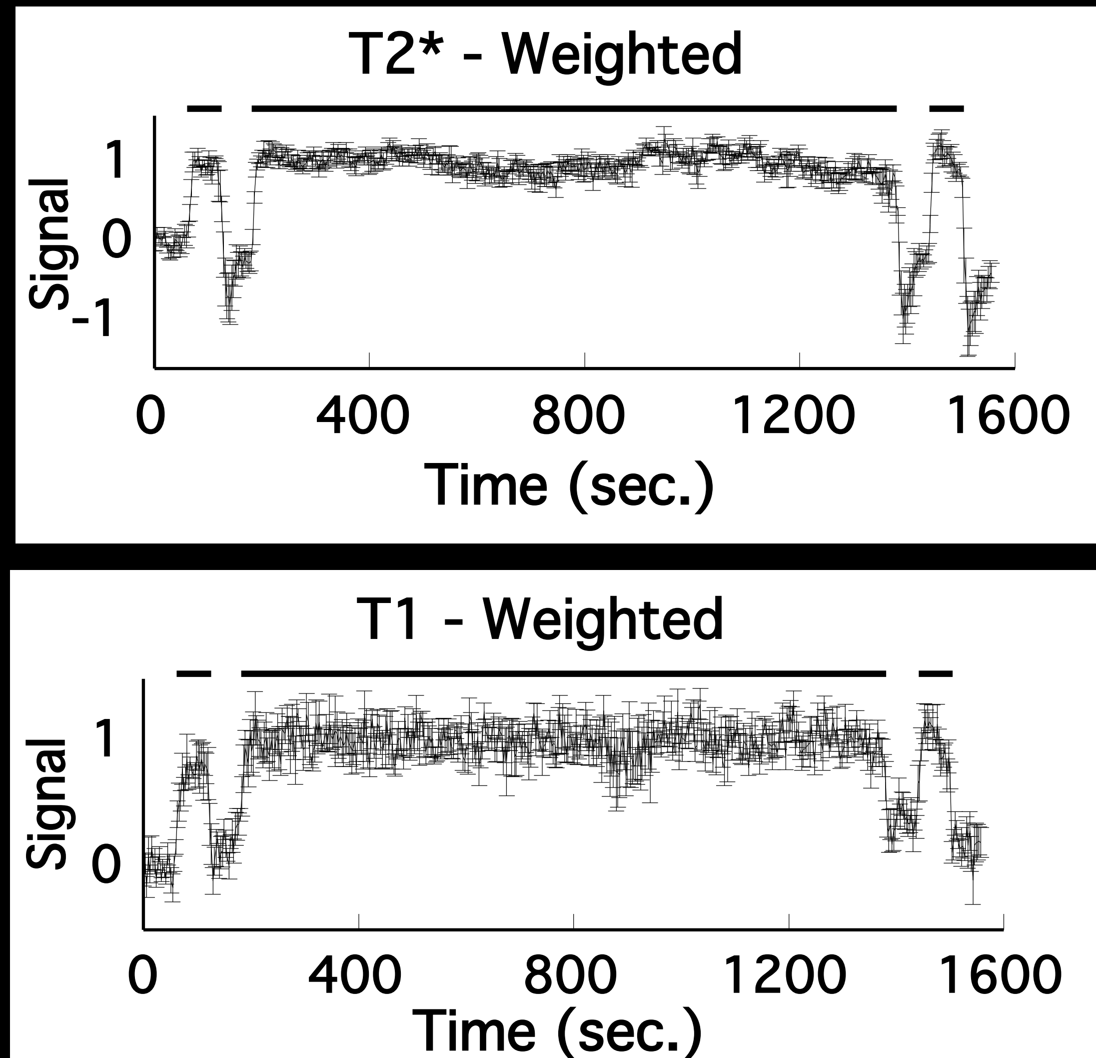



MRI Signal
0.021 Hz ("on/off" = 24/24 sec)
0.042 Hz ("on/off" = 12/12 sec)
0.055 Hz ("on/off" = 9/9 sec)
0.083 Hz ("on/off" = 6/6 sec)
0.167 Hz ("on/off" = 3/3 sec)
0.500 Hz ("on/off" = 1/1 sec)
Time (seconds)


Relative Activation - Induced MR Signal Change
On - Off Cycle Length (sec)
∞ 0.100 0.050 0.033 0.025 0.020
On - Off Frequency (Hz)

² HbO_2

² Flow



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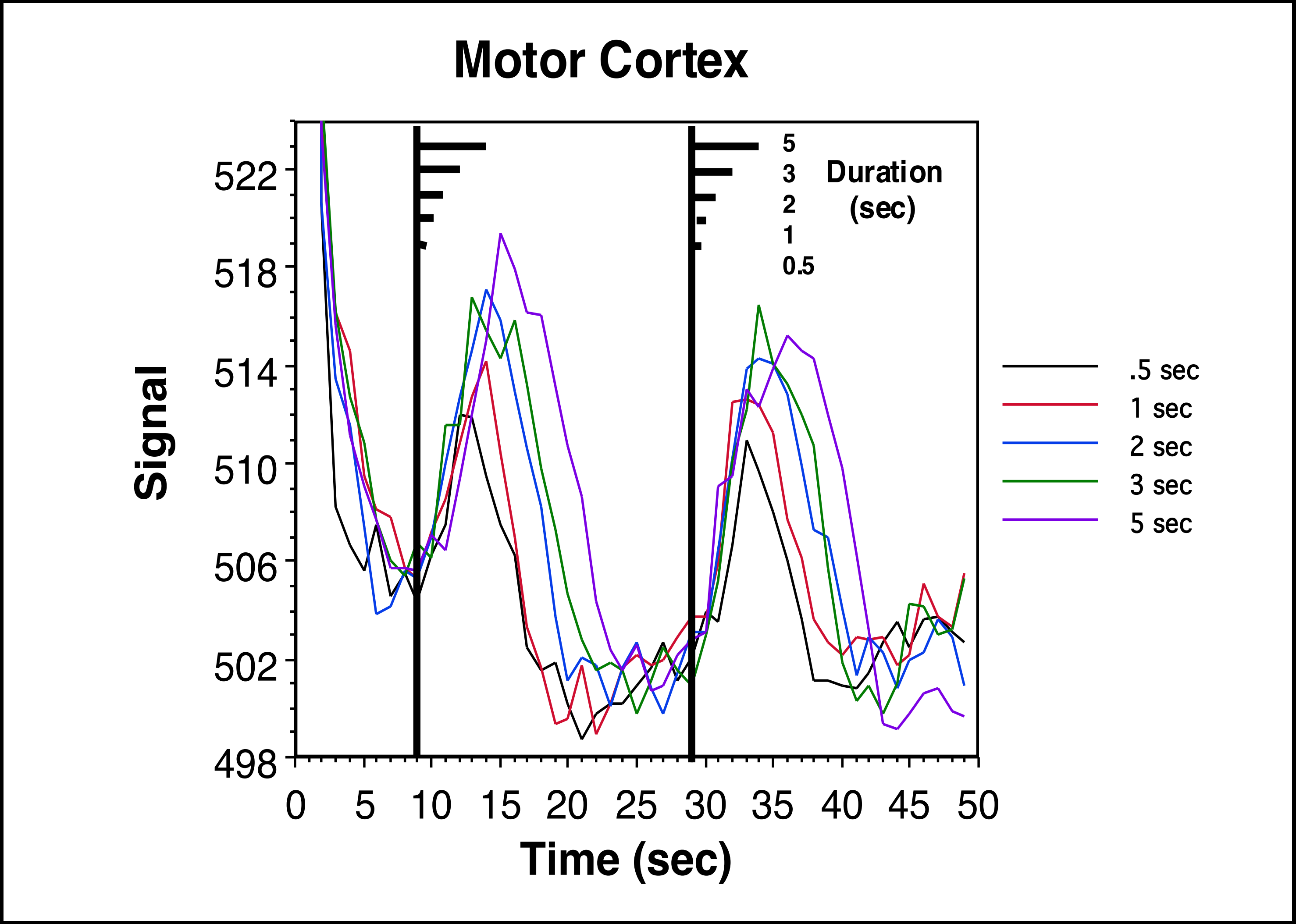
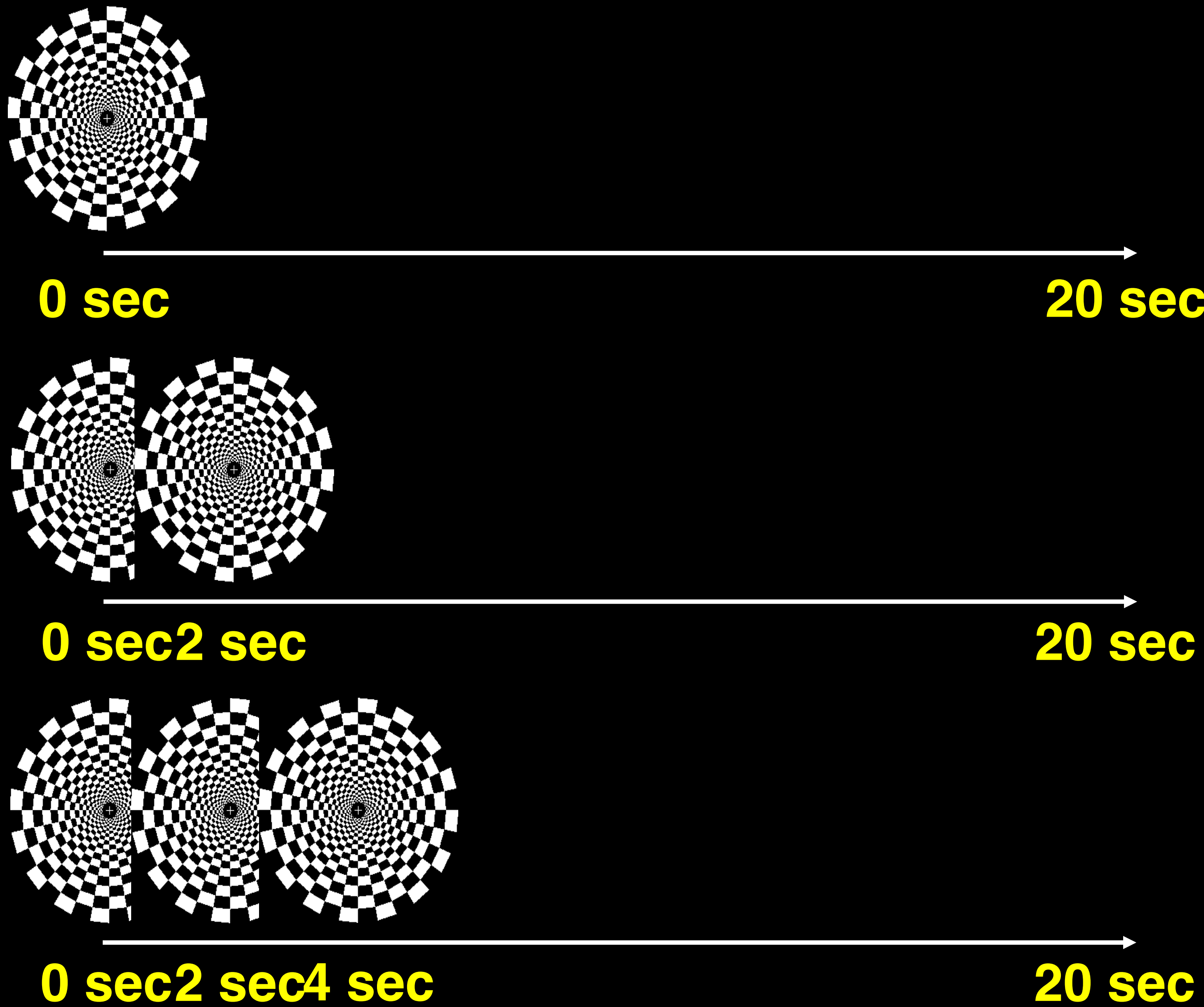
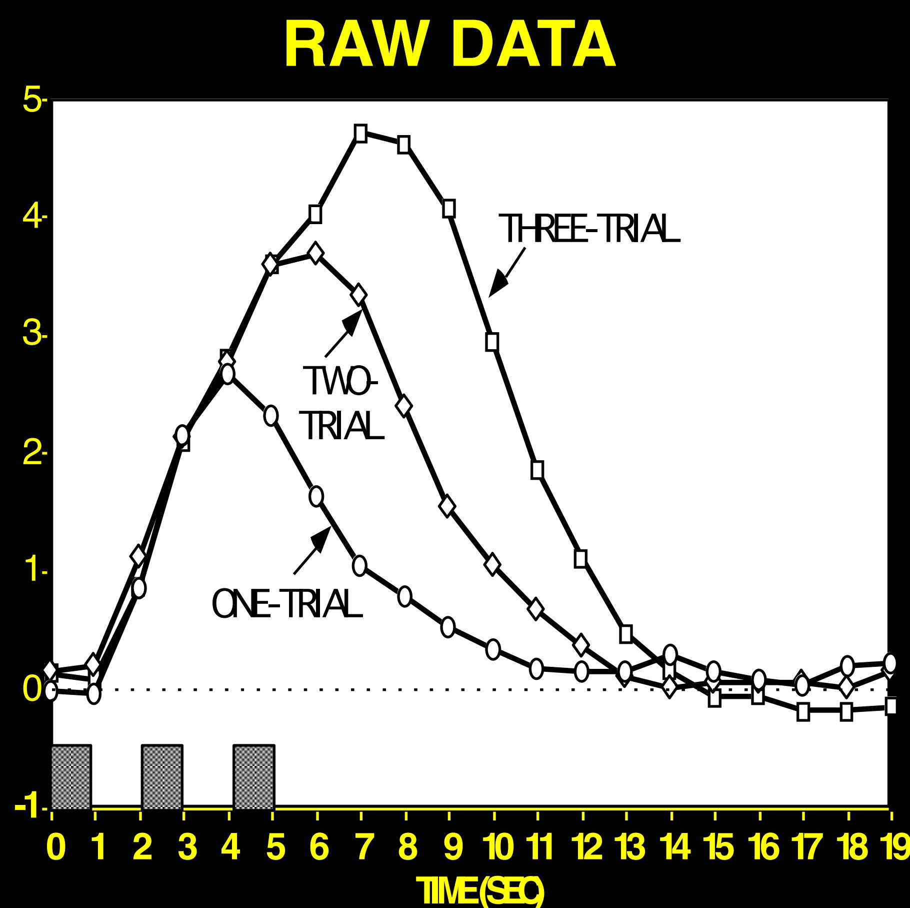


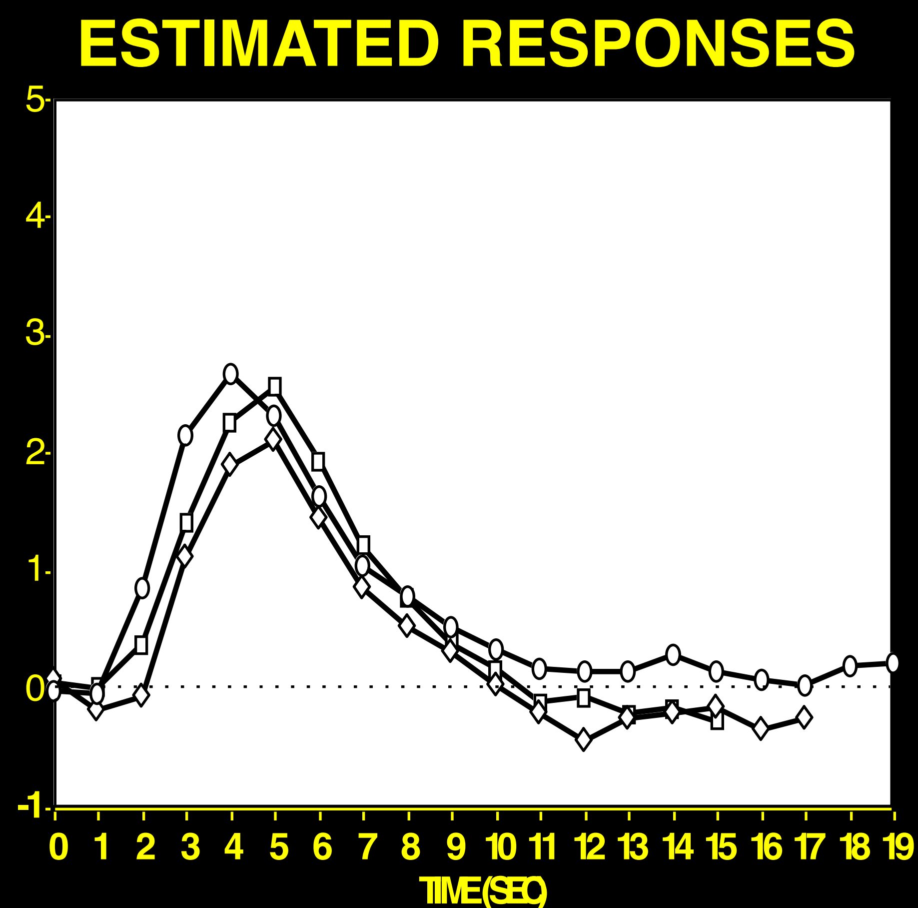
Motor Cortex
Signal
Time (sec)
522
518
514
510
506
502
498
0
5
10
15
20
25
30
35
40
45
50
5
3
2
1
0.5
Duration
(sec)
.5 sec
1 sec
2 sec
3 sec
5 sec

