What fMRI Can, Can't, and Might Do

Peter A. Bandettini, Ph.D.

Section on Functional Imaging Methods

http://fim.nimh.nih.gov

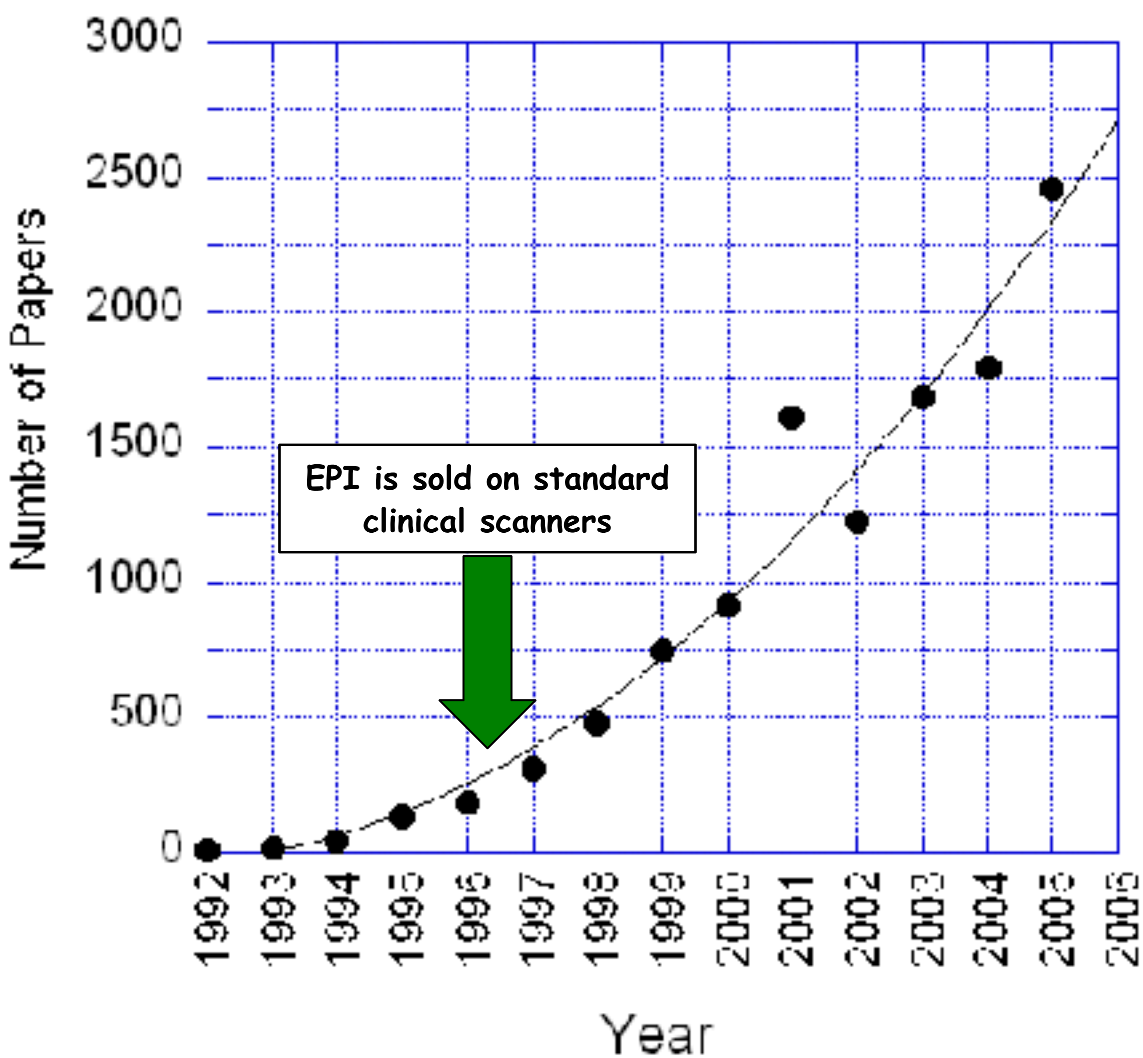
Laboratory of Brain and Cognition

&

Functional MRI Facility

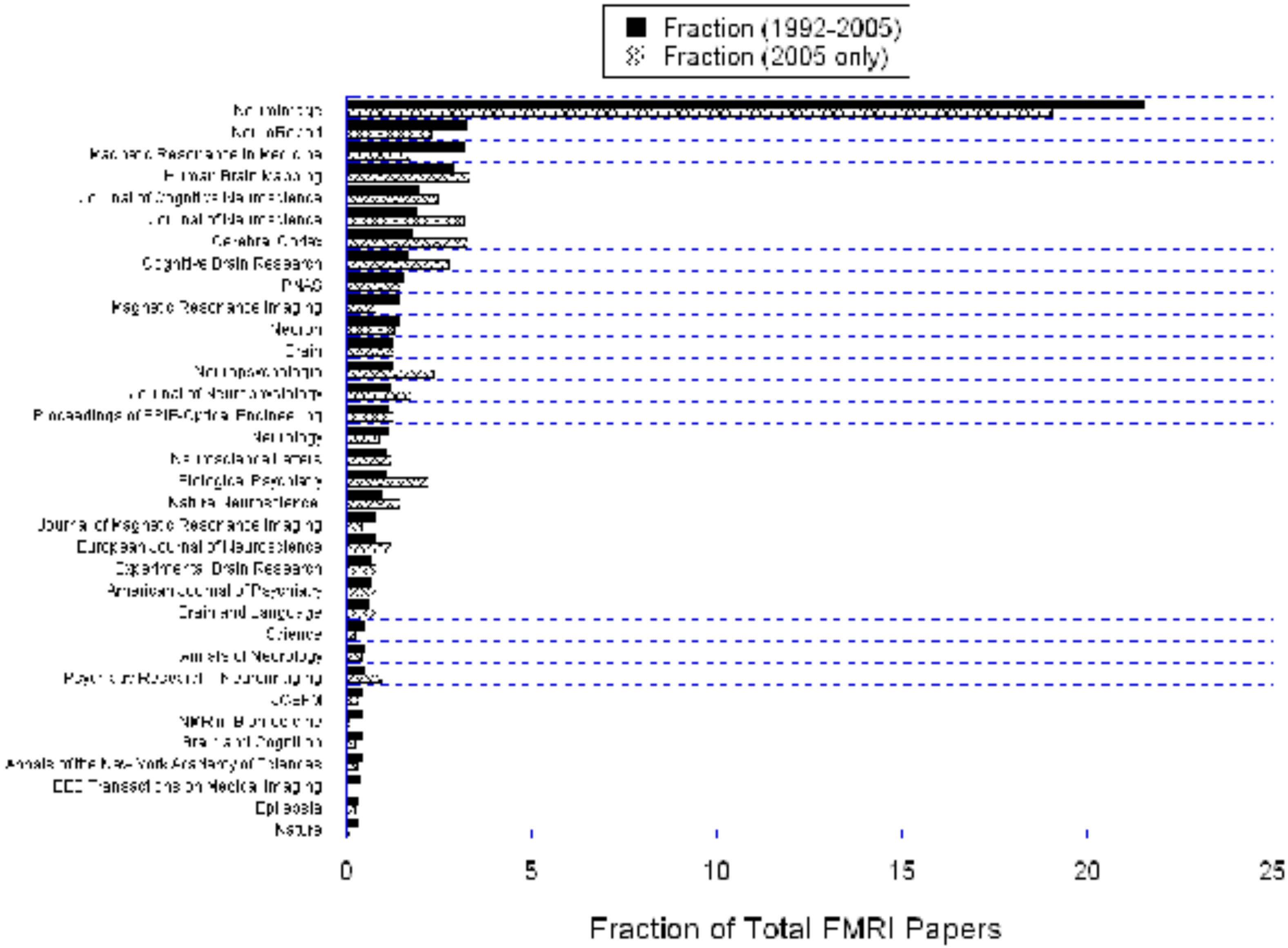
http://fmrif.nimh.nih.gov

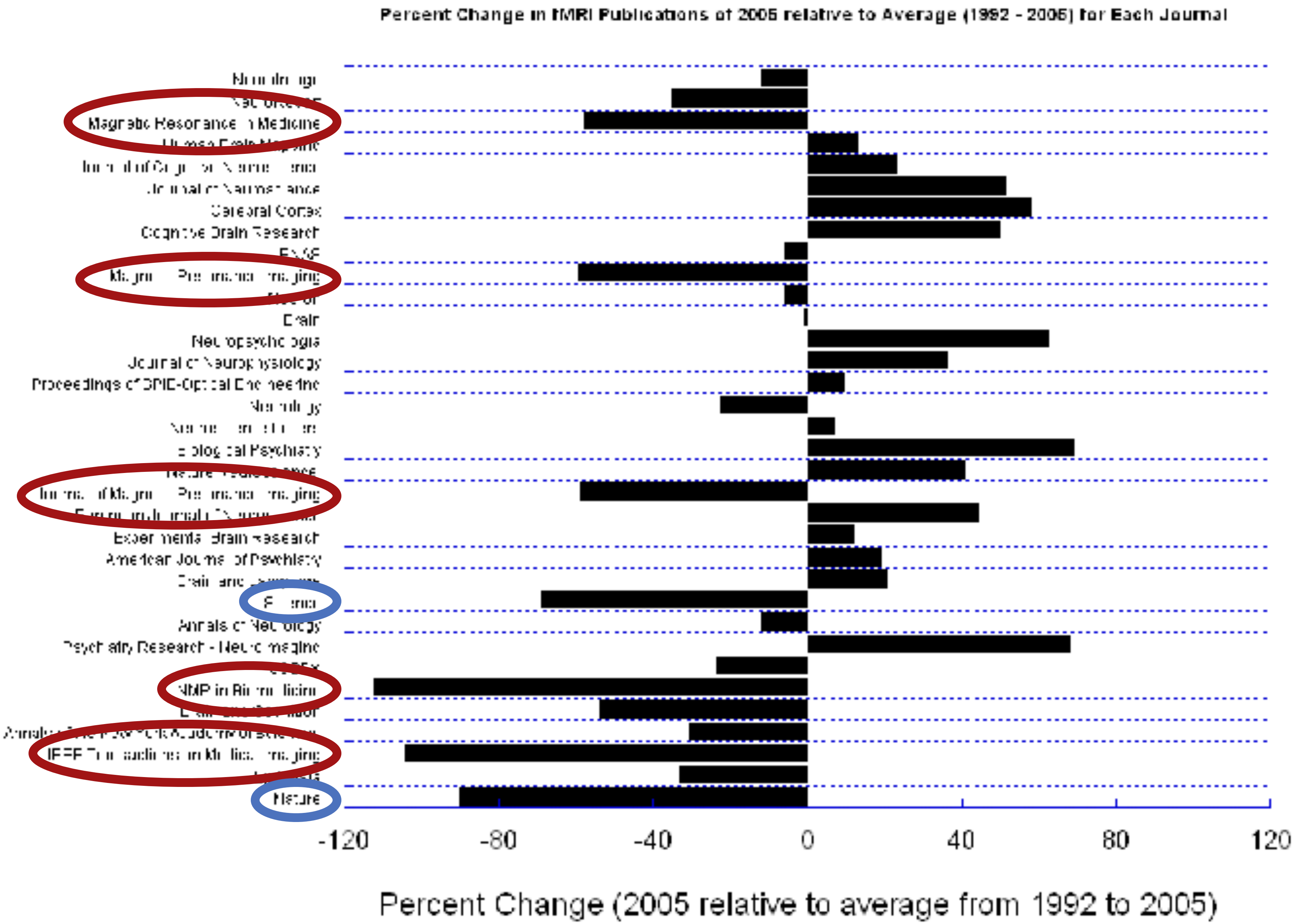
fMRI Papers Published per Year

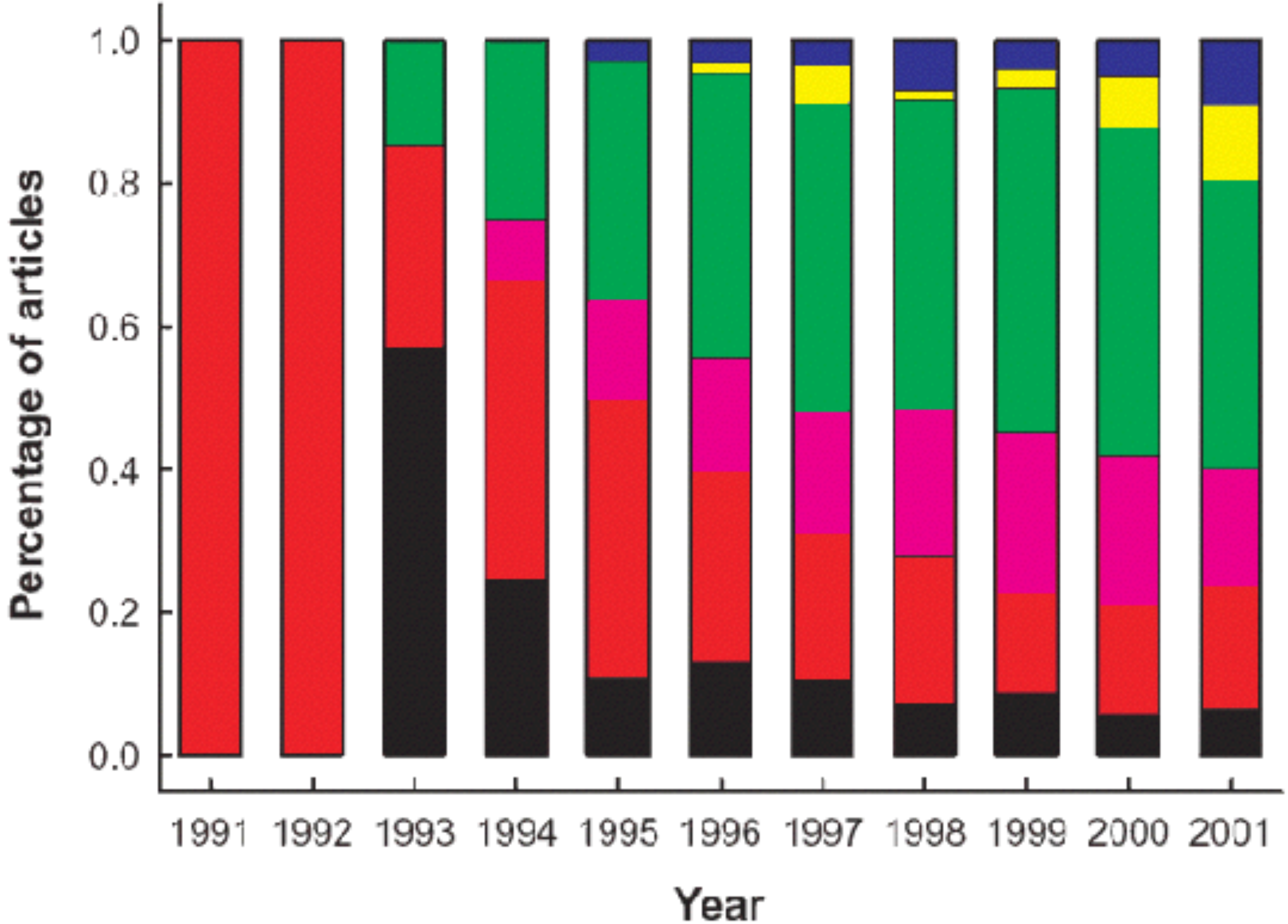


"fMRI" or "functional MRI"

Breakdown of fMRI papers by Journal




Percent Change in fMRI Publications of 2005 relative to Average (1992 - 2005) for Each Journal
Magnetic Resonance in Medicine
Cerebral Cortex
Cognitive Brain Research
Brain
Neuropsychologia
Journal of Neurophysiology
Nature
-120
-80
-40
0
40
80
120
Percent Change (2005 relative to average from 1992 to 2005)



Motor (black)
Primary Sensory (red)
Integrative Sensory (violet)
Basic Cognition (green)
High-Order Cognition (yellow)
Emotion (blue)

J. Illes, M. P. Kirschen, J. D. E. Gabrielli, Nature Neuroscience, 6 (3)m p.205

How most fMRI studies are performed

MRI parameters:

1.5T - 3T, 64 x 64 matrix, 3mm x 3mm x 5mm voxel size, whole brain, TR = 2 sec.

Paradigm:

Block design or event-related, single or multiple conditions.

Analysis:

Motion correct, multi-regression, spatial smoothing and spatial normalization, standard classical statistical tests, multi-subject averaging.

Hypothesis:

A region or network of regions show modulation with a task. This modulation is unique to the task and/or population.

How fMRI might be be performed

MRI parameters:

3T - 11.7T, 256 x 256 matrix, 0.5 x 0.5 x 0.5 voxel size, whole brain TR = 1sec or select slab TR = 100 ms.

Paradigm:

Natural, continuous, or no stimuli/task. Simultaneous multi-modal, or multiple contrast measurements.

Analysis:

Motion correct, dynamic Bo-field correction, no spatial or temporal smoothing, machine learning algorithms, pattern classification, hemodynamic parameter assessment, correlation with behavior.

Hypothesis:

Similar to previous but using the high resolution patterns, fluctuations, dynamics, and contrast mechanisms that we are still figuring out how to interpret and extract.

Technology

- Coil arrays
- High field strength
- High resolution
- Novel functional contrast

Methodology

- Connectivity assessment
- Multi-modal integration
- Pattern classification
- Task design

Interpretation

- Fluctuations
- Dynamics
- Cross - modal comparison

Applications

- Basic Neuroscience
- Behavior correlation/prediction
- Pathology correlation

Technology

Coil arrays
High field strength
High resolution
Novel functional contrast

Methodology

Connectivity assessment
Multi-modal integration
Pattern classification
Task design

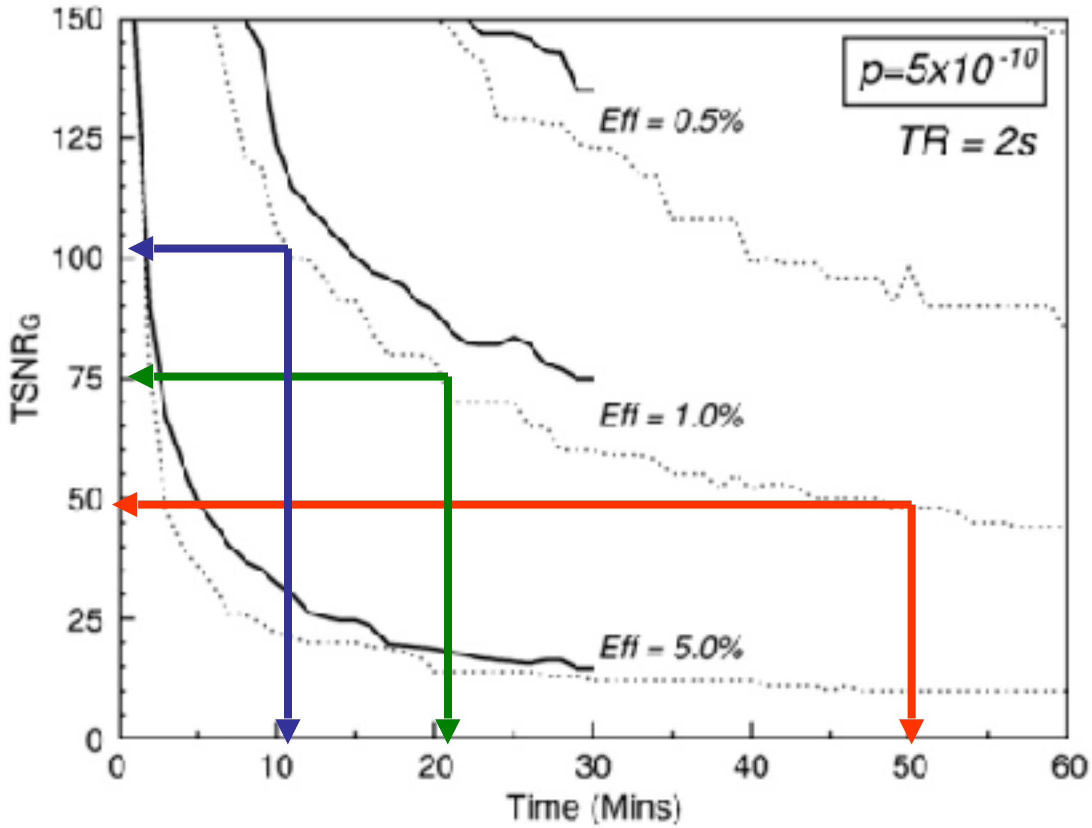
Fluctuations
Dynamics
Cross - modal comparison

Interpretation

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

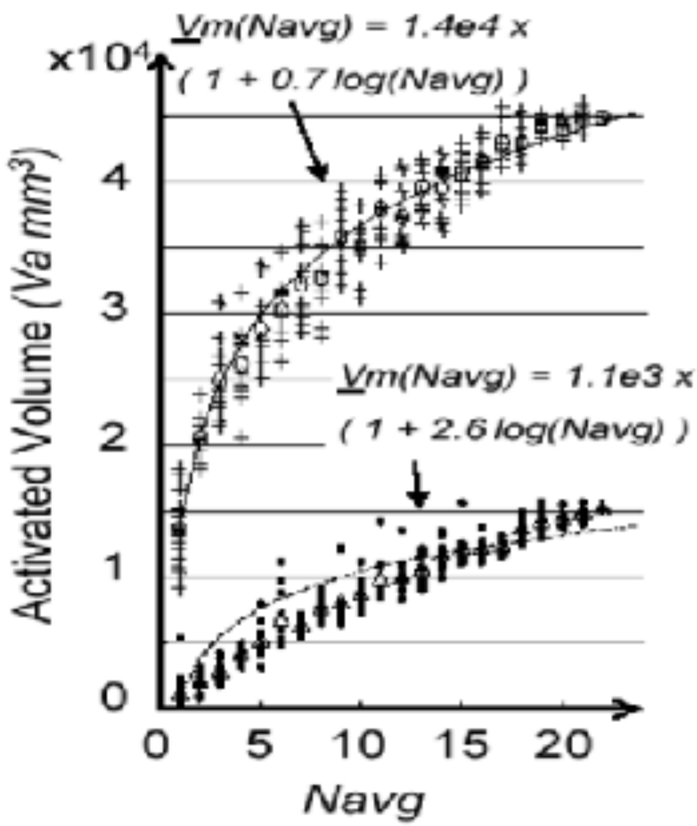
Applications

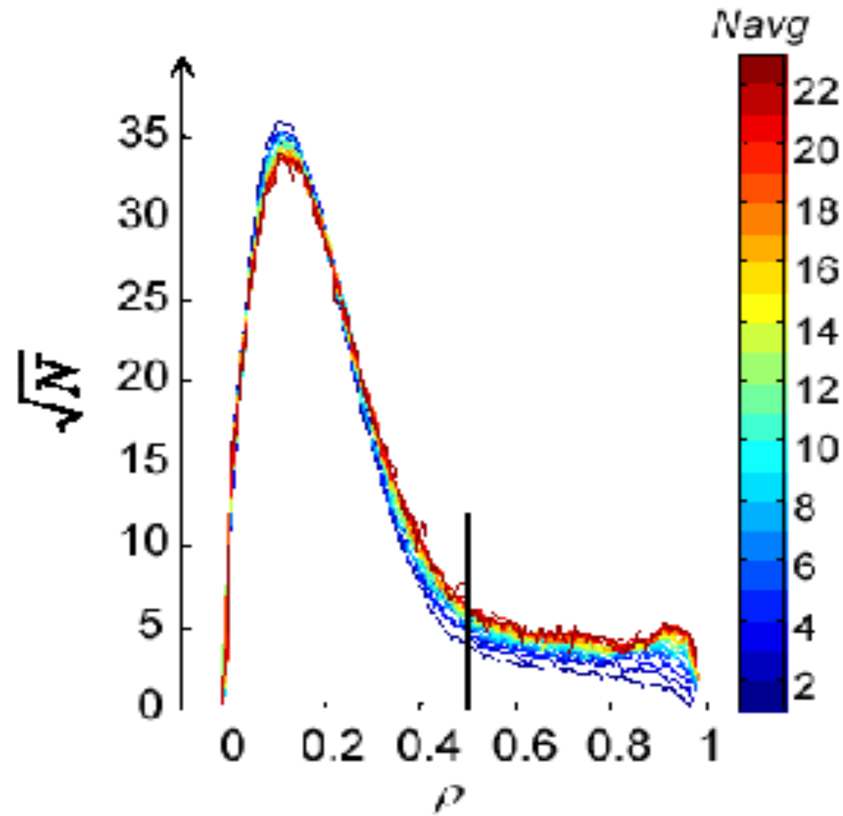
Time series improvement



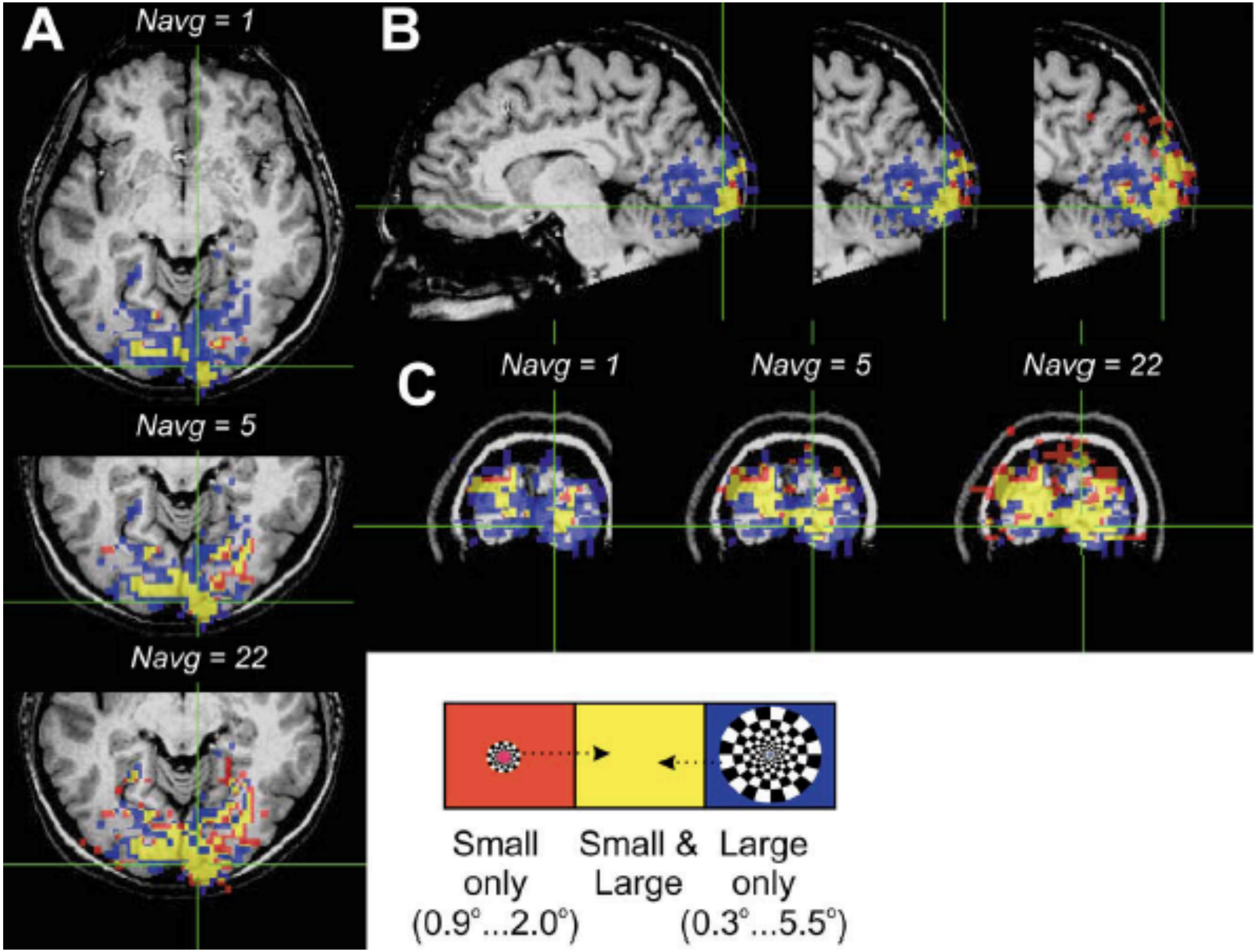
K. Murphy, J. Bodurka, P. A. Bandettini, How long to scan? The relationship between fMRI temporal signal to noise and the necessary scan duration. NeuroImage, 34, 565-574 (2007)

Technology





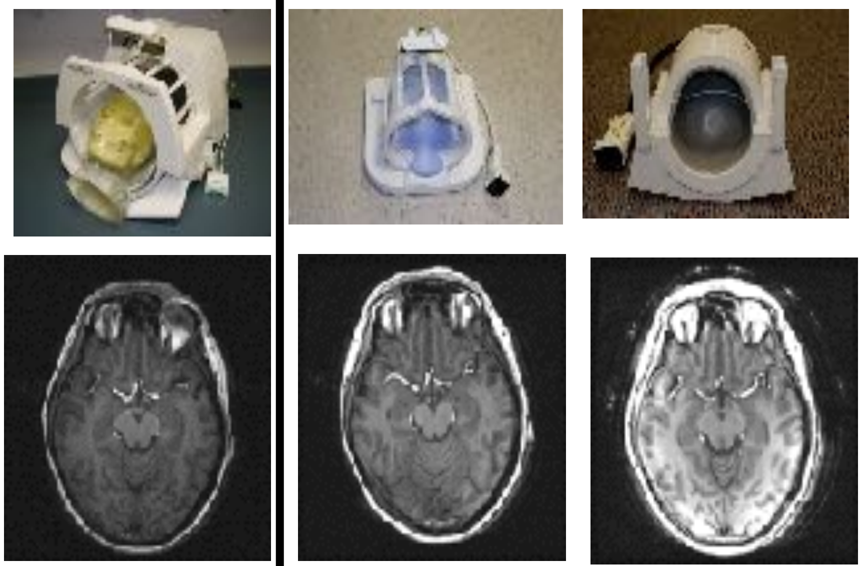
Z. S. Saad, K. M. Ropella, E. A. DeYoe, P. A. Bandettini, The spatial extent of the BOLD response. NeuroImage, 19: 132-144, (2003)



