Peering Inside Your Brain Via its Neural Magnetic Fields

With Applications to Solving the "Cocktail Party" Problem

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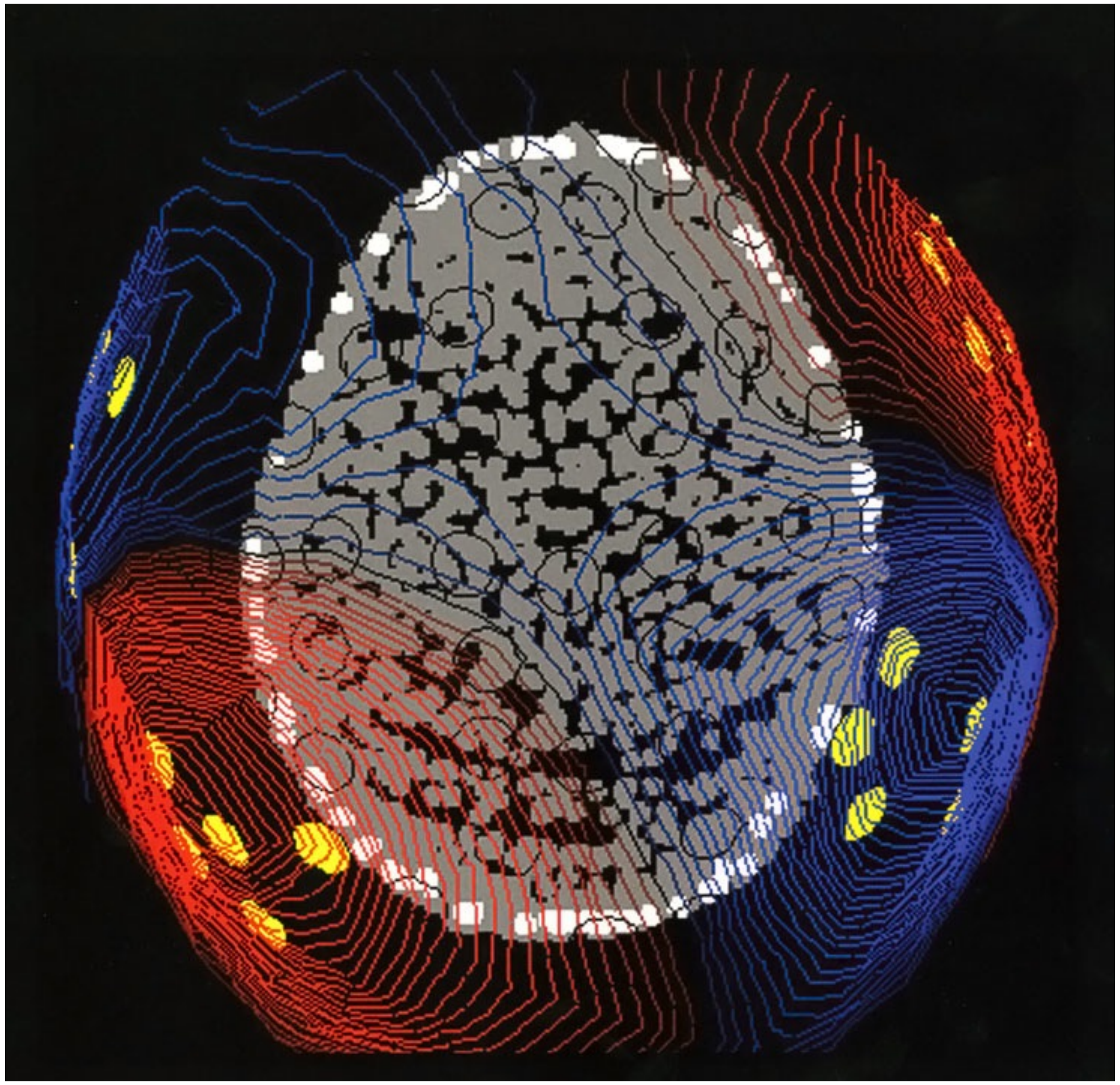
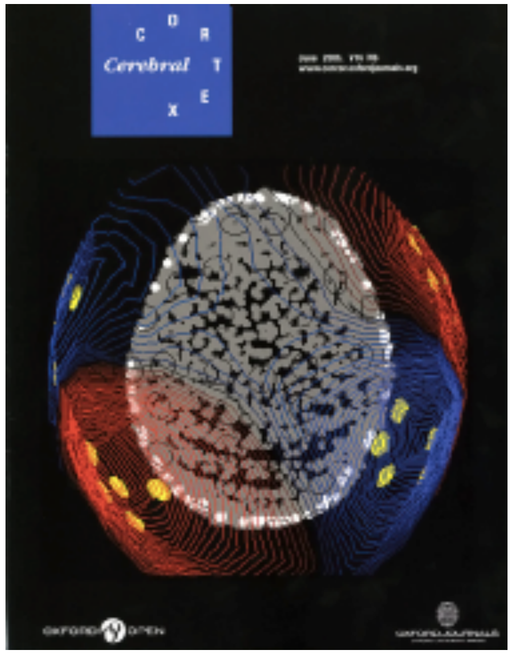
Magnetoencephalography

- Non-invasive, Passive, Silent Neural Recordings
- Simultaneous Whole-Head Recording (~200 sensors)
- Sensitivity
  - high: ~100 fT (10^{-13} Tesla)
  - low: ~10^4 – ~10^6 neurons
- Temporal Resolution: ~1 ms
- Spatial Resolution
  - coarse: ~1 cm
  - ambiguous