Visual Activation Paradigm: 1 , 2, & 3 Trials

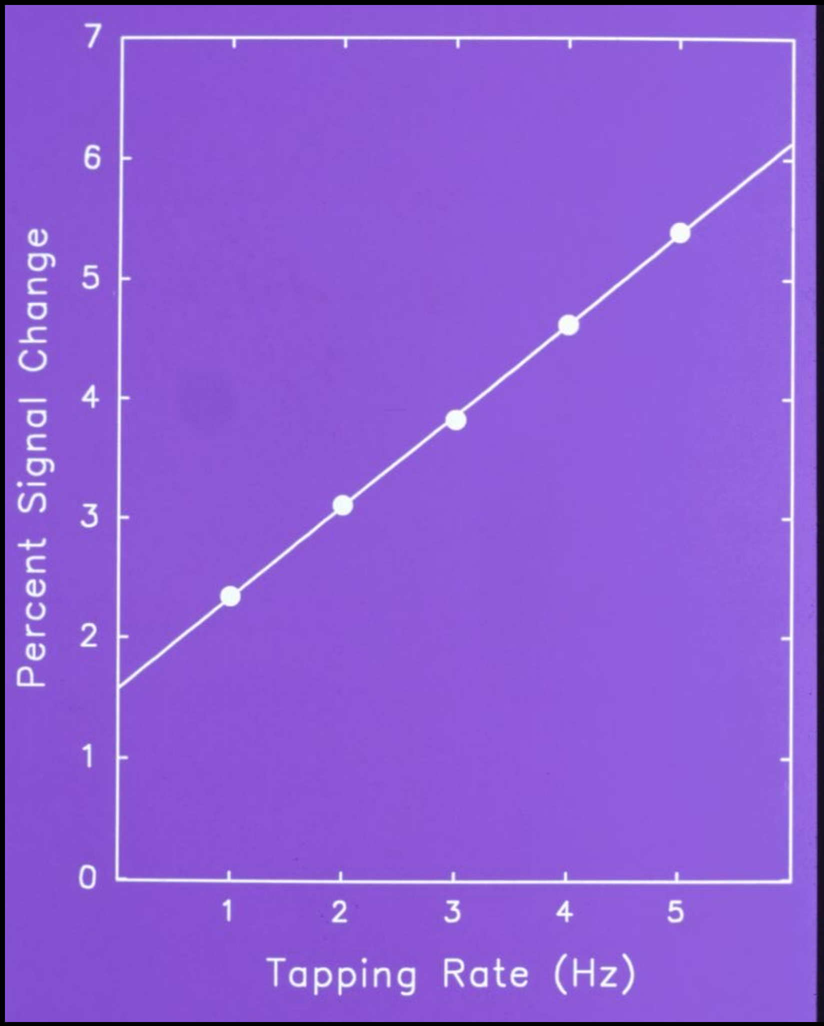


Response to Multiple Trials: Subject RW

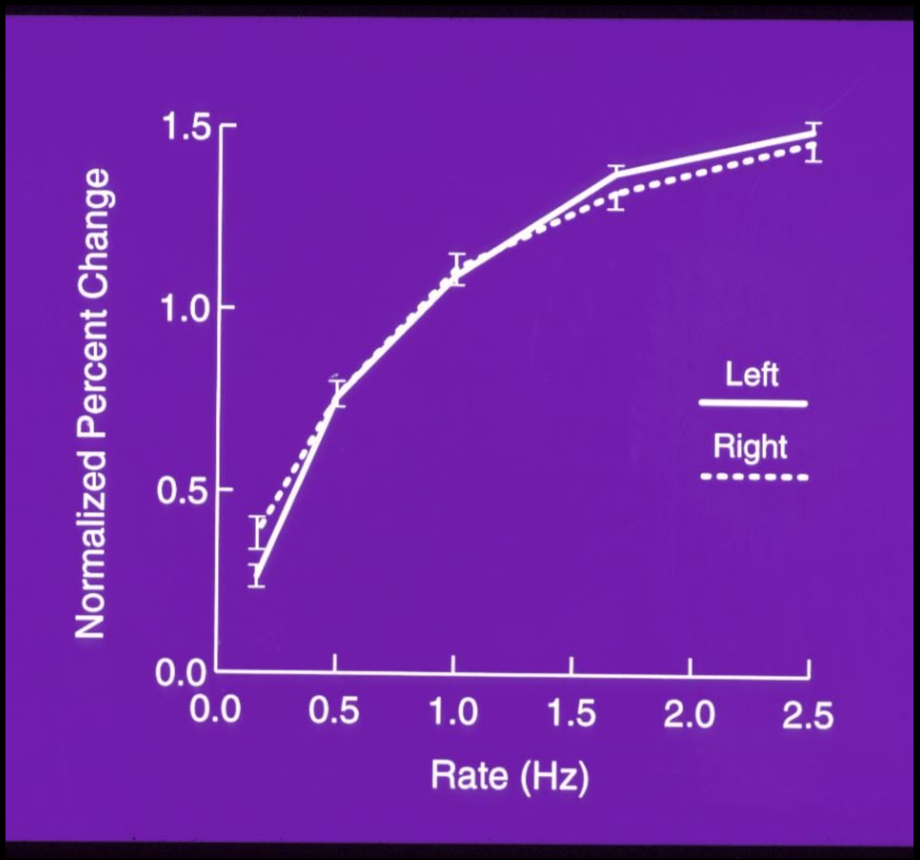




Motor Cortex



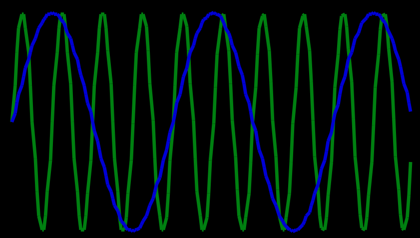
Auditory Cortex



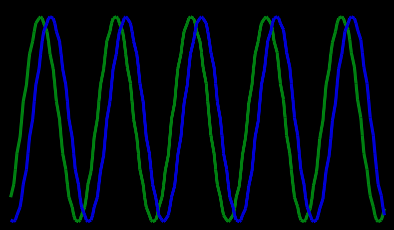
Neuronal Activation Input Strategies

1. Block Design

2. Frequency Encoding

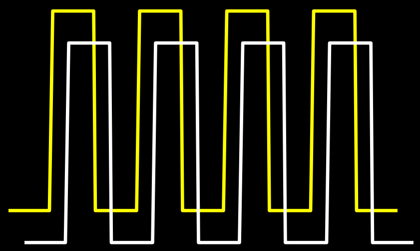


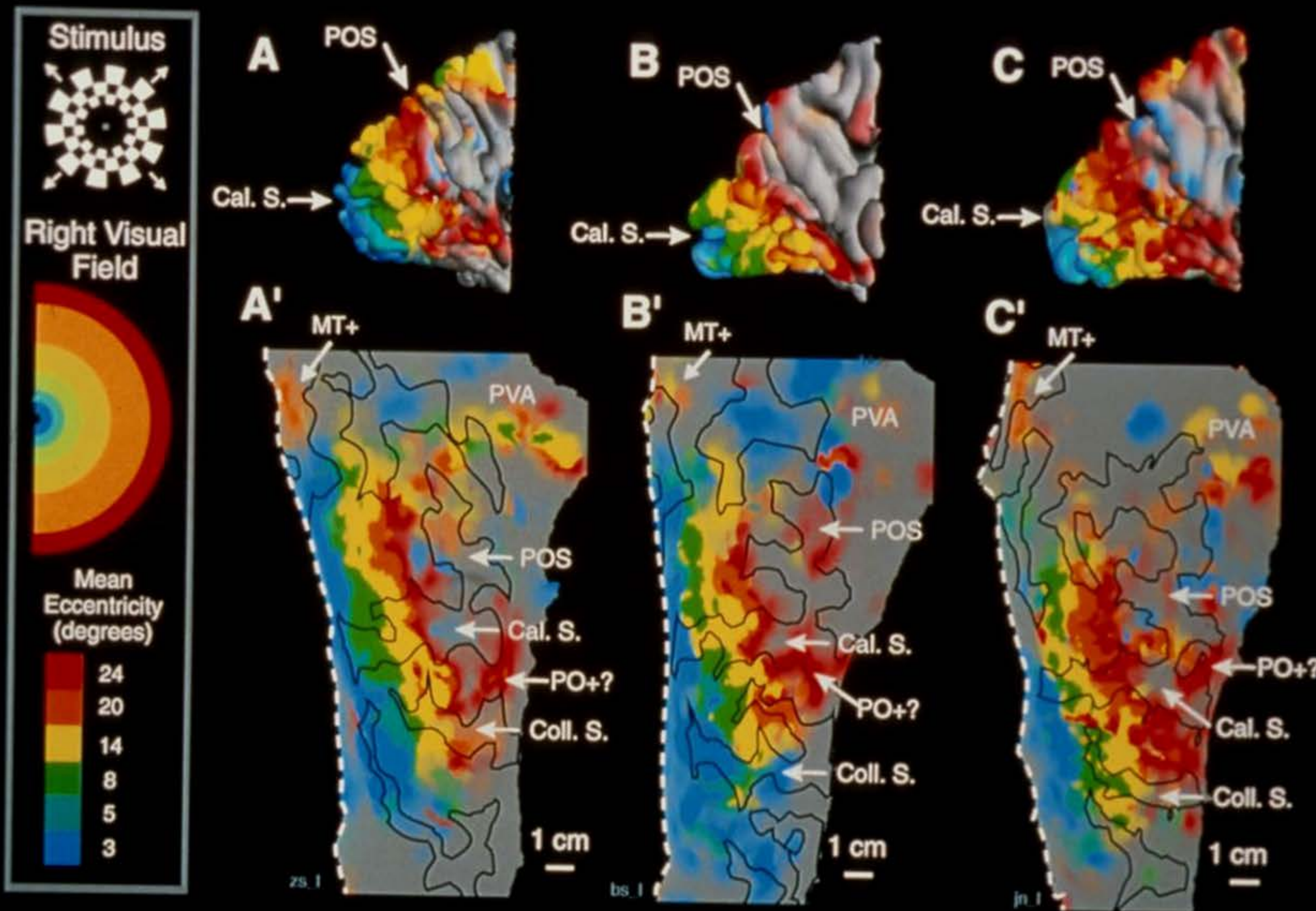
3. Phase Encoding



4. Event Related

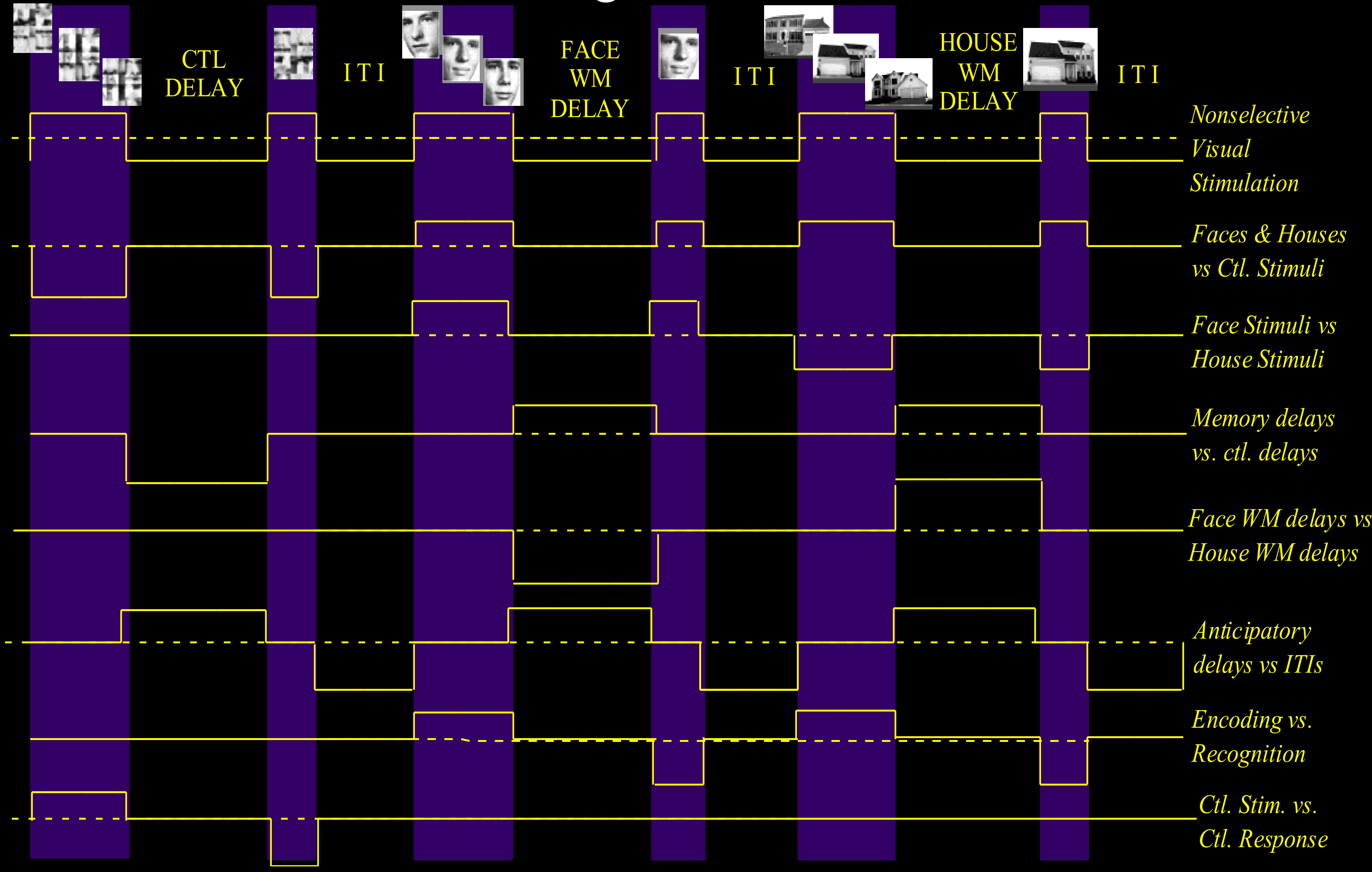
5. Orthogonal Block Design





Stimulus
Right Visual Field
Mean Eccentricity (degrees)
24
20
14
8
5
3
A
POS
Cal. S.
B
POS
Cal. S.
C
POS
Cal. S.
A'
MT+
PVA
POS
Cal. S.
PO+?
Coll. S.
1 cm
B'
MT+
PVA
POS
Cal. S.
PO+?
Coll. S.
1 cm
C'
MT+
PVA
POS
PO+?
Cal. S.
Coll. S.
1 cm