Z. S. Saad, K. M. Ropella, E. A. DeYoe, P. A. Bandettini, The spatial extent of the BOLD response. NeuroImage, 19: 132-144, (2003)

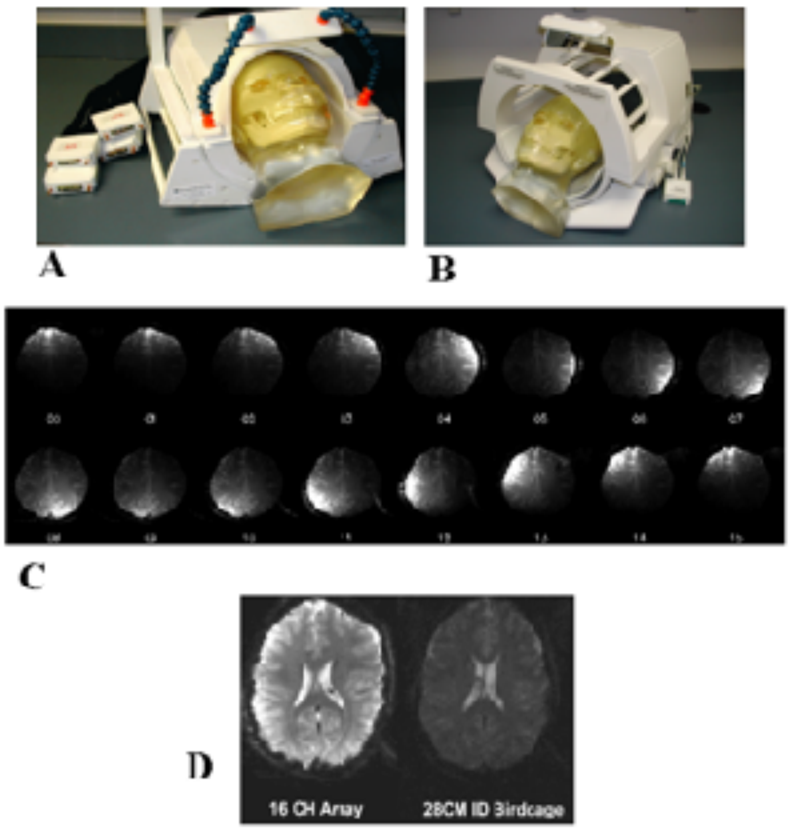
Technology

8 channel parallel receiver coil



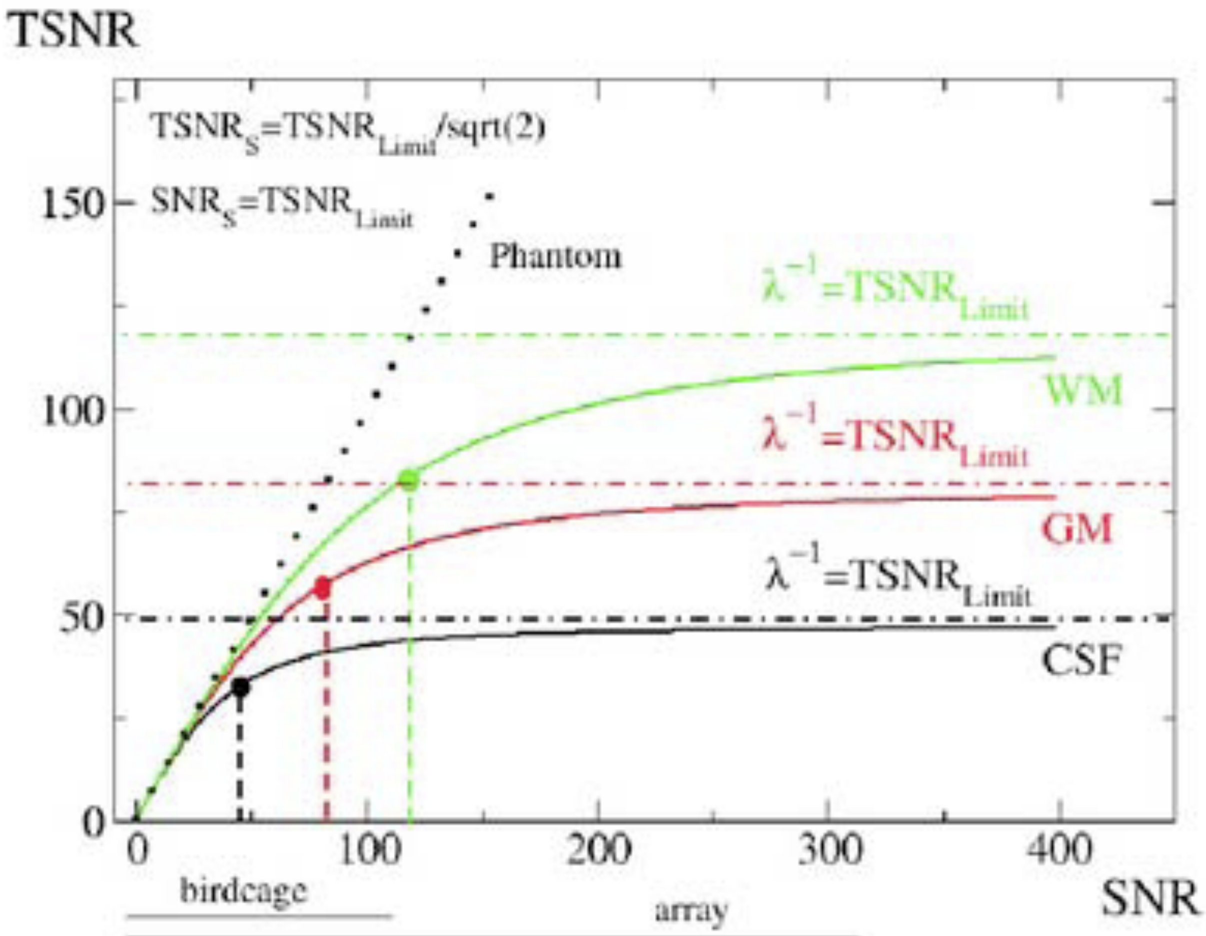
GE birdcage | GE 8 channel coil | Nova 8 channel coil

16 channel parallel receiver coil



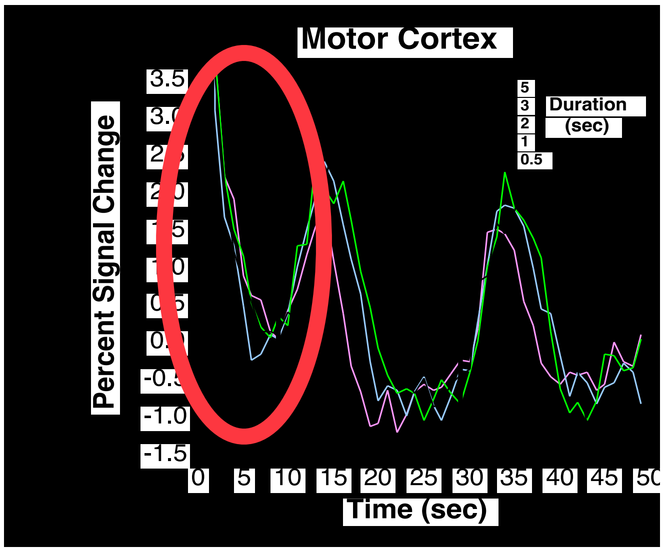
J. Bodurka, et al, Magnetic Resonance in Medicine 51 (2004) 165-171.

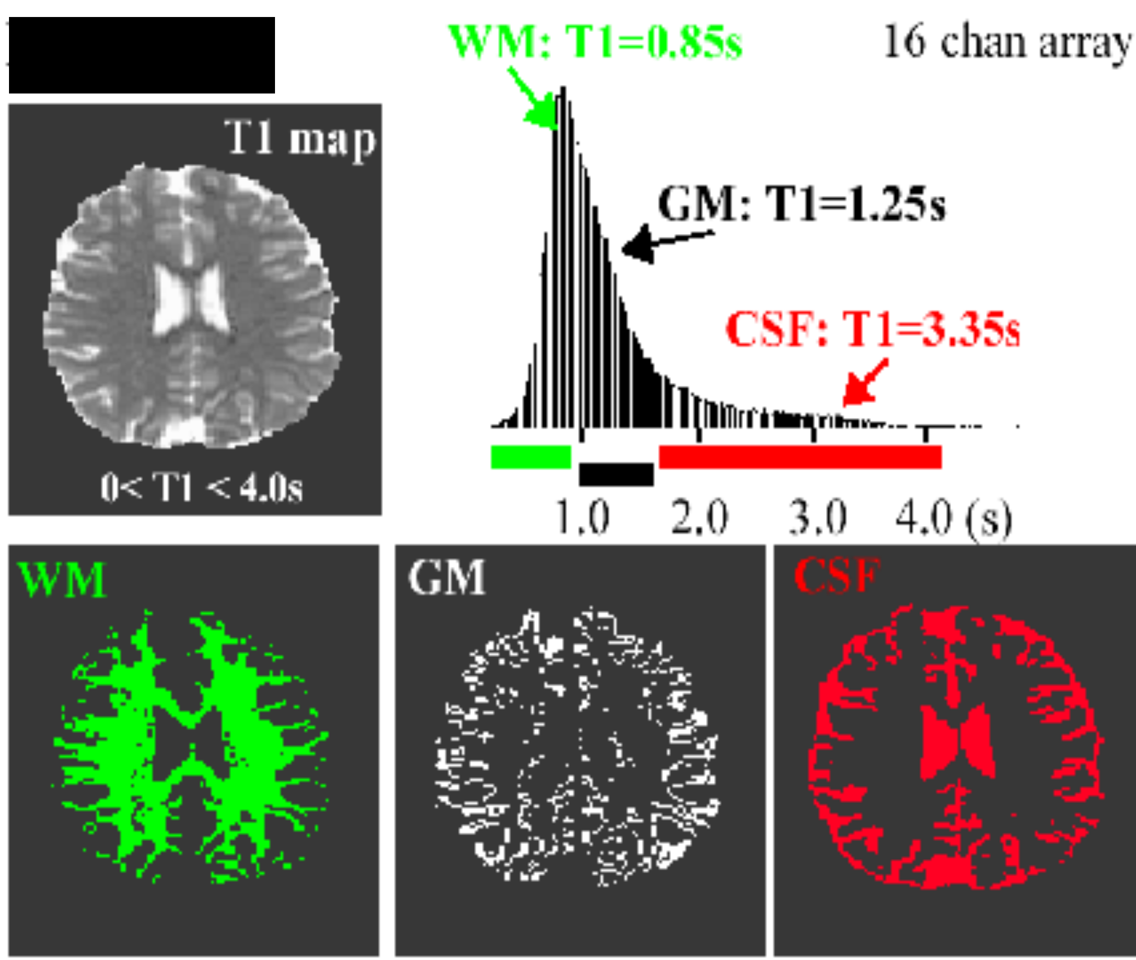
SNR vs TSNR



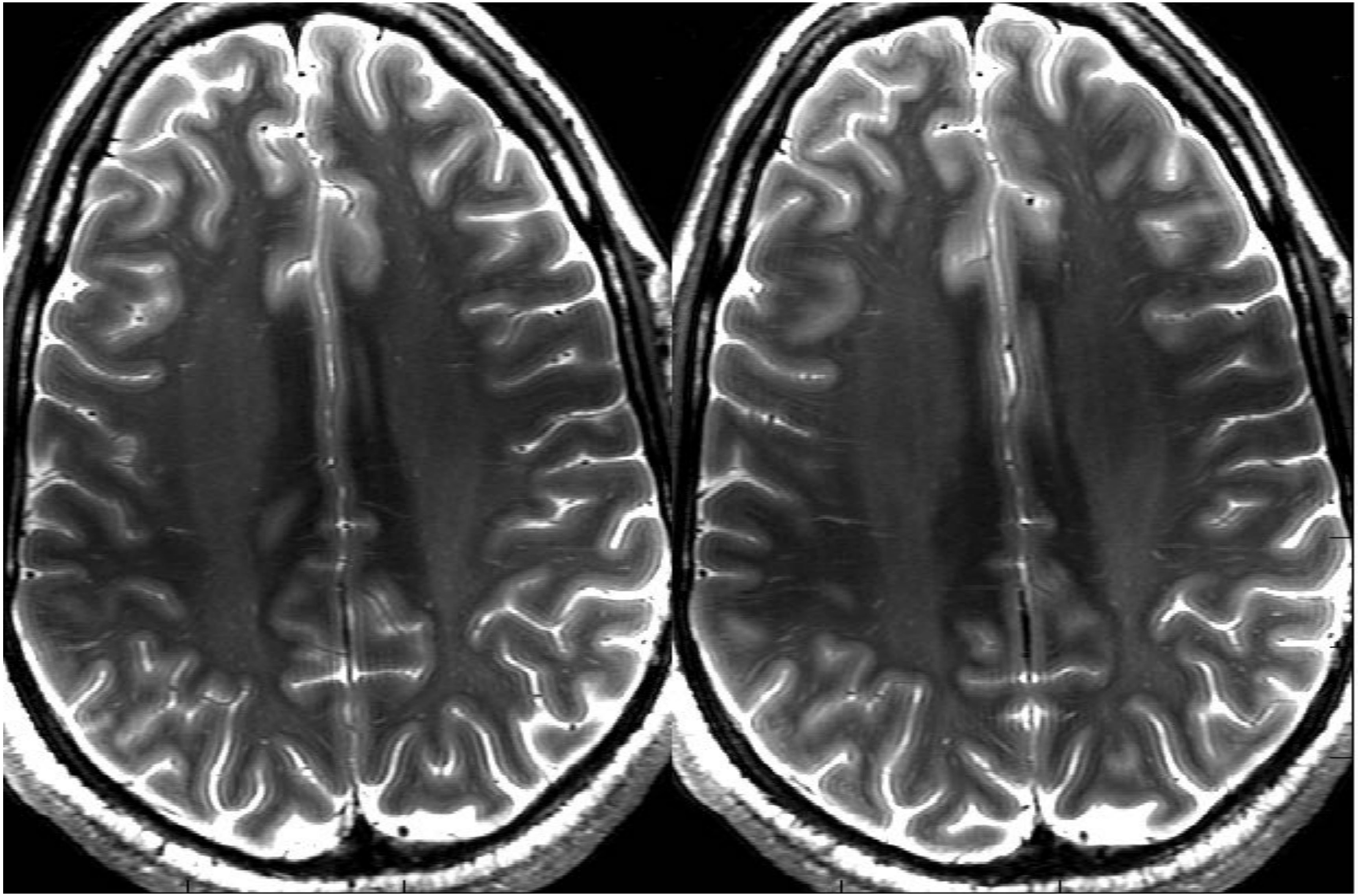
J. Bodurka, F. Ye, N Petridou, P. A. Bandettini, Mapping the MRI voxel volume in which thermal noise matches physiological noise – implications for fMRI. NeuroImage, 34, 542-549 (2007)

Segmentation using EPI Transient





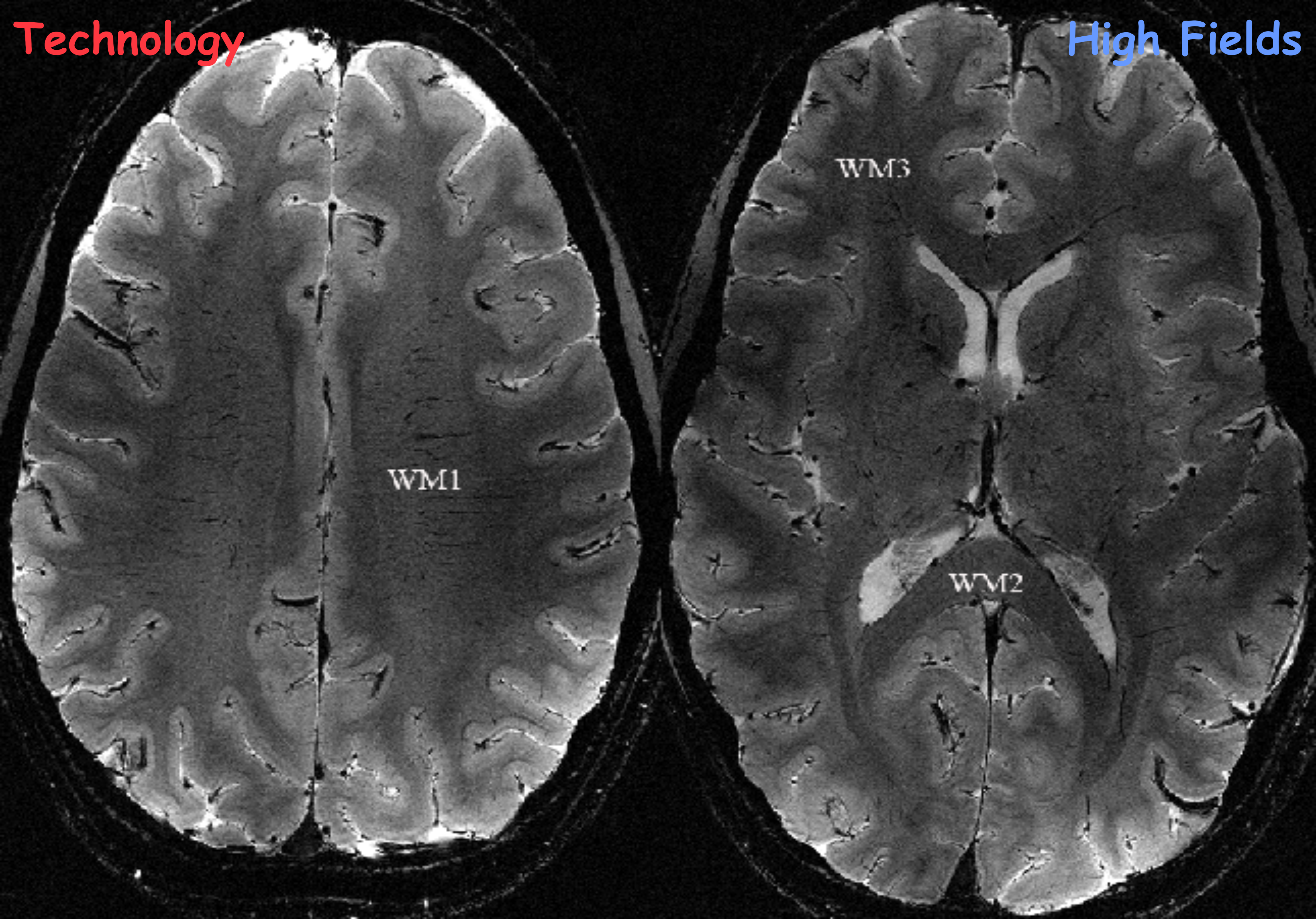
J. Bodurka, F. Ye, N Petridou, P. A. Bandettini, Mapping the MRI voxel volume in which thermal noise matches physiological noise – implications for fMRI. NeuroImage, 34, 542-549 (2007)

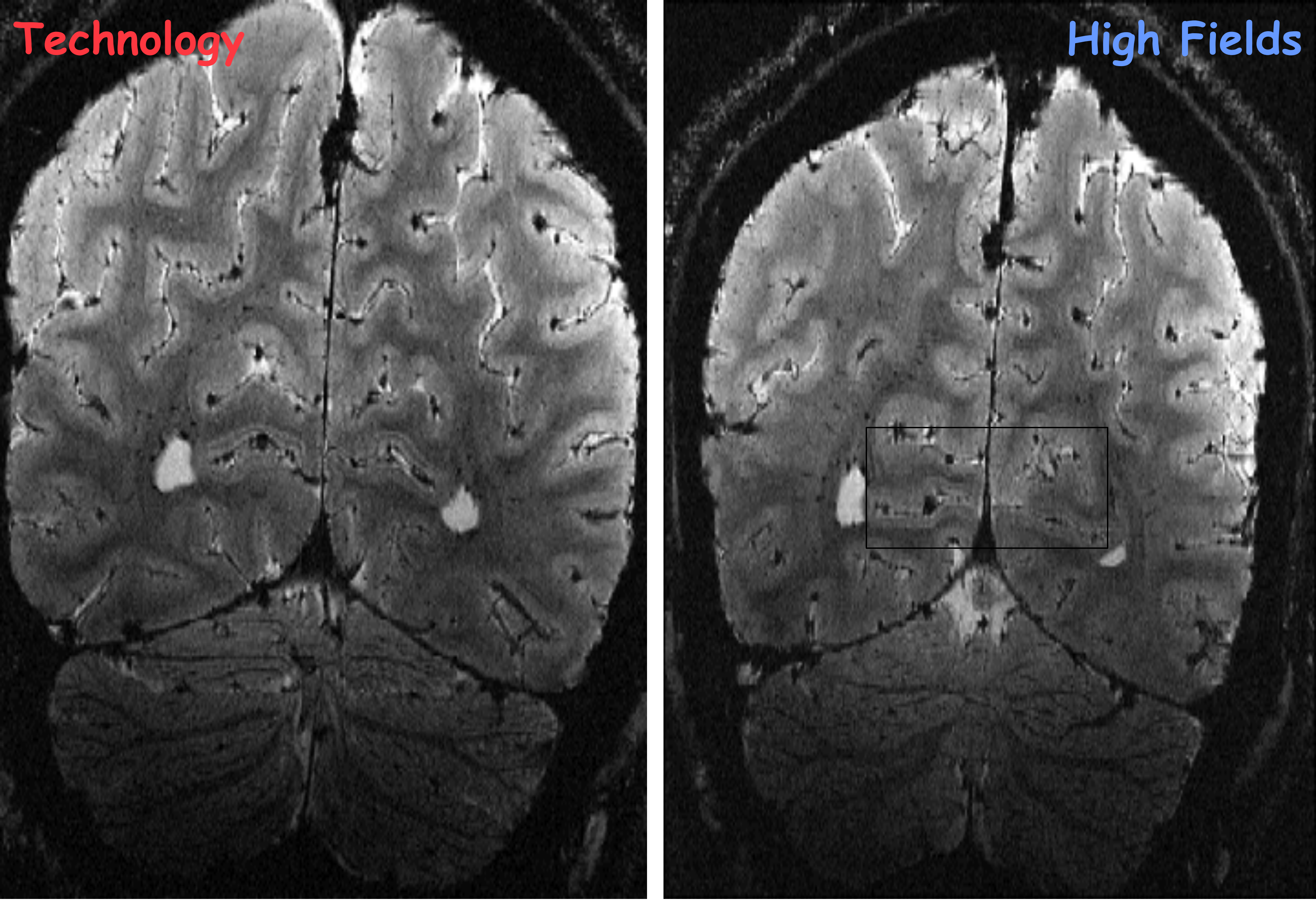


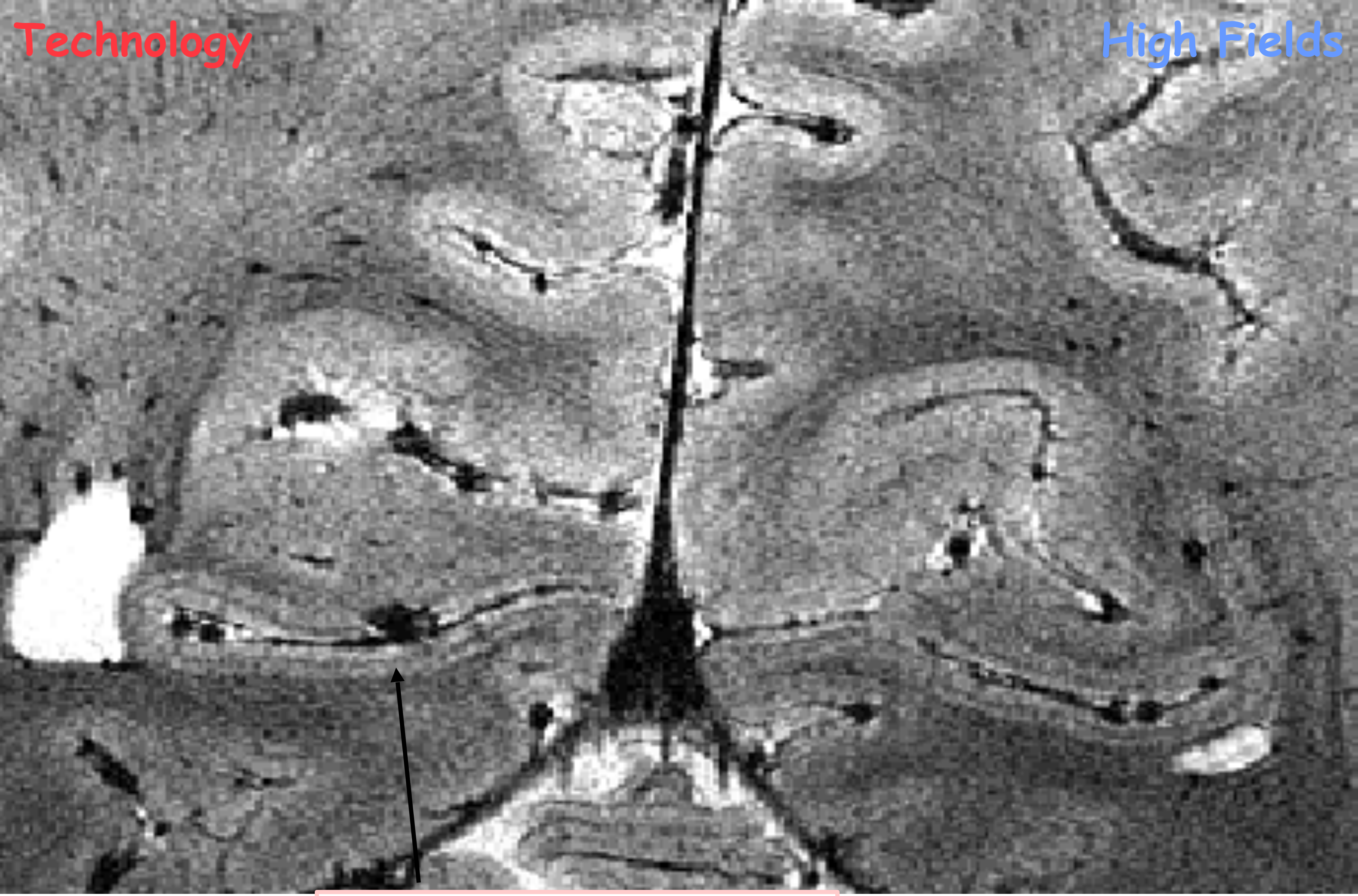
FSE **images** at 0.2x.2x1mm^3

Technology

High Fields

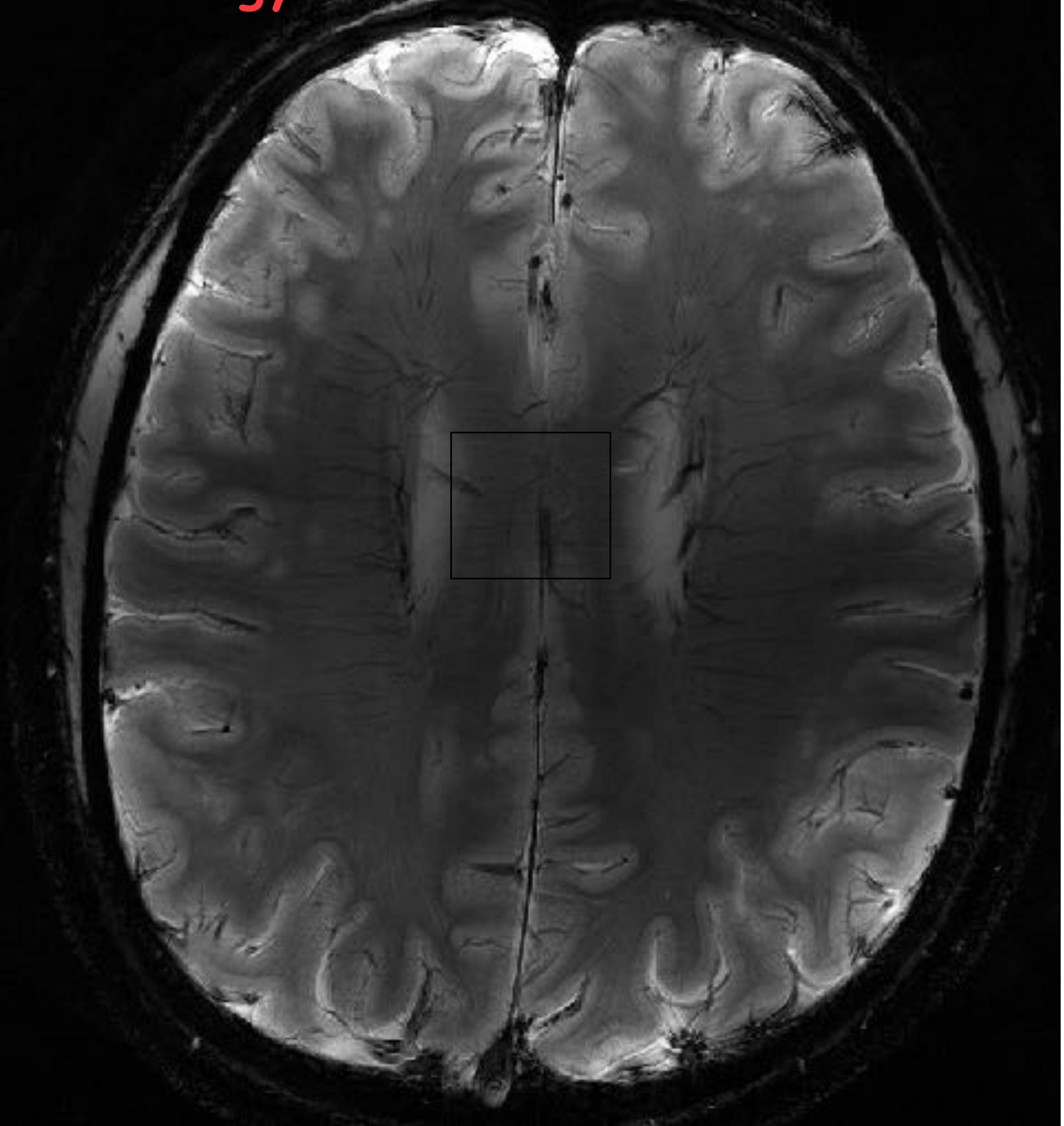



Technology
High Fields



Layered structure in the visual cortex

Technology



Courtesy Tie-Qiang Li, NINDS

fMRI Contrast

- Volume (gadolinium)
- BOLD
- Perfusion (ASL)
- $\Delta CMRO_2$
- ΔVolume (VASO)
- Neuronal Currents
- Diffusion coefficient
- Temperature