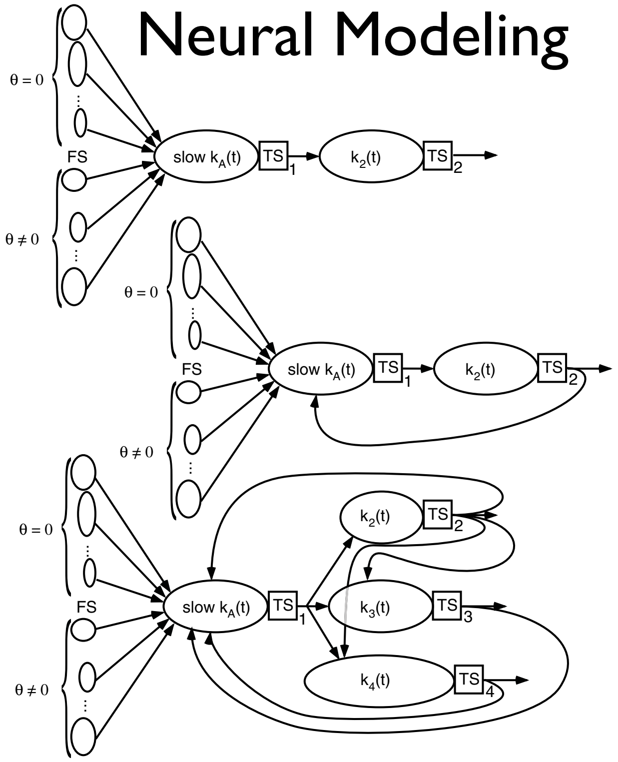


Neural processing of speech and complex auditory scenes

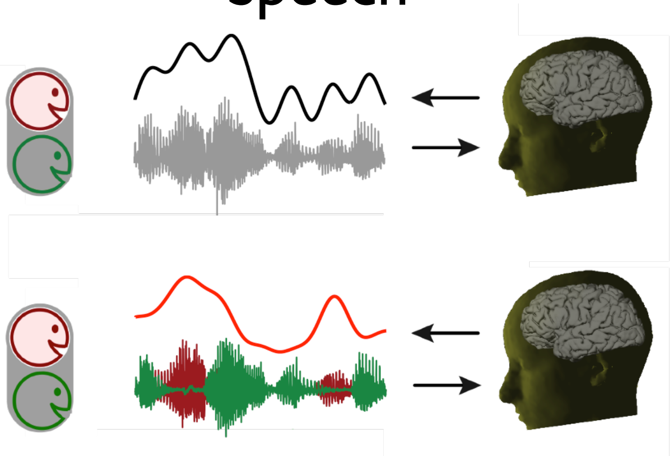
Magnetoencephalography



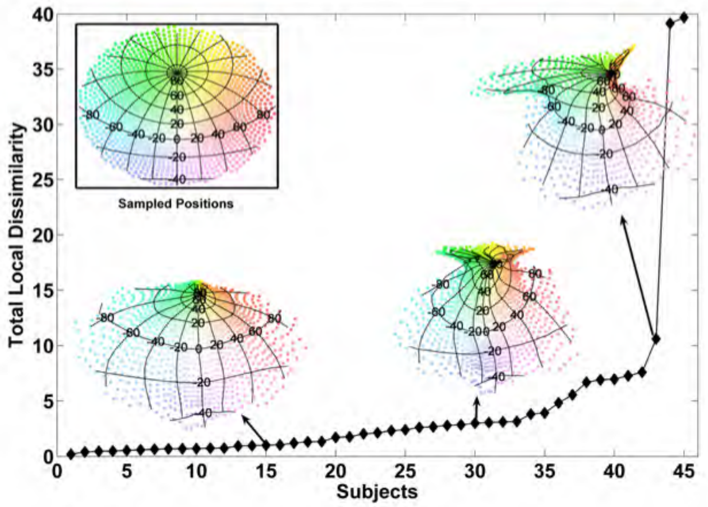
Neural Modeling



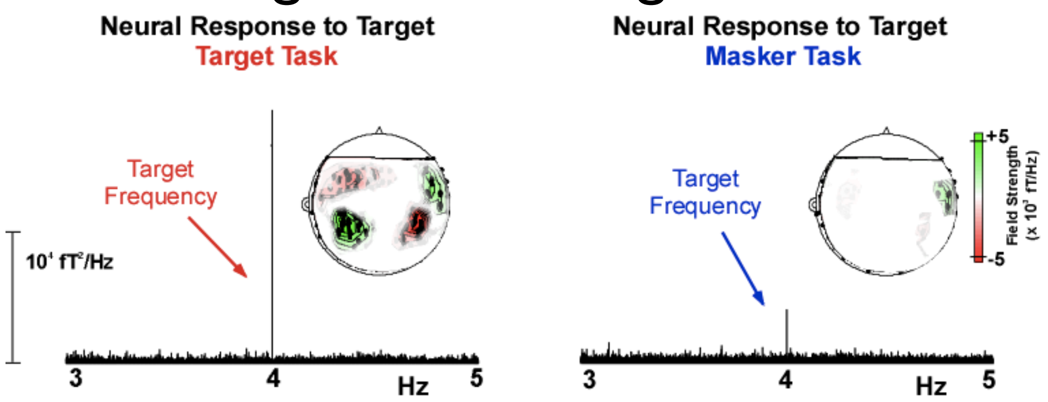
Neural Un-Mixing of Speech



Neurally Inspired Algorithms

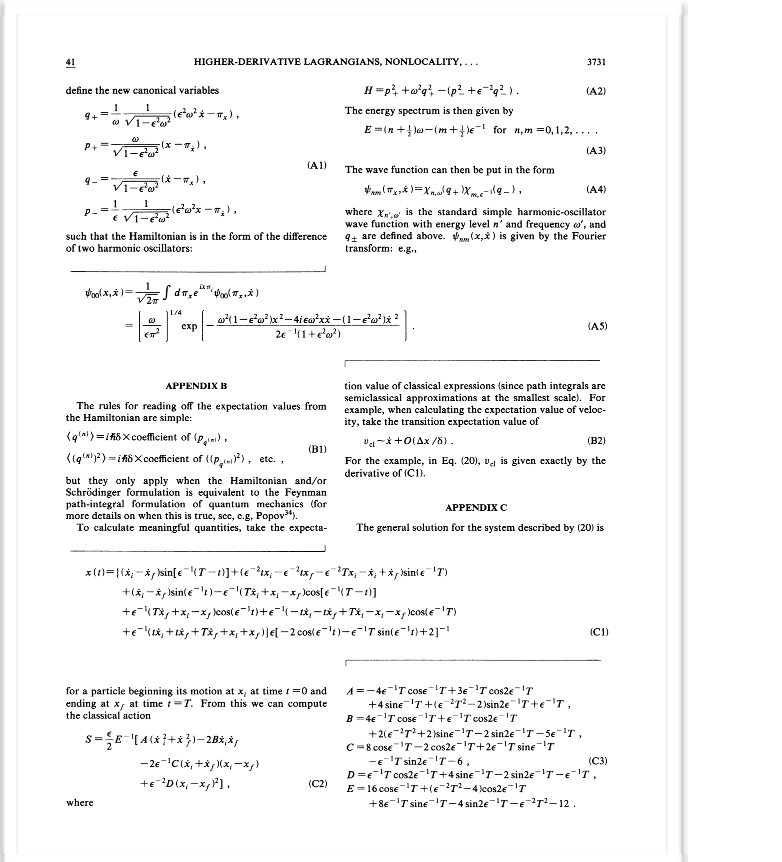


Neural Signal Processing



Advanced Neuroimaging

But back in the day…



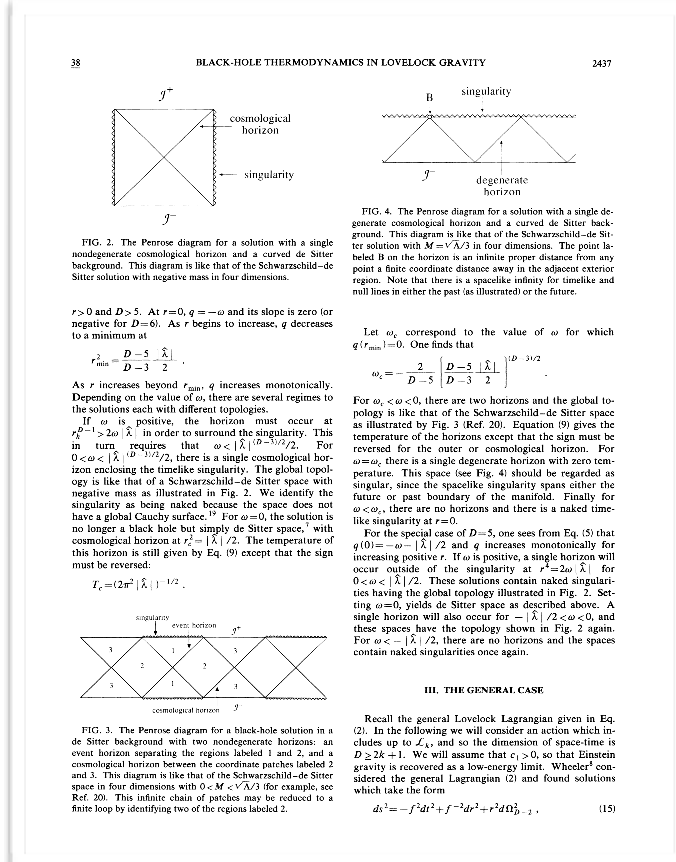
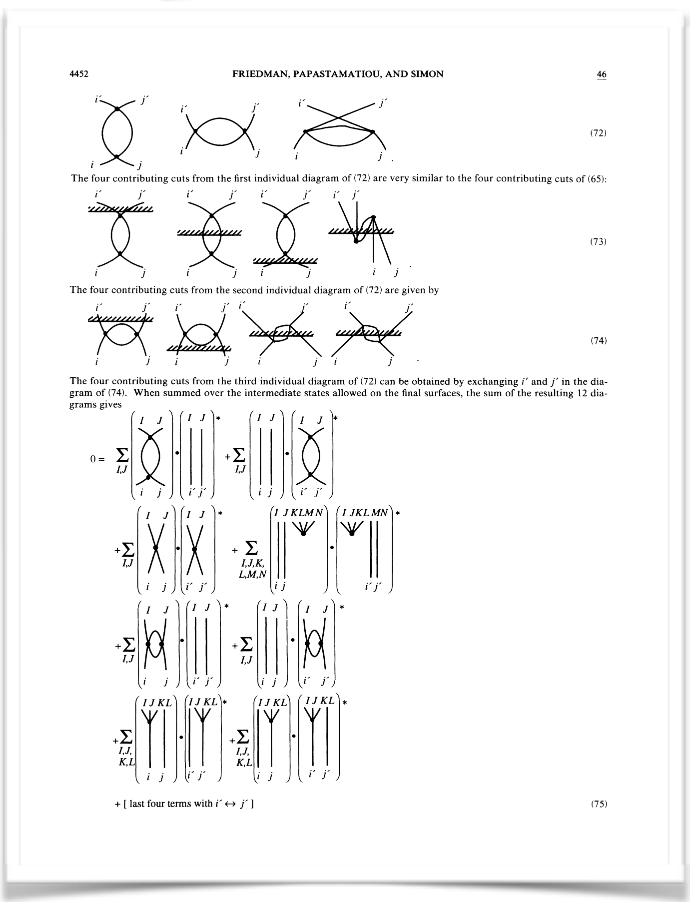


FIG. 2. The Penrose diagram for a solution with a single nondegenerate cosmological horizon and a curved de Sitter background. This diagram is like that of the Schwarzschild–de Sitter solution with negative mass in four dimensions.

FIG. 3. The Penrose diagram for a black-hole solution in a de Sitter background with two nondegenerate horizons: an event horizon separating the regions labeled 1 and 2, and a cosmological horizon between the coordinate patches labeled 2 and 3. This diagram is like that of the Schwarzschild–de