Example of a Set of Orthogonal Contrasts for Multiple Regression



Refinements

BOLD Contrast Interpretation

Dynamics, Paradigm Design and Processing

Applications

Applications

Clinical Populations

Presurgical mapping
Volume/Perfusion assessment
Acute stroke characterization

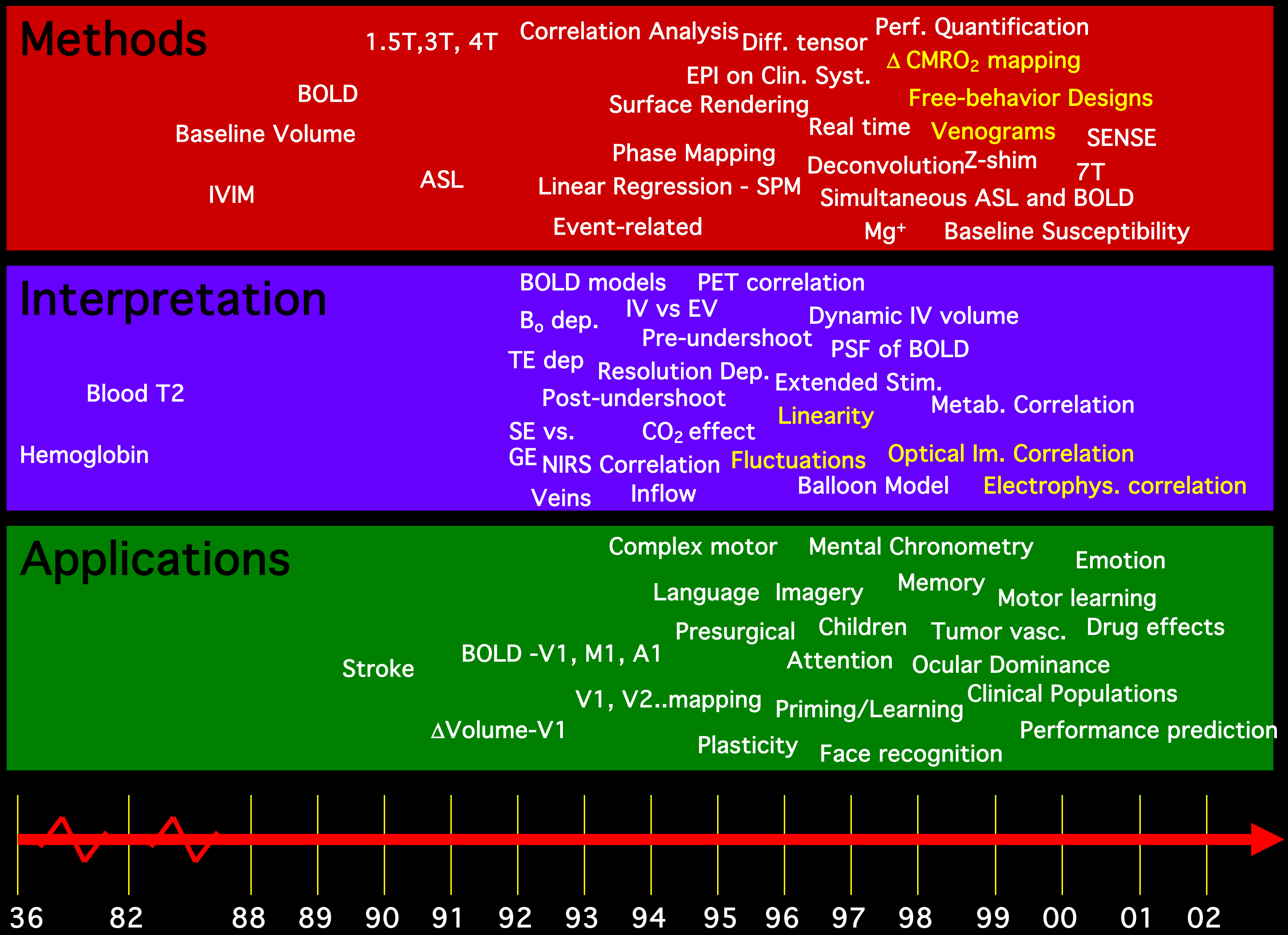
Healthy Volunteers

Brain mapping

Past

Present

Future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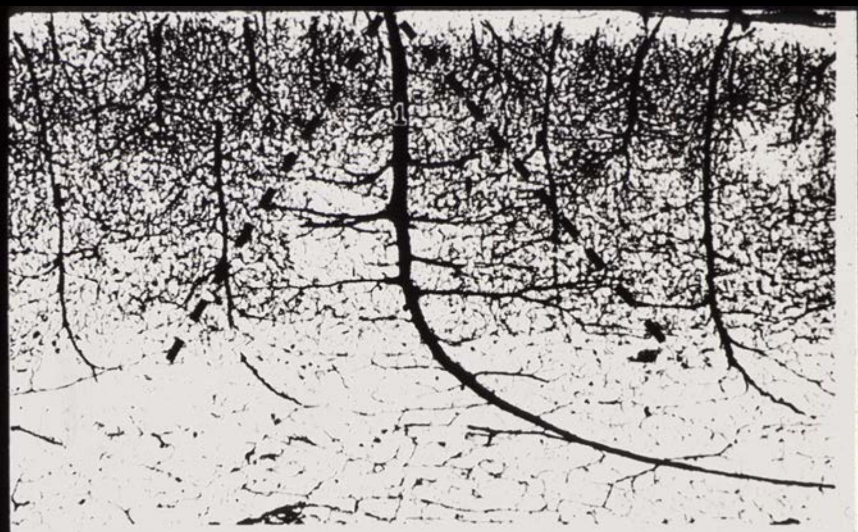
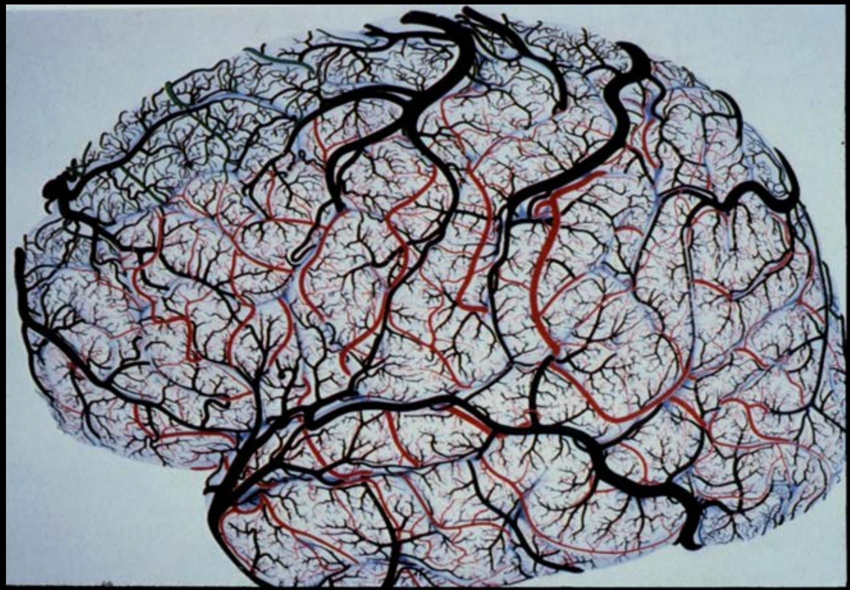
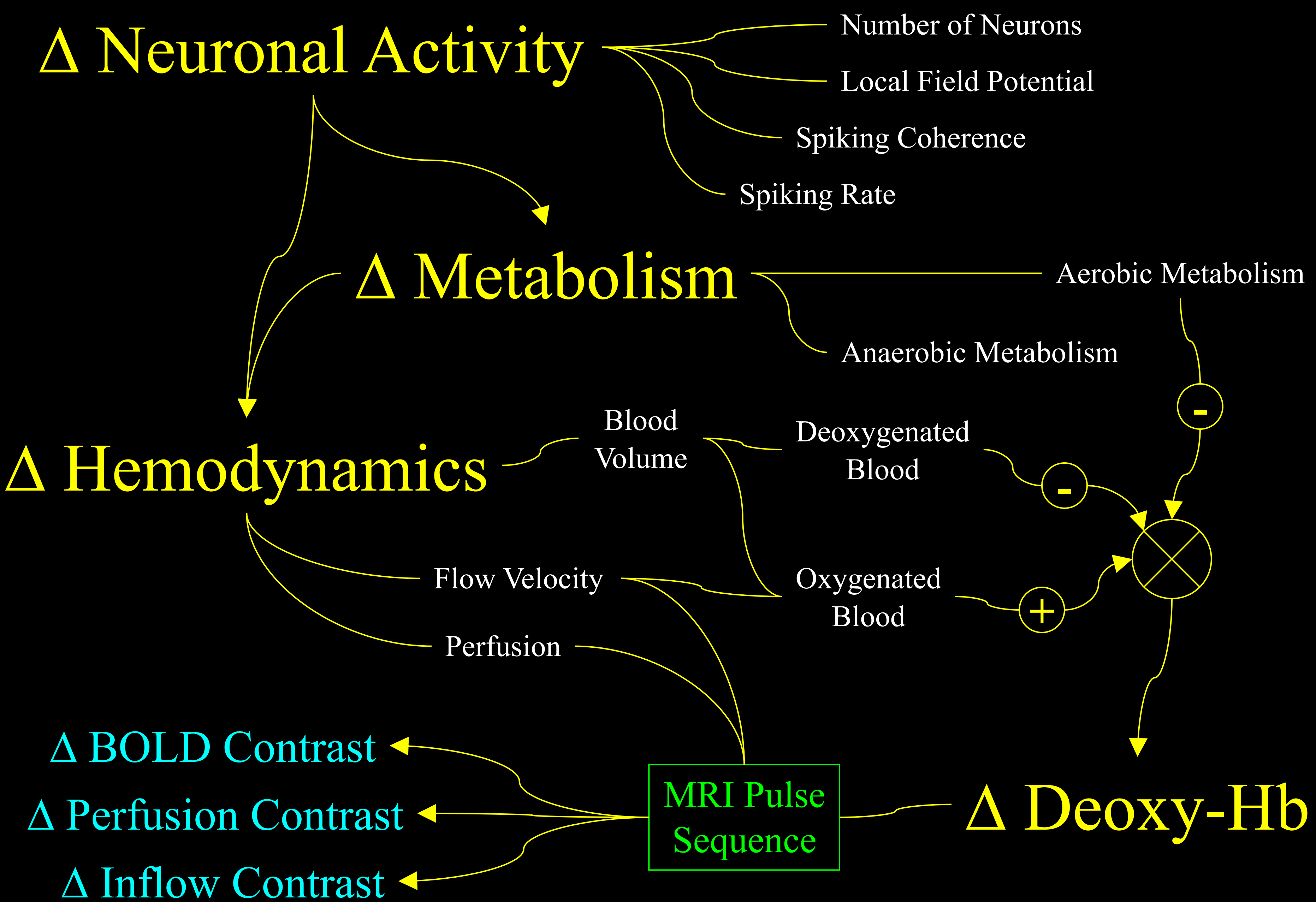
The Neuroscientists' Challenge:

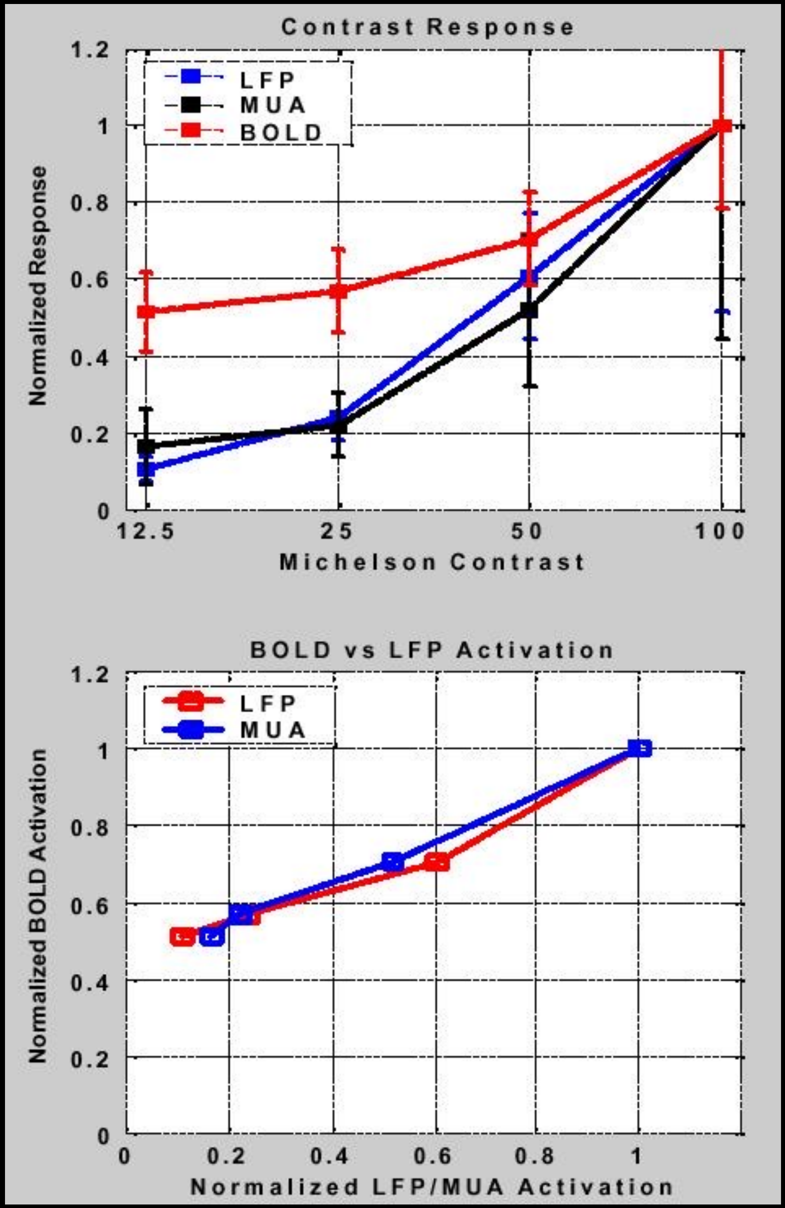
...to make progressively more precise inferences using fMRI without making too many assumptions about non-neuronal physiologic factors.



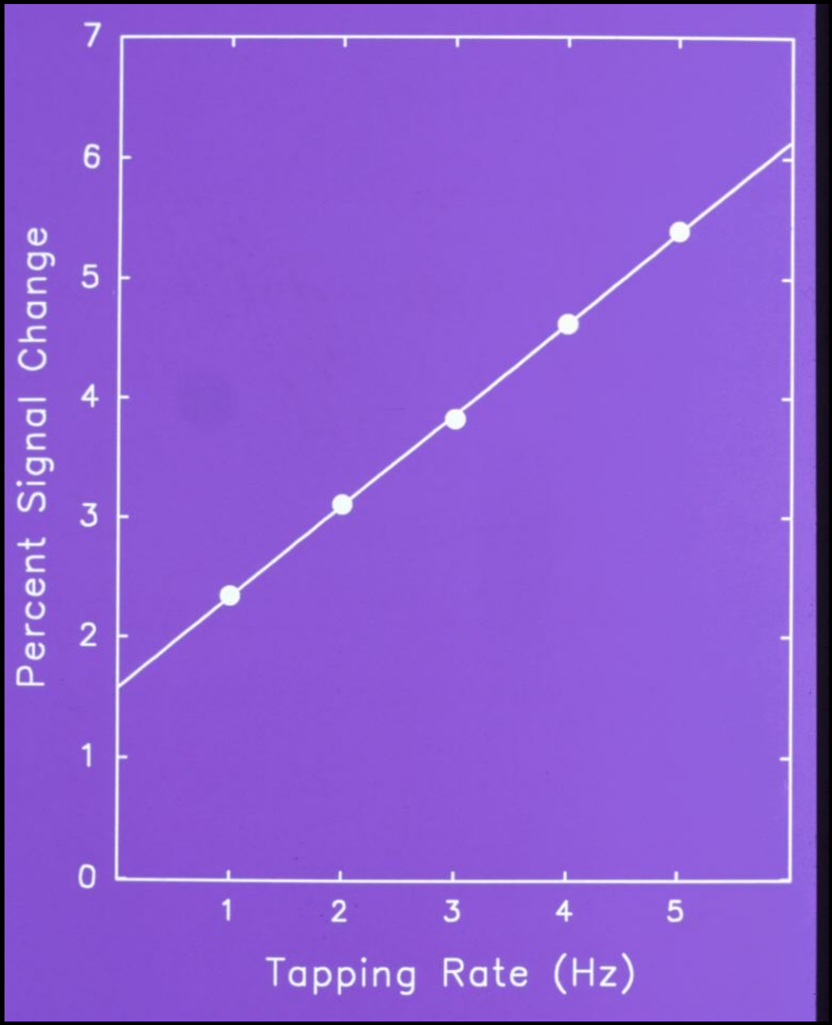
IG. 43. Middle temporal gyrus. Female, 60 years. (1) Principal intracortical vein. The branches length regularly decreases from deep wards superficial cortical regions; thus, the vascular territory of the principal vein has a conical appearance (dotted line) (×28)




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
Oxygenated Blood
Flow Velocity
Perfusion
-
-
+
Δ BOLD Contrast
Δ Perfusion Contrast
Δ Inflow Contrast
MRI Pulse Sequence
Δ Deoxy-Hb



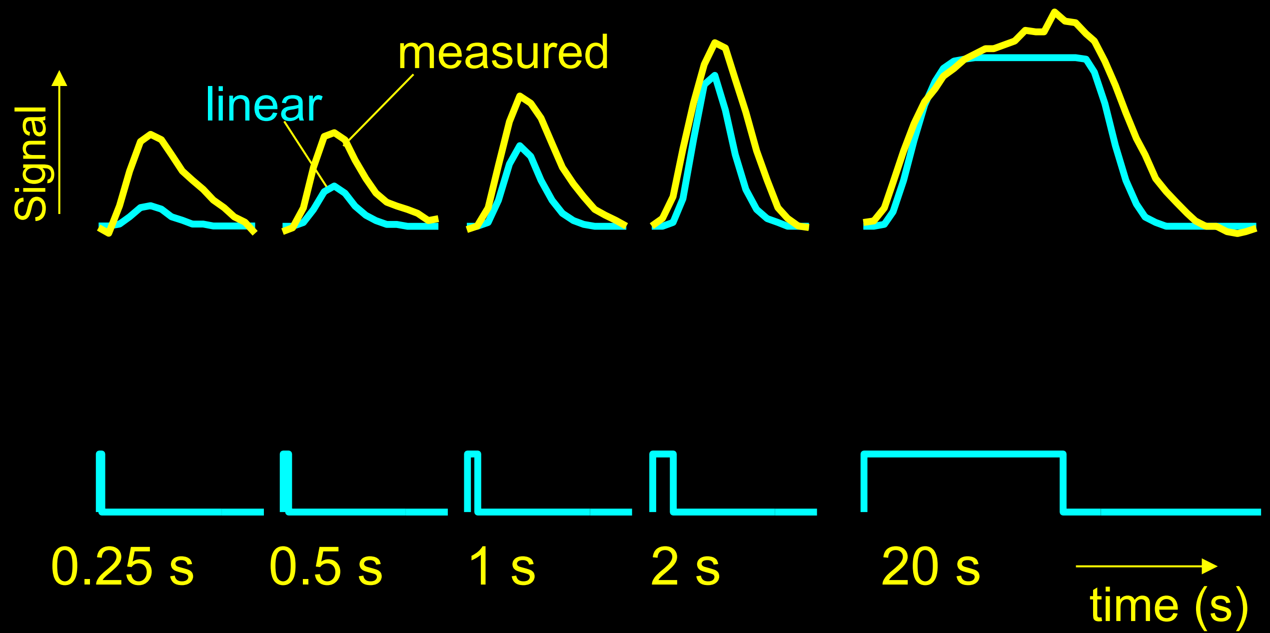
Logothetis et al. Nature, 412, 150-157



Different stimulus “ON” periods

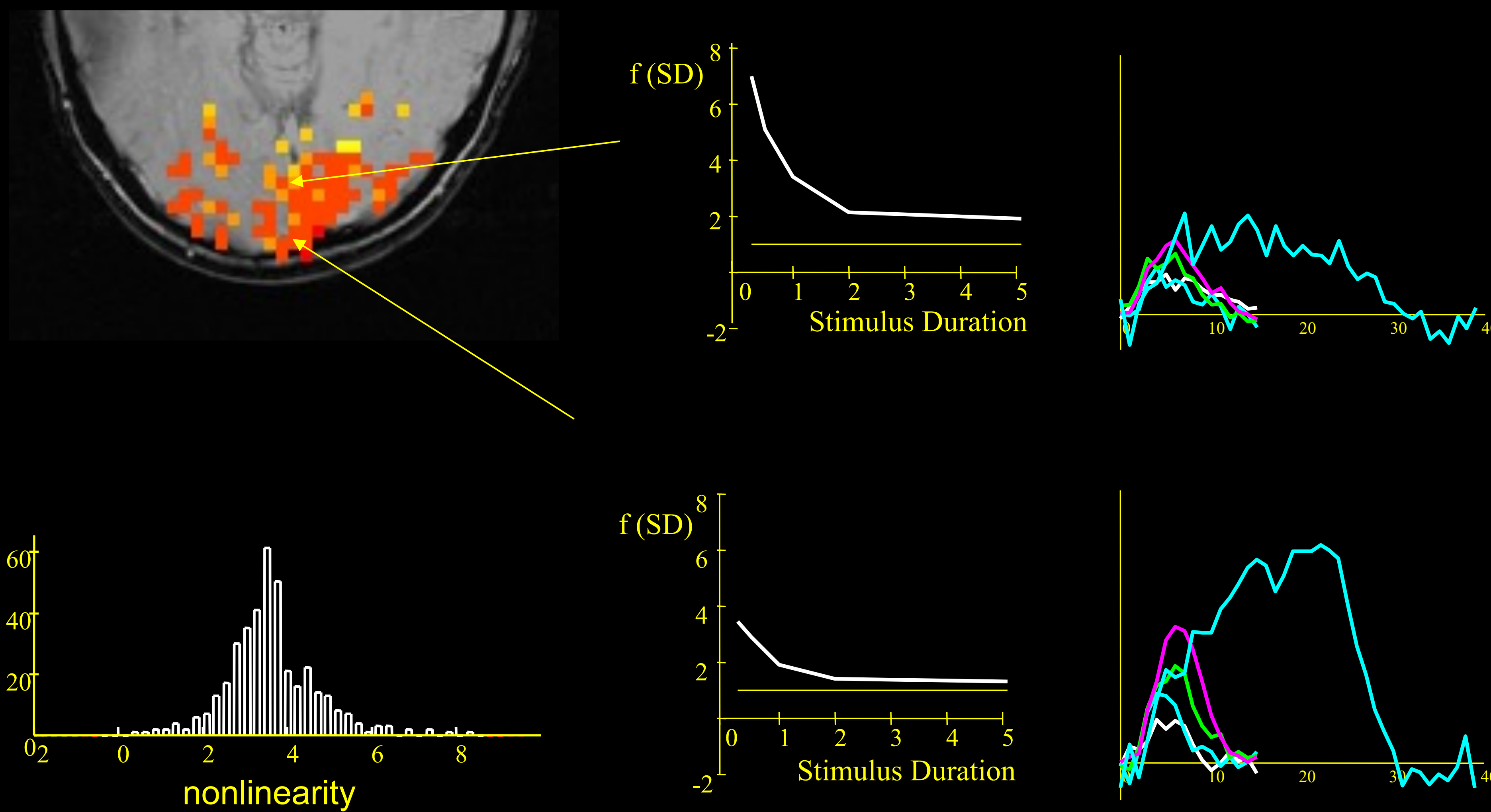
BOLD
Response

Stimulus
timing



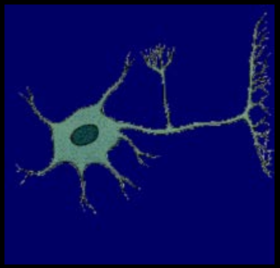
Brief stimuli produce larger responses than expected

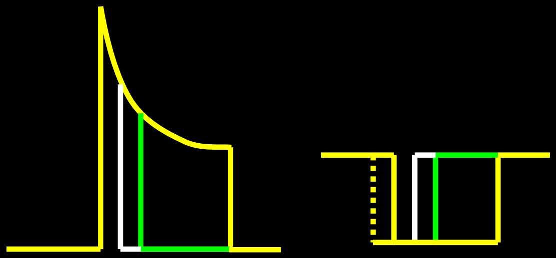
Results – visual task



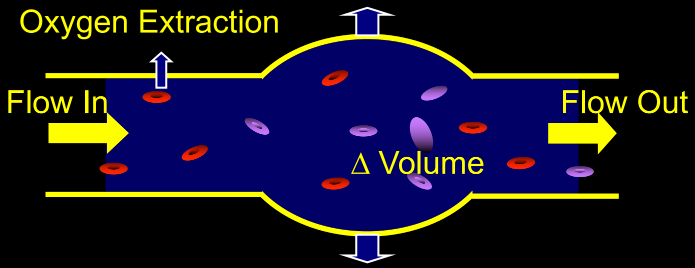
Sources of this Nonlinearity

- Neuronal

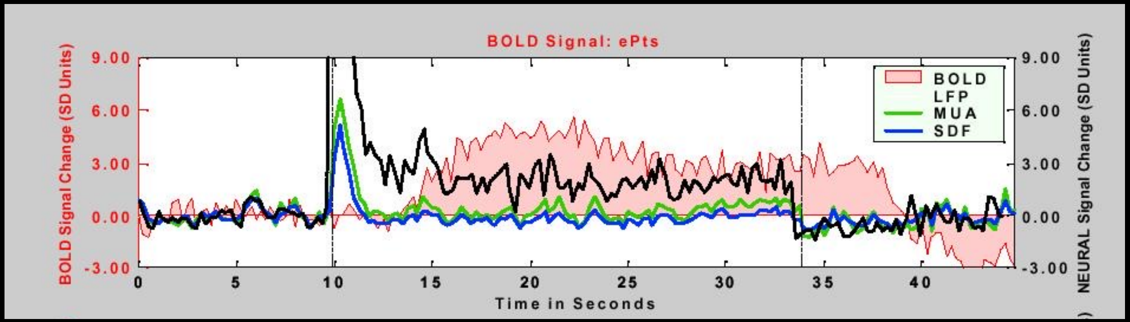




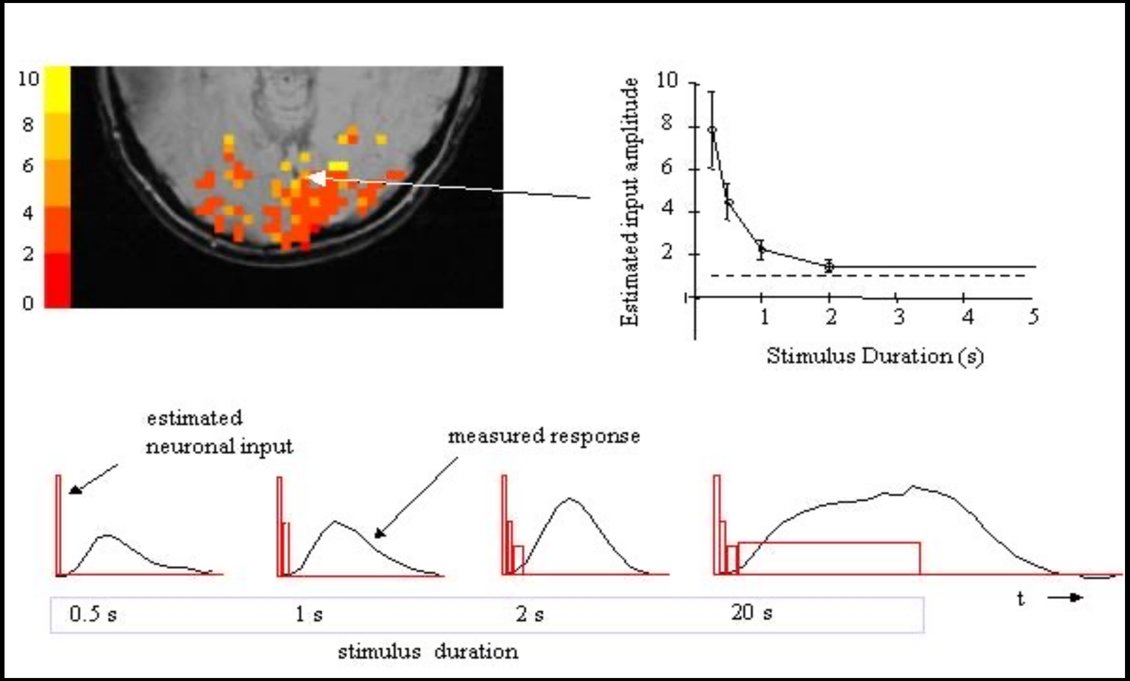
- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics