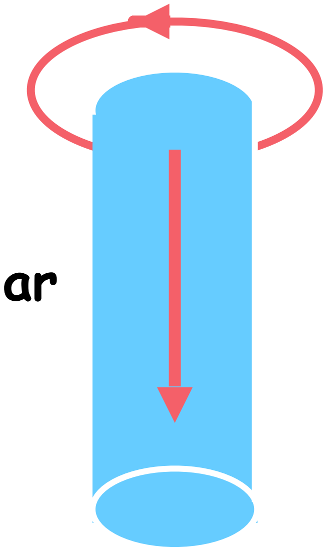
Technology

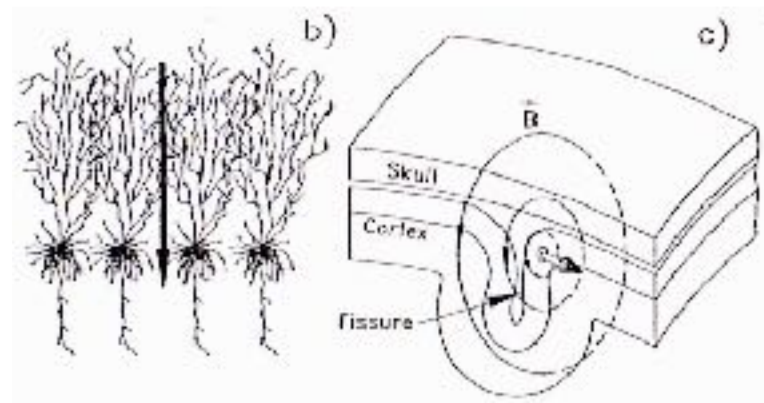
New Contrasts

Neuronal Currents

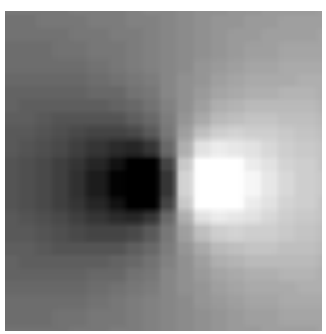
Magnetic Field

Intracellular Current





Surface Fields



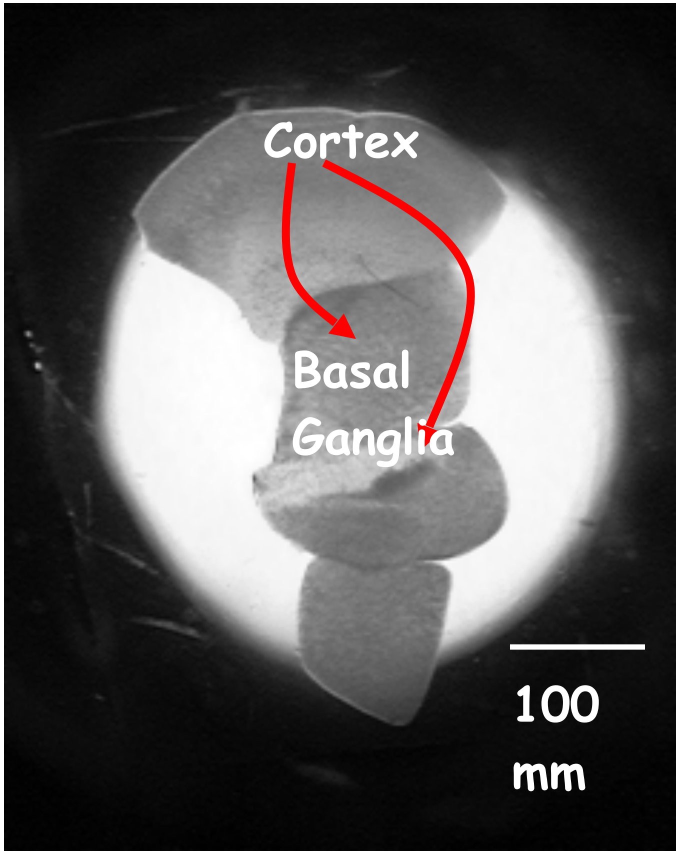
100 fT at on surface of skull

And 0.2 nT near source

P. A. Bandettini, N. Petridou, J. Bodurka, Direct detection of neuronal activity with MRI: fantasy, possibility, or reality? Applied MRI 29 (1) pp. 65-88

In Vitro Results

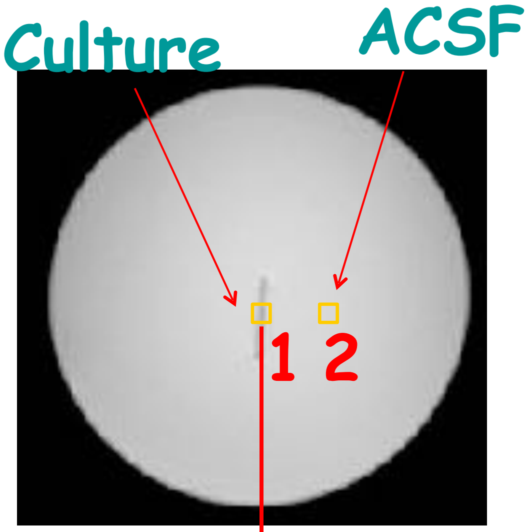
Organotypic (no blood supply or hemoglobin traces) sections of newborn-rat somato-sensory Cortex, or somato-sensory Cortex & Basal Ganglia



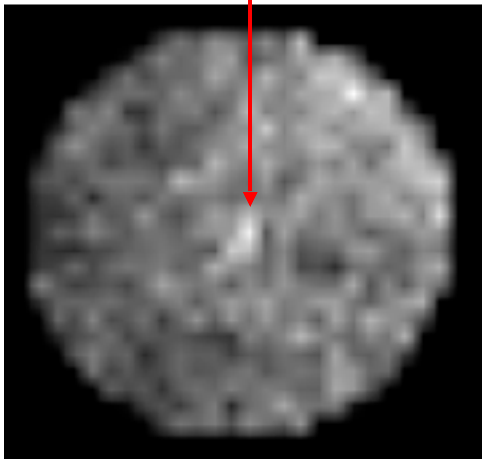
- Size: in-plane:~1-2mm^2, thickness: 60-100μm
- Neuronal Population: 10,000-100,000

- Spontaneous synchronized activity < 2Hz
- Epileptiform activity
- Spontaneous beta freq. activity (20-30Hz)
- Network Activity Range: ~ 0.5-15μV

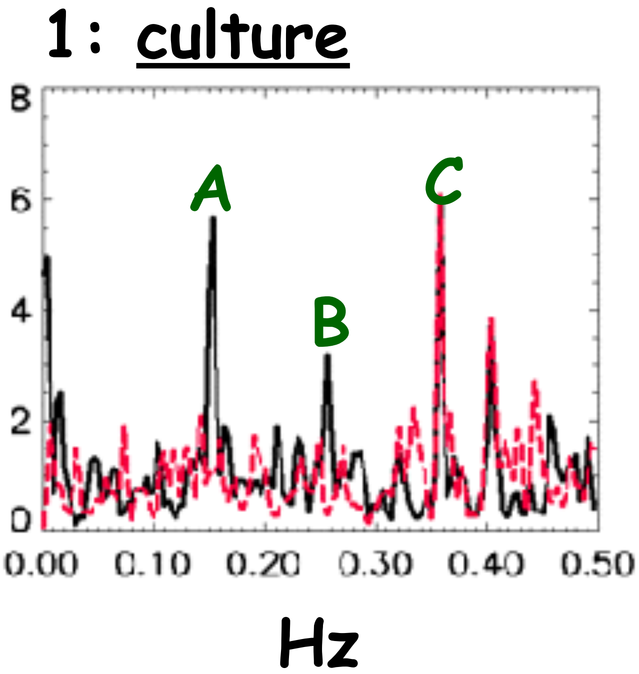
Plenz, D. et al. Neurosci 70(4): 861-924, 1996

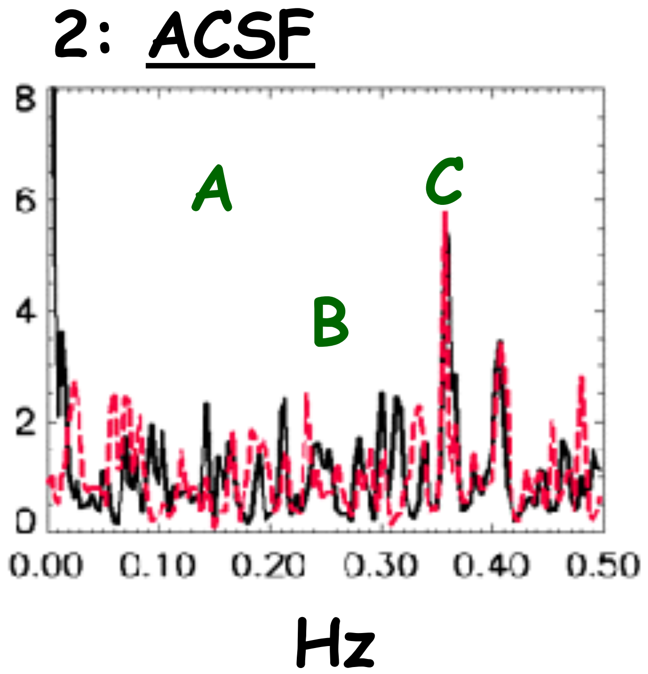


FSE image



0.15Hz map





Active condition: black line

Inactive condition: red line

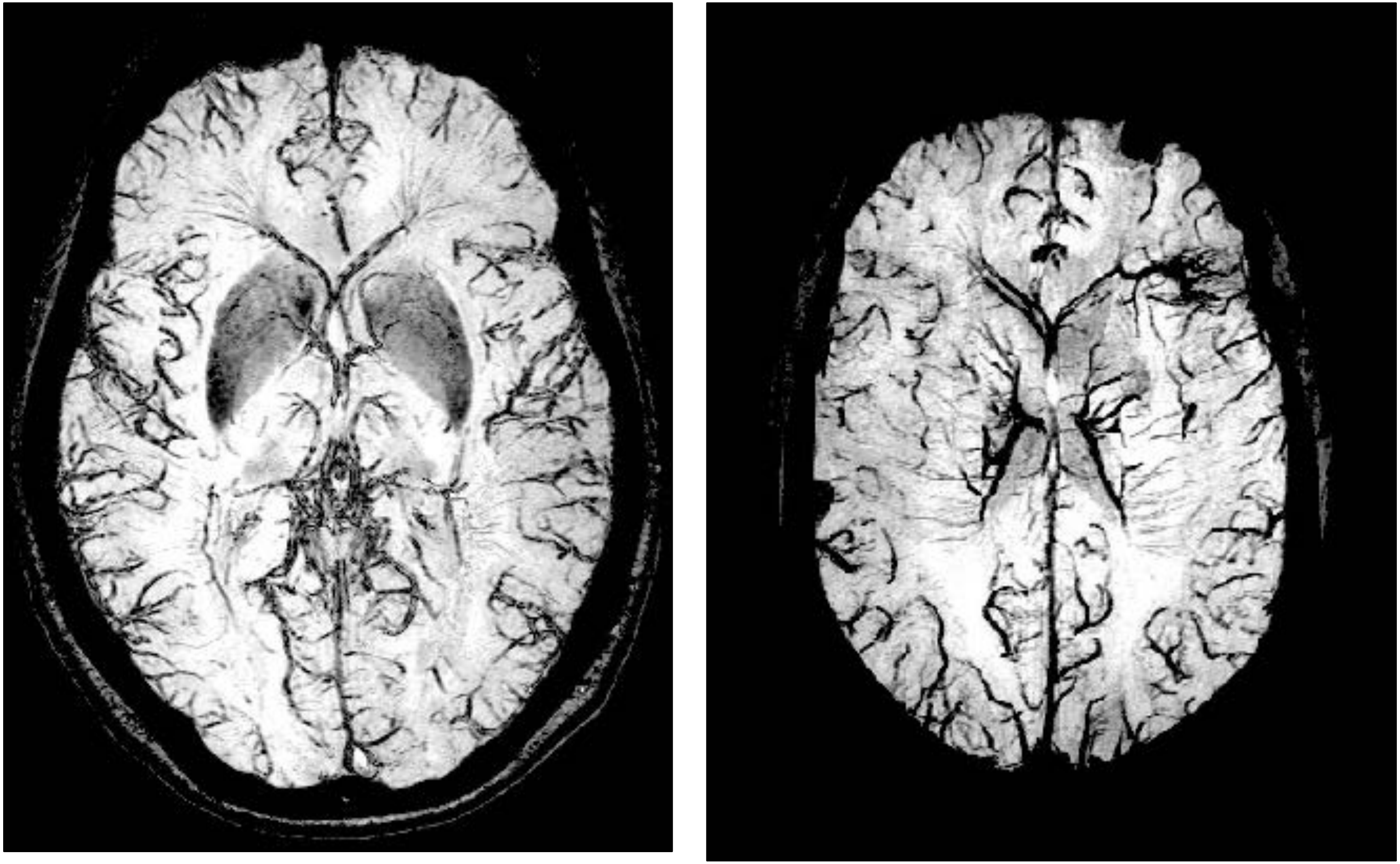
A: 0.15 Hz activity, on/off frequency

B: activity

C: scanner noise (cooling-pump)

N. Petridou, D. Plenz, A. C. Silva, J. Bodurka, M. Loew, P. A. Bandettini, Direct Magnetic Resonance detection of neuronal electrical activity, Proc. Nat'l. Acad. Sci. USA. 103, 16015-16020 (2006).

BOLD effect to highlight veins: 3 Tesla



Bove-Bettis, et al (2004), SMRT

Technology

ELSEVIER

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 29 (2006) 1013 – 1022

Rapid Communication

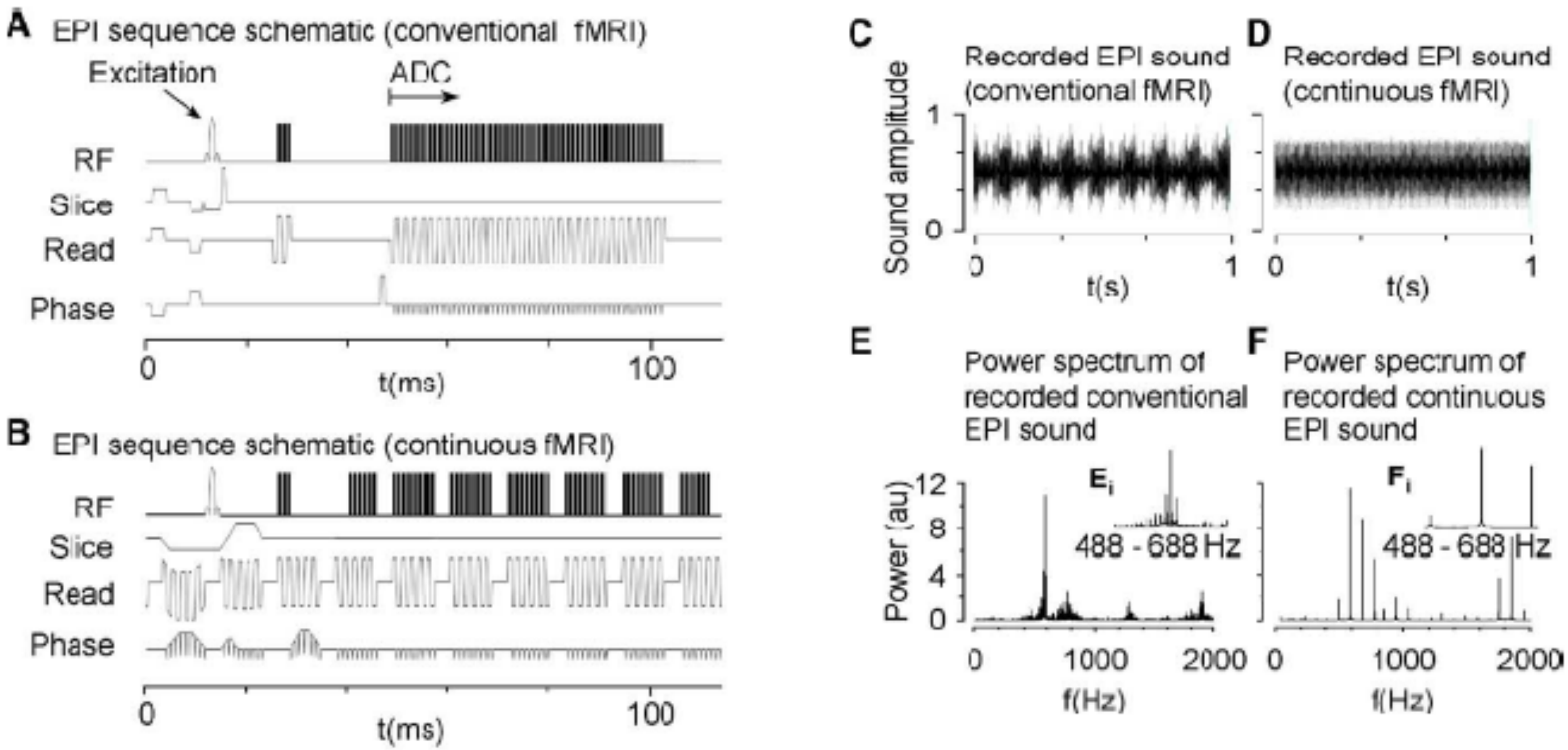
Enhancing BOLD response in the auditory system by neurophysiologically tuned fMRI sequence

Erich Seifritz,[a,b,*] Francesco Di Salle,[c] Fabrizio Esposito,[d] Marcus Herdener,[a,b] John G. Neuhoff,[e] and Klaus Scheffler[f]

[a]*University Hospital of Clinical Psychiatry, University of Bern, 3000 Bern, Switzerland*
[b]*Department of Psychiatry, University of Basel, 4025 Basel, Switzerland*
[c]*Department of Neurosciences, University of Pisa, 56126 Pisa, Italy*
[d]*Department of Neurological Sciences, University of Naples Federico II, 80127 Naples, Italy*
[e]*Department of Psychology, The College of Wooster, Wooster, OH 44691, USA*
[f]*MR-Physics, Department of Medical Radiology, University of Basel, 4031 Basel, Switzerland*

Received 26 May 2005; revised 22 July 2005; accepted 23 August 2005
Available online 25 October 2005

Technology



A EPI sequence schematic (conventional fMRI)
Excitation
ADC
RF
Slice
Read
Phase
0
t(ms)
100
B EPI sequence schematic (continuous fMRI)
RF
Slice
Read
Phase
0
t(ms)
100
C
Recorded EPI sound (conventional fMRI)
Sound amplitude
1
0
0
t(s)
1
D
Recorded EPI sound (continuous fMRI)
0
t(s)
1
E
Power spectrum of recorded conventional EPI sound
Power (au)
12
8
4
0
E_i
488 - 688 Hz
0
1000
2000
f(Hz)
F
Power spectrum of recorded continuous EPI sound
F_i
488 - 688 Hz
0
1000
2000
f(Hz)

Technology

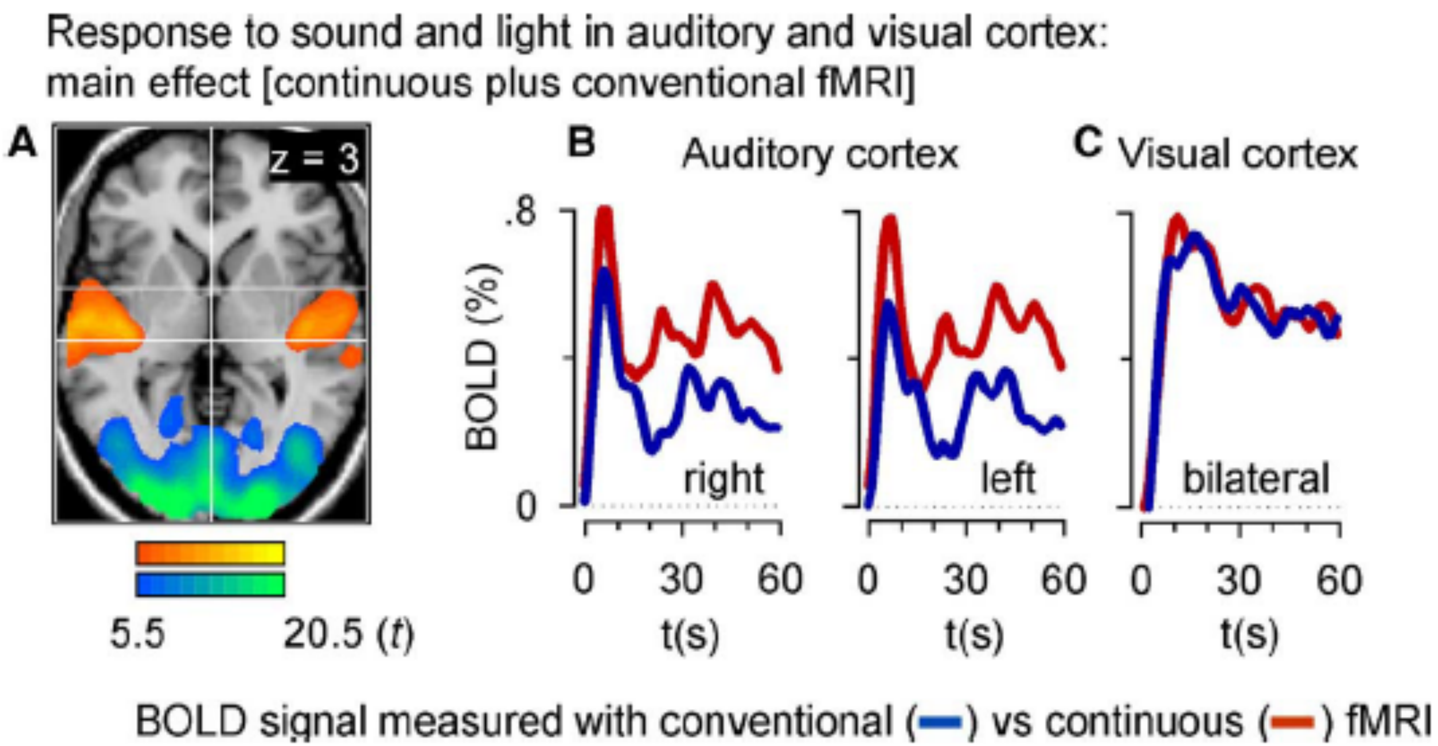


Fig. 4. (A) Main effects of response to pulsed sound and light measured with continuous-sound and conventional fMRI ($P_{corrected} \leq 0.001$). Corresponding BOLD signal time-course in auditory (B) and visual (C) cortex (red, measured with continuous-sound fMRI; blue, measured with conventional fMRI). Note, continuous-sound fMRI produced an enhanced BOLD signal only in the auditory but not in the visual system, demonstrating a domain-specific physiological effect.

Technology

Coil arrays
High field strength
High resolution
Novel functional contrast

Methodology

Connectivity assessment
Multi-modal integration
Pattern classification
Task design

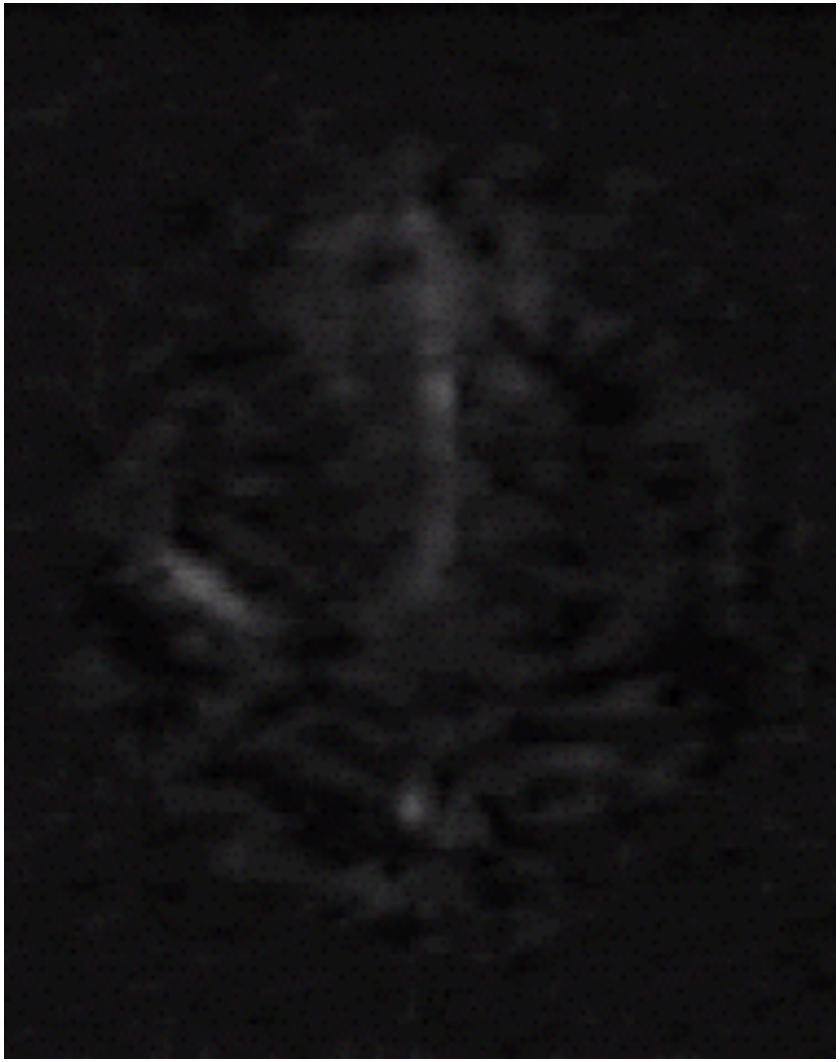
Fluctuations
Dynamics
Cross - modal comparison

Interpretation

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

Applications

Methodology



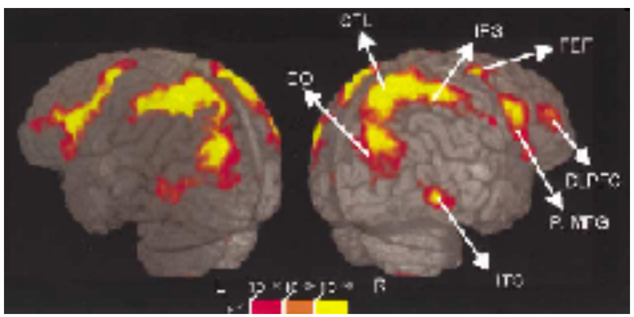
Mapping ⟷ "Reading"

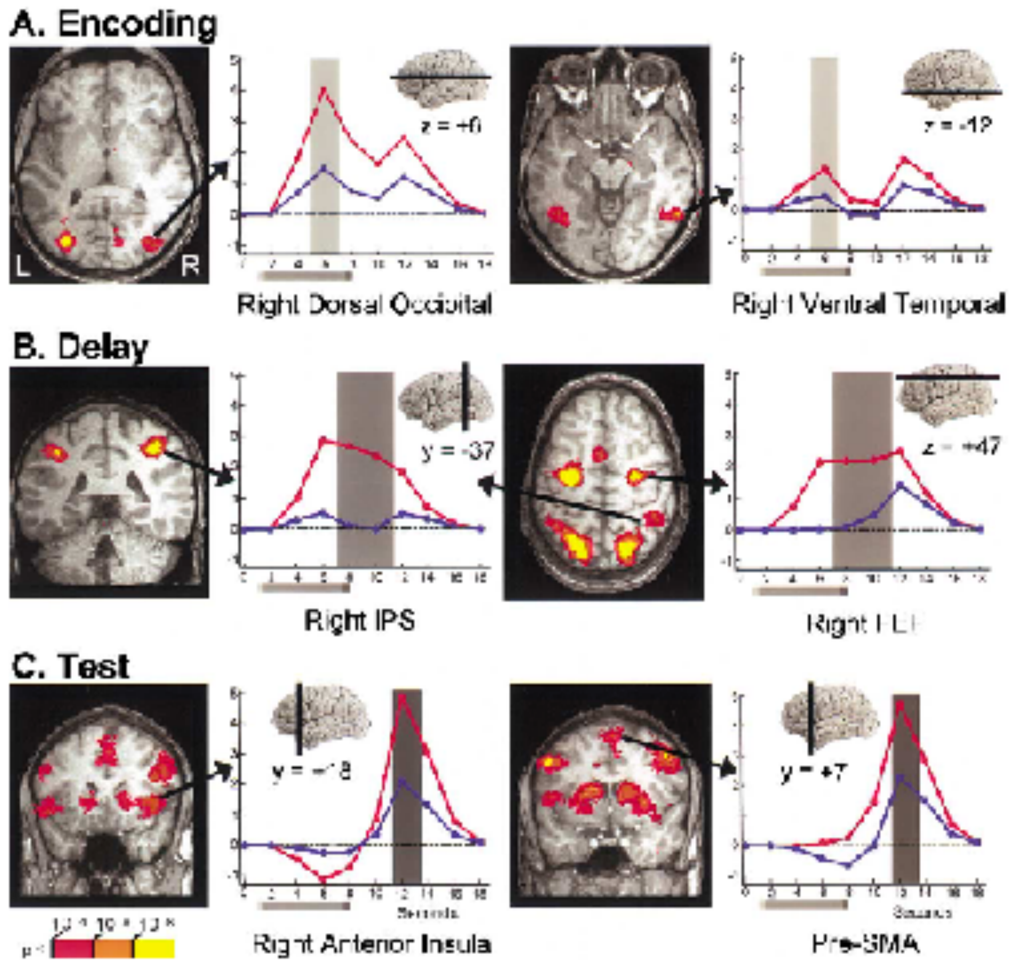
Methodology

Neuron, Vol. 35, 975–987, August 29, 2002, Copyright ©2002 by Cell Press

Neural Correlates of Visual Working Memory: fMRI Amplitude Predicts Task Performance