Sitter space in four dimensions with $0<M<\sqrt{\lambda}/3$ (for example, see Ref. 20). This infinite chain of patches may be reduced to a finite loop by identifying two of the regions labeled 2.

FIG. 4. The Penrose diagram for a solution with a single degenerate cosmological horizon and a curved de Sitter background. This diagram is like that of the Schwarzschild–de Sitter solution with $M=\sqrt{\lambda}/3$ in four dimensions. The point labeled B on the horizon is an infinite proper distance from any point a finite coordinate distance away in the adjacent exterior region. Note that there is a spacelike infinity for timelike and null lines in either the past (as illustrated) or the future.



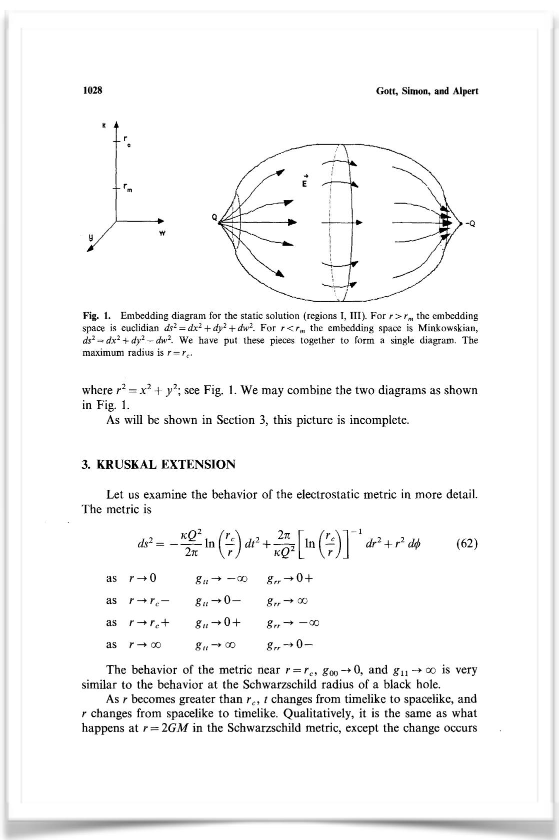


Fig. 1. Embedding diagram for the static solution (regions I, III). For $r>r_m$ the embedding space is euclidian $ds^2=dz^2+dy^2+dw^2$. For $r<r_m$ the embedding space is Minkowskian, $ds^2=dx^2+dy^2-dw^2$. We have put these pieces together to form a single diagram. The maximum radius is $r=r_c$.