BOLD Correlation with Neuronal Activity



Logothetis et al. Nature, 412, 150-157

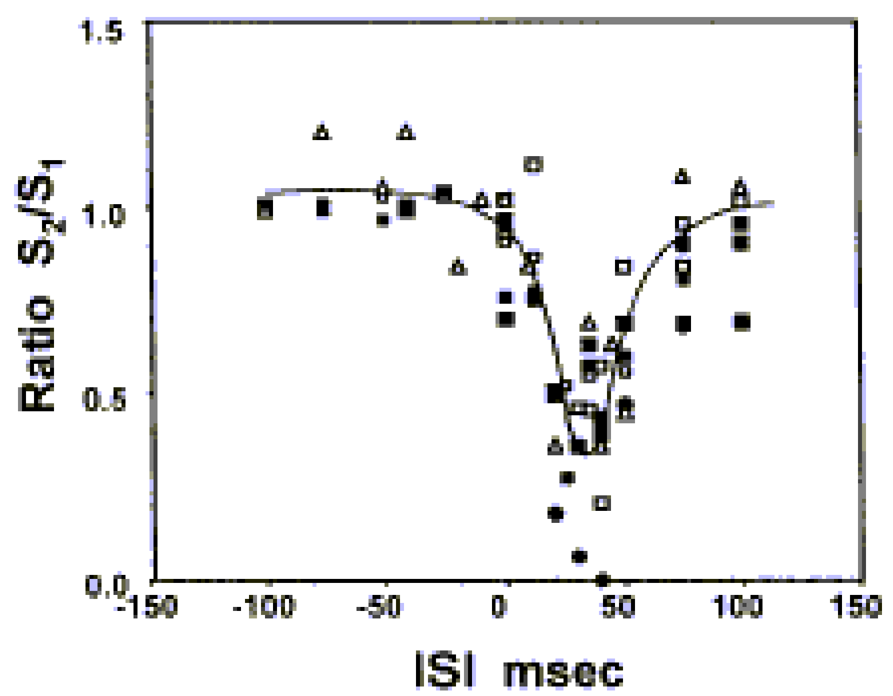


Bandettini and Ungerleider, Nature Neuroscience, 4, 864-866

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

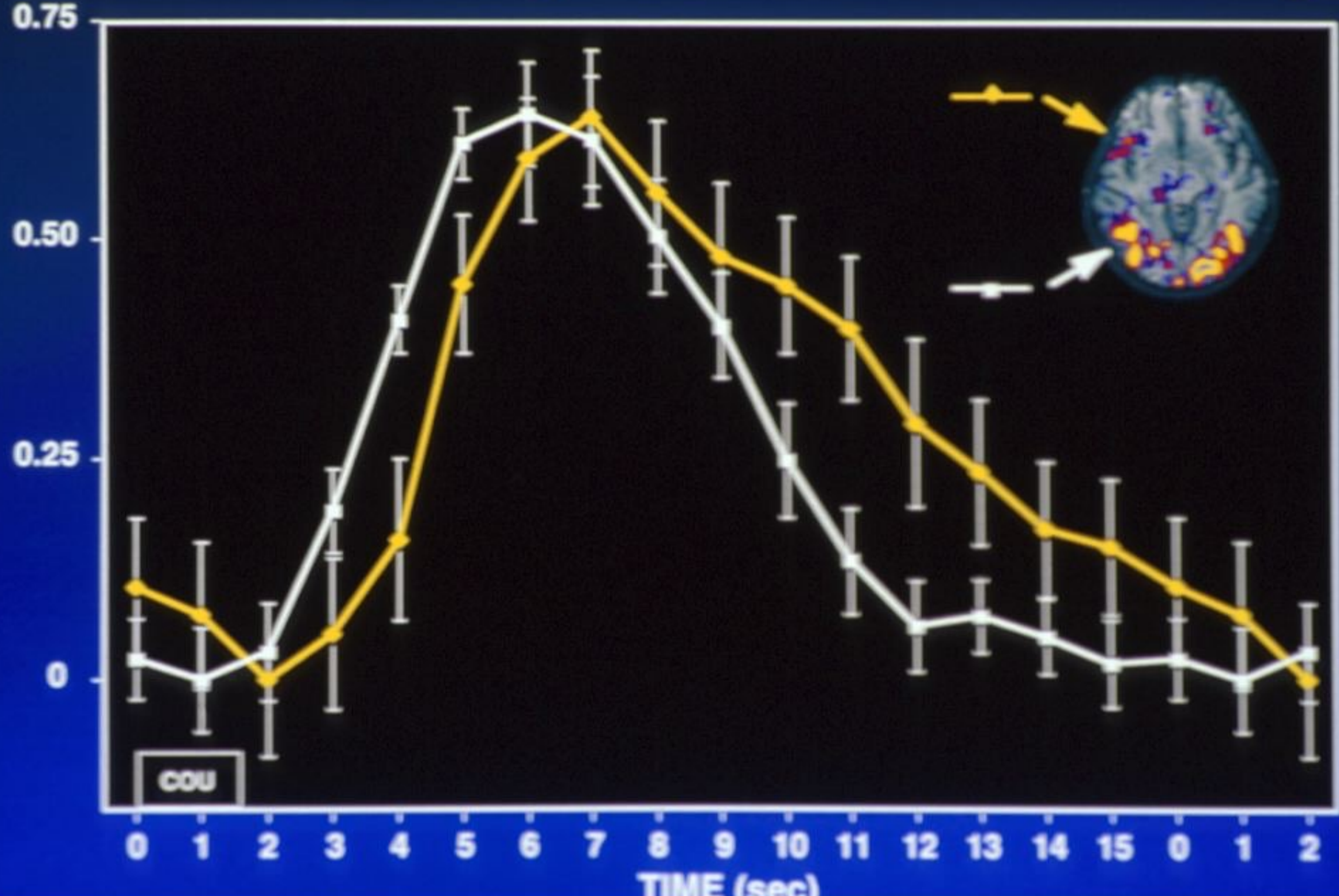
Seiji Ogawa[*,†], Tso-Ming Lee[*], Ray Stepnoski[*], Wei Chen[§], Xiao-Hong Zhu[§], and Kamil Ugurbil[§]

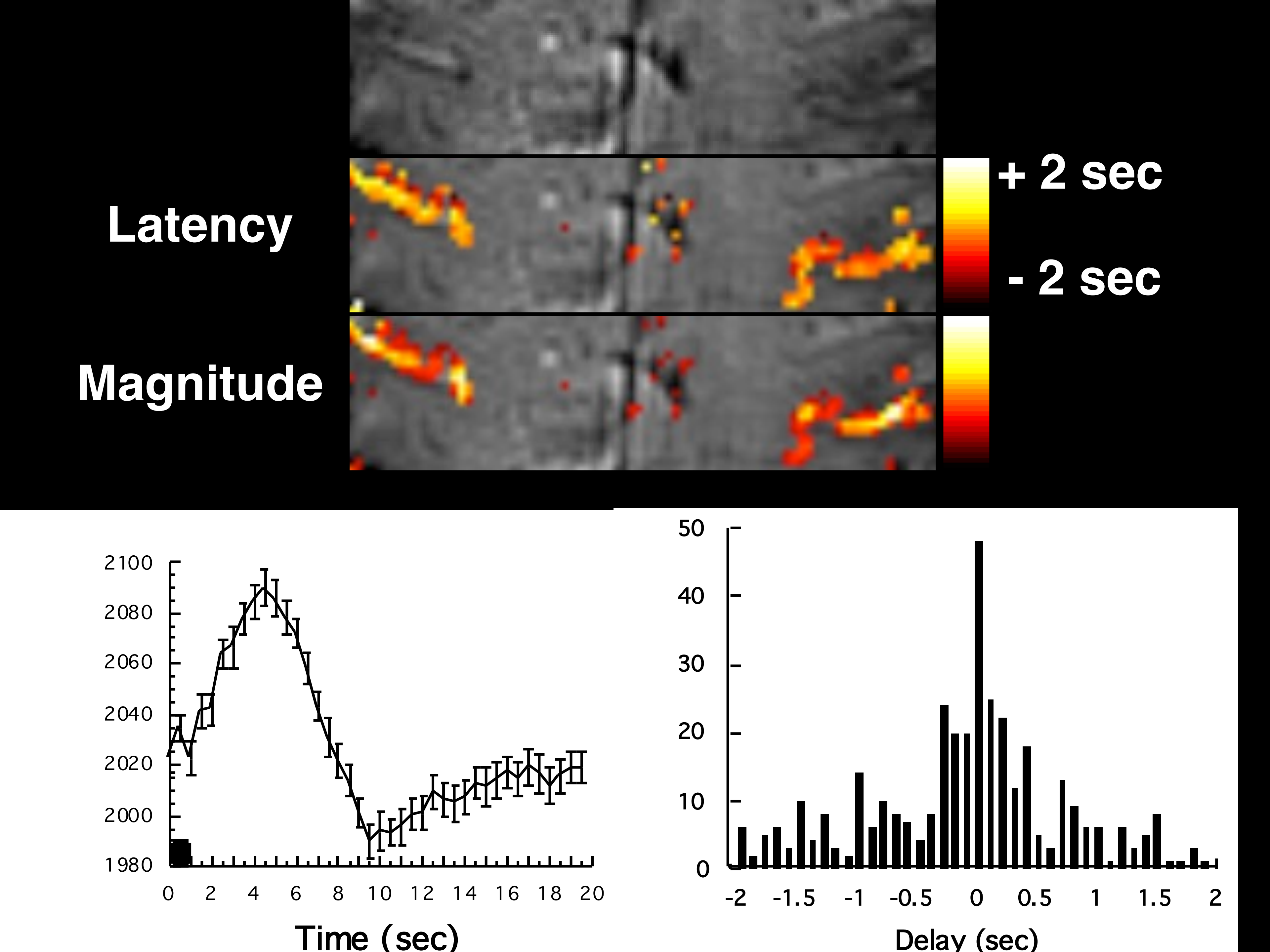
[*]Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974; and [§]Center for Magnetic Resonance Research, University of Minnesota Medical School, Minneapolis, MN 55455



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

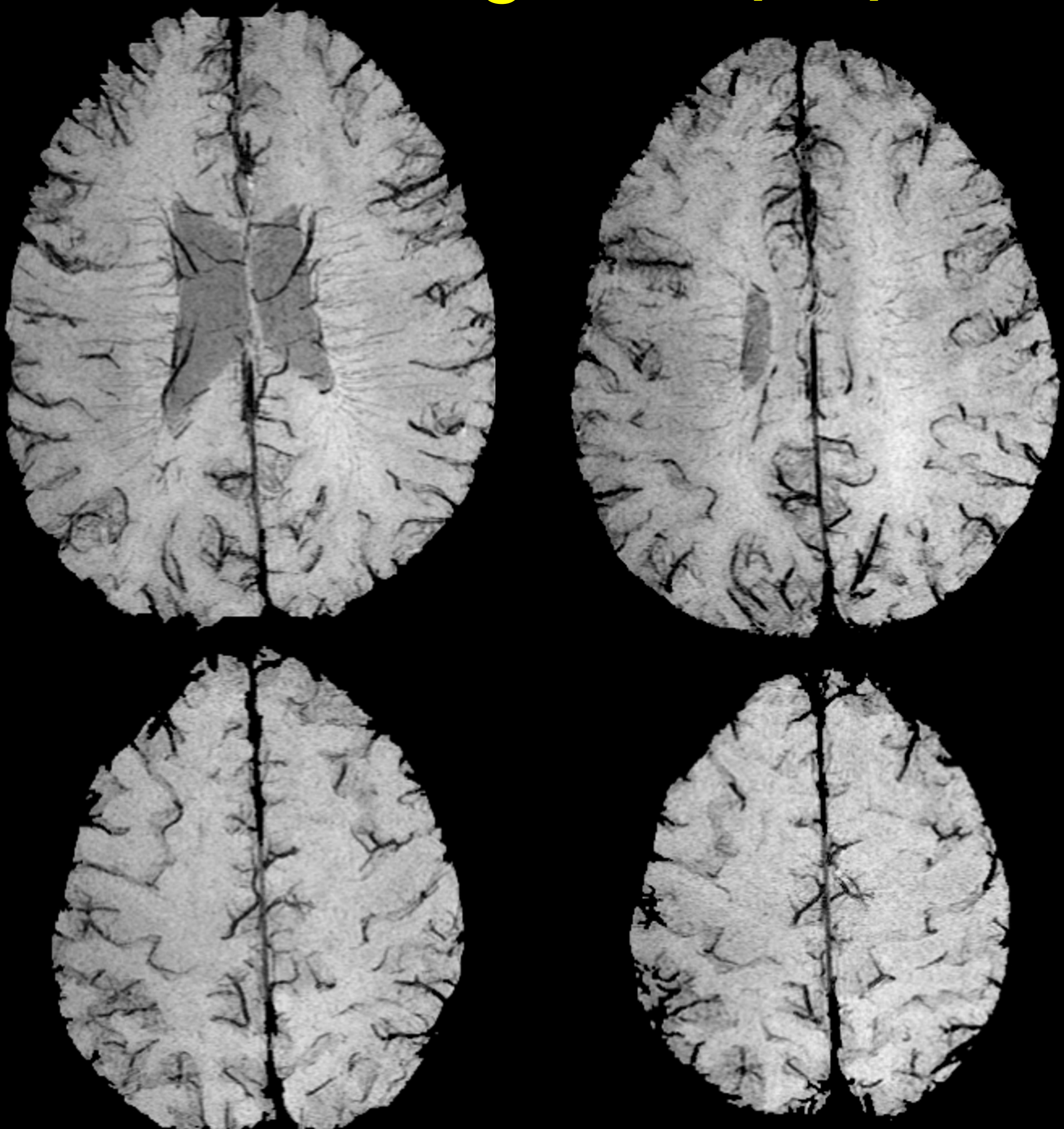
Time Course Comparison Across Brain Regions

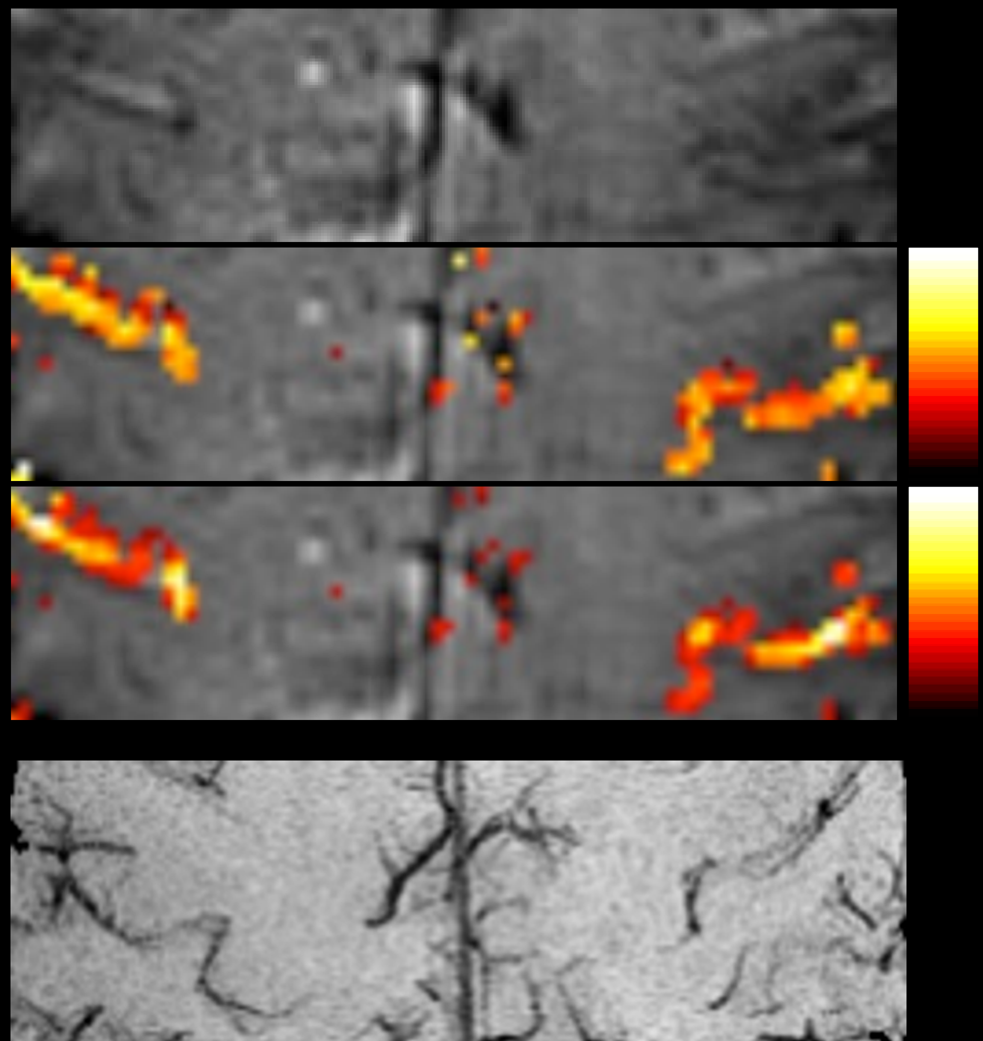




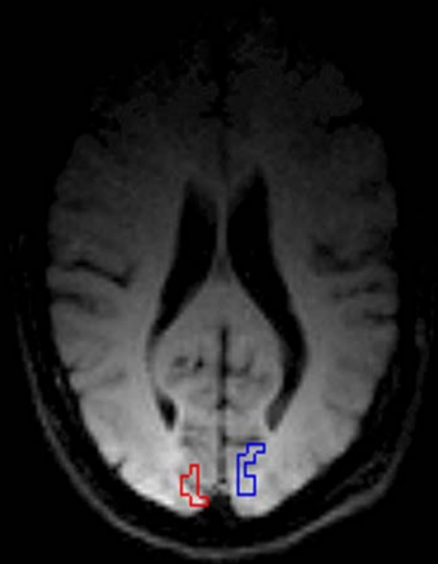
Latency
Magnitude
+ 2 sec
- 2 sec
2100
2080
2060
2040
2020
2000
1980
0 2 4 6 8 10 12 14 16 18 20
Time (sec)
50
40
30
20
10
0
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
Delay (sec)