Luiz Pessoa,[1] Eva Gutierrez, Peter A. Bandettini, and Leslie G. Ungerleider
Laboratory of Brain and Cognition
National Institute of Mental Health
National Institutes of Health
Bethesda, Maryland 20892

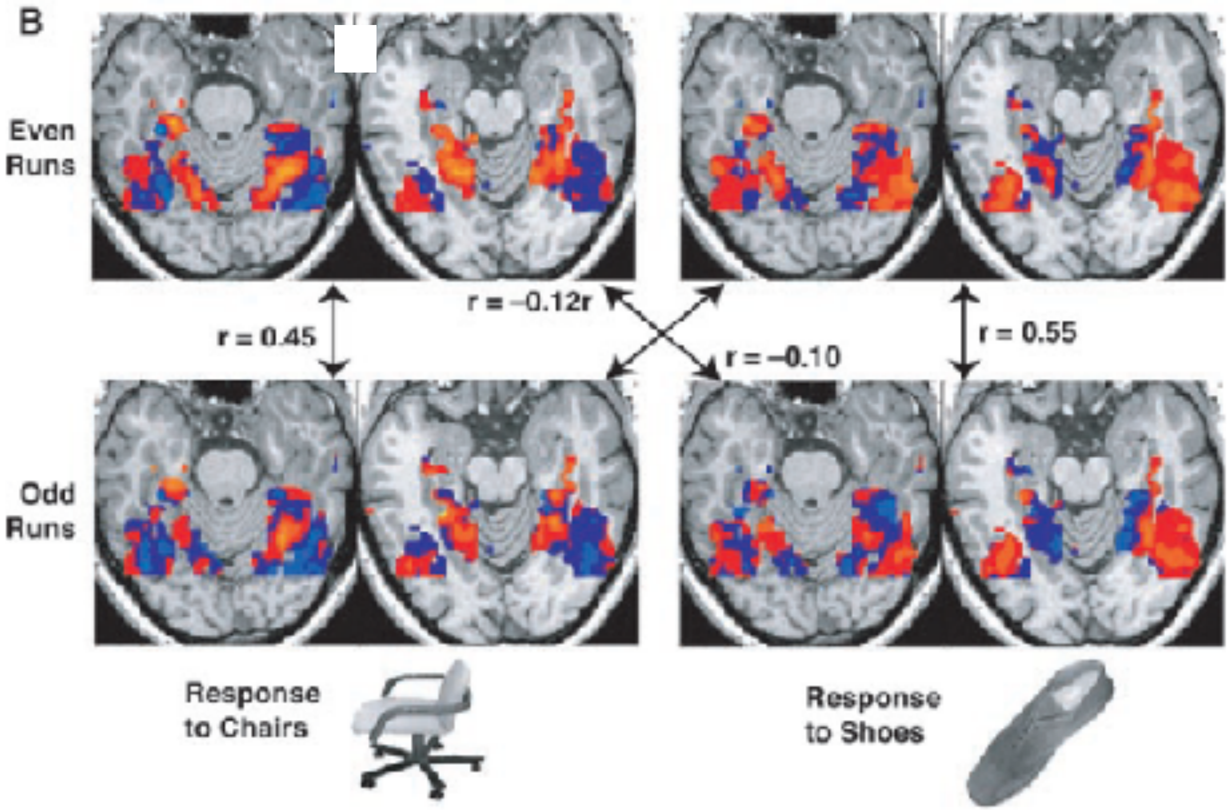




Methodology

Ventral temporal category representations

Object categories are associated with distributed representations in ventral temporal cortex



Haxby et al. 2001

Methodology

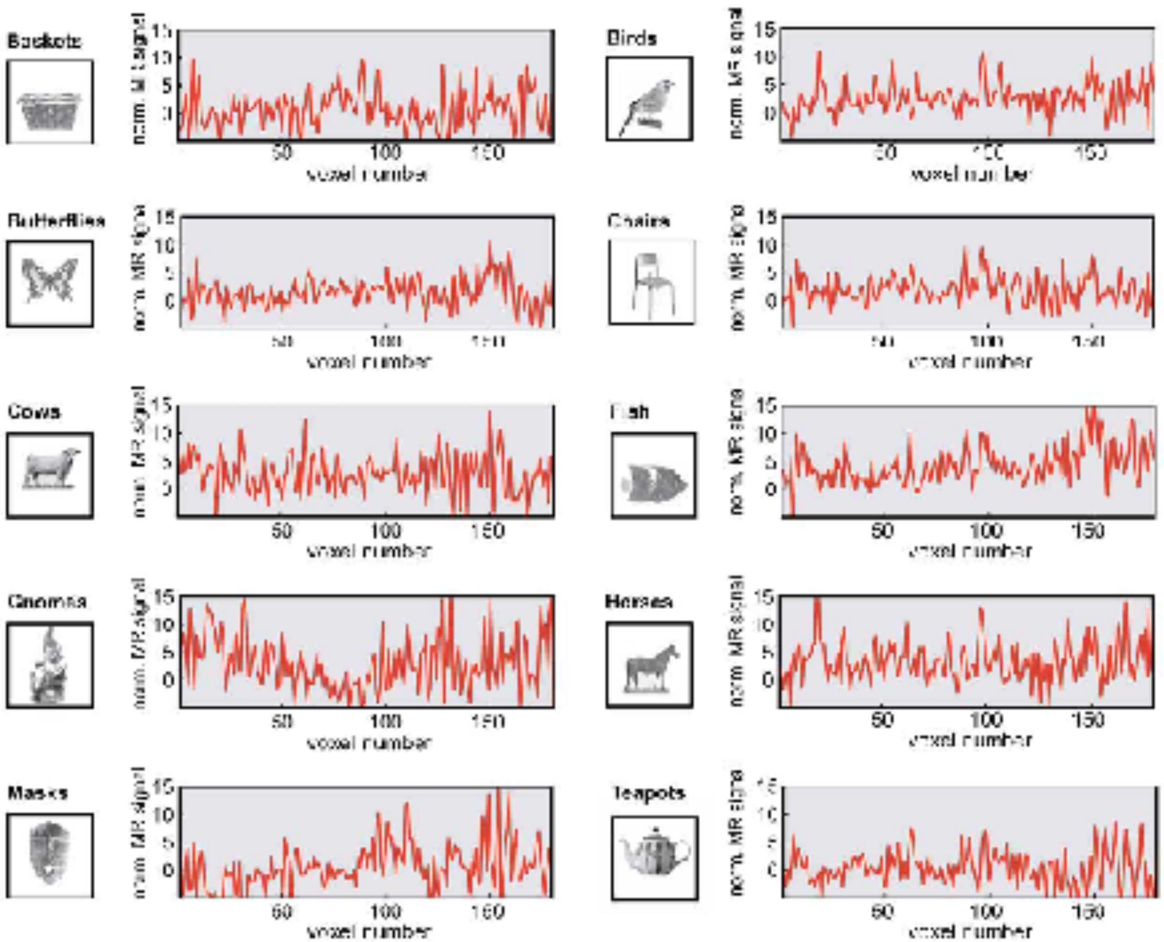
Functional magnetic resonance imaging (fMRI) "brain reading": detecting and classifying distributed patterns of fMRI activity in human visual cortex

David D. Cox[a,b,*] and Robert L. Savoy[a,b,c]

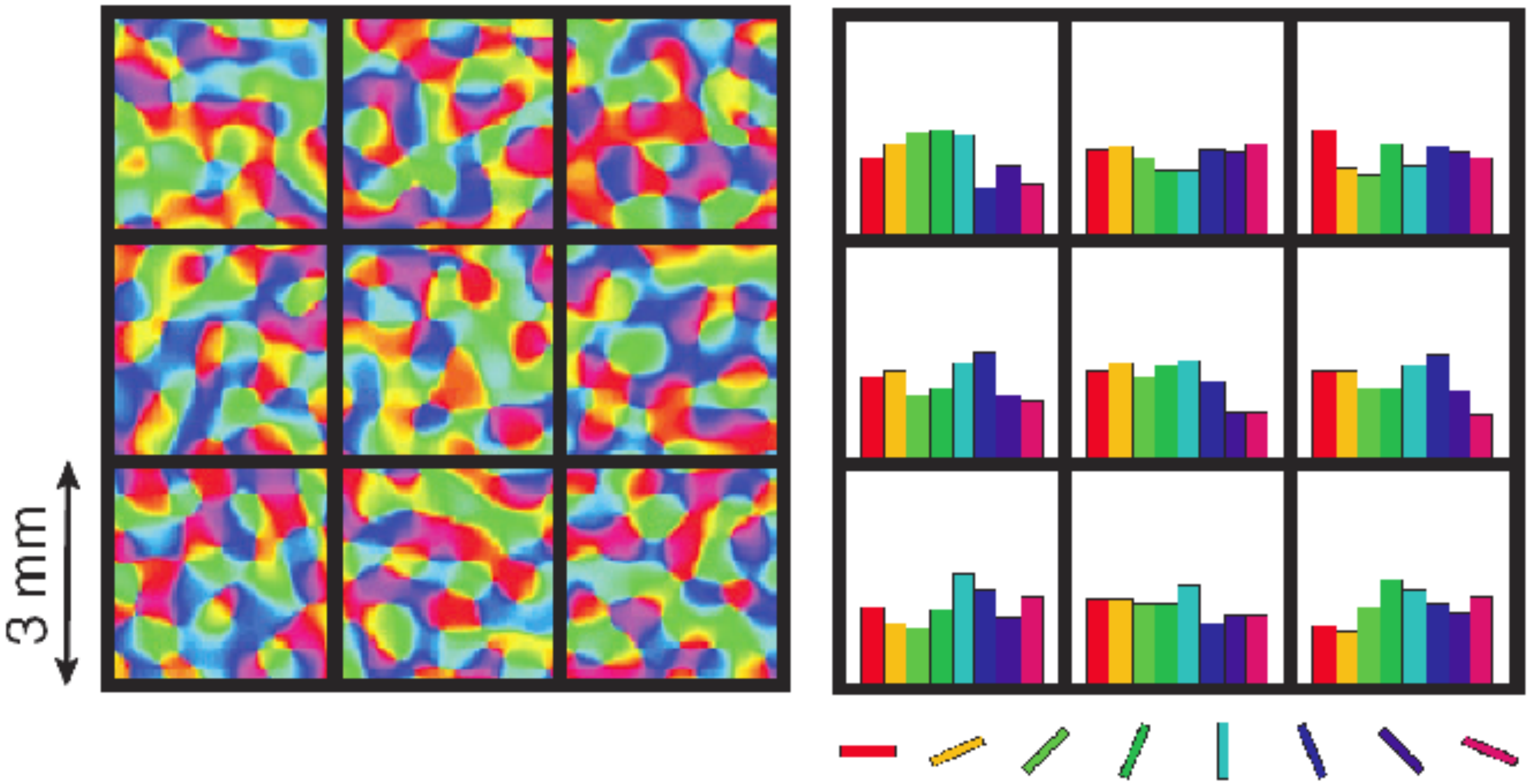
[a] Rowland Institute for Science, Cambridge, MA 02142, USA
[b] Athinoula A. Martinos Center for Structural and Functional Biomedical Imaging, Charlestown, MA 02129, USA
[c] HyperVision, Inc., P.O. Box 158, Lexington, MA 02420, USA

Received 15 July 2002; accepted 10 December 2002

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



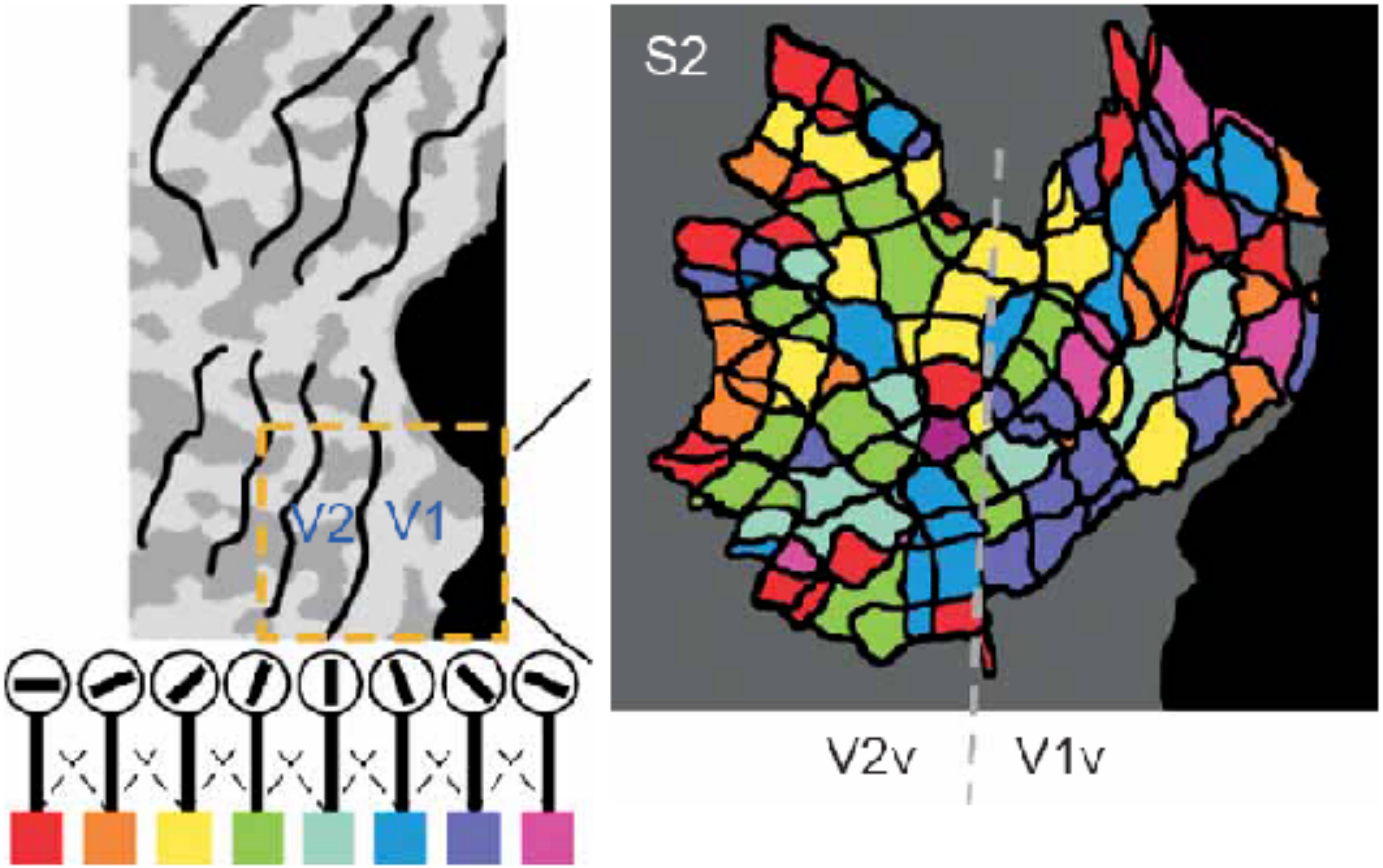
Methodology



Boynton (2005), News & Views on Kamitani & Tong (2005) and Haynes & Rees (2005)

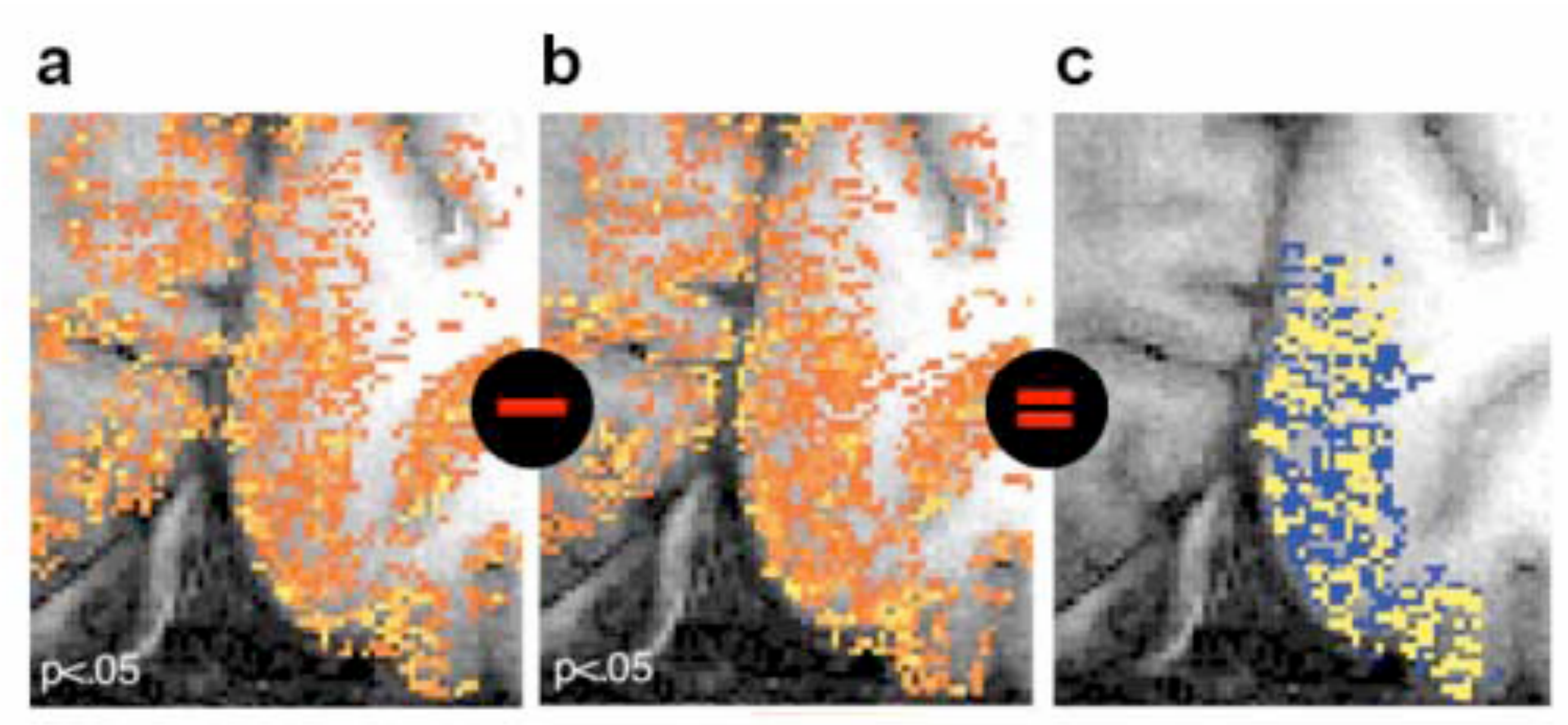
Methodology

Lower spatial frequency clumping



Kamitani & Tong (2005)

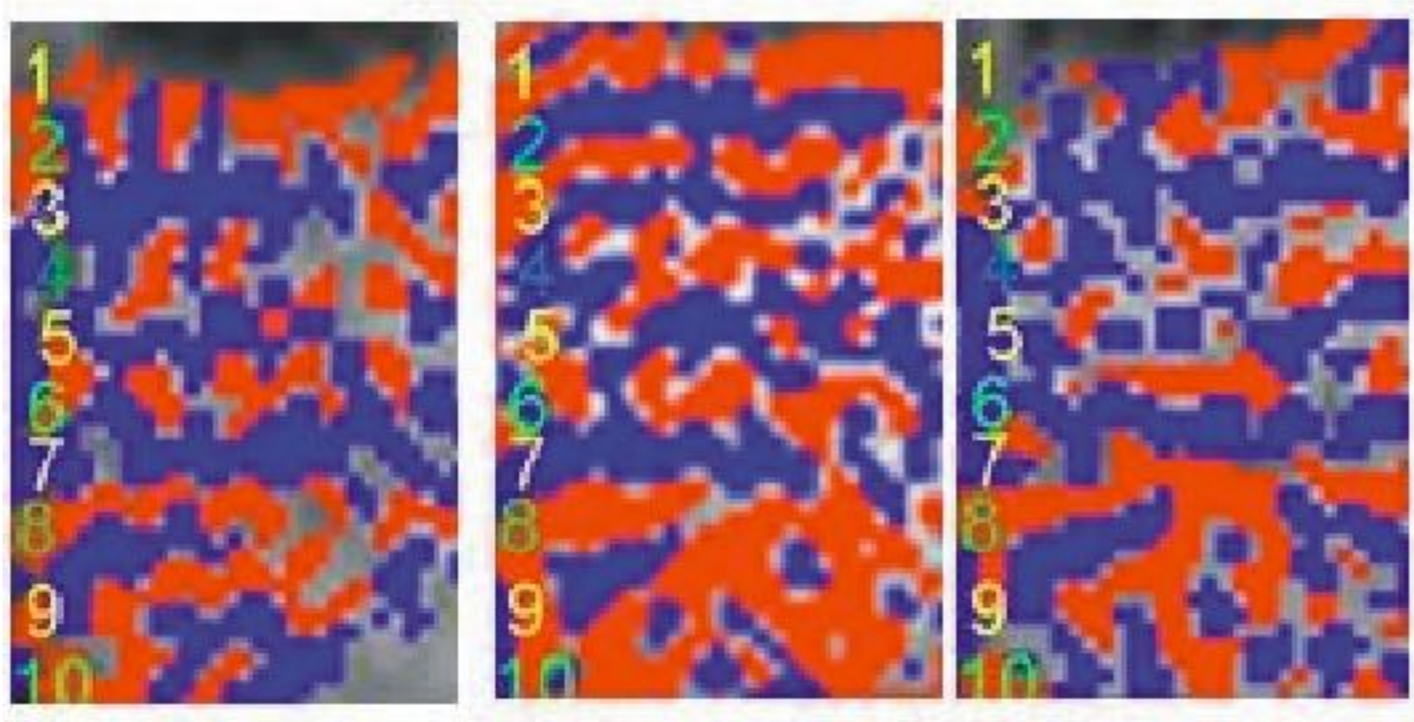
What to do with high resolution data?



What to do with high resolution data?

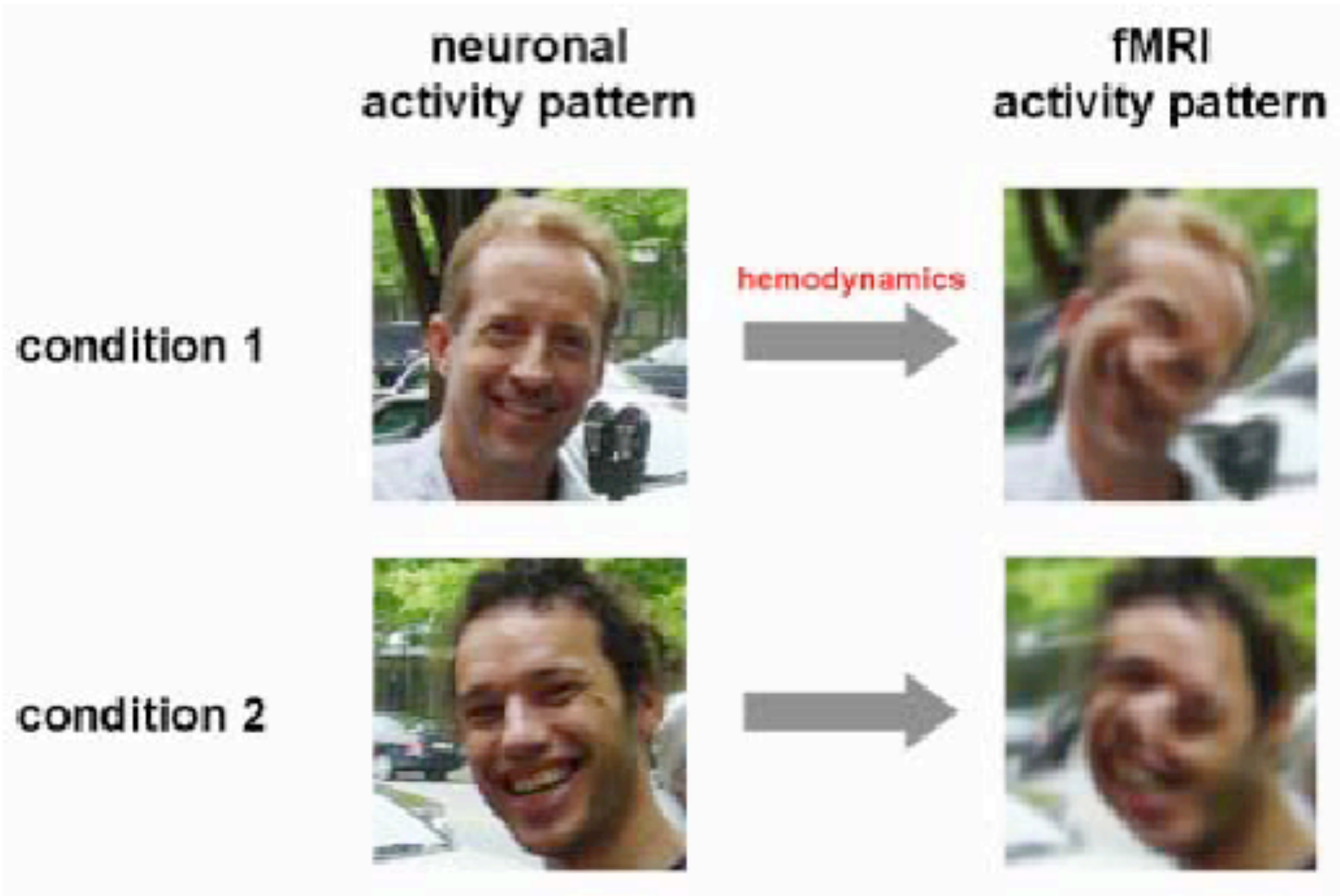
HSE-BOLD demonstration of ocular dominance columns

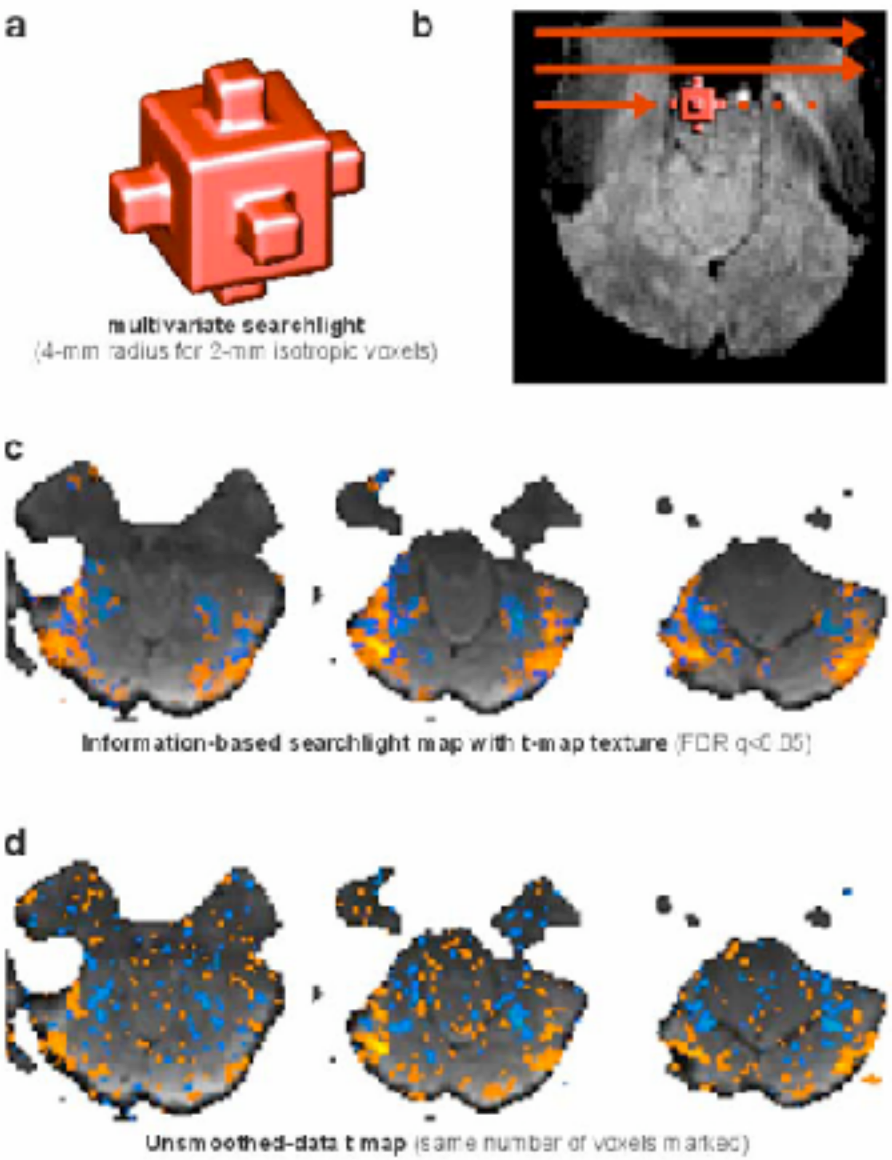
human, 7T, 0.5×0.5×3 mm^3

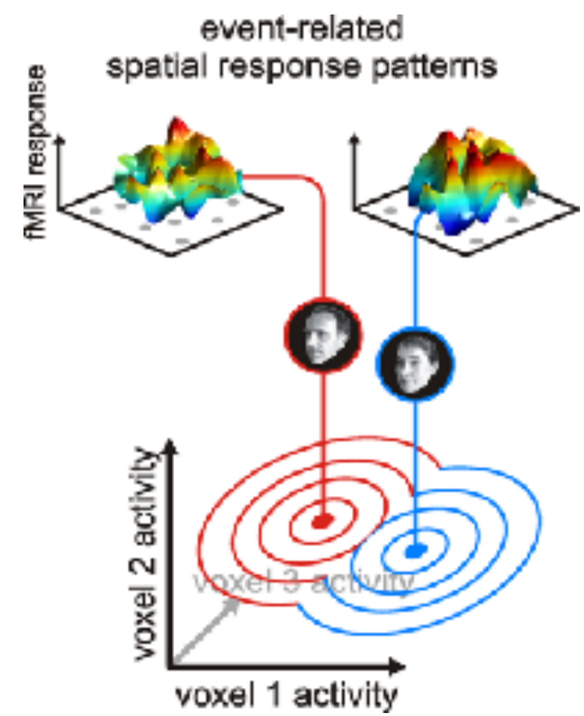


day 1 **day 2** **day 3**

Yacoub et al: differential maps contrasting stimulation of the left and right eye


neuronal
activity pattern
fMRI
activity pattern
condition 1
hemodynamics
condition 2





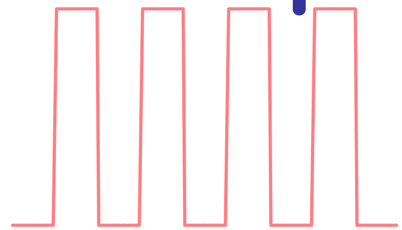
N. Kriegeskorte, R. Goebel, P. Bandettini, Information-based functional brain mapping. Proc. Nat'l. Acad. Sci. USA, 103, 3863-3868 (2006).