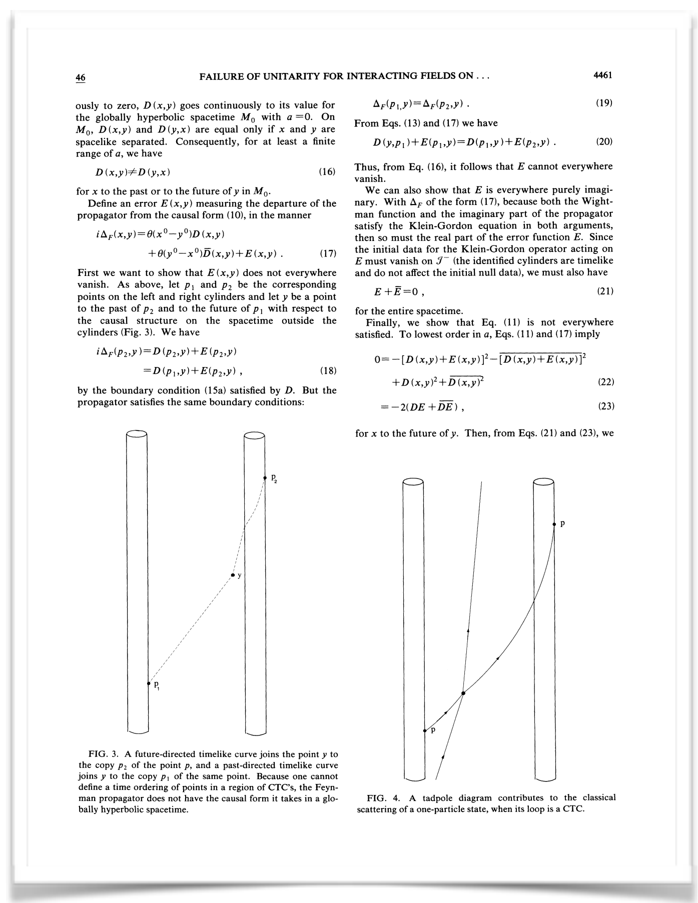


FIG. 3. A future-directed timelike curve joins the point y to the copy p_2 of the point p, and a past-directed timelike curve joins y to the copy p_1 of the same point. Because one cannot define a time ordering of points in a region of CTC's, the Feynman propagator does not have the causal form it takes in a globally hyperbolic spacetime.

FIG. 4. A tadpole diagram contributes to the classical scattering of a one-particle state, when its loop is a CTC.

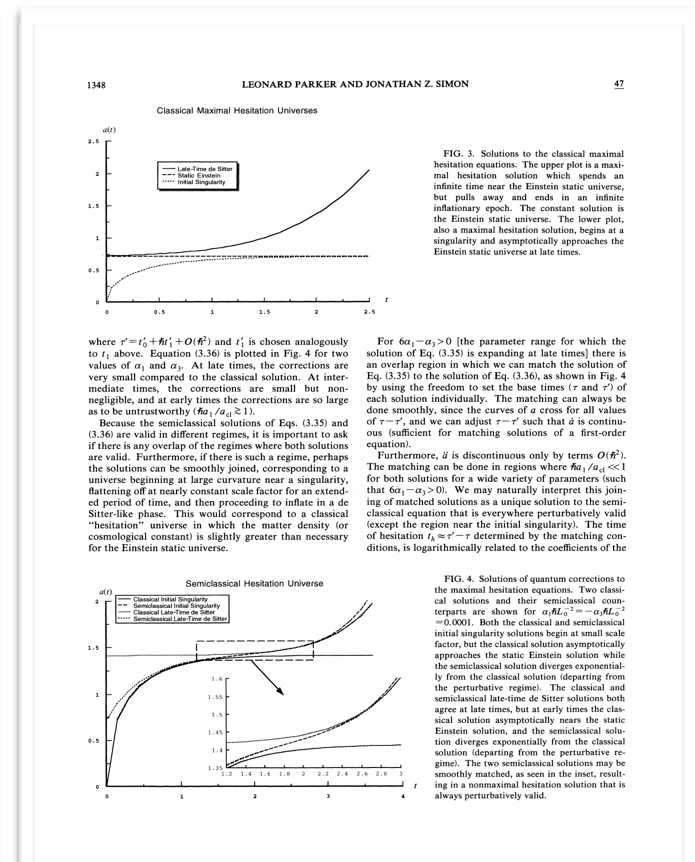


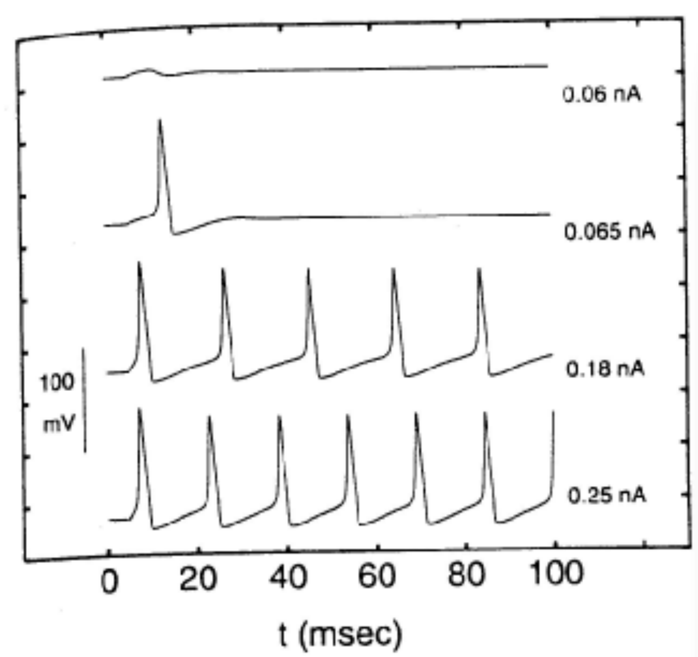
FIG. 3. Solutions to the classical maximal hesitation equations. The upper plot is a maximal hesitation solution which spends an infinite time near the Einstein static universe, but pulls away and ends in an infinite inflationary epoch. The constant solution is the Einstein static universe. The lower plot, also a maximal hesitation solution, begins at a singularity and asymptotically approaches the Einstein static universe at late times.