Venograms (3T)



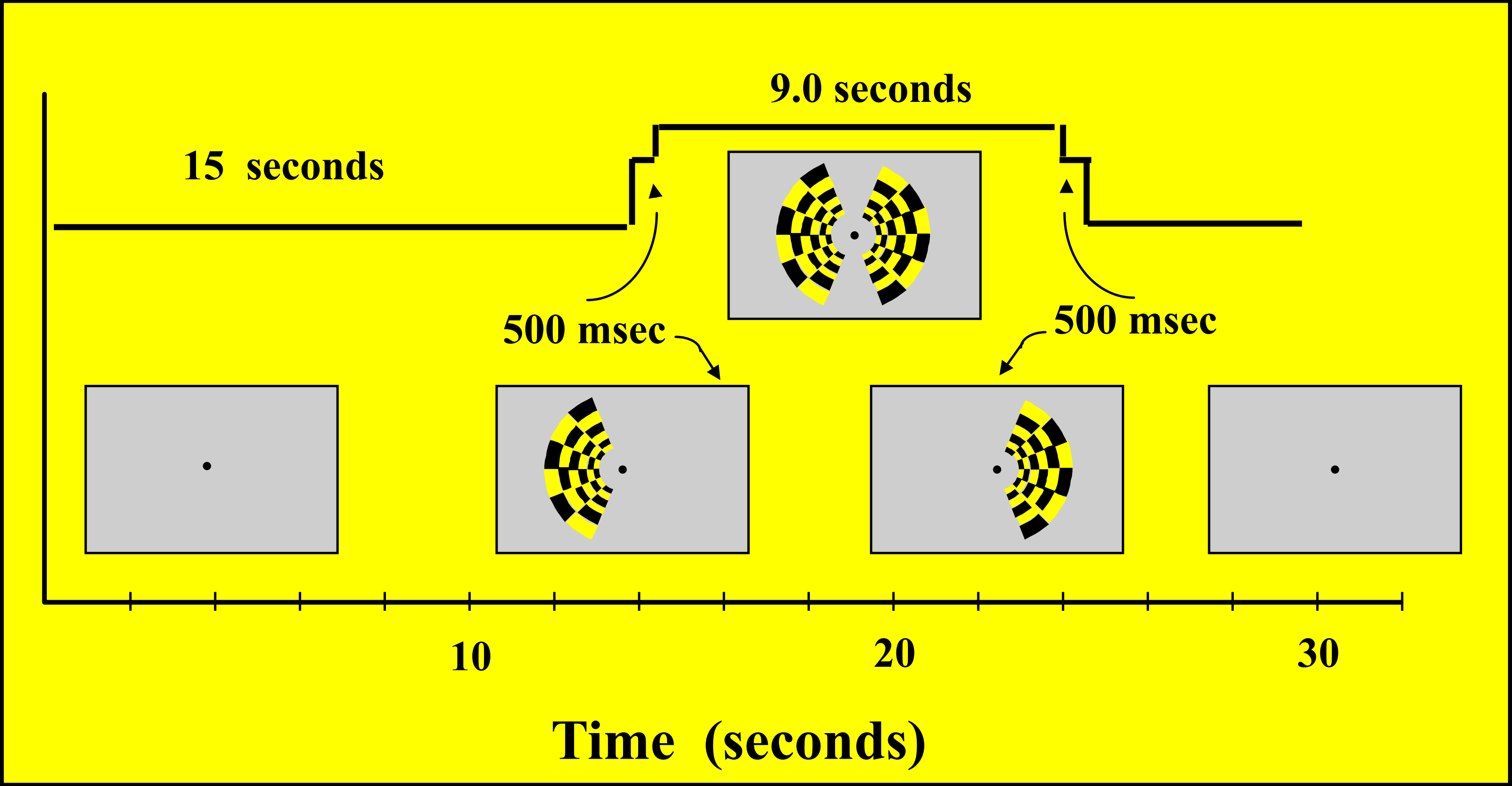


Regions of Interest Used for Hemi-Field Experiment

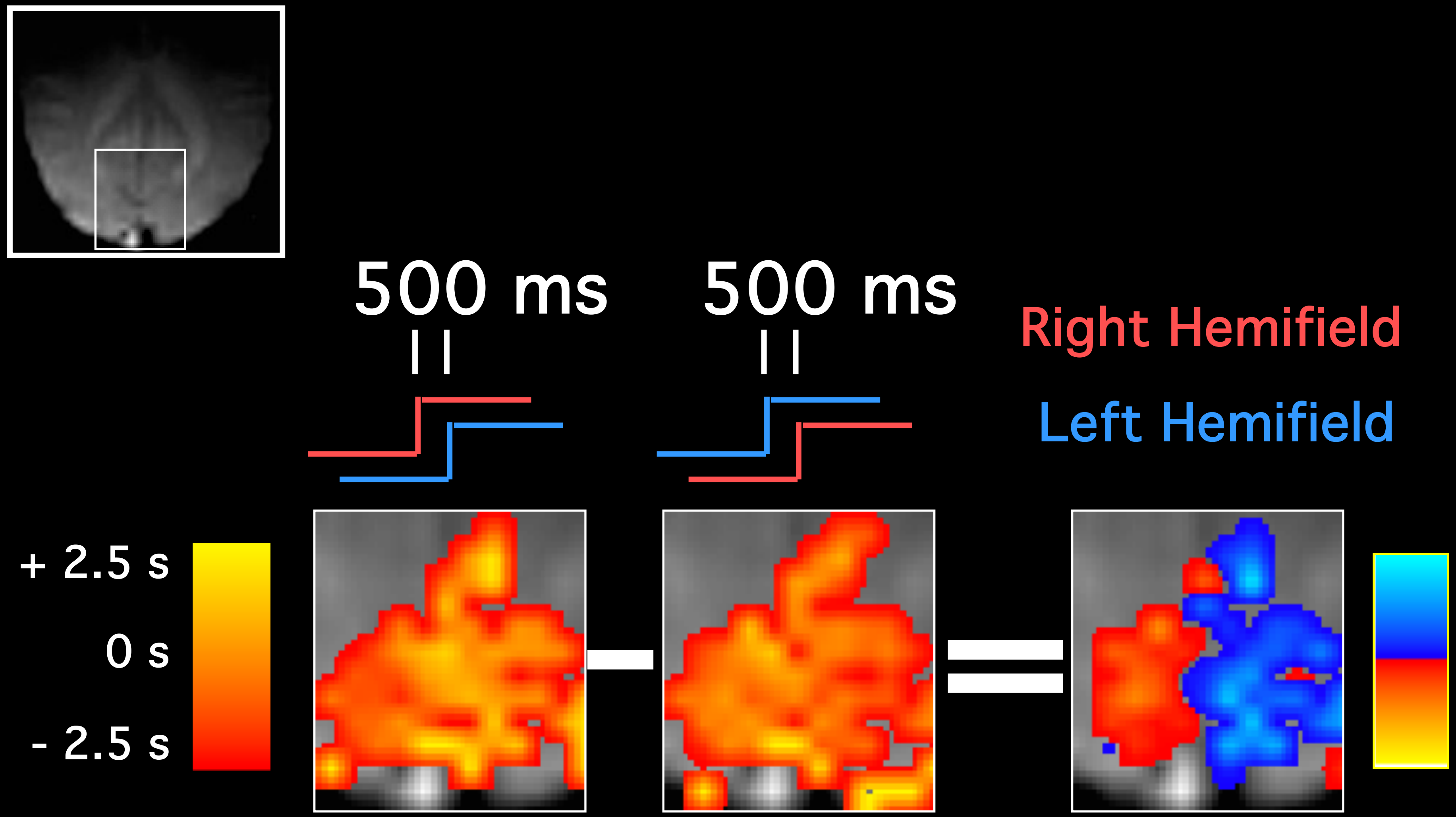


Right Hemisphere

Left Hemisphere

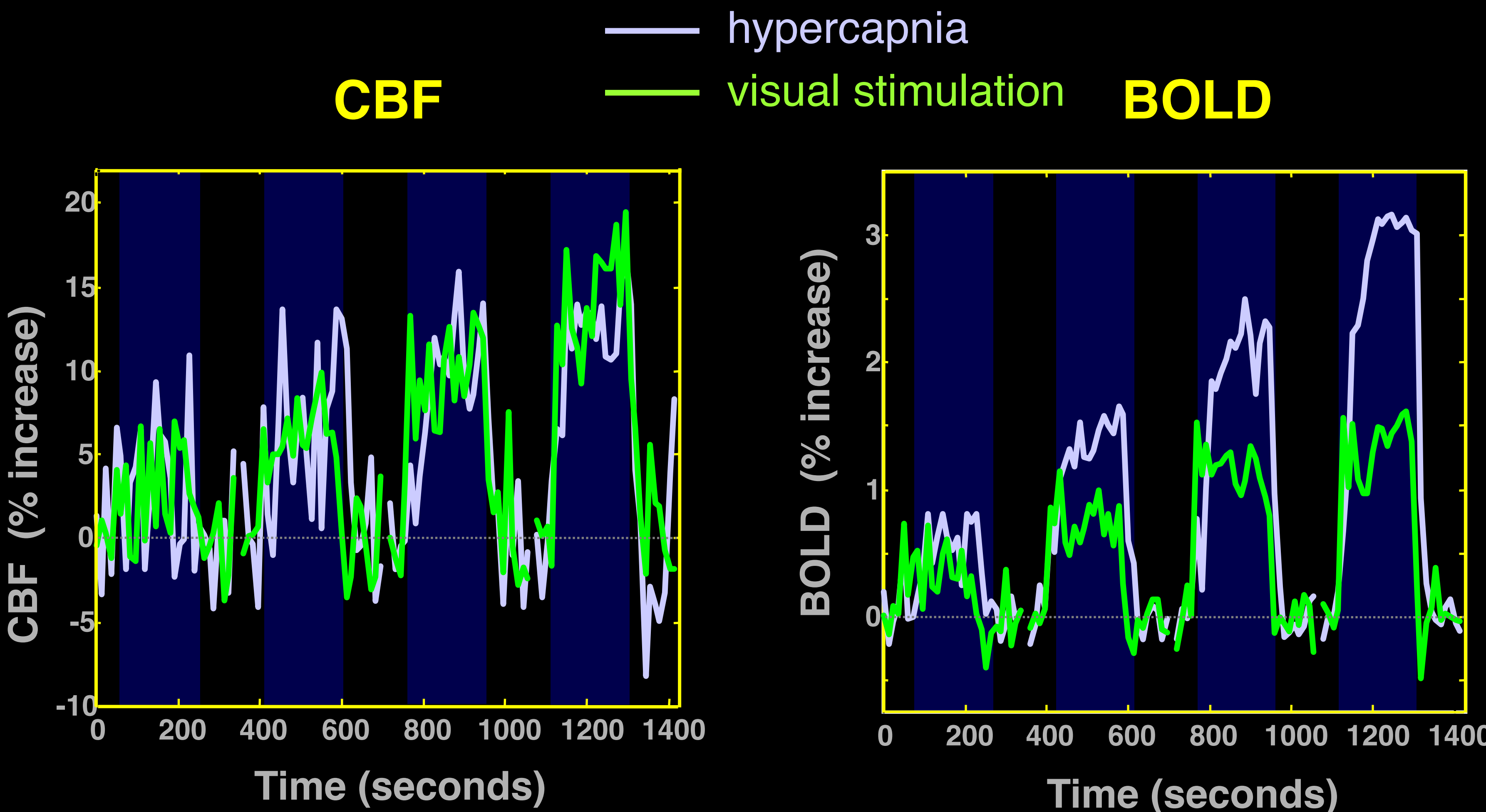


9.0 seconds
15 seconds
500 msec
500 msec
10
20
30
Time (seconds)


500 ms
500 ms
Right Hemifield
Left Hemifield
+ 2.5 s
0 s
- 2.5 s

$CMRO_2$-related BOLD signal deficit:

Hoge, et al.

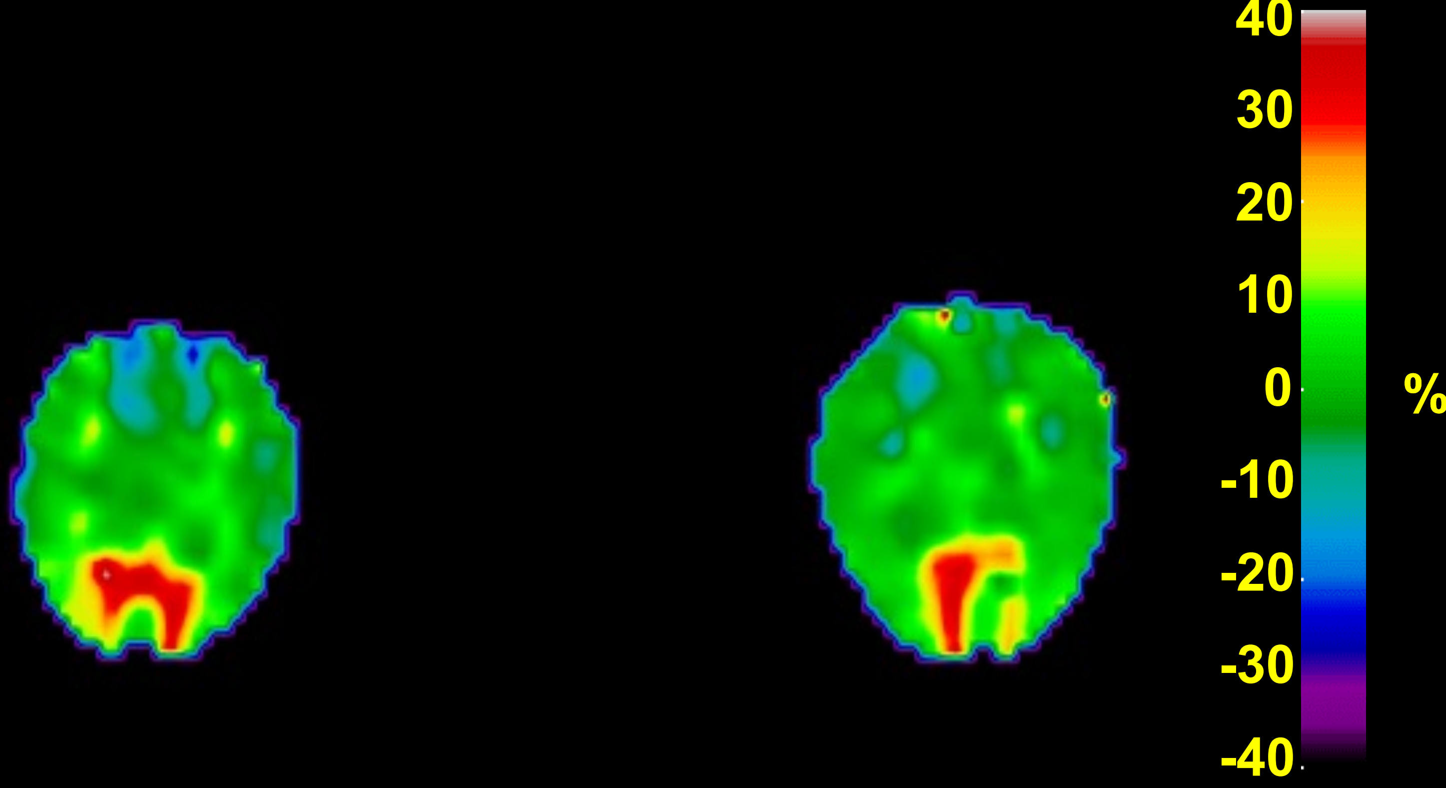


Simultaneous Perfusion and BOLD imaging during graded visual activation and hypercapnia

N=12

Hoge, et al.

Computed $CMRO_2$ Changes



Subject 1 **Subject 2**

Quantitative Measurements of Cerebral Metabolic Rate of Oxygen (CMRO2) Using MRI: A Volunteer Study

Hongyu AN[1], Weili LIN[2], Azim CELIK[3], Yueh Z. LEE[4]

[1]Washington University, 600 Airport Road, Chapel Hill, NC USA; [2]UNC-Chapel Hill, Department of Radiology, CB#7515, Chapel Hill, NC USA; [3]GE Medical Systems, ; [4]UNC-Chapel Hill, ;