Pattern-recognition analysis of fMRI activity patterns

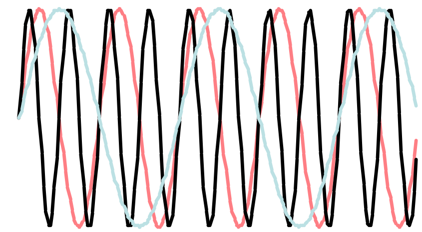
- Haxby et al. (2001)
- Cox & Savoy (2003)
- Carlson et al. (2003)
- Kamitani & Tong (2005)
- Haynes & Rees (2005)
- Kriegeskorte et al (2006)

Neuronal Activation Input Strategies

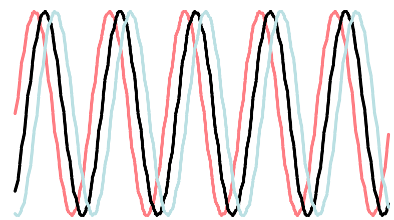
1. Block Design



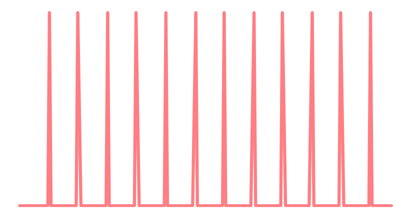
2. Frequency Encoding



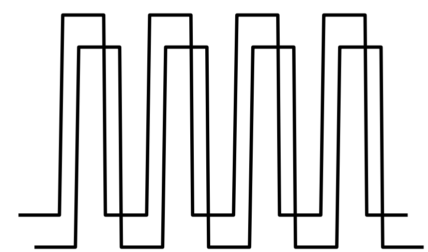
3. Phase Encoding



4. Event-Related

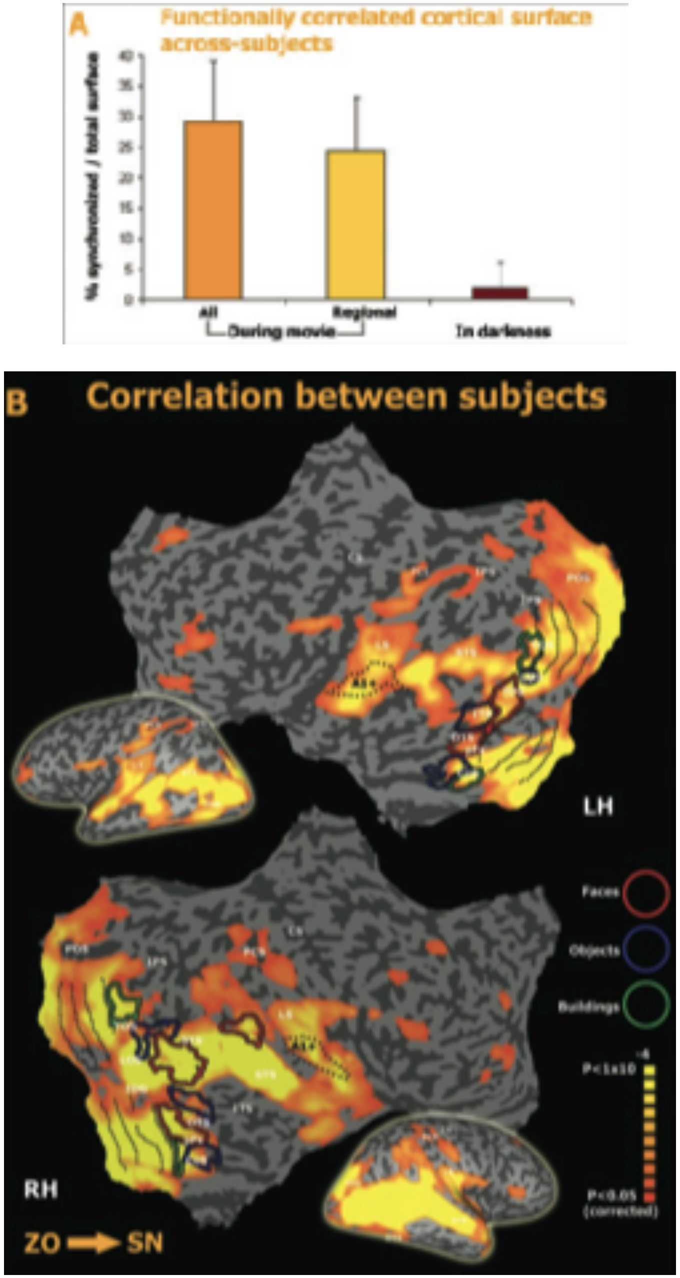


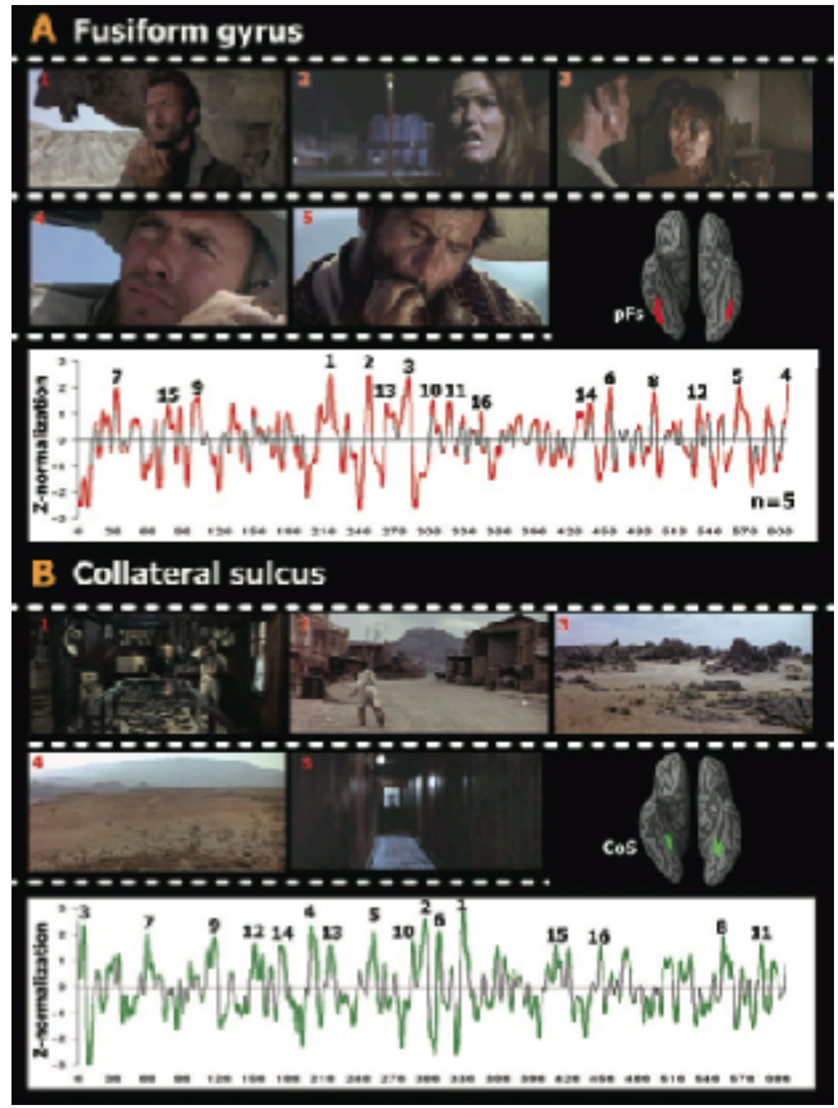
5. Orthogonal Block Design



6. Free Behavior Design.

Methodology

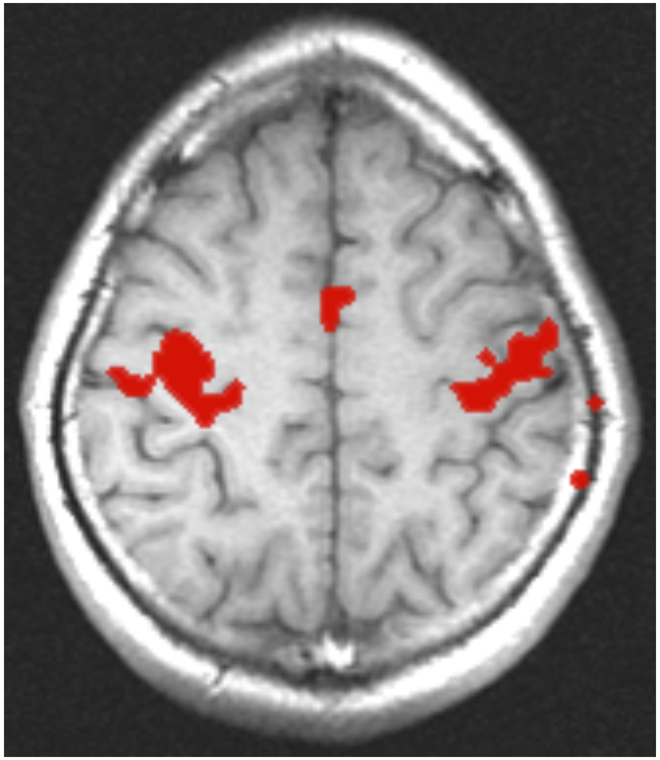




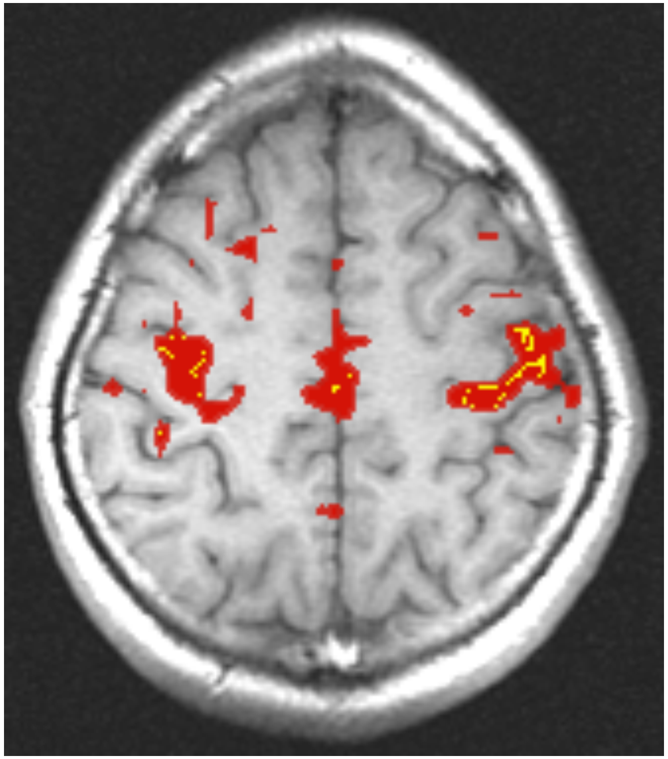
Hasson, et al (2004), Science, 303, 1634-1640

Resting State

Resting State Correlations



Activation:
correlation with reference function



Rest:
seed voxel in motor cortex

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

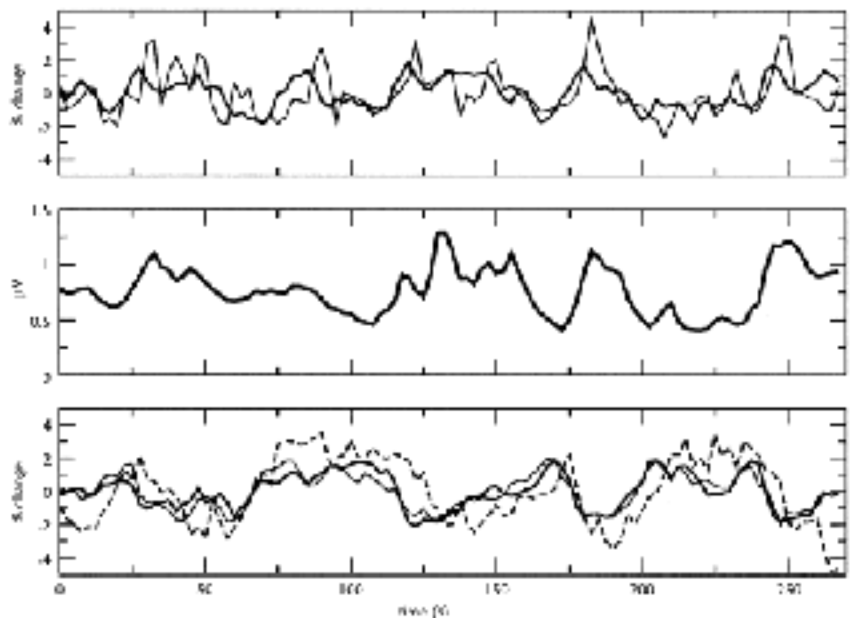
Resting State

BOLD correlated with 10 Hz power during "Rest"

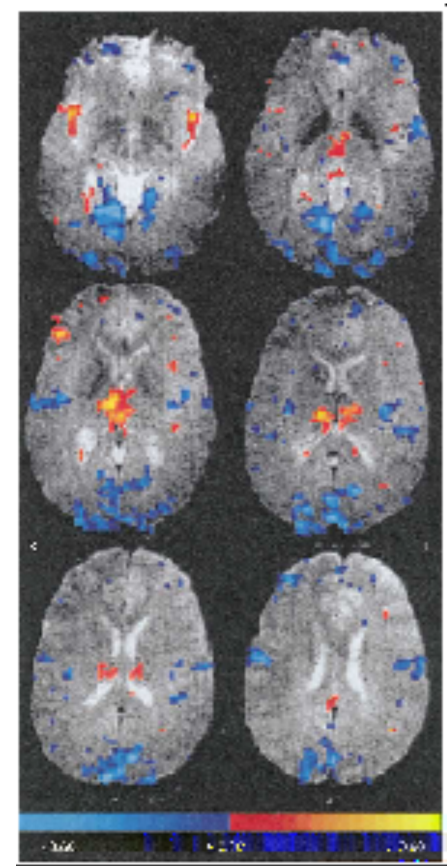
Positive

10 Hz power

Negative

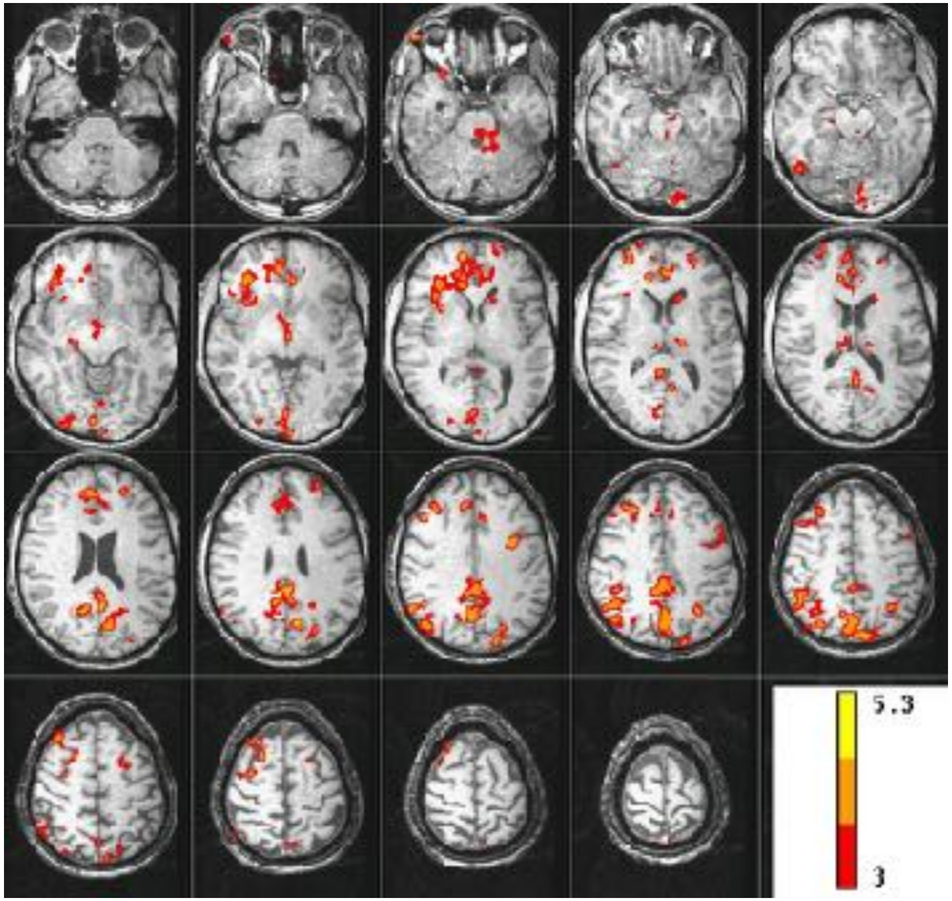


Goldman, et al (2002), Neuroreport



Resting State

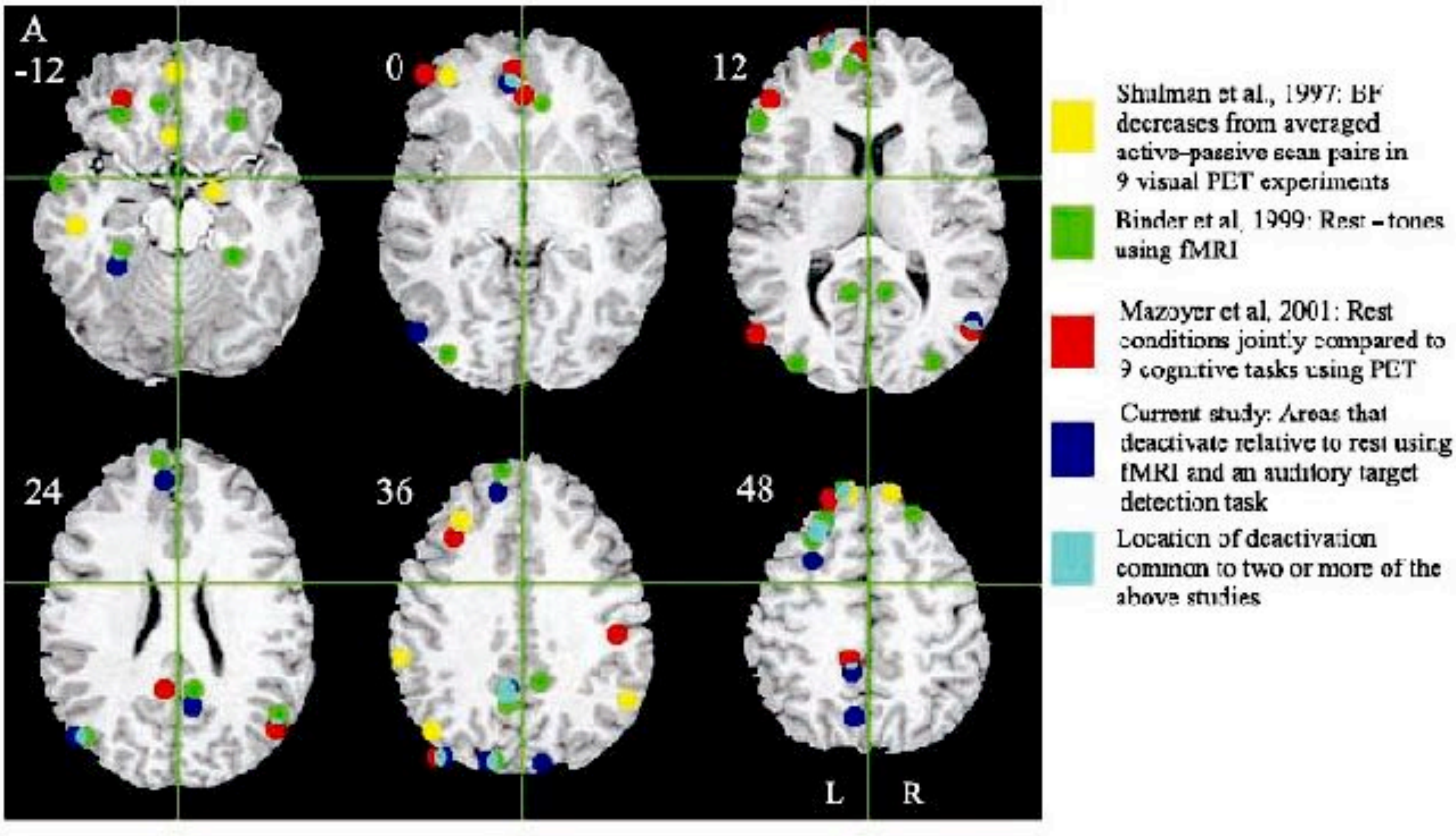
BOLD correlated with SCR during "Rest"



J. C. Patterson II, L. G. Ungerleider, and P. A Bandettini, NeuroImage 17: 1787-1806, (2002).

Resting State

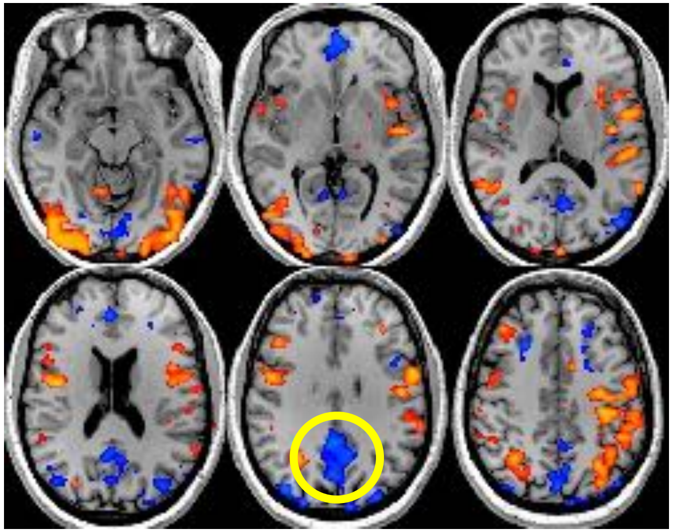
Regions showing decreases during cognitive tasks



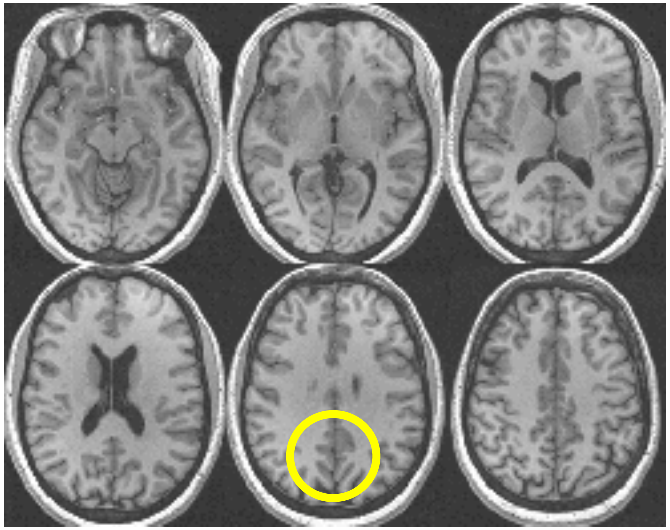
McKiernan, et al (2003), Journ. of Cog. Neurosci. 15 (3), 394-408

Resting State Correlations vs Signal Decreases

- Filter (respiration (0.3Hz), cardiac (1 Hz))
- Define ROI (e.g. deactivations in posterior cingulate)
- Average time courses (at rest) in ROI
- Correlate average time course with all voxels



Lexical task



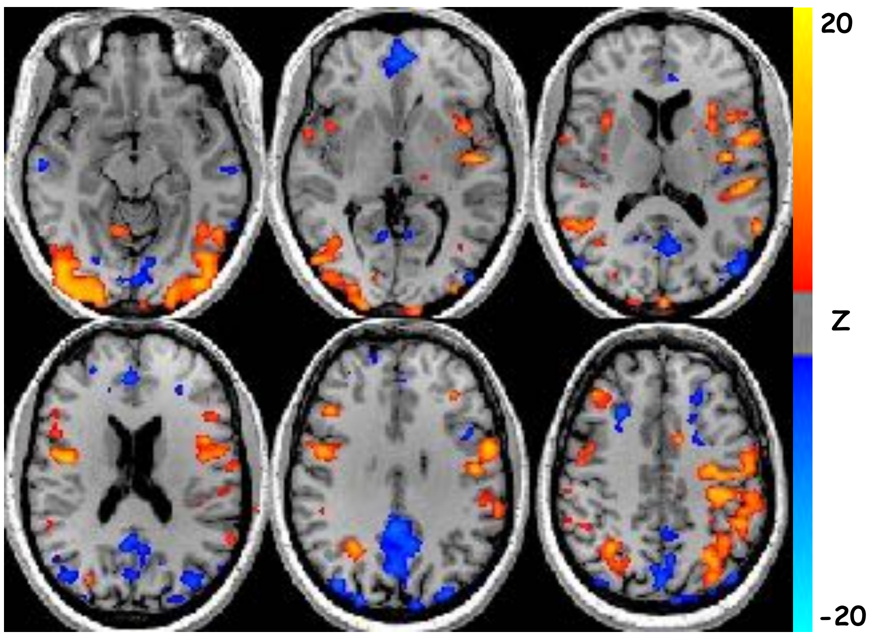
Rest

R. M. Birn, J. B. Diamond, M. A. Smith, P. A. Bandettini, Separating respiratory variation-related fluctuations from neuronal activity-related fluctuations in fMRI, NeuroImage 31, 1536-1548 (2006)