Topics

- The Brain
- Magnetoencephalography (MEG)
- Applications & Tangents
- MEG & the "Cocktail Party"

The Brain = Connected Neurons

- Neural signals = spikes in voltage
- Spikes are "all-or-none"
  - Digital in amplitude
  - Asynchronous in time
- Neural Input ≈ current



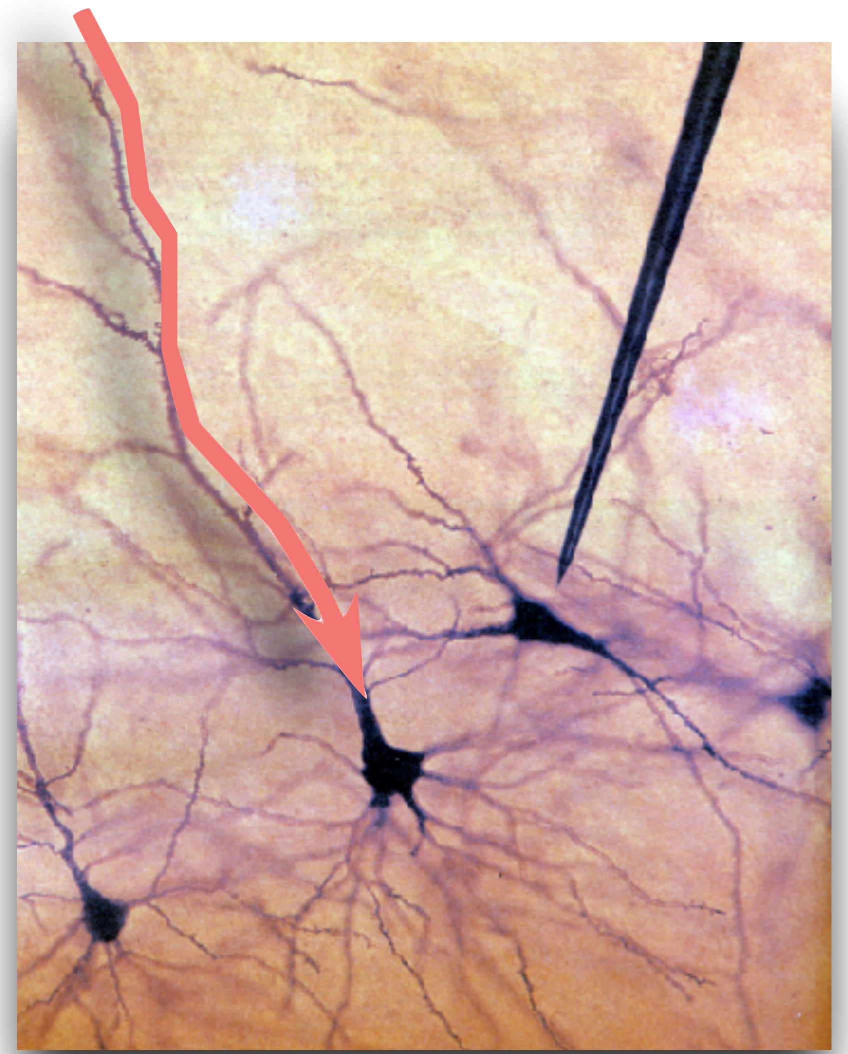


Photo by Fritz Goro

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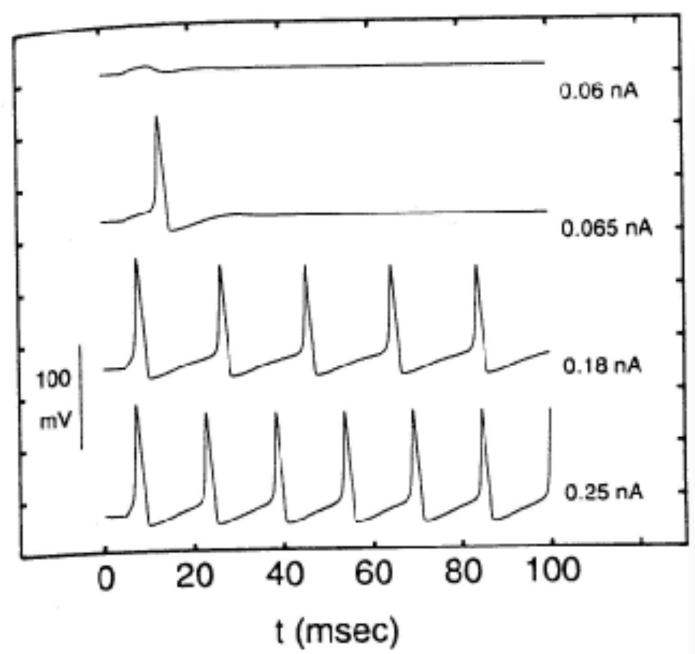