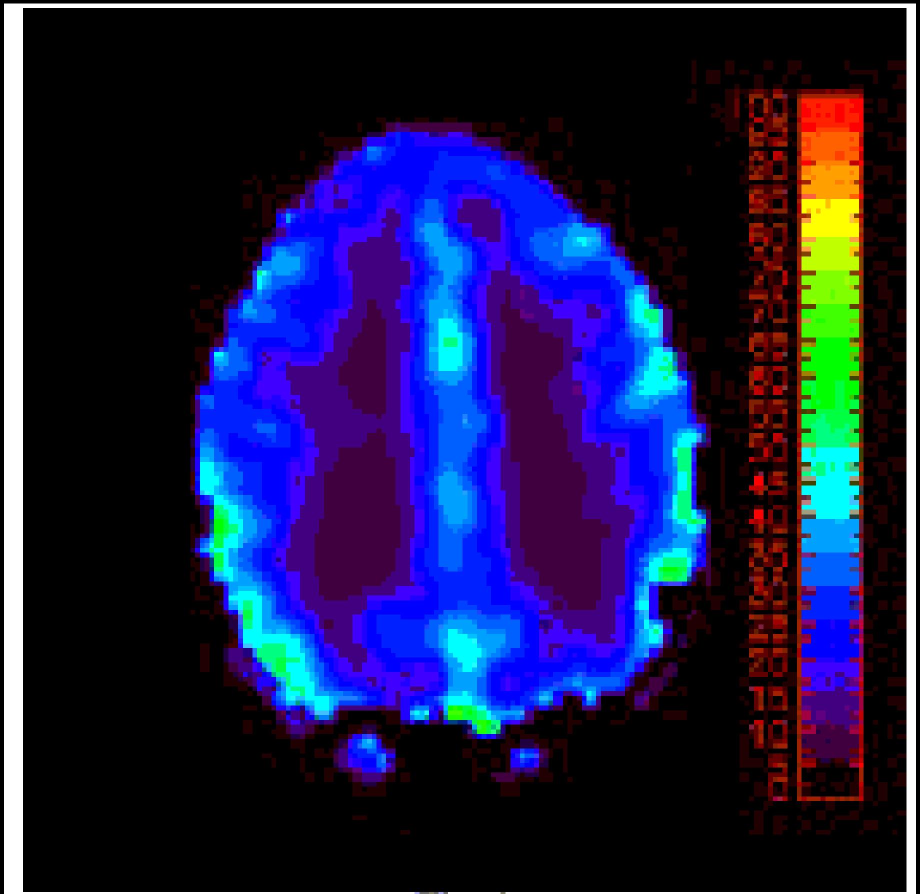
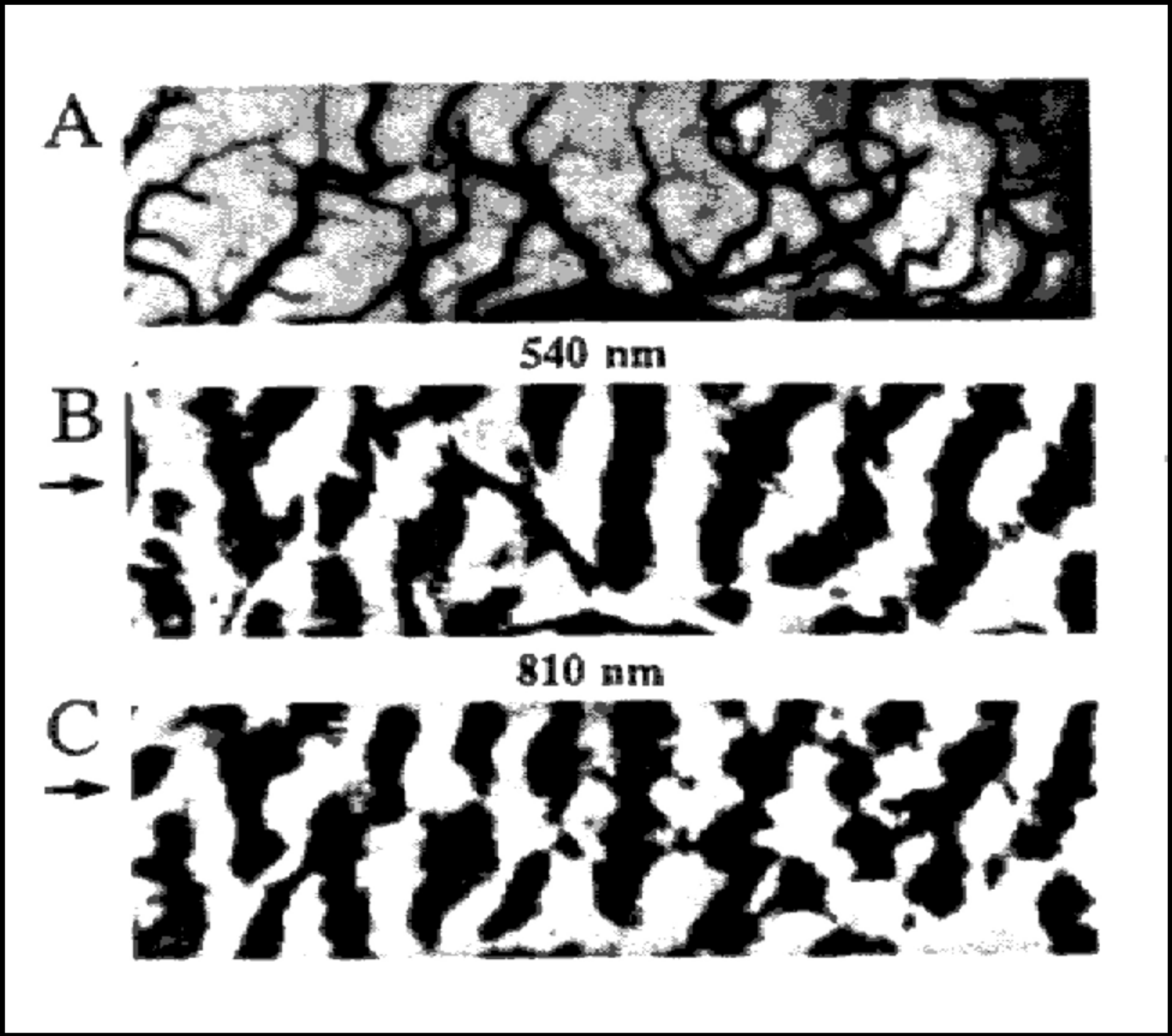
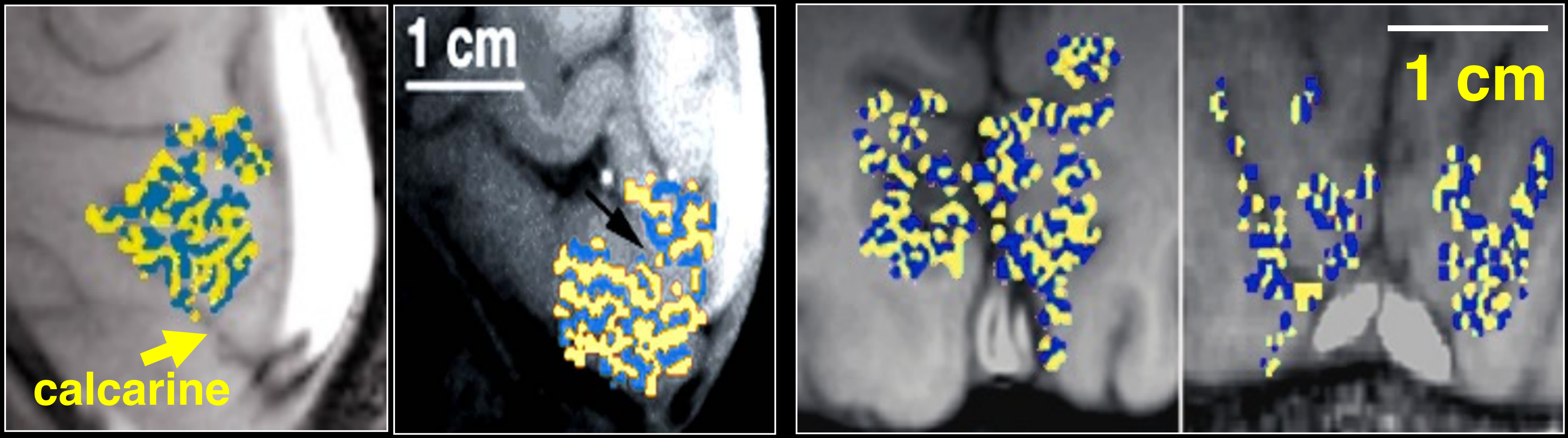


Fig. 1



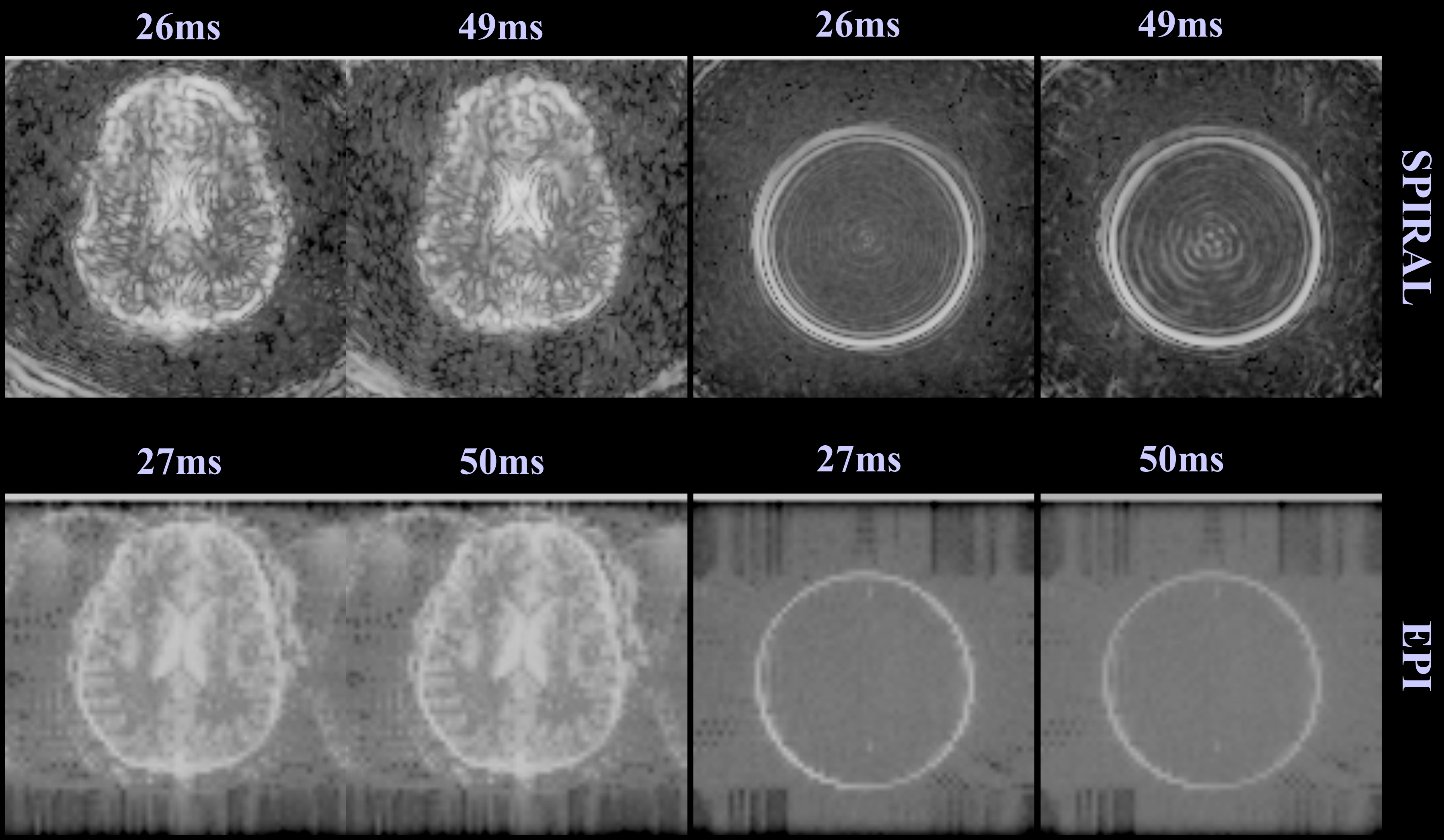
R. D. Frostig et. al, PNAS 87: 6082-6086, (1990).

ODC Maps using fMRI

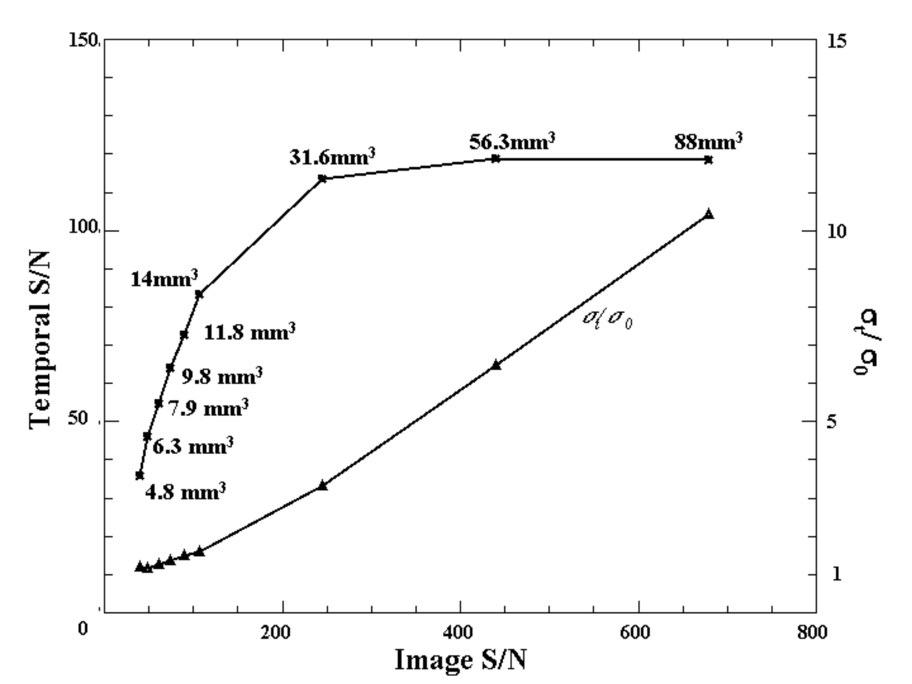


Menon, R. S., S. Ogawa, et al. (1997). "Ocular dominance in human V1 demonstrated by functional magnetic resonance imaging." J Neurophysiol **77**(5): 2780-7.