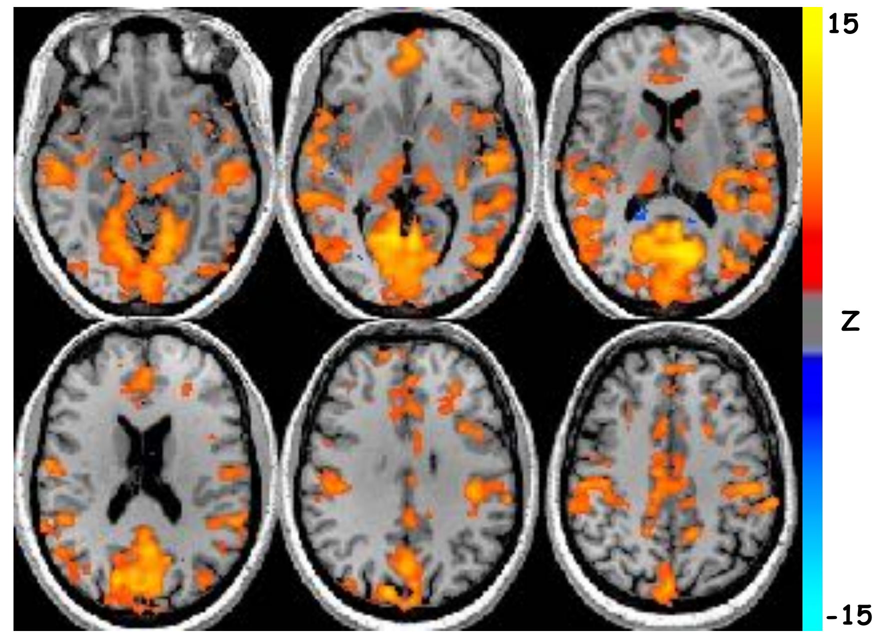
Resting State

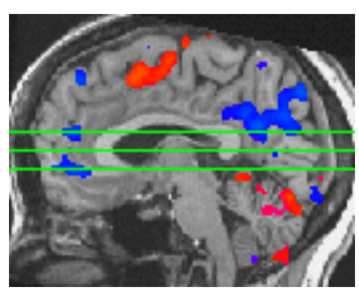
1 subject

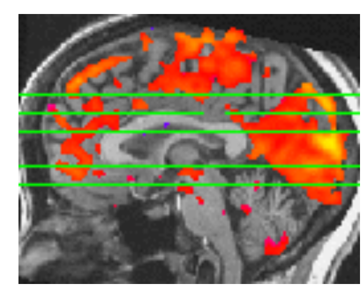
Activations during lexical task



Correlation (of PC) at Rest



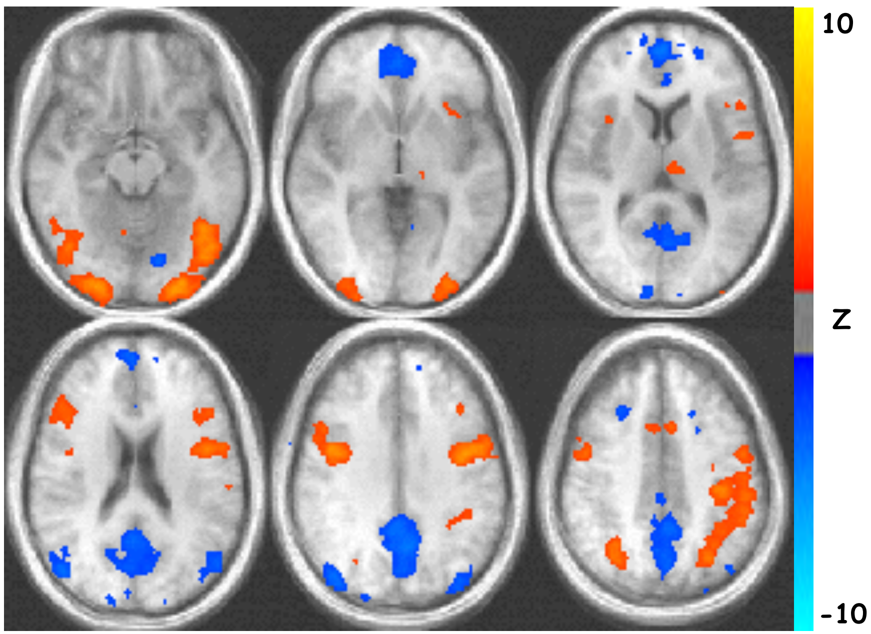


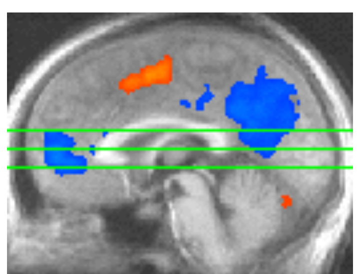


Resting State

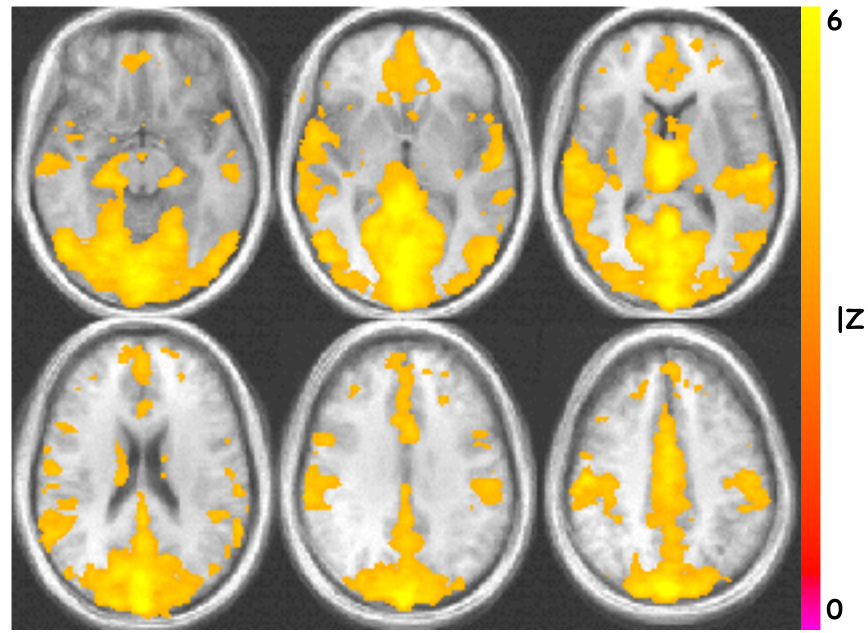
Group (n=10)

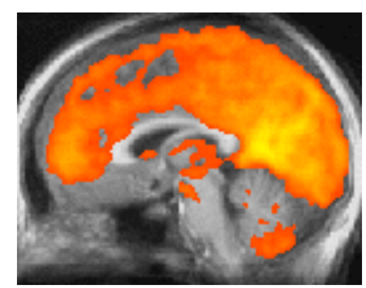
Activations during lexical task





Correlation (of PC) at Rest





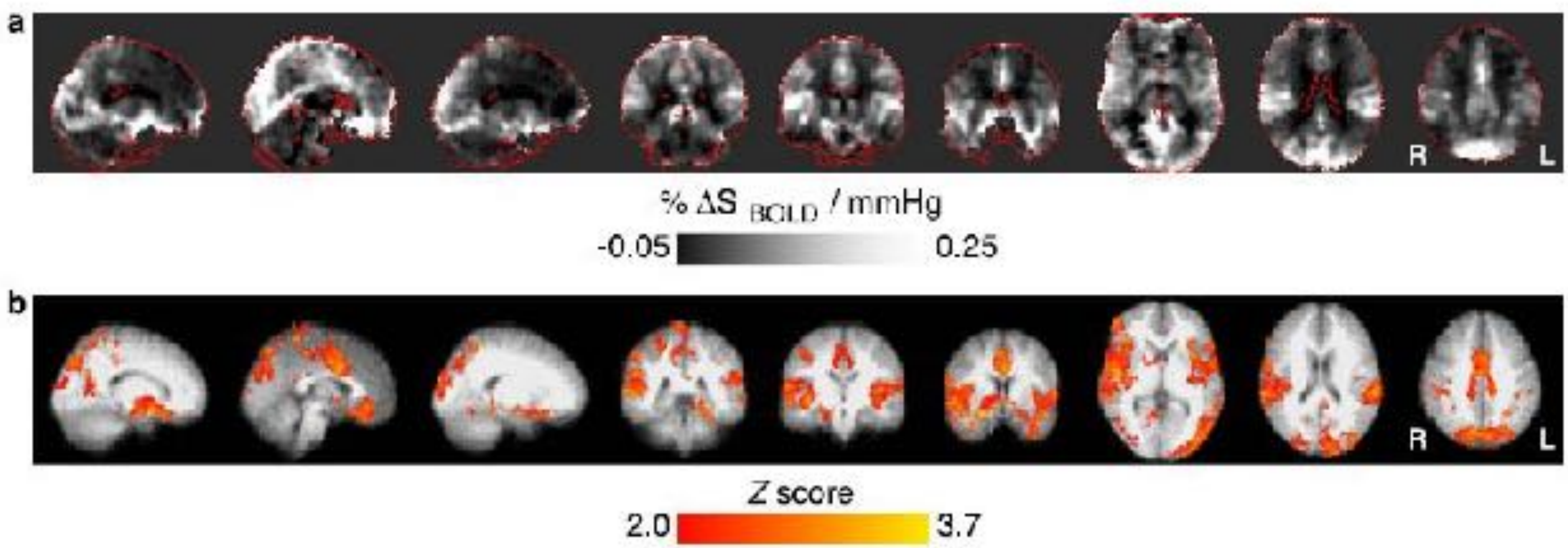
Respiration related

Resting fluctuations in respiration

Resting fluctuations in arterial carbon dioxide induce significant low frequency variations in BOLD signal

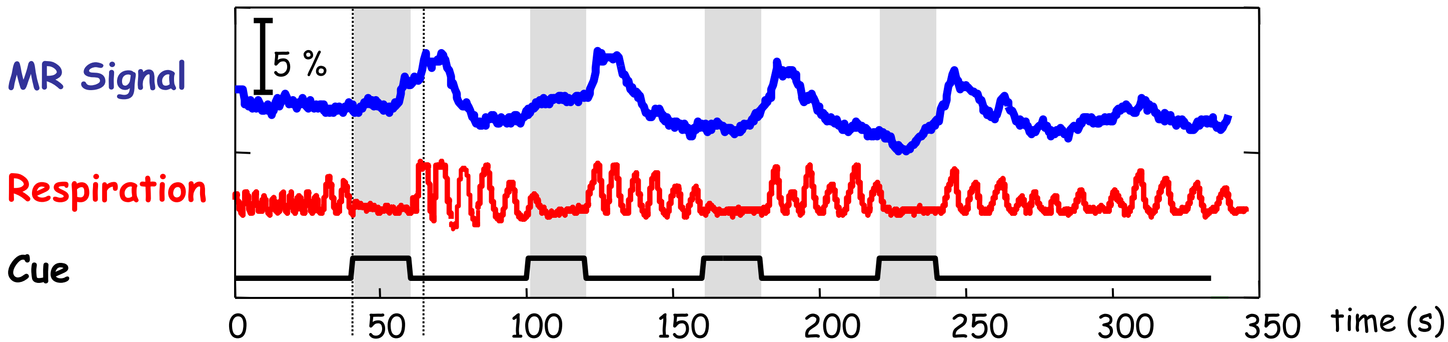
Richard G. Wise,[a,b,*] Kojiro Ide,[c,d] Marc J. Poulin,[c,d] and Irene Tracey[a,b]

NeuroImage 21, 2004

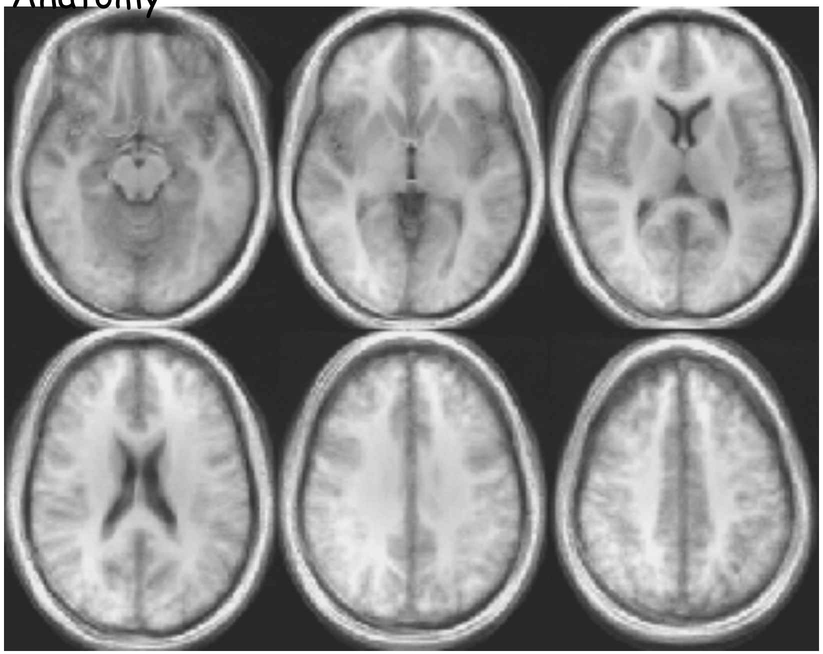


Respiration related

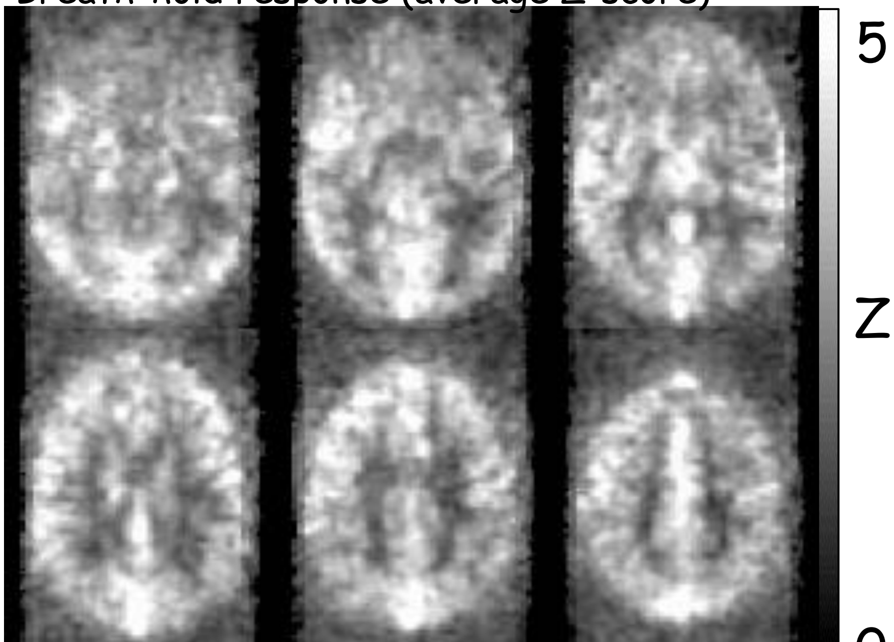
Breath-holding Group Maps (N = 7)



Anatomy

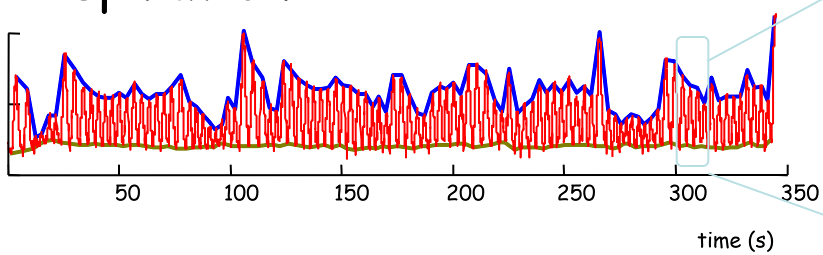


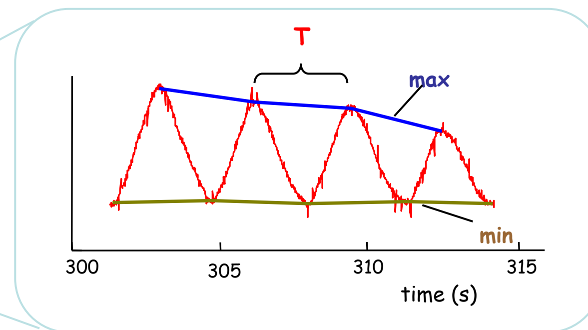
Breath-hold response (average Z-score)



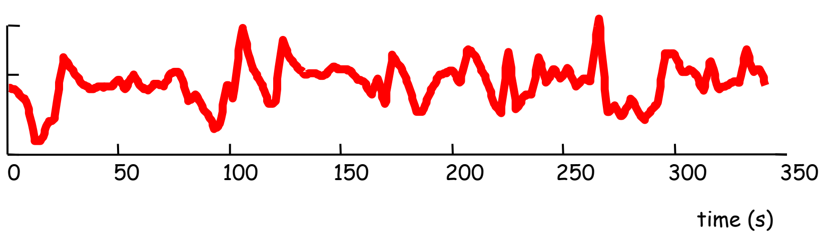
Estimating respiration volume changes

Respiration





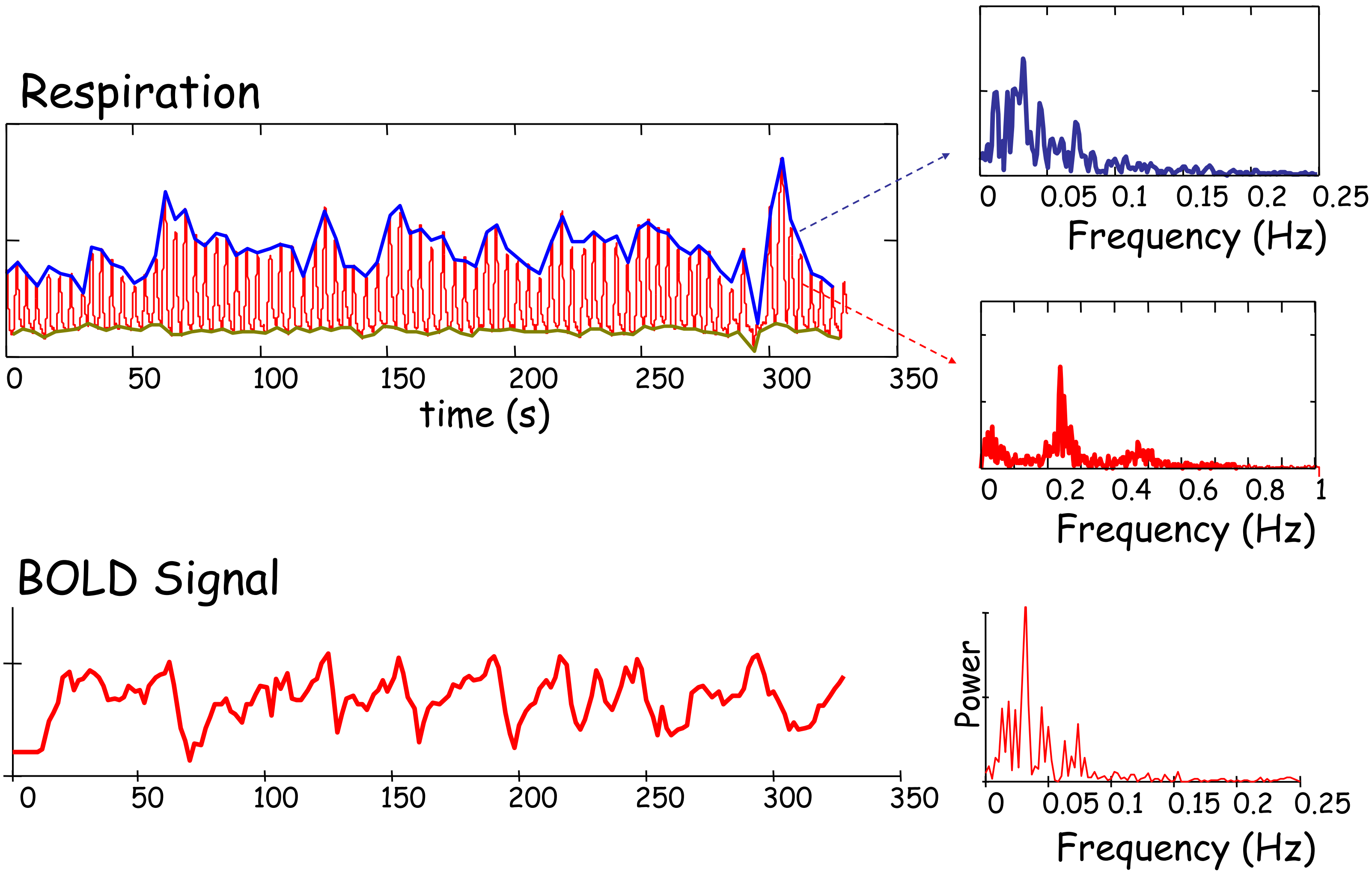
Respiration Volume / Time (**RVT**)



$$\mathbf{RVT} = \frac{\text{max} - \text{min}}{T}$$

Respiration related

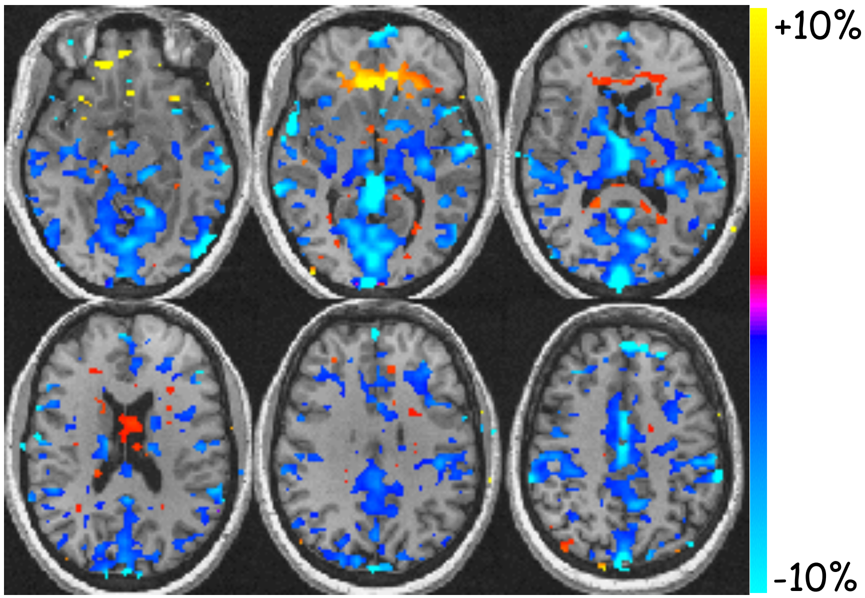
Resting fluctuations in respiration



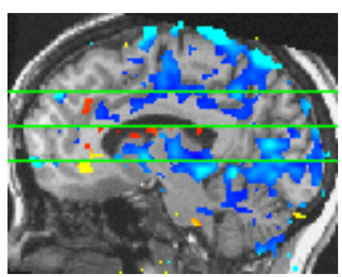
Respiration related

RVT related fluctuations

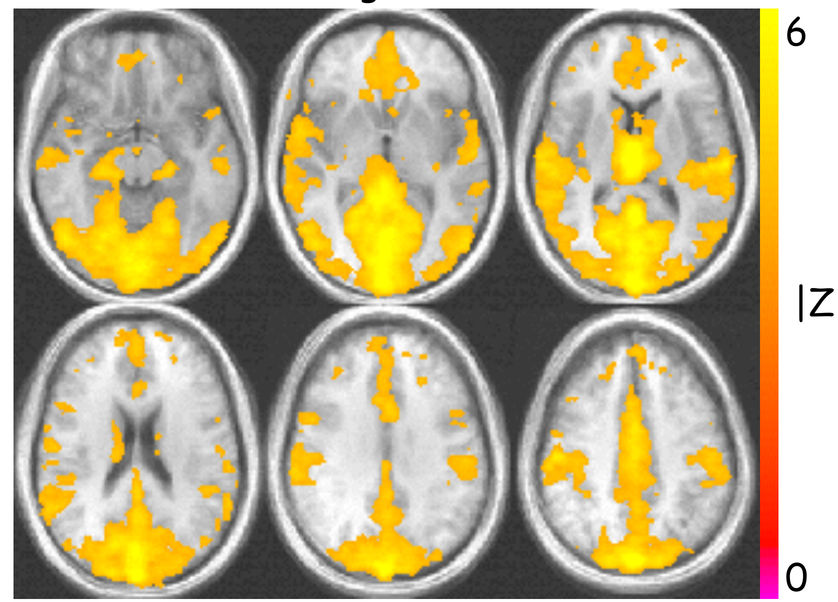
Amplitude of BOLD signal correlated w/ RVT



1 subject



Z-score of BOLD signal correlated w/ RVT

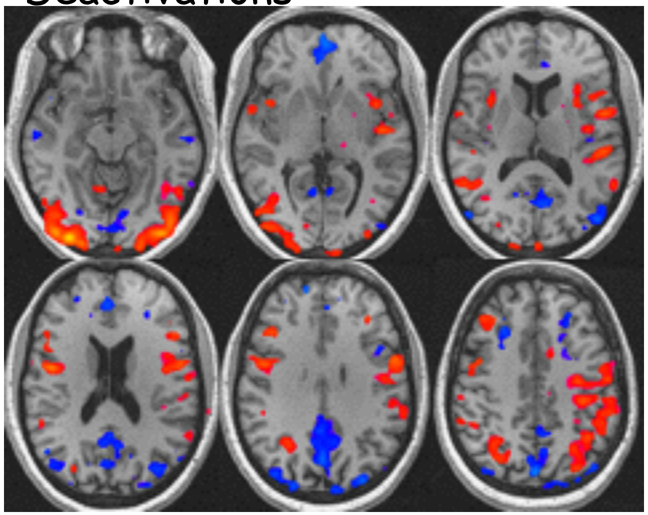


group (n=11)