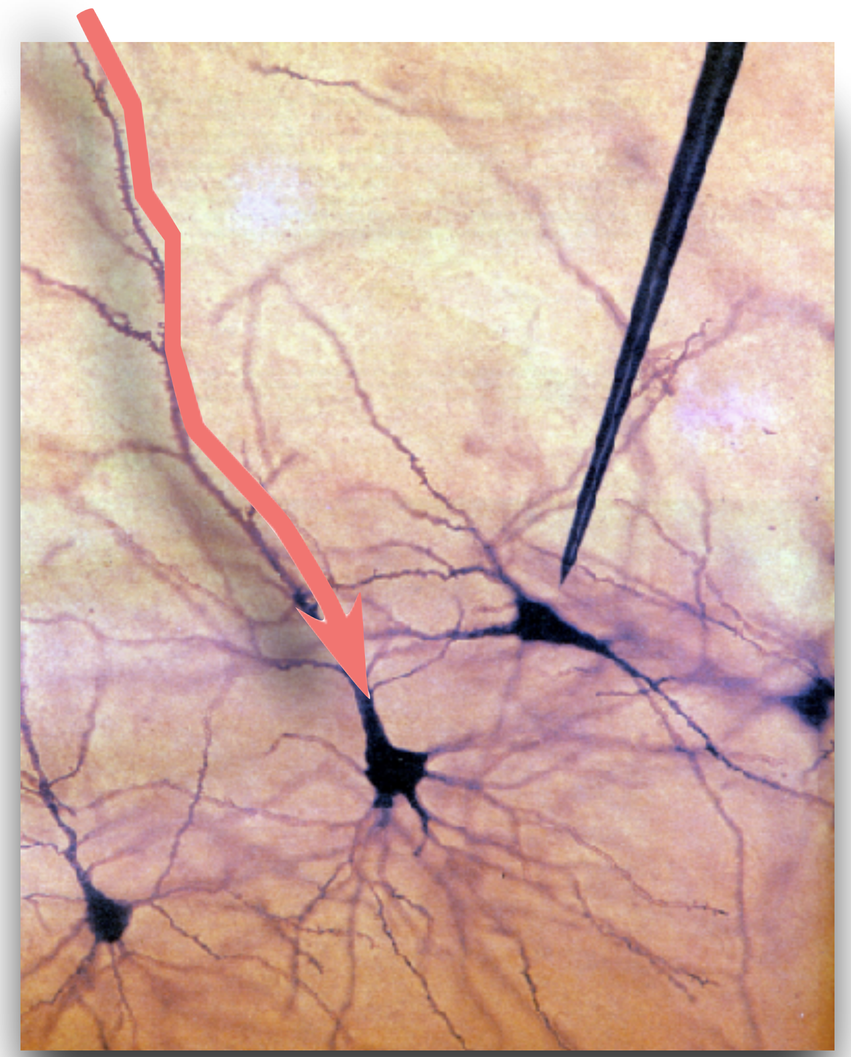
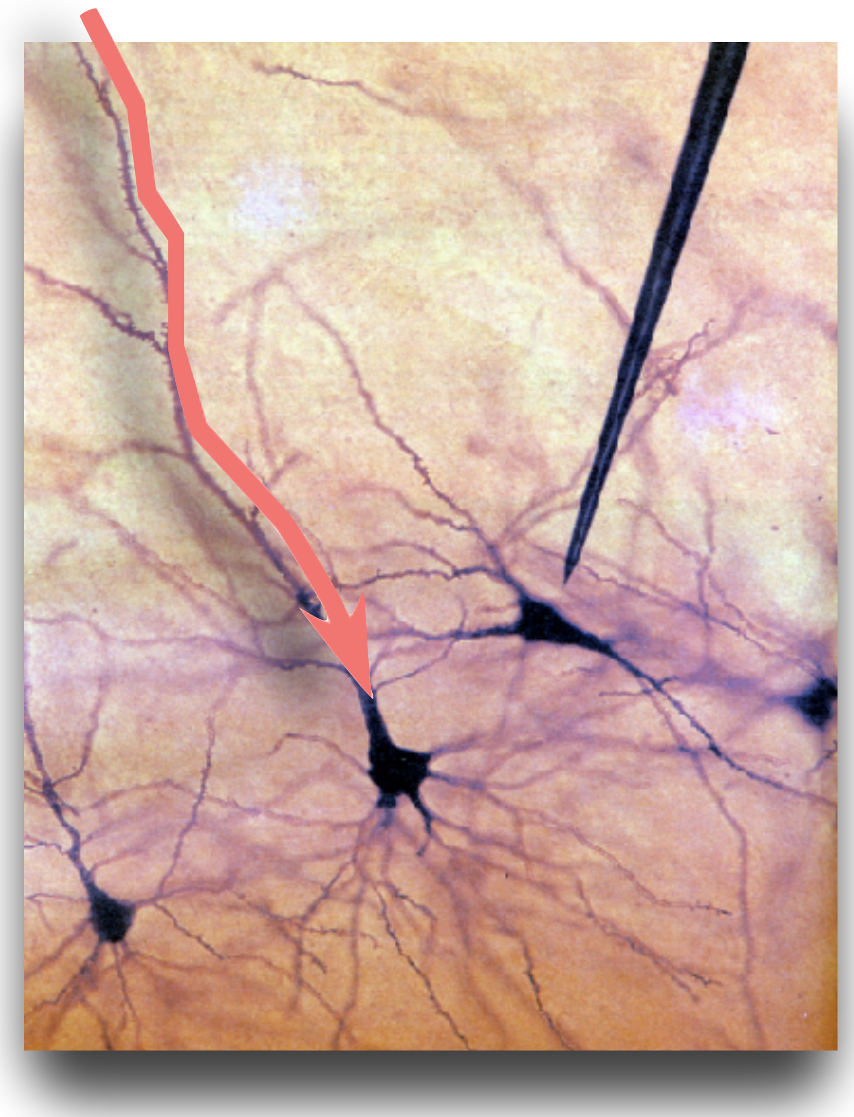


Photo by Fritz Goro

Origin of MEG Neural Signal

Dendritic current
– not axonal currents
inputs, not outputs

Primary current
– not return currents
neural currents, not side-effects



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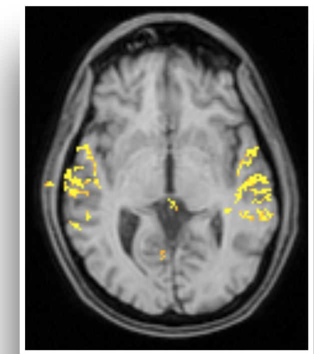
Functional Brain Imaging

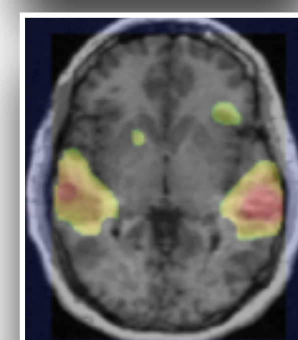
Functional Brain Imaging
= Non-invasive recording from human brain

Hemodynamic techniques

fMRI
functional magnetic resonance imaging



PET
positron emission tomography



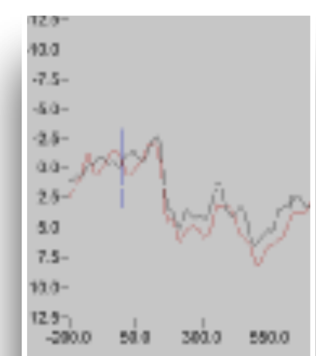
Excellent Spatial Resolution (~1 mm)

Poor Temporal Resolution (~1 s)

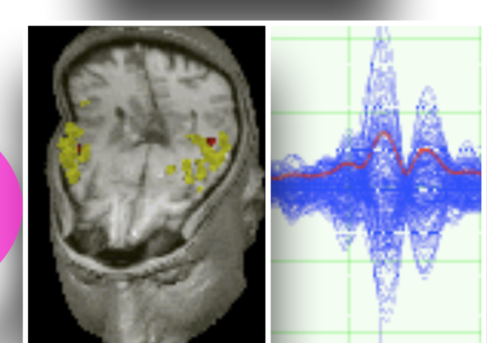
fMRI & MEG can capture effects in single subjects

Electromagnetic techniques

EEG
electroencephalography



MEG
magnetoencephalography



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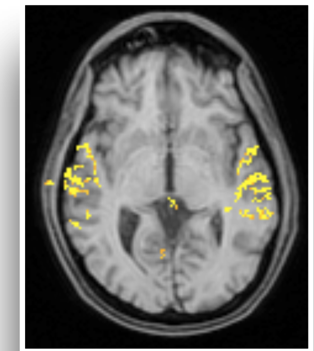

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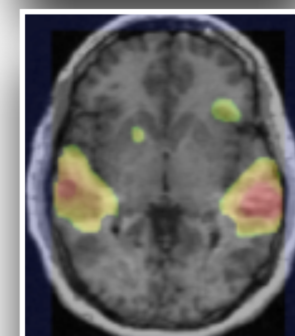