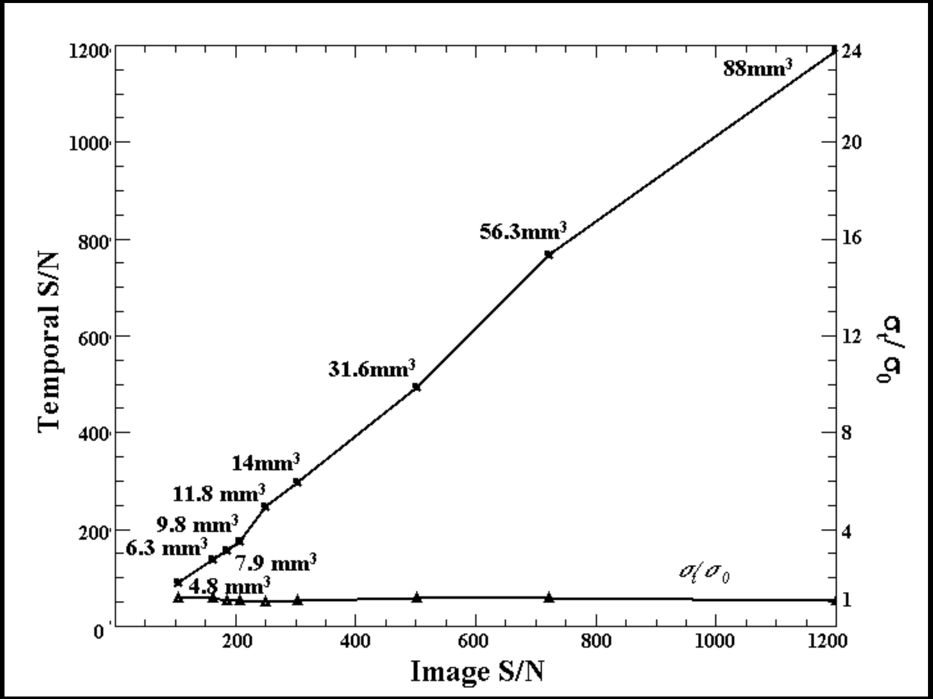
Temporal vs. Spatial SNR- 3T



Temporal vs. Image S/N Optimal Resolution Study



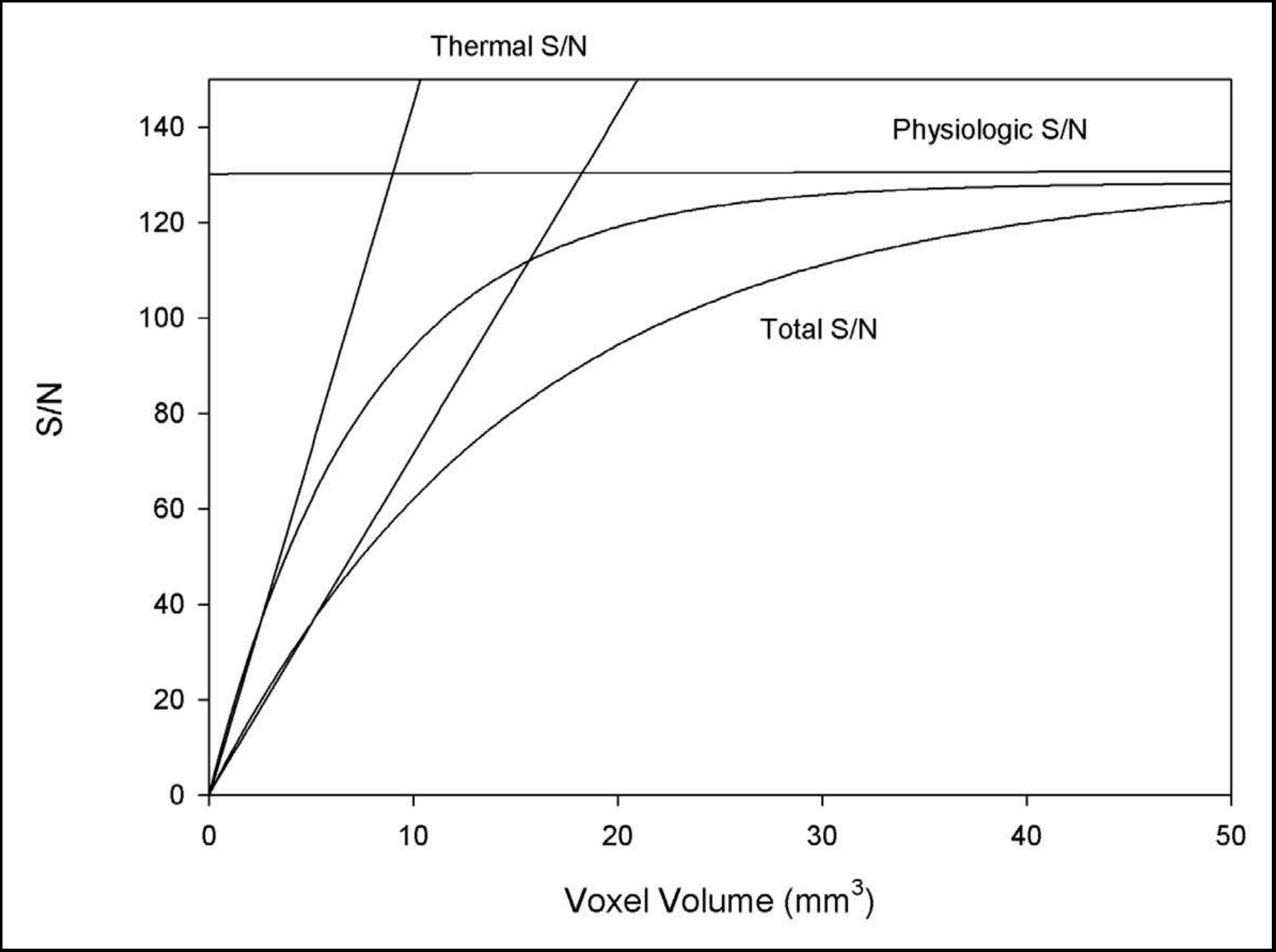
Human data



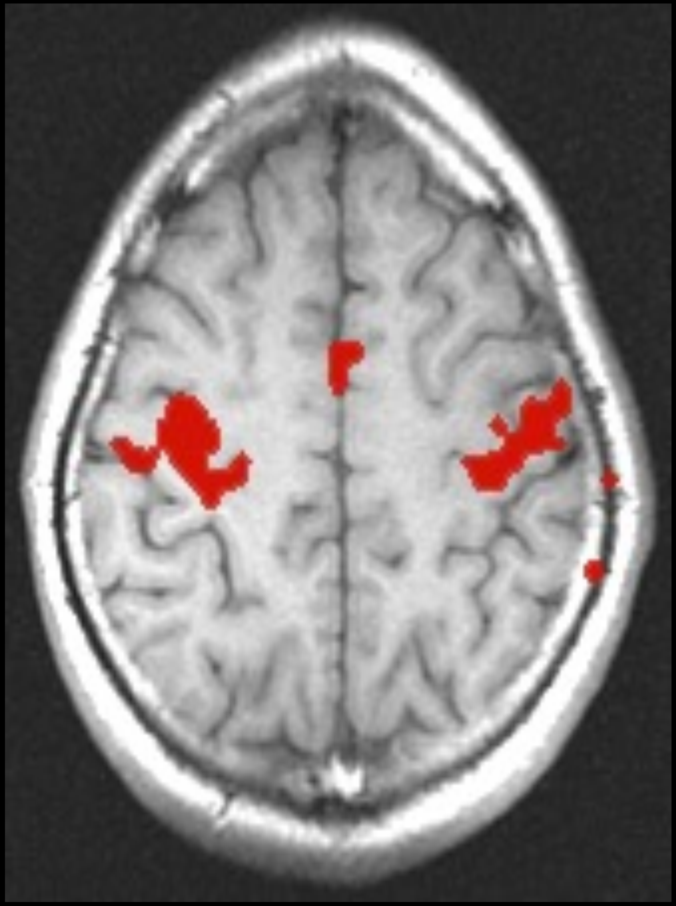
Phantom data

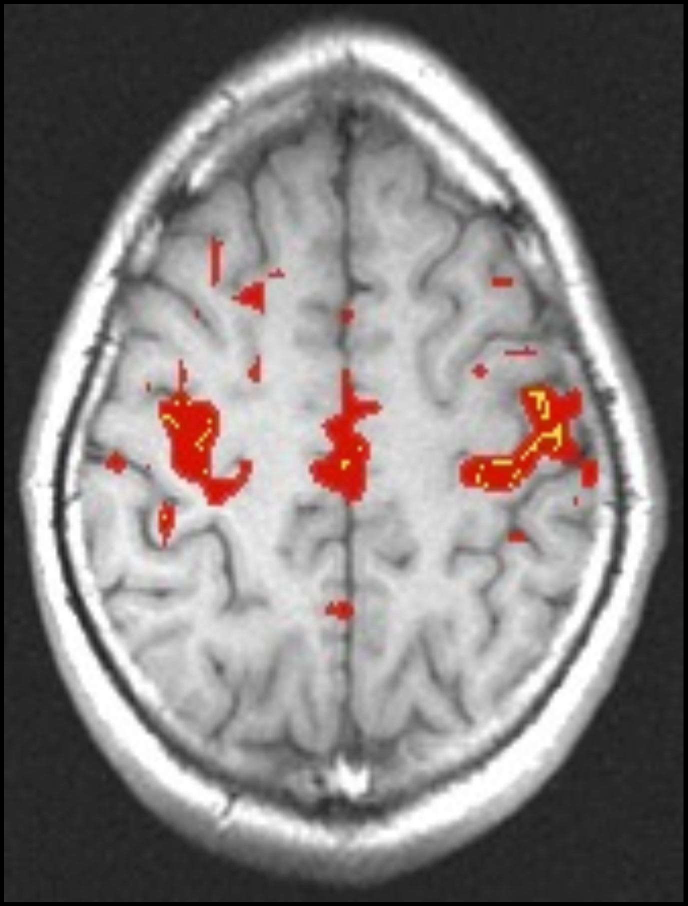
4mm slice thickness

Petridou et al


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

Resting Hemodynamic Autocorrelations



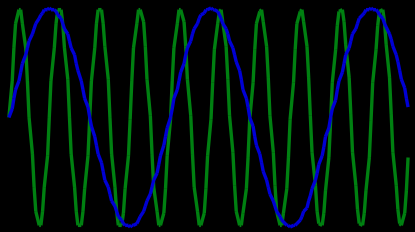


B. Biswal *et al.*, MRM, 34:537 (1995)

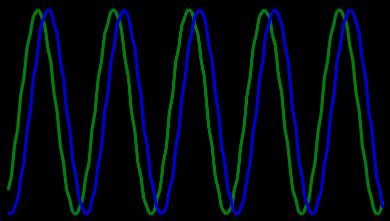
Neuronal Activation Input Strategies

1. Block Design

2. Frequency Encoding

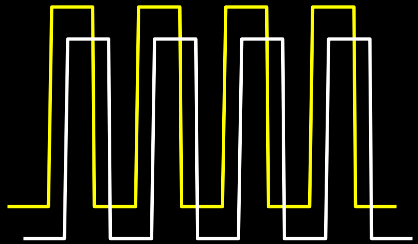


3. Phase Encoding



4. Event Related

5. Orthogonal Block Design



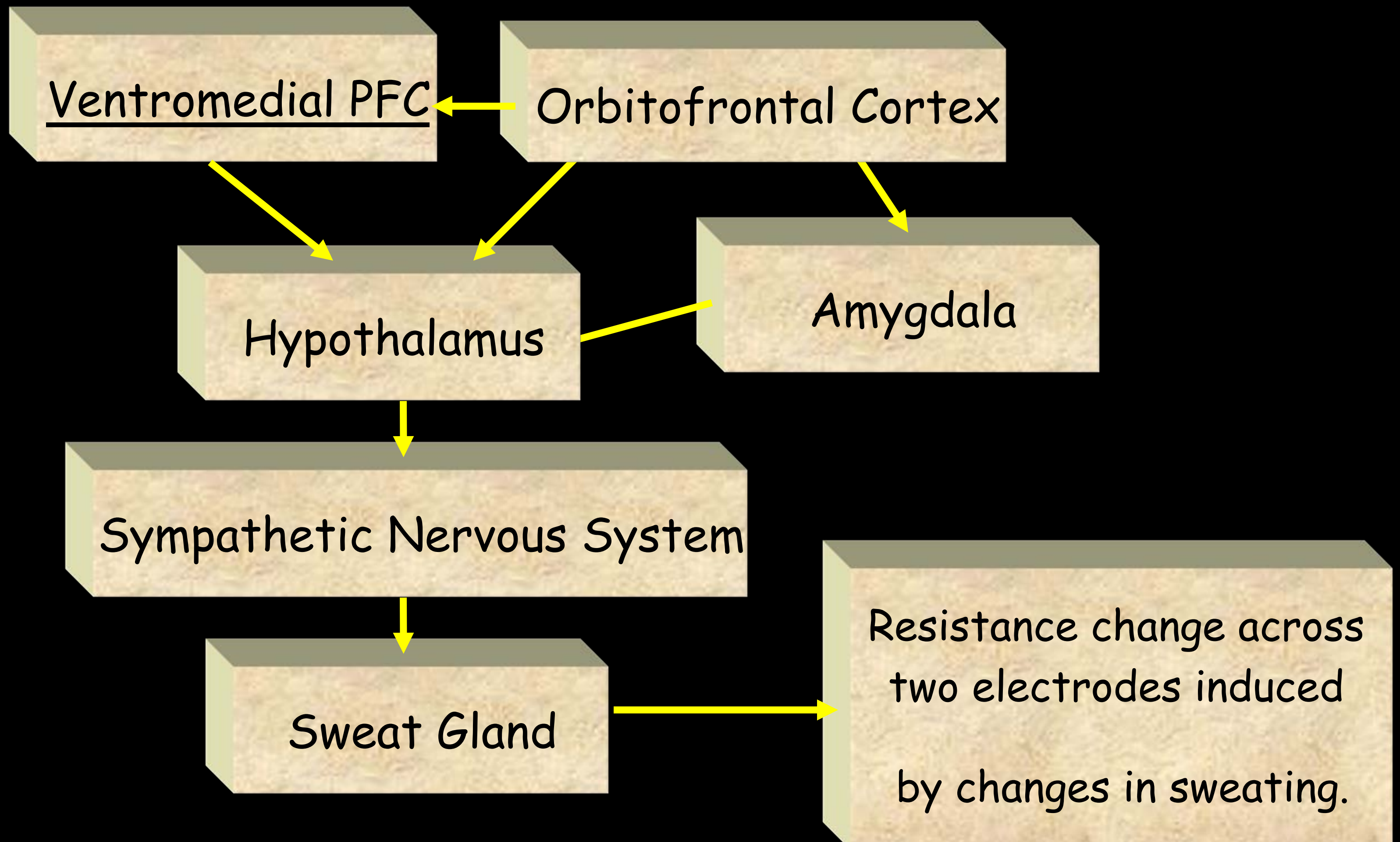
6. Free Behavior Design

Free Behavior Design

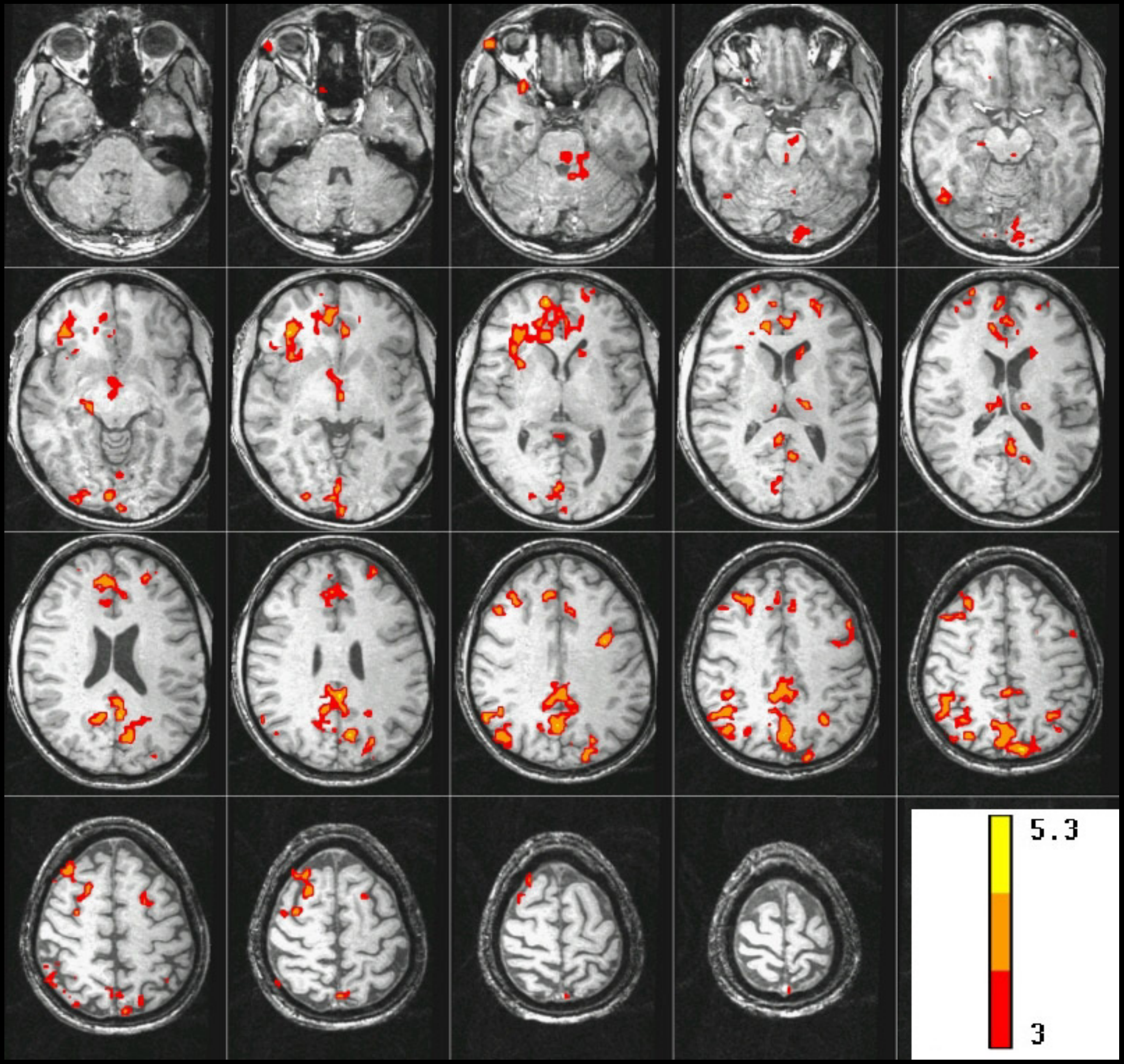
Use a continuous measure as a reference function:

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

The Skin Conductance Response (SCR)



Brain activity correlated with SCR during "Rest"



Past

Present

Future

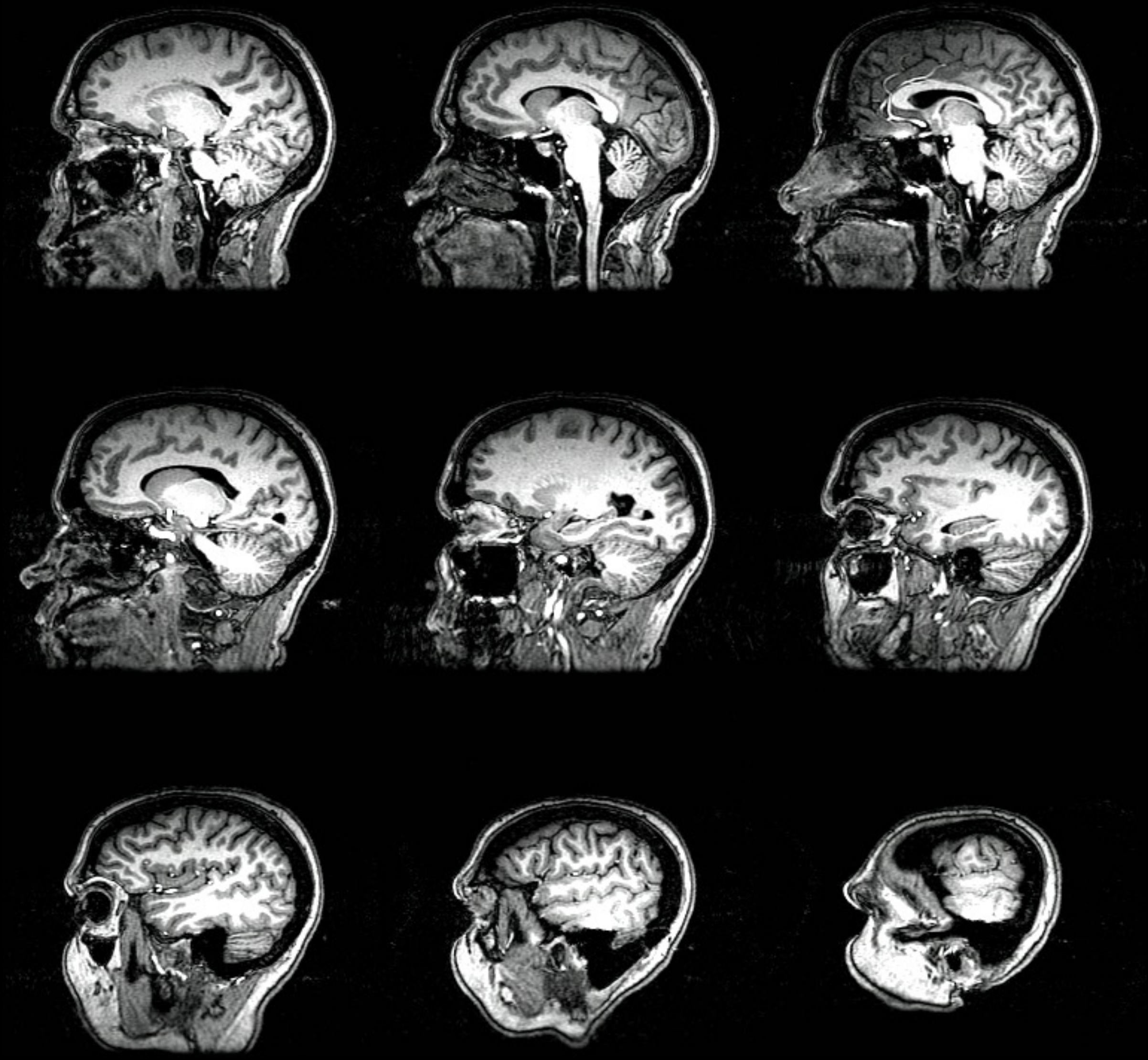
Future

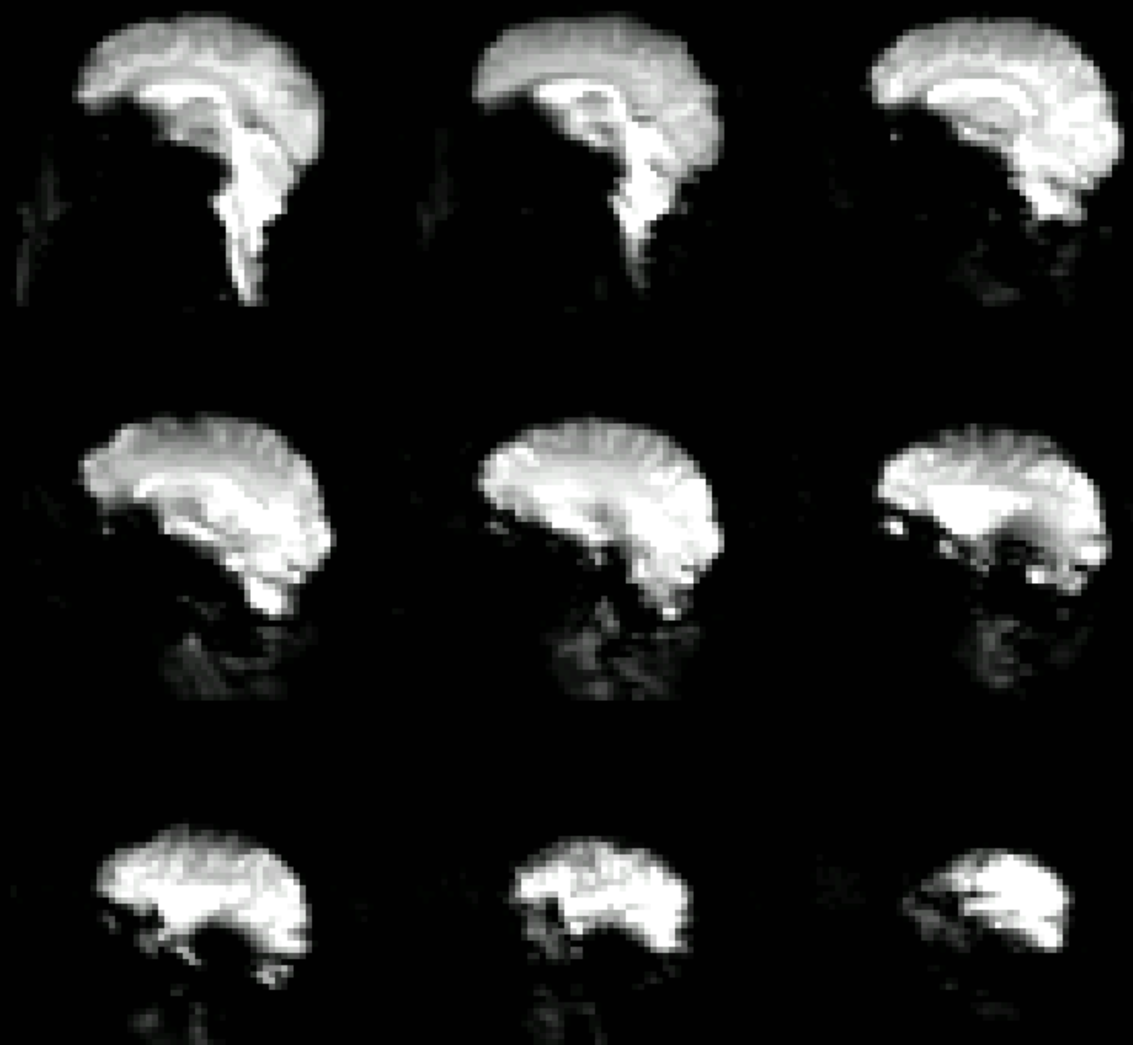
Imaging Methods

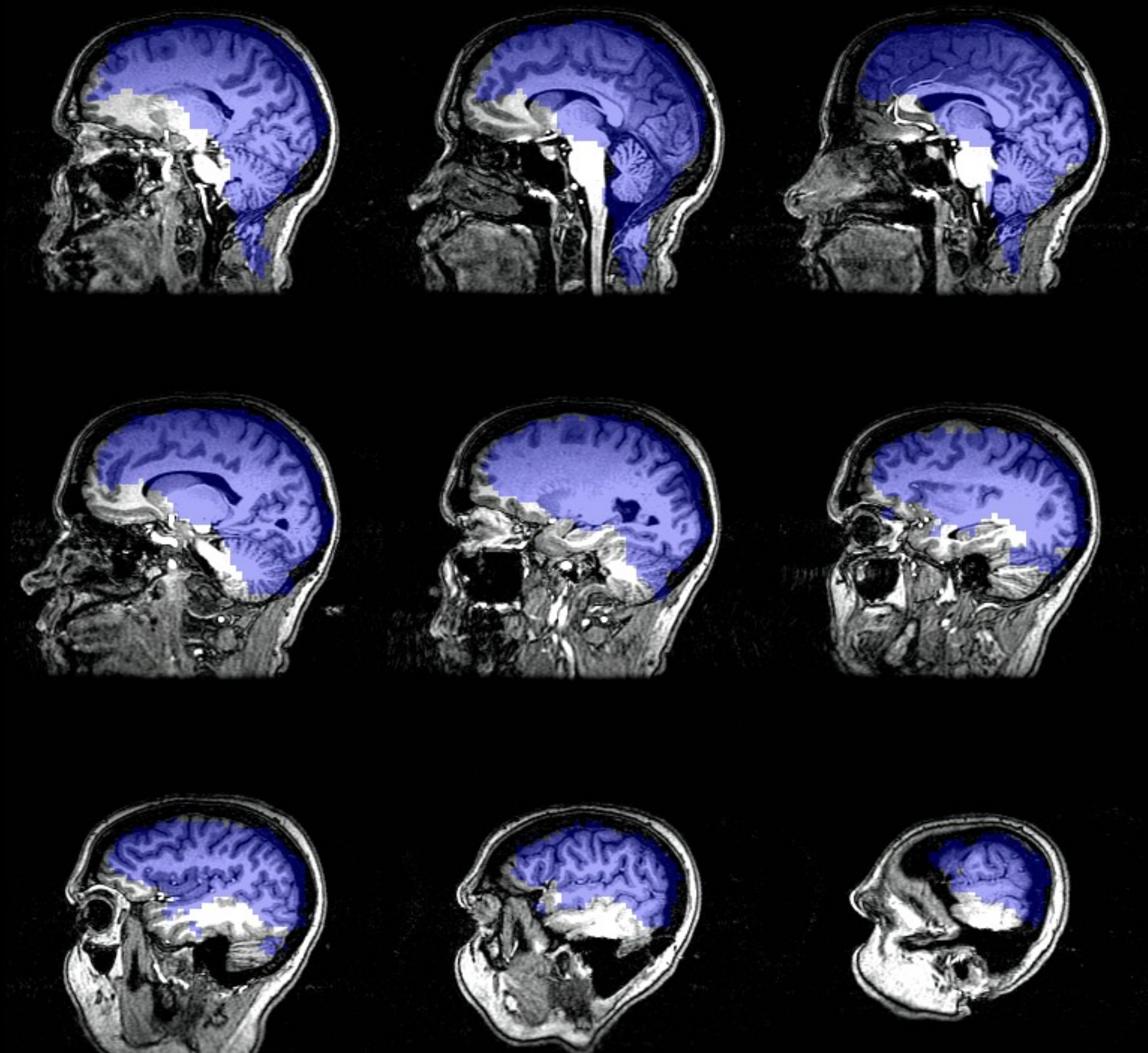
Clinical Implementation

Imaging Methods

- Shimming
- Acoustic Noise
- Multishot Techniques
- Increased Gradient Performance
- Higher Field Strengths
- Surface Coil Arrays (SENSE..)
- Calibration / Quantification
- Noise / Fluctuations
- Direct Neuronal Current Imaging