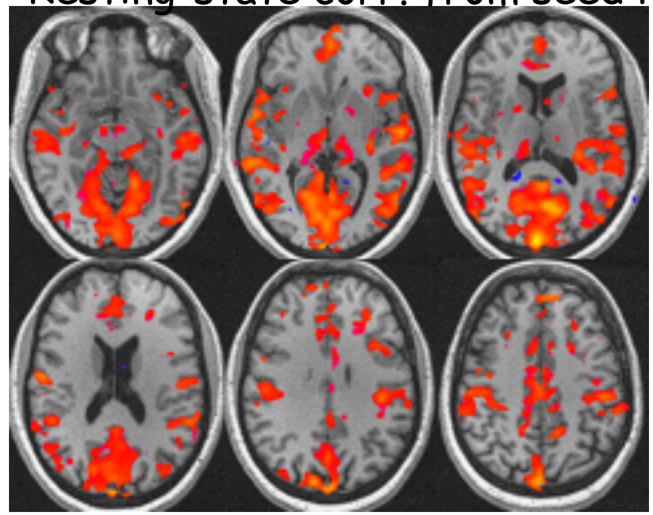
RVT = Respiration Volume per Time

RVT changes co-localize

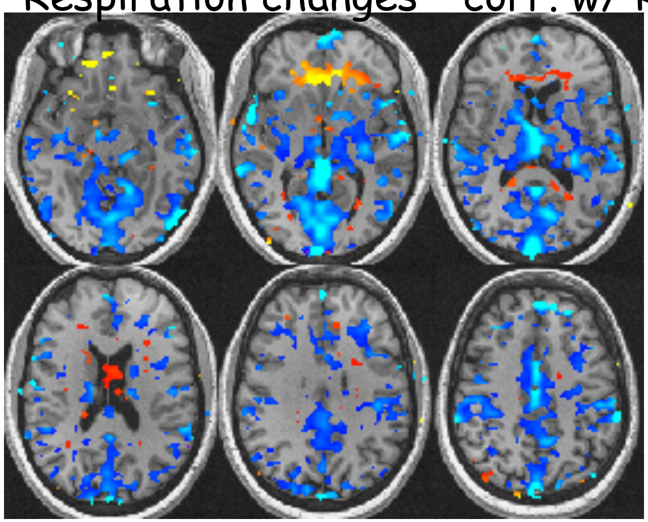
Deactivations

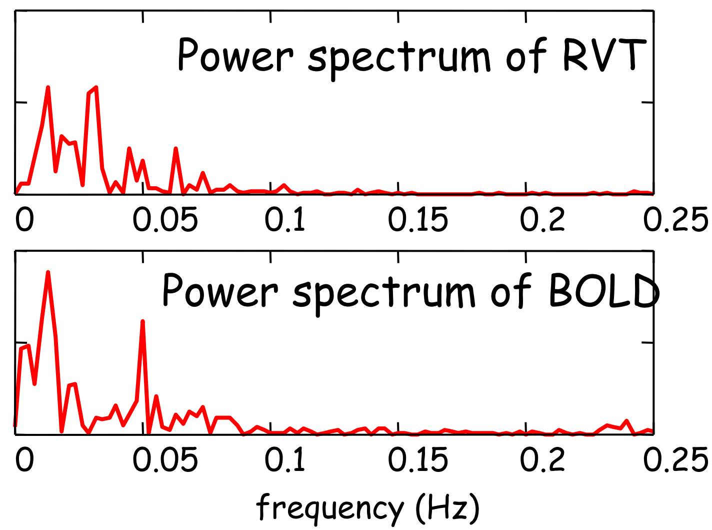


Resting-state corr. from seed ROI



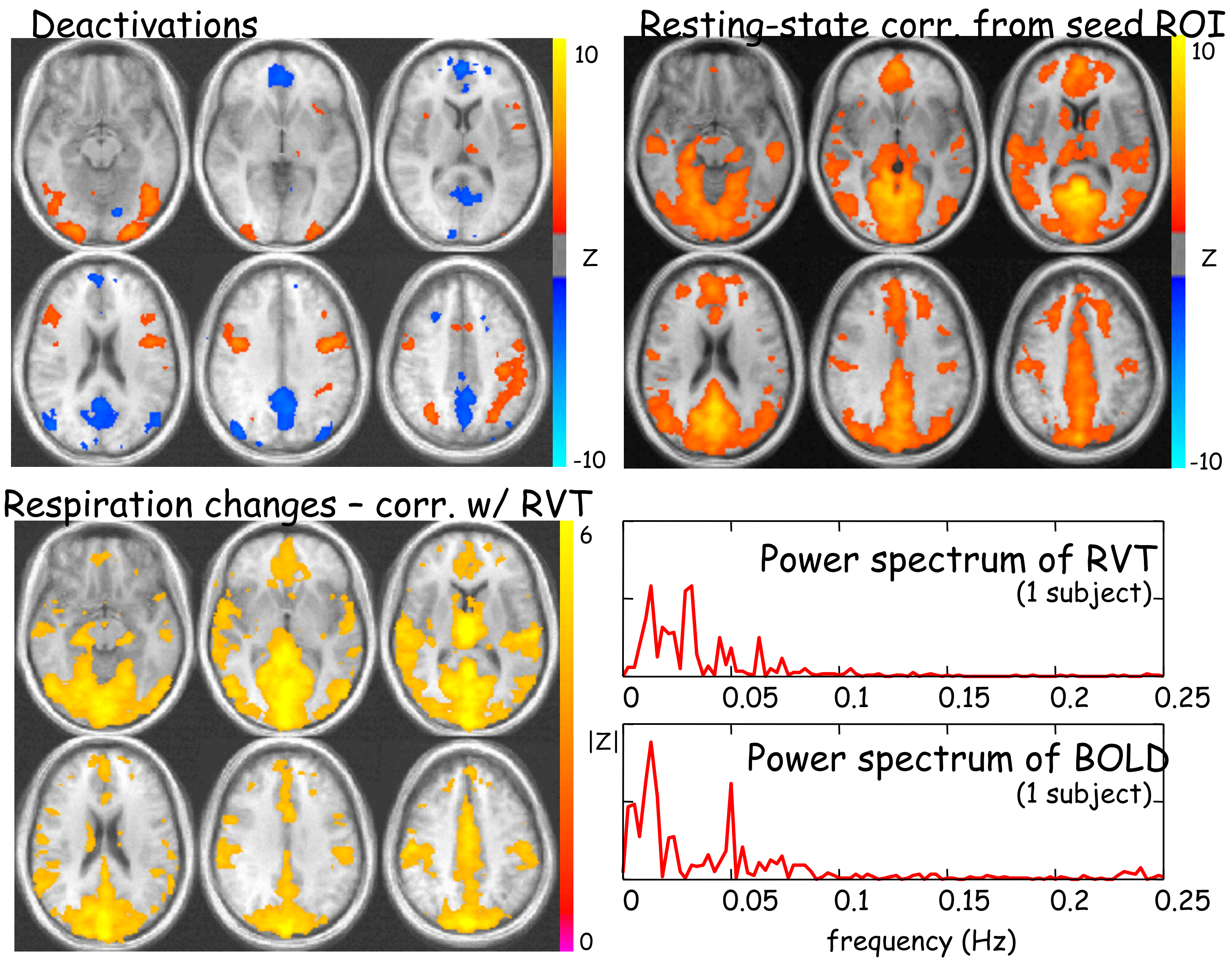
Respiration changes – corr. w/ RVT





Respiration related

RVT changes co-localize

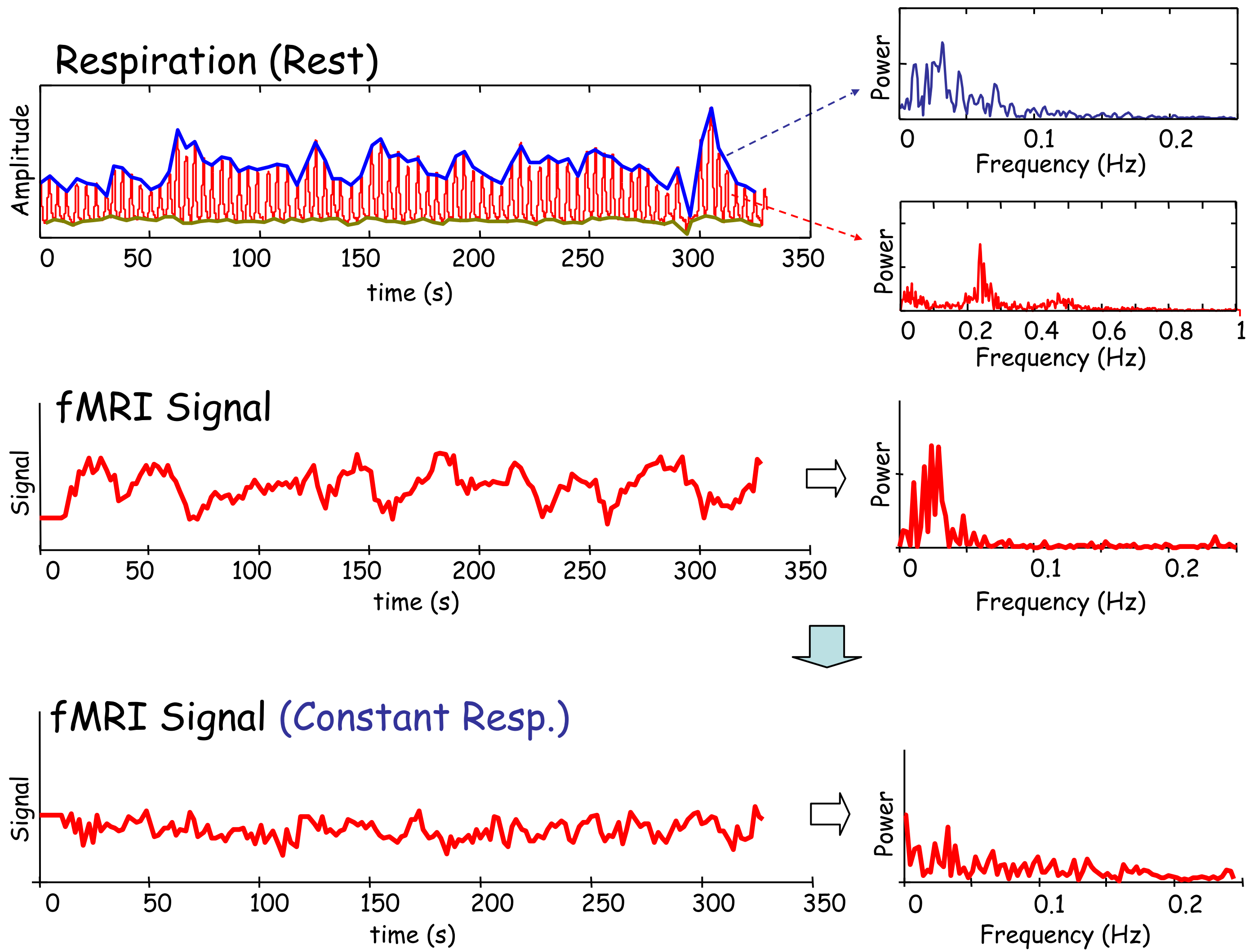


Correcting for changes in respiration

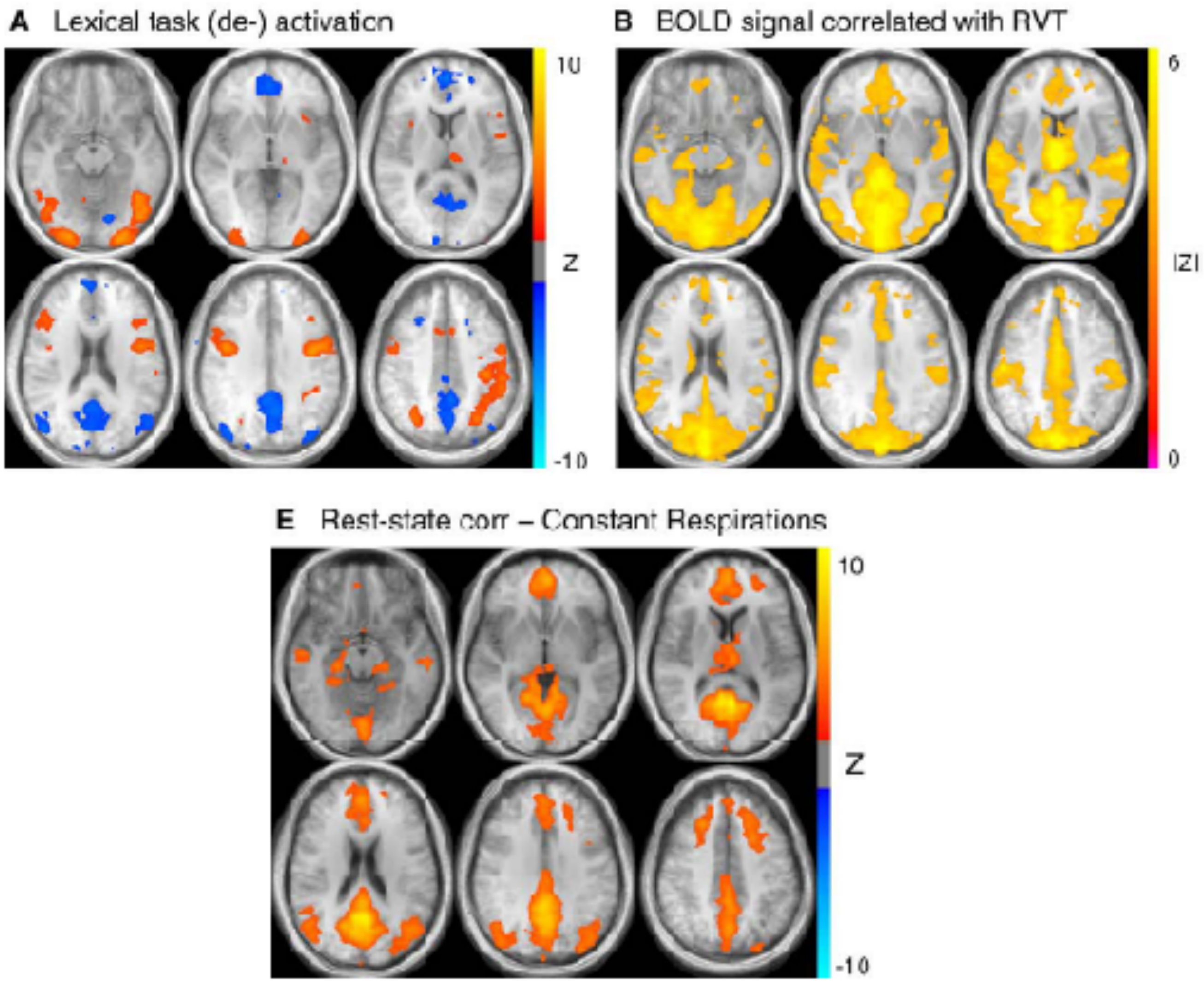
- Regress out RVT
- Keep respirations constant

Time series improvement

Cue subject to keep breathing constant



Time series improvement



Technology

Coil arrays
High field strength
High resolution
Novel functional contrast

Methodology

Connectivity assessment
Multi-modal integration
Pattern classification
Task design

Interpretation

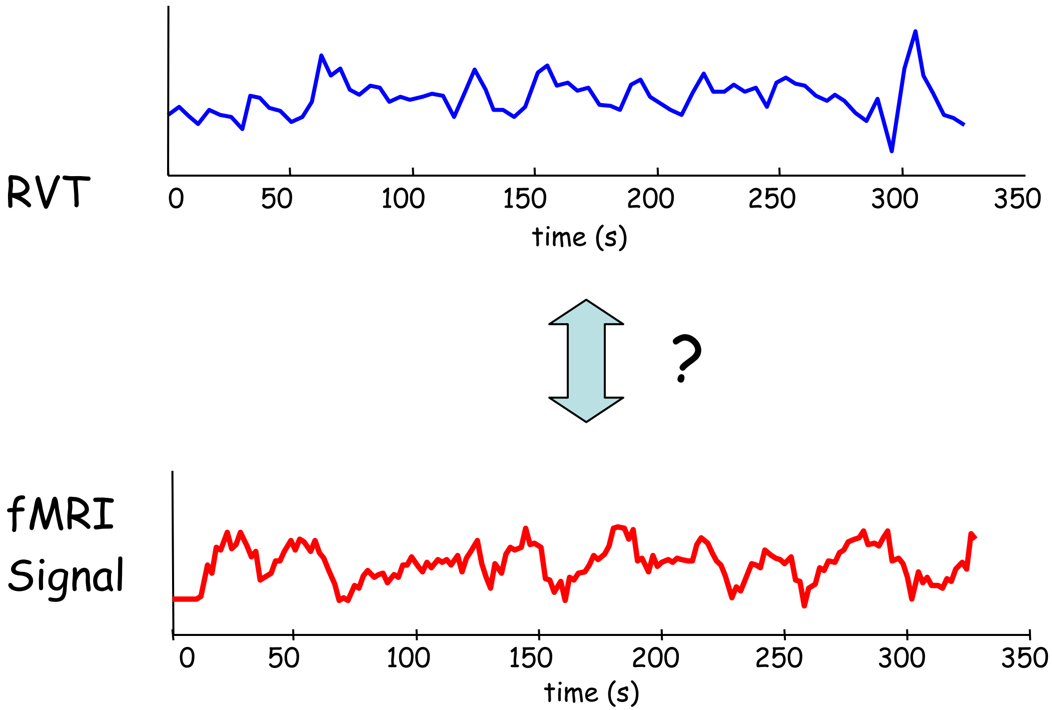
Fluctuations
Dynamics
Cross - modal comparison

Applications

Basic Neuroscience
Behavior correlation/prediction
Pathology correlation

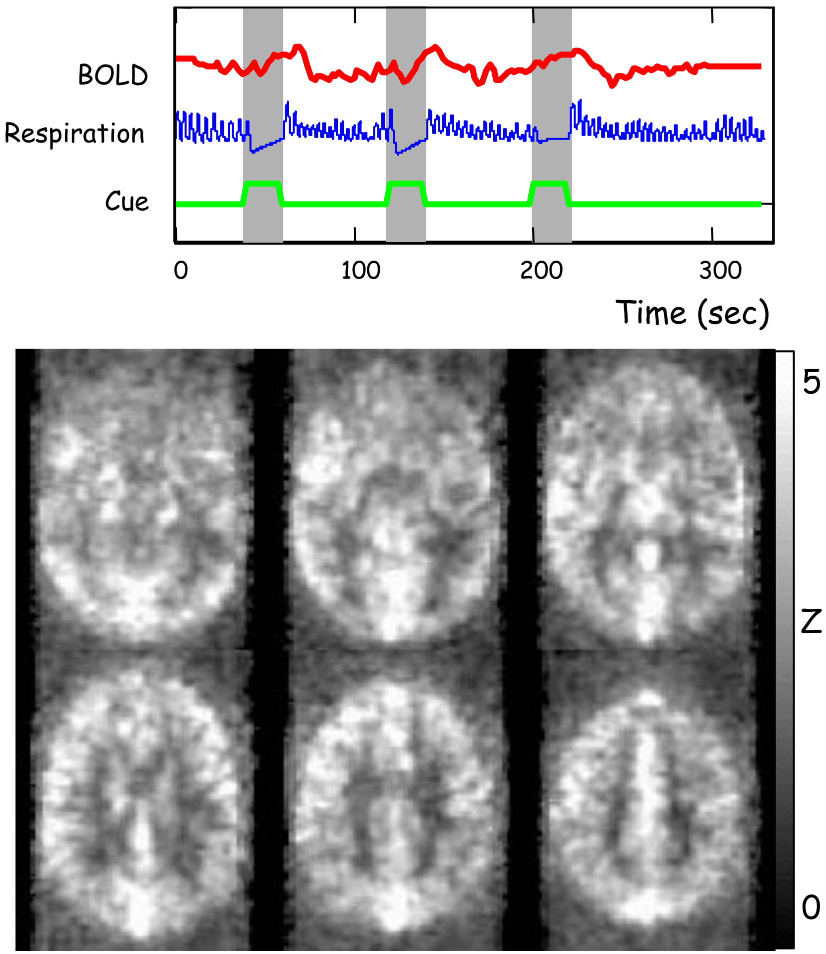
Respiration Changes vs. BOLD

How are the BOLD changes related to respiration variations?



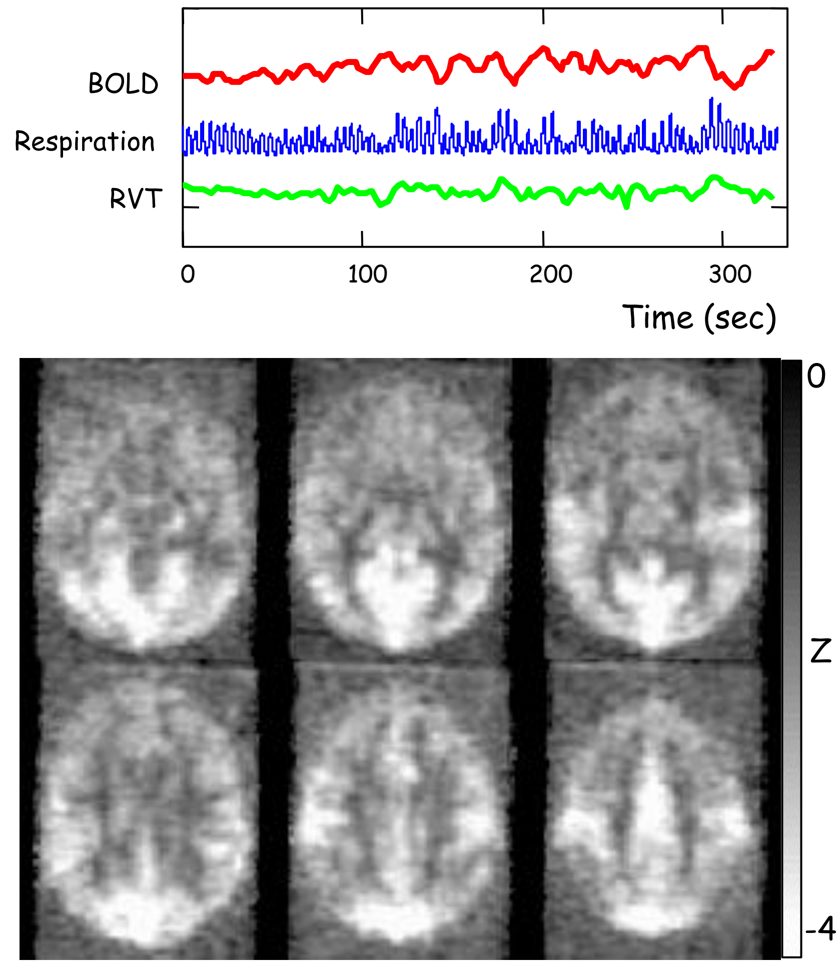
Respiration induced signal changes

Breath-holding



(N=7)

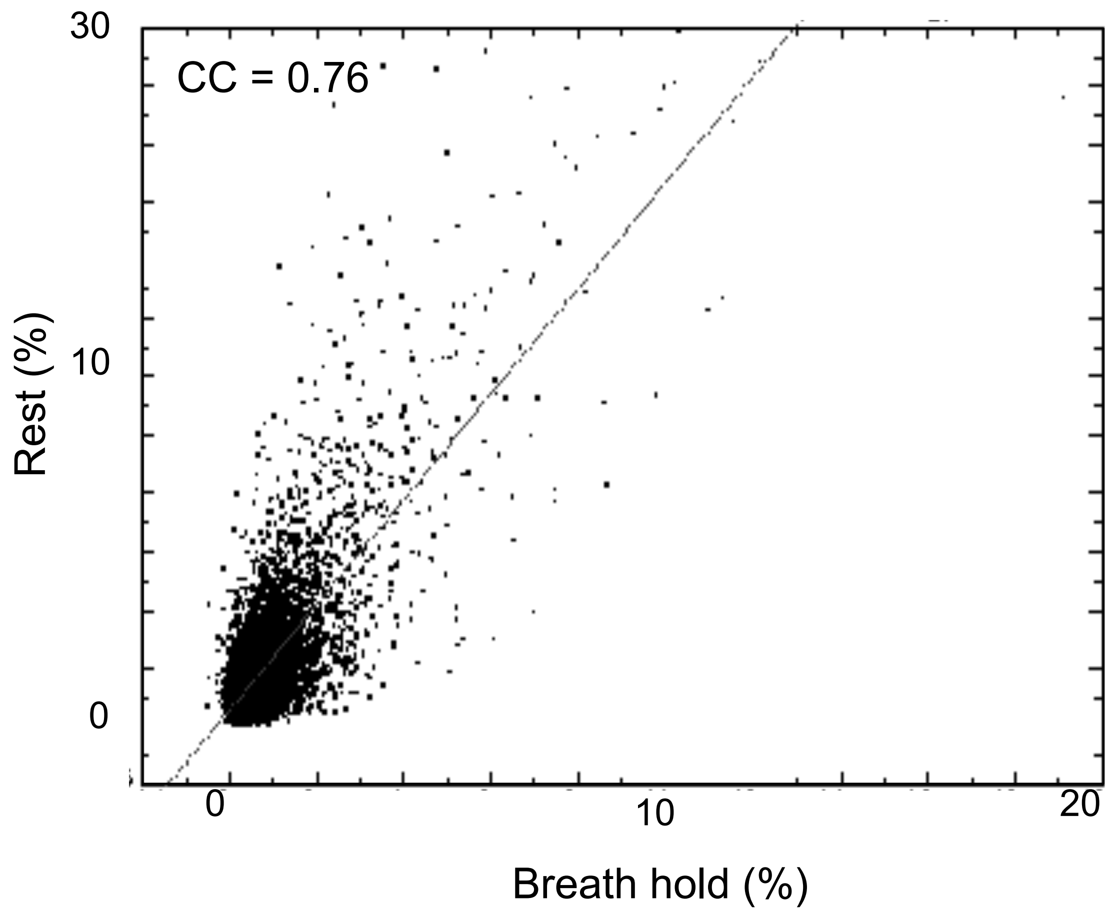
Rest



Respiration Response Function

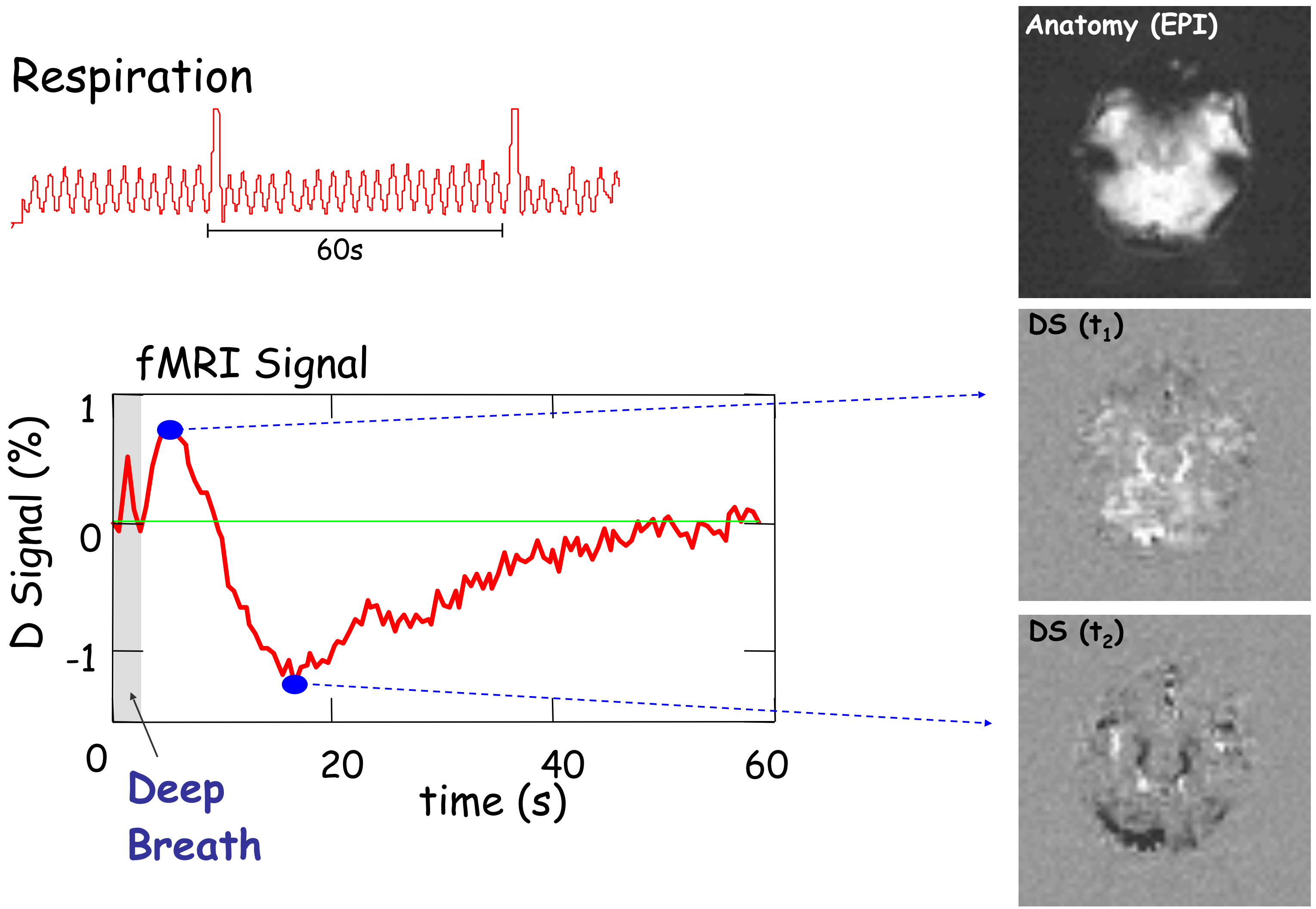
Resting changes in breathing vs. Breath-holding

Correlation with Respiration Volume / Time (RVT)

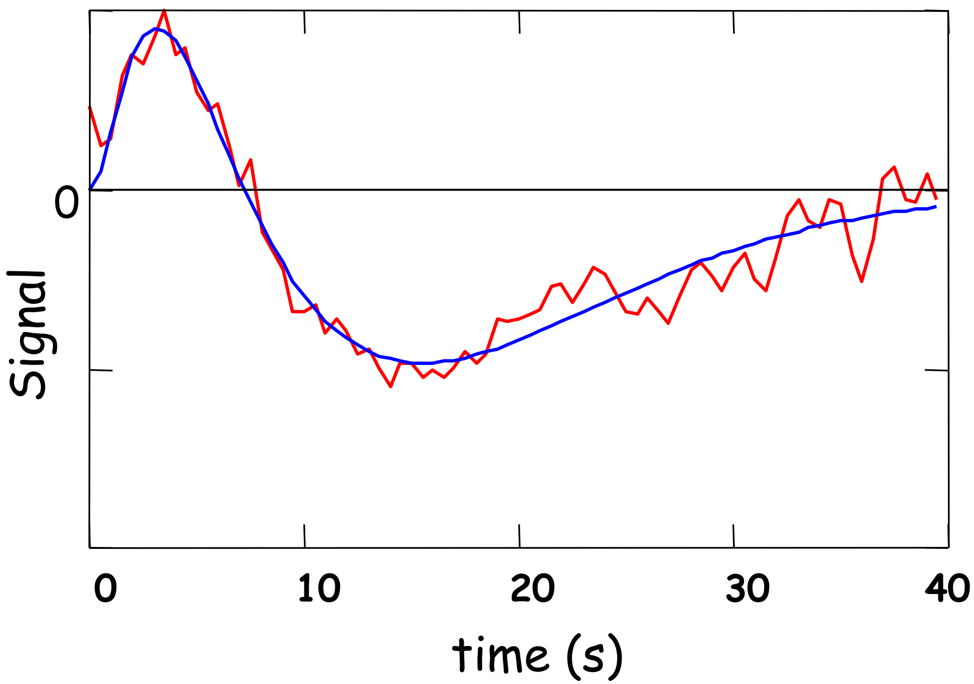


Respiration Response Function

fMRI response to a single Deep Breath



Respiration response function

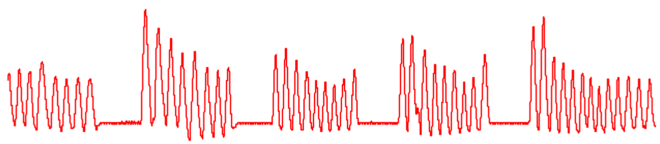


Average of 3 subjects

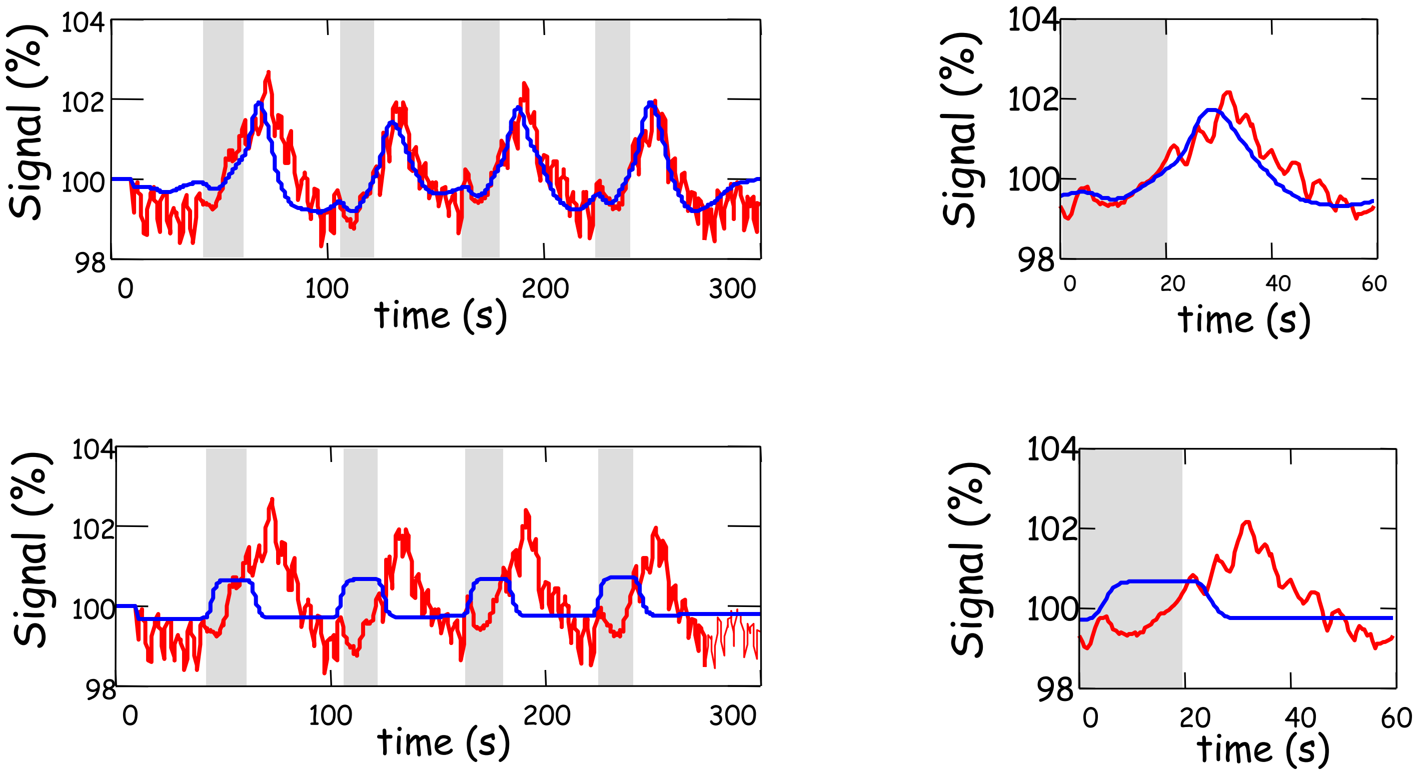
$$RRF(t) = 0.6\, t^{2.1} e^{-\frac{t}{1.6}} - 0.0023\, t^{3.54} e^{-\frac{t}{4.25}}$$