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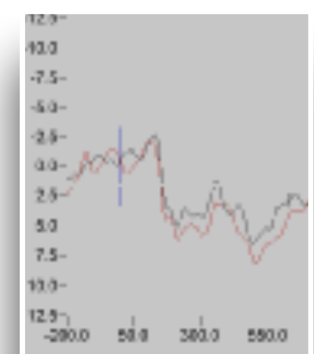

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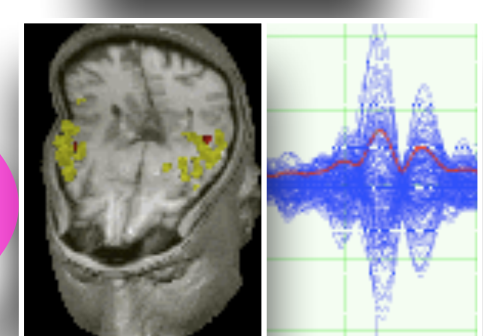

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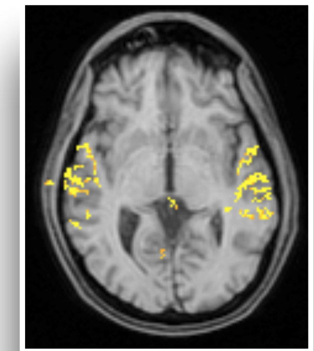

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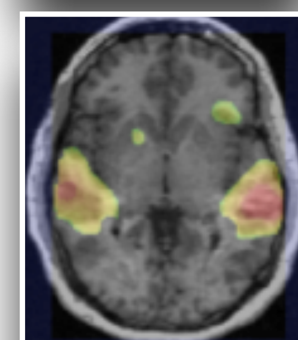

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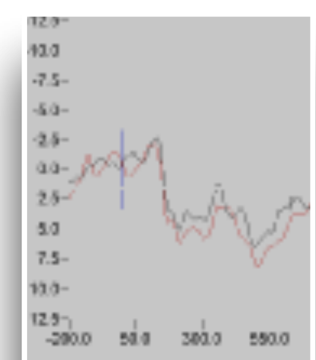

MEG
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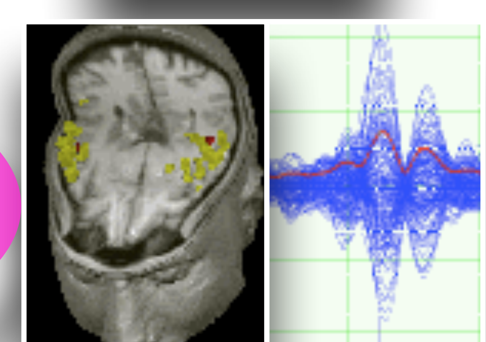

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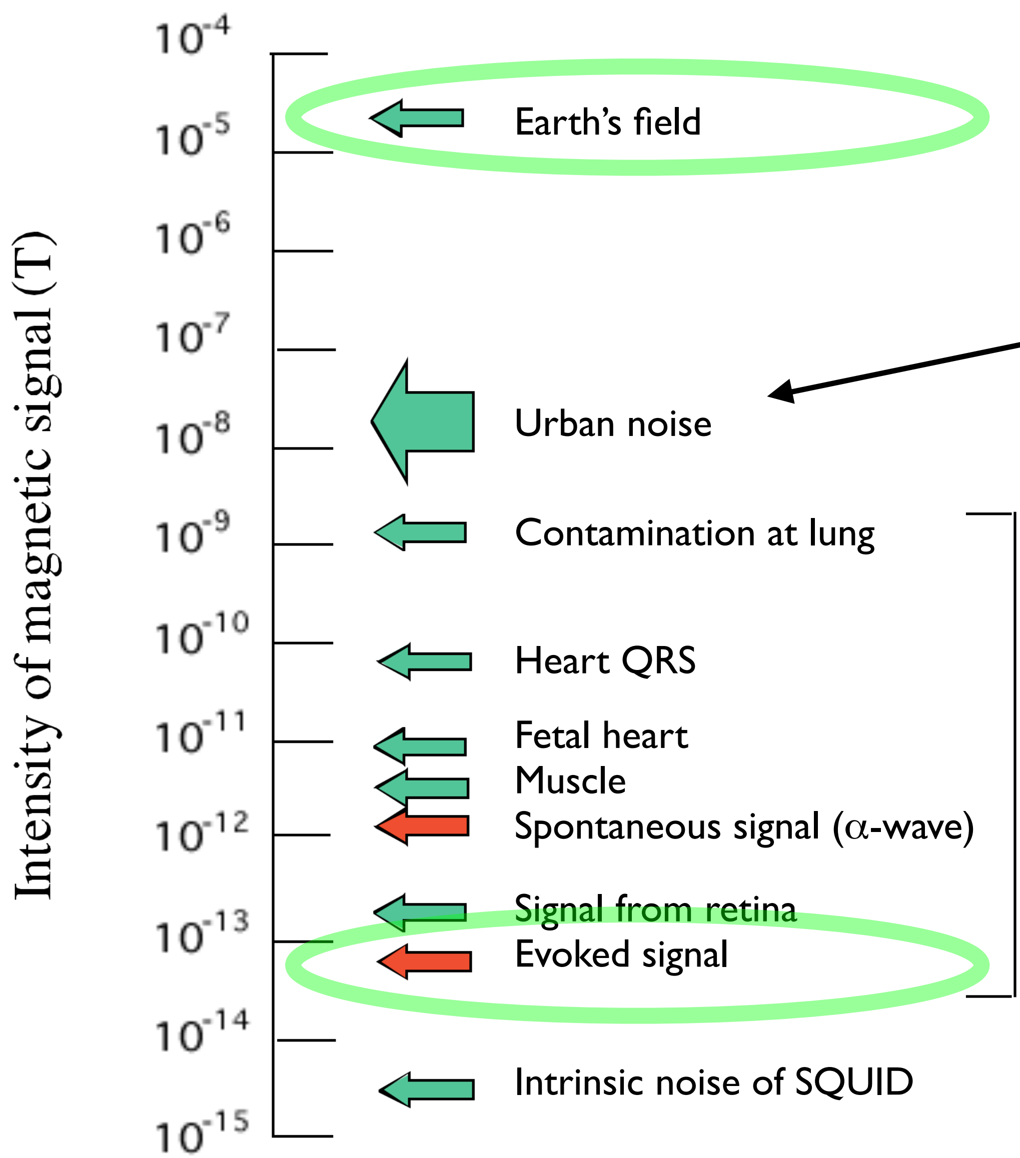
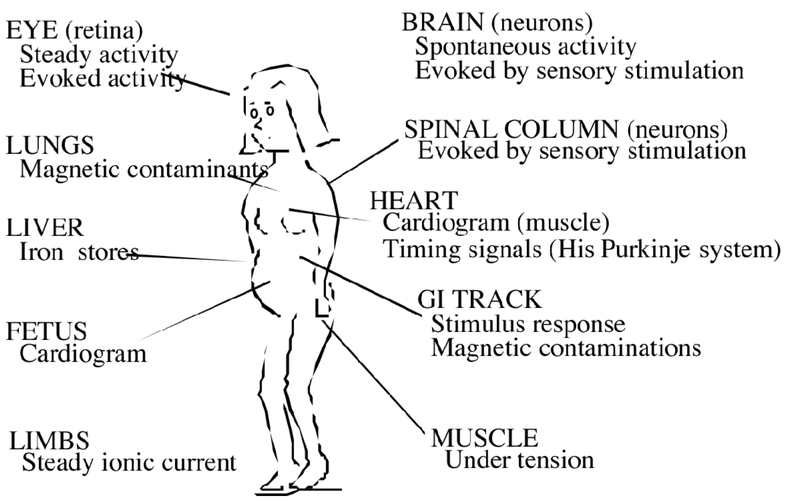
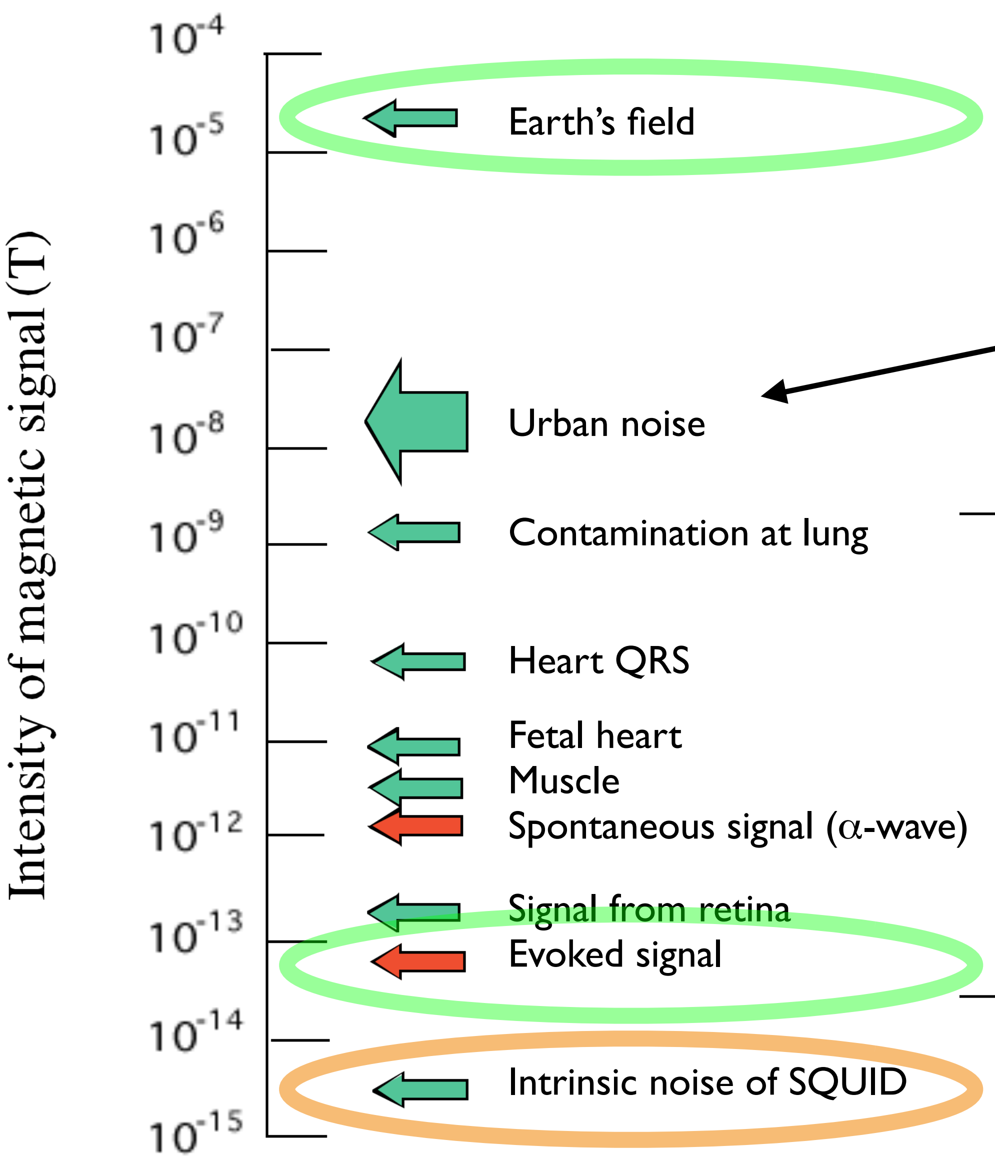
Magnetic Field Strengths

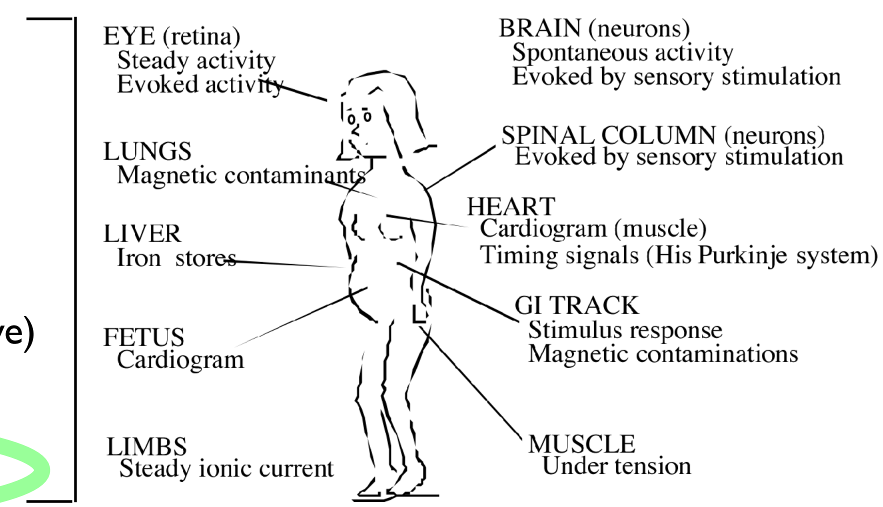




Biomagnetic Signals

Magnetic Field Strengths