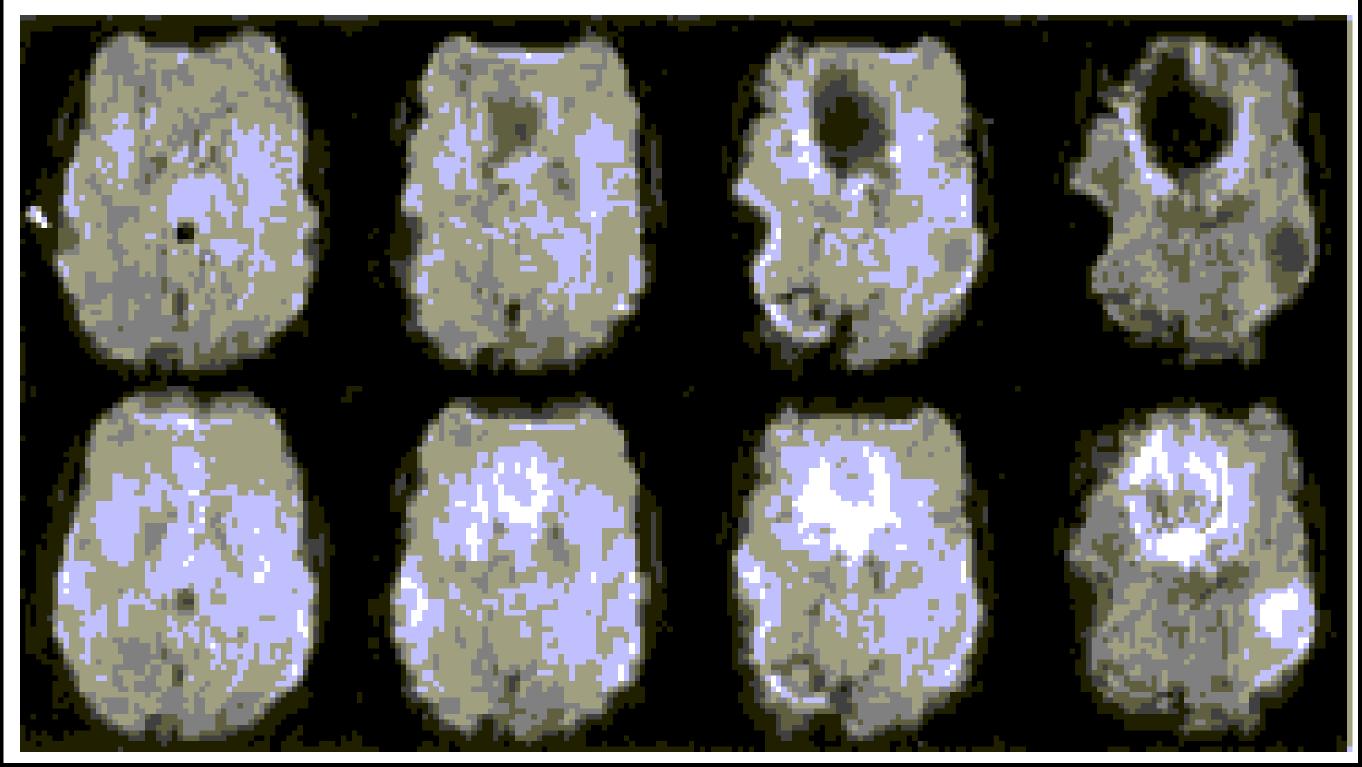




Magnetic Resonance in Medicine 42:290–299 (1999)

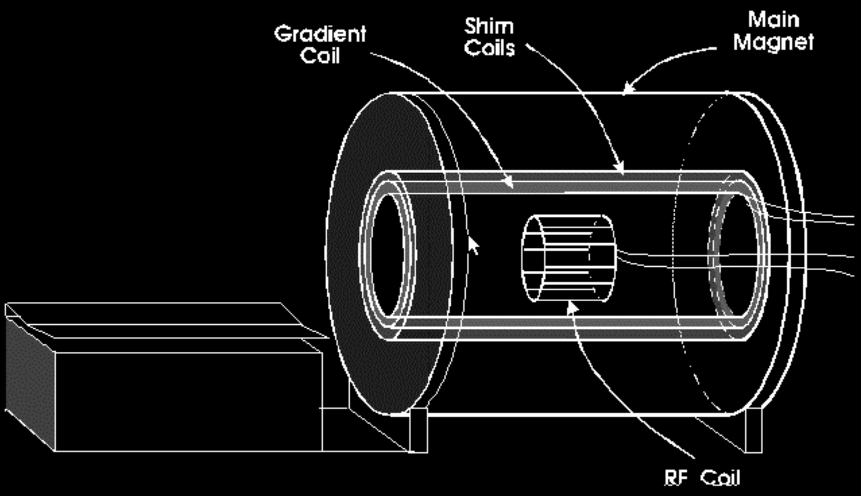
3D z-Shim Method for Reduction of Susceptibility Effects in BOLD fMRI

Gary H. Glover*



2 G/cm, 350 T/m/s

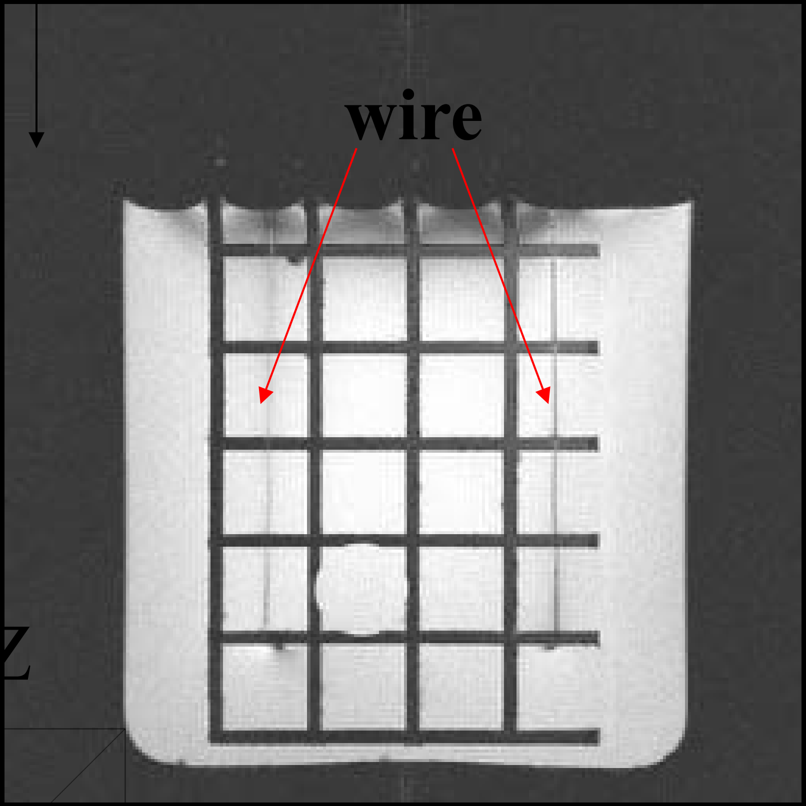
4 G/cm, 150 T/m/s

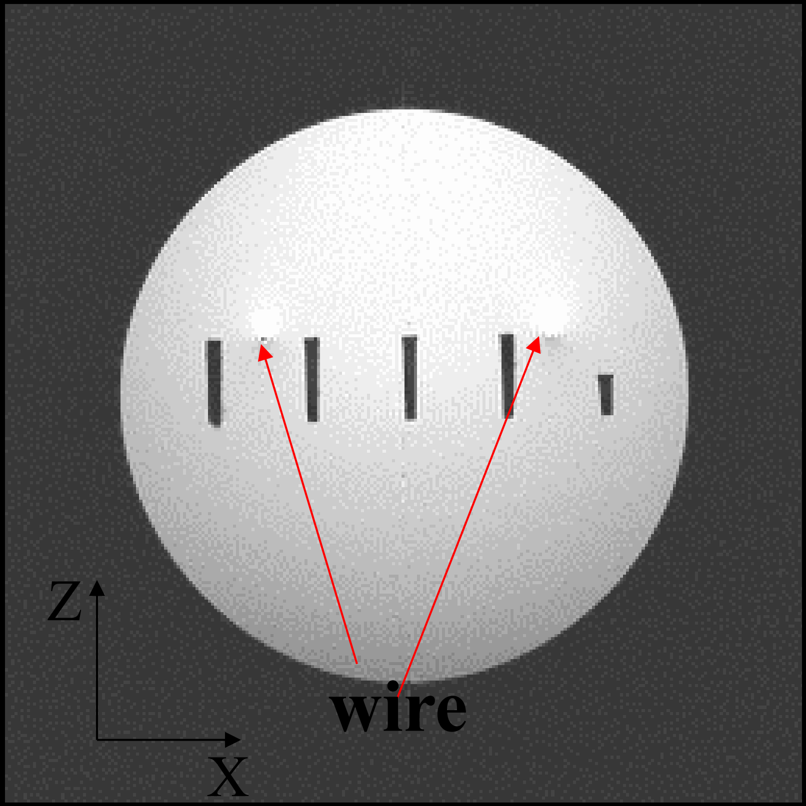


10 G/cm, 1000 T/m/s

➡ Diffusion imaging
Faster imaging
Higher resolution

Current Phantom Experiment

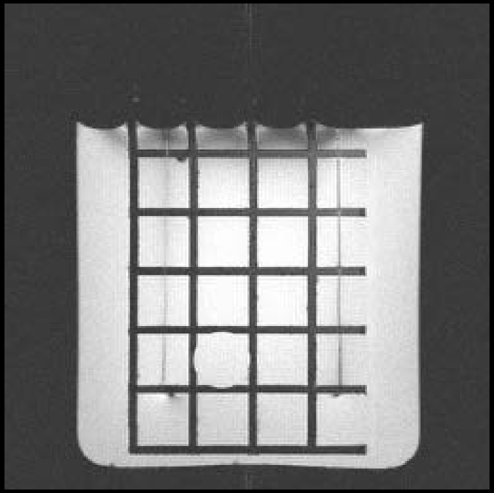


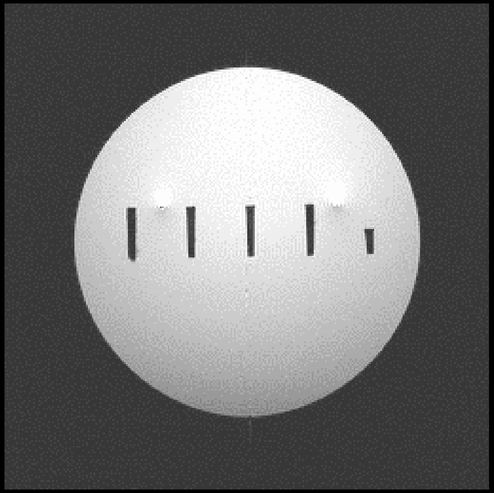


MRI phase:

$\Delta\phi \cong \gamma \Delta B_C TE$

Neuronal Current Imaging





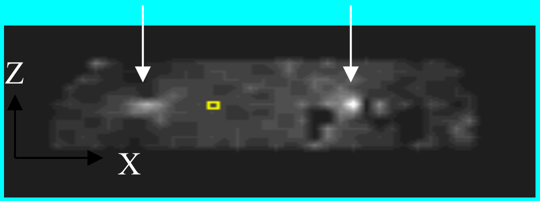
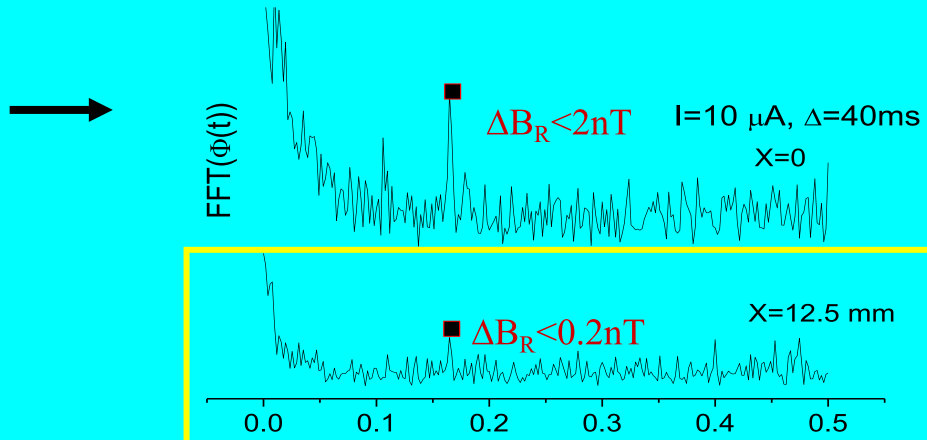


Figure 1

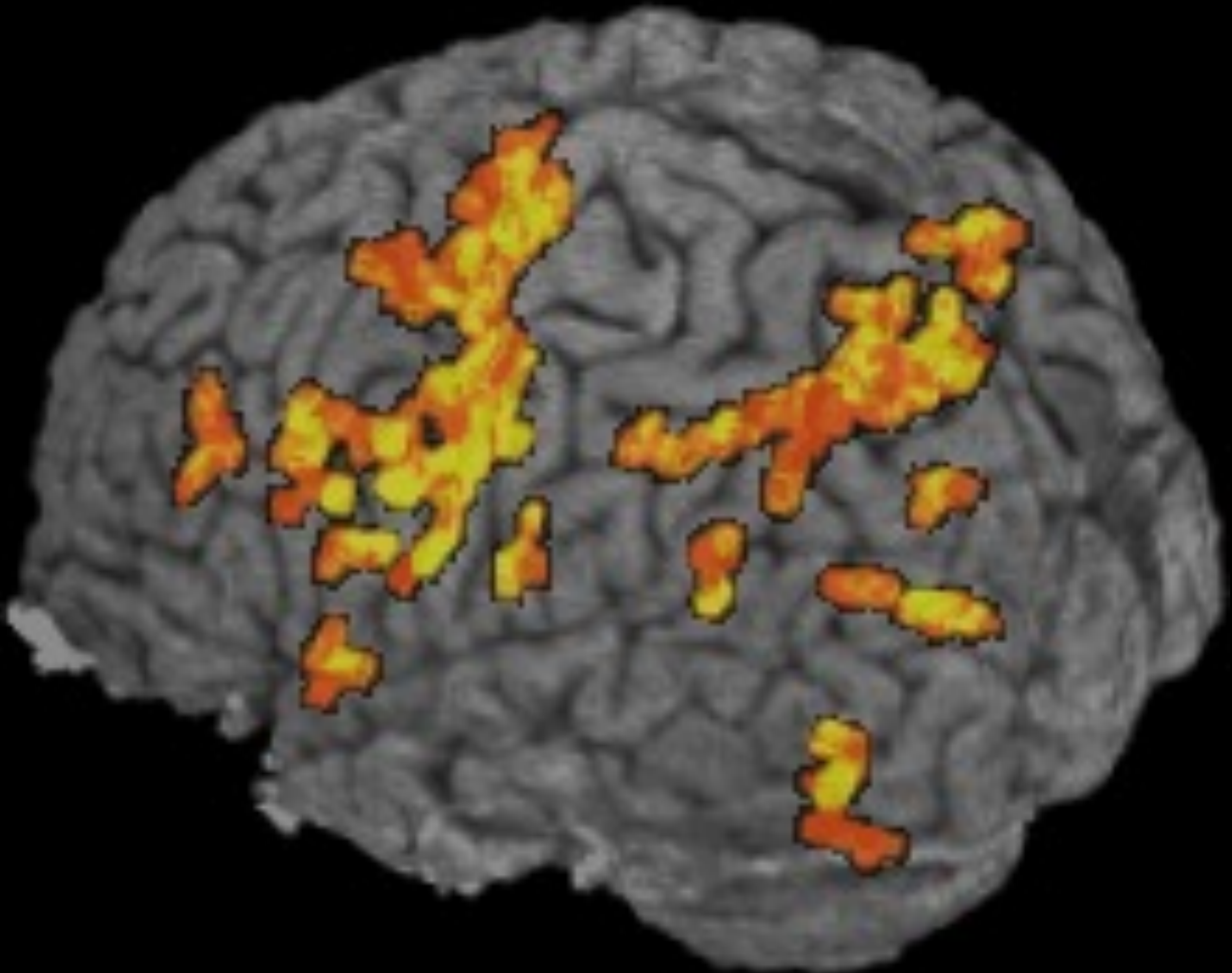


Clinical Implementation

- Real Time fMRI (immediate feedback)
- Elipepsy (foci localization)
- Metabolic / Vascular Disorders

- fMRI correlation with clinical populations

End of Acquisition



< 1 s to render

Blocked trials:
20 s on/20 s off
8 blocks

Blocks: <u>12345678</u>

Color shows
through brain

Correlation > 0.45

The End

Functional Imaging Methods / 3T Group

Staff Scientists:

Sean Marrett

Jerzy Bodurka

Post Docs:

Rasmus Birn

Patrick Bellgowan

Ziad Saad

Graduate Student:

Natalia Petridou

Summer Student:

Dan Kelley

Program Assistant:

Kay Kuhns

August, 2000