fMRI response to breathing modulations

Breath-holding



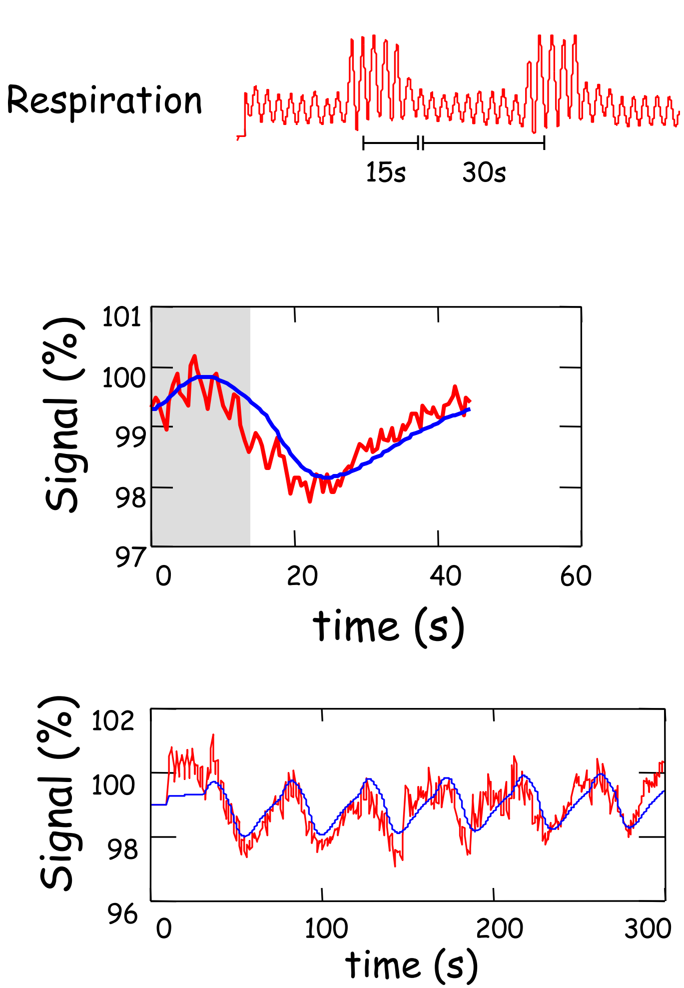
Respiration



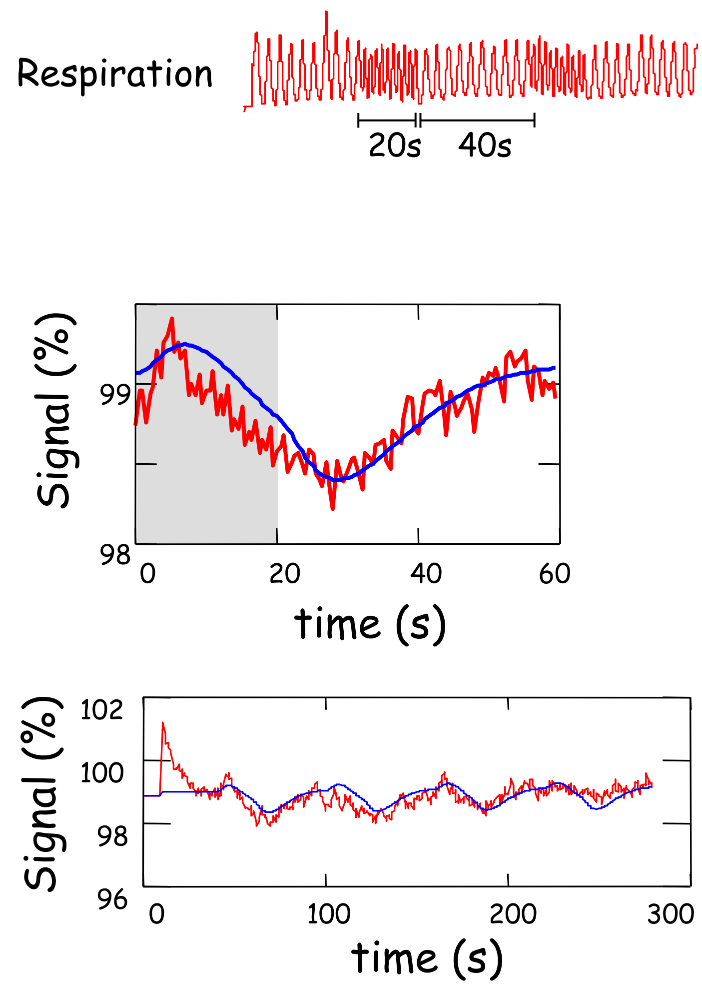
Respiration Response Function

fMRI response to breathing modulations

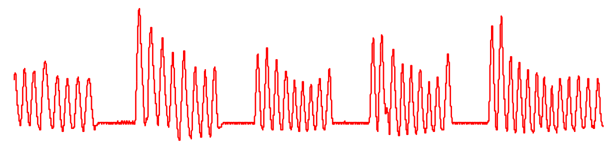
Changes in Depth



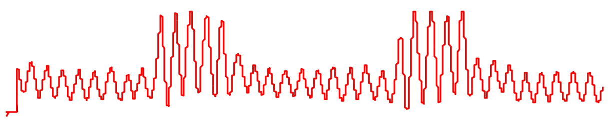
Changes in Rate



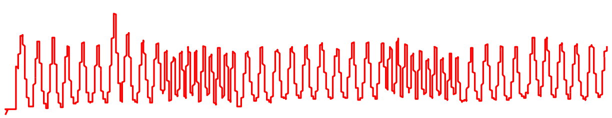
Calibration using other respiration changes



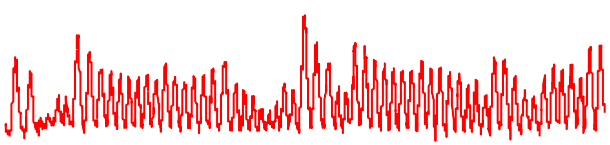
Breath-holding



Depth changes

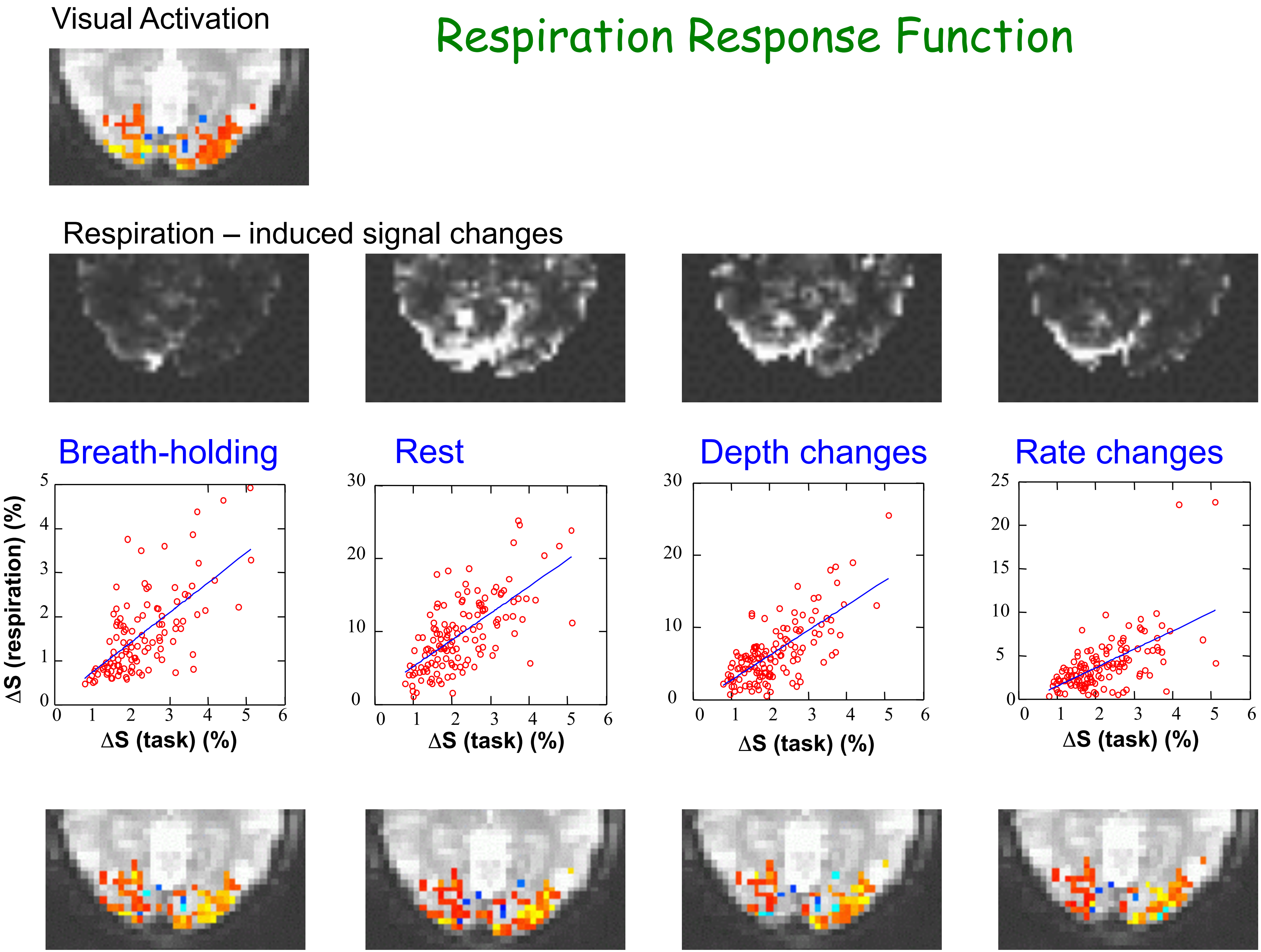


Rate changes

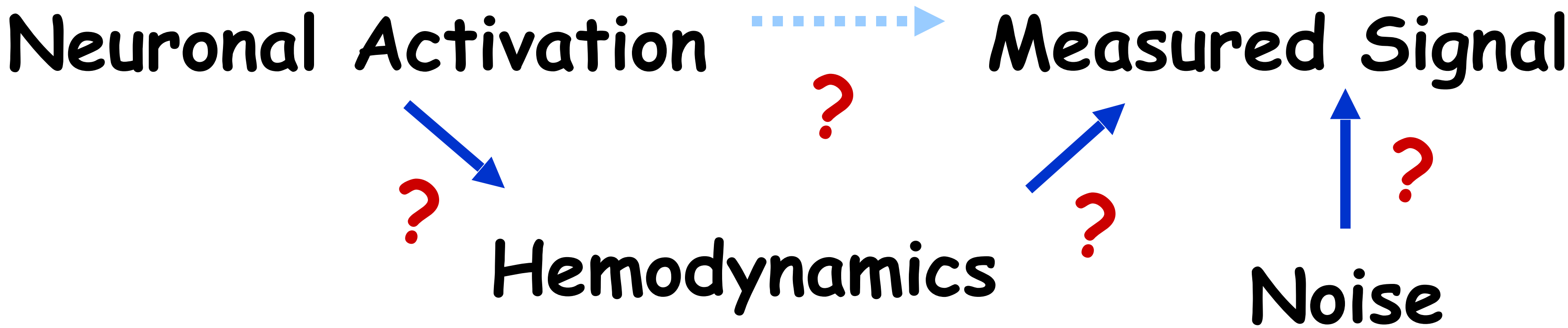


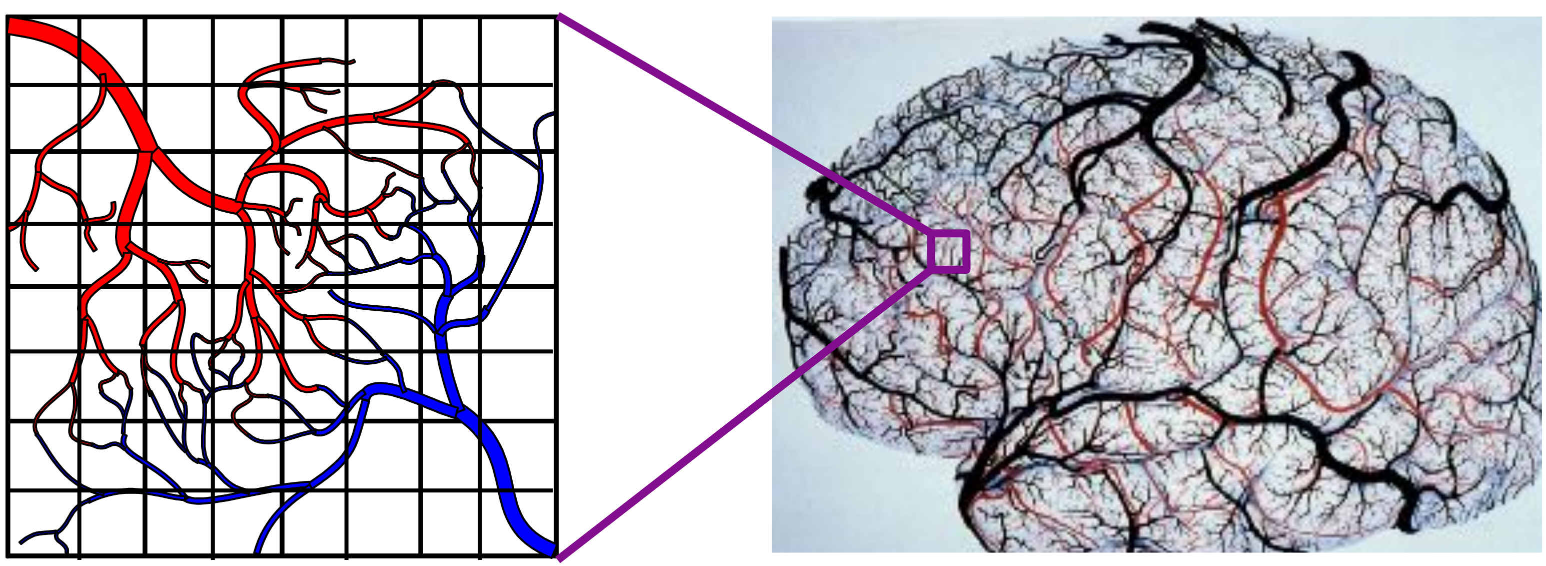
spontaneous fluctuations
in respiration during rest

Respiration Response Function



Interpretation





NeuroImage 16, 103–114 (2002)
doi:10.1006/nimg.2001.1050, available online at http://www.idealibrary.com on IDEAL

Task-Related Changes in Cortical Synchronization Are Spatially Coincident with the Hemodynamic Response

Krish D. Singh,*†‡ Gareth R. Barnes,* Arjan Hillebrand,* Eimer M. E. Forde,* and Adrian L. Williams§

*The Wellcome Trust Laboratory for MEG Studies, Neurosciences Research Institute, Aston University, Birmingham, United Kingdom; †MARIARC, Liverpool University, Liverpool, United Kingdom; ‡Walton Centre for Neurology and Neurosurgery, Liverpool, United Kingdom; and §Department of Psychology, Royal Holloway, University of London, Egham, United Kingdom

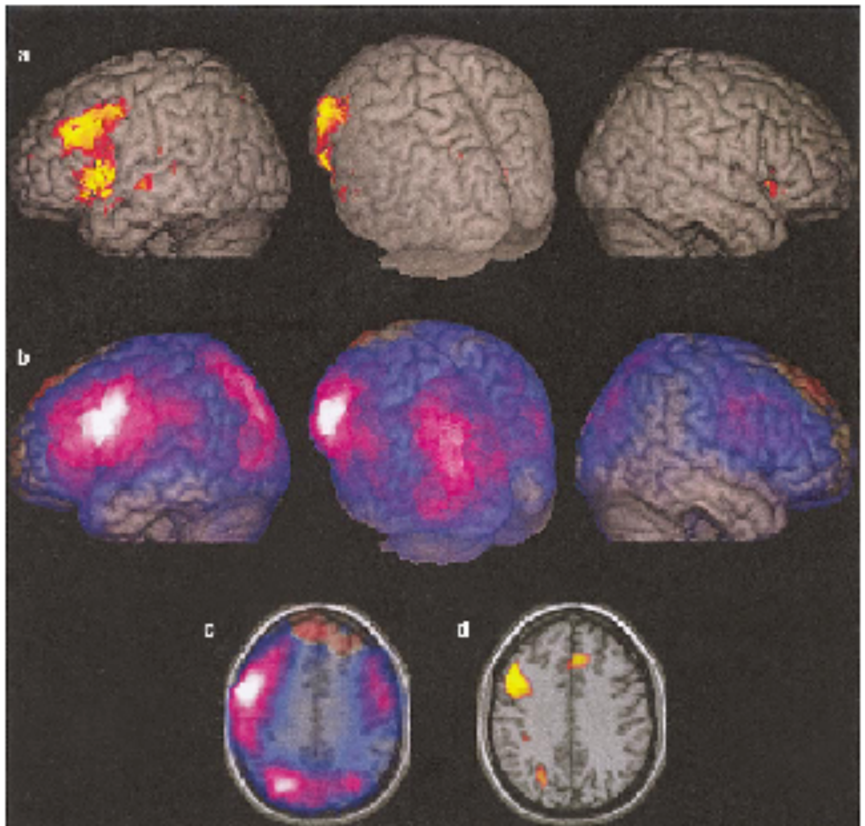


FIG. 2. The results of the group fMRI experiment and the group MEG experiment for the letter fluency task, superimposed onto a template brain. The color scales are as described in the legend of Fig. 1. (a) Group fMRI data. Only those clusters significant at $P < 0.05$ (corrected) are shown. (b) The peak group SAM image. This shows the peak power decrease, at each voxel in the brain, irrespective of which frequency band the power change occurred in. This image can be thought of as an amalgam of Figs. 1b to 1f. (c) The peak group SAM data superimposed on a slice through the template brain at an MNI Z coordinate of +28. This image shows bilateral, but strongly left lateral, activation within the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex. (d) The group fMRI data superimposed on the $Z = +28$ slice. Note the left DLPFC and left posterior parietal activation which match the group SAM results. However, there is also a small cluster in a more anterior portion of the parietal lobe, and another in the medial frontal gyri, which are visible in the group fMRI data but not in the group MEG data.

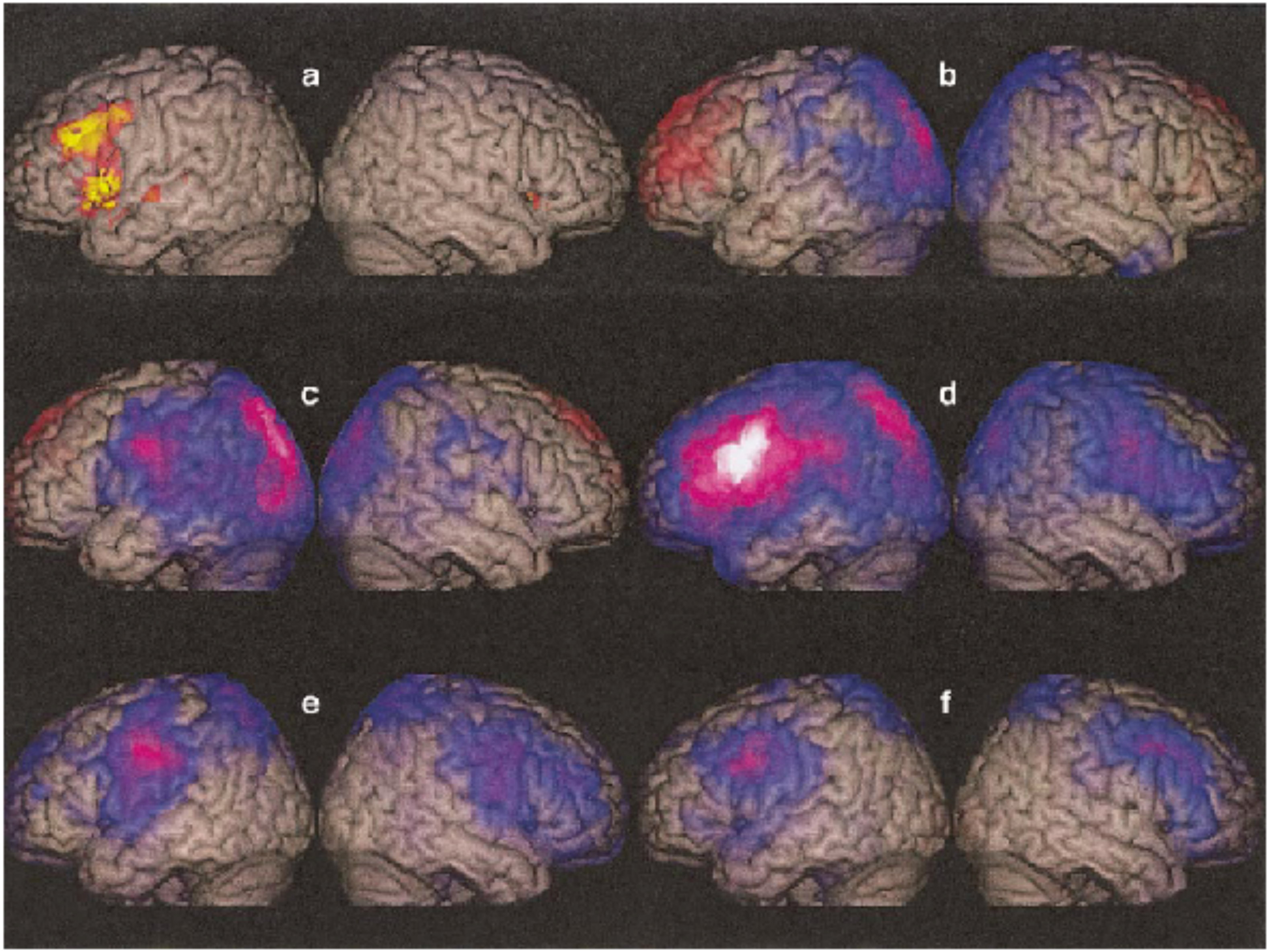


FIG. 1. The results of the group fMRI experiment and the group MEG experiment for the covert letter fluency task, superimposed on a template brain. (a) Group fMRI data. Only those clusters significant at $P < 0.05$ (corrected) are shown. The red–orange–yellow color scale depicts increasing BOLD amplitude. (b–f) The results of the group SAM analysis of the MEG data. Increases in signal power in the Active phase, compared to the Passive baseline are shown using a red–orange–yellow color scale. Decreases in signal power in the Active phase are shown using a blue–purple–white color scale. The power changes are in the following frequency bands (b) 1–10 Hz; (c) 5–15 Hz; (d) 15–25 Hz; (e) 25–35 Hz; and (f) 35–45 Hz.

Technology

- Coil arrays
- High field strength
- High resolution
- Novel functional contrast

Methodology

- Connectivity assessment
- Multi-modal integration
- Pattern classification
- Task design

- Fluctuations
- Dynamics
- Cross - modal comparison

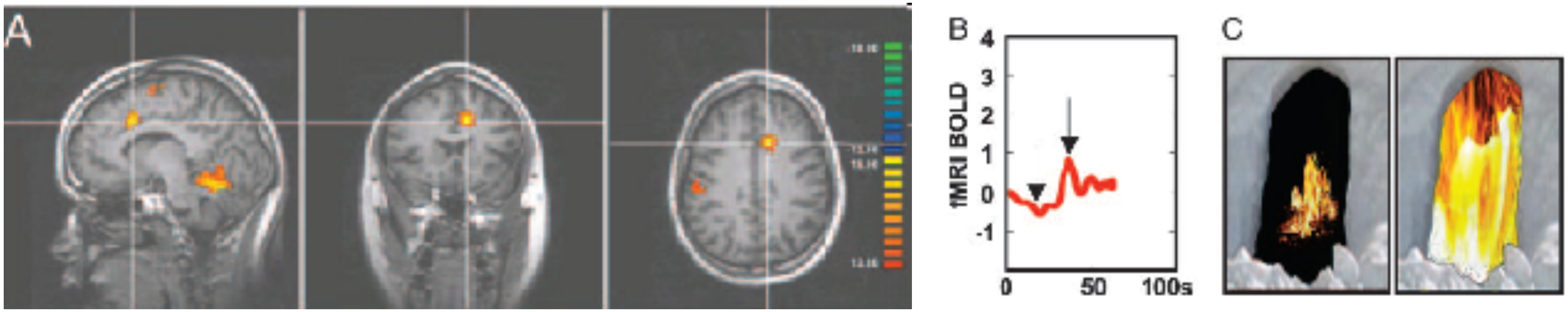
Interpretation

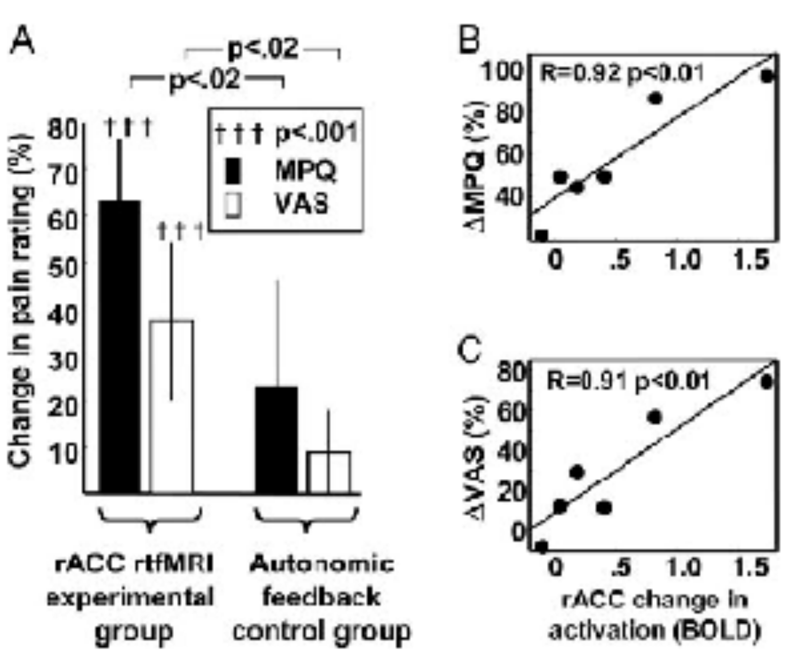
- Basic Neuroscience
- Behavior correlation/prediction
- Pathology correlation

Applications

Applications

Real time fMRI feedback to reduce chronic pain



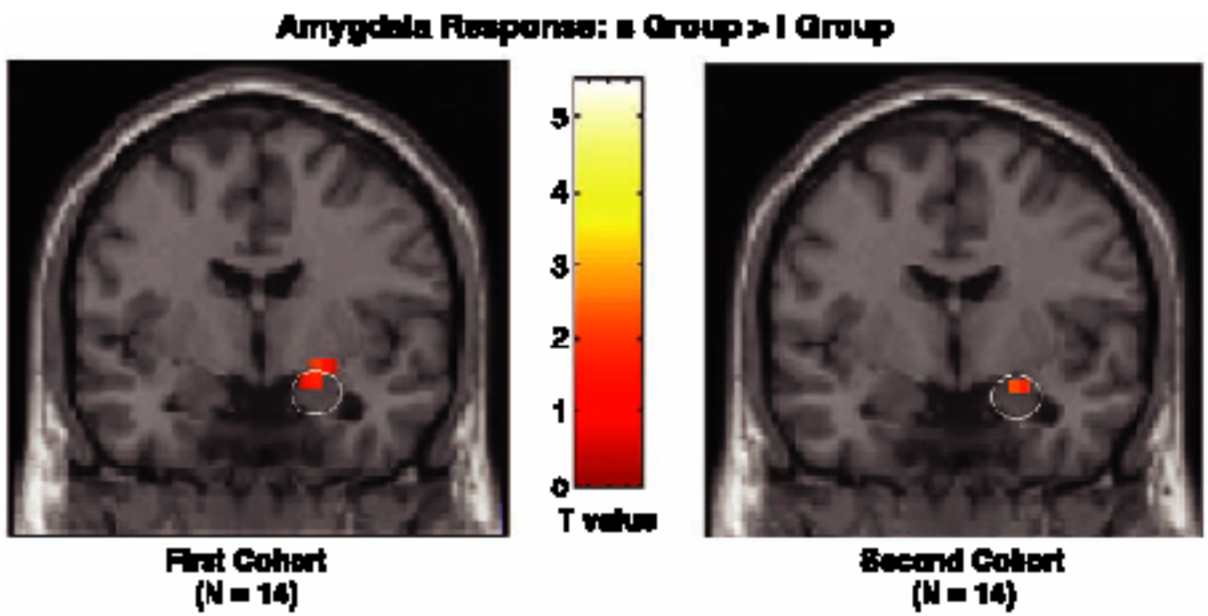


Control over brain activation and pain learned by using real-time functional MRI, R. C. deCharms, et al. PNAS, 102; 18626-18631 (2005)

Comparison of two groups of normal individuals with differences in the Serotonin Transporter Gene

Serotonin Transporter Genetic Variation and the Response of the Human Amygdala

Ahmad R. Hariri,[1] Venkata S. Mattay,[1] Alessandro Tessitore,[1] Bhaskar Kolachana,[1] Francesco Fera,[1] David Goldman,[2] Michael F. Egan,[1] Daniel R. Weinberger[1*]



SCIENCE VOL 297 19 JULY 2002

What fMRI Can Do

Understanding normal brain organization and changes

- -networks involved with specific tasks (low to high level processing)
- -changes over time (seconds to years)
- -correlates of behavior (response accuracy, performance changes…)

Clinical research

- -correlates of specifically activated networks to clinical populations
- -presurgical mapping

What fMRI Might Do

Complementary use for clinical diagnosis

- -utilization of clinical research results
- -prediction of pathology

Clinical treatment and assessment

- -drug, therapy, rehabilitation, biofeedback
- -epileptic foci mapping
- -drug effects

Non clinical uses

- -complementary use with behavioral, anatomical, other modality results
- -lie detection
- -prediction of behavior tendencies
- -brain/computer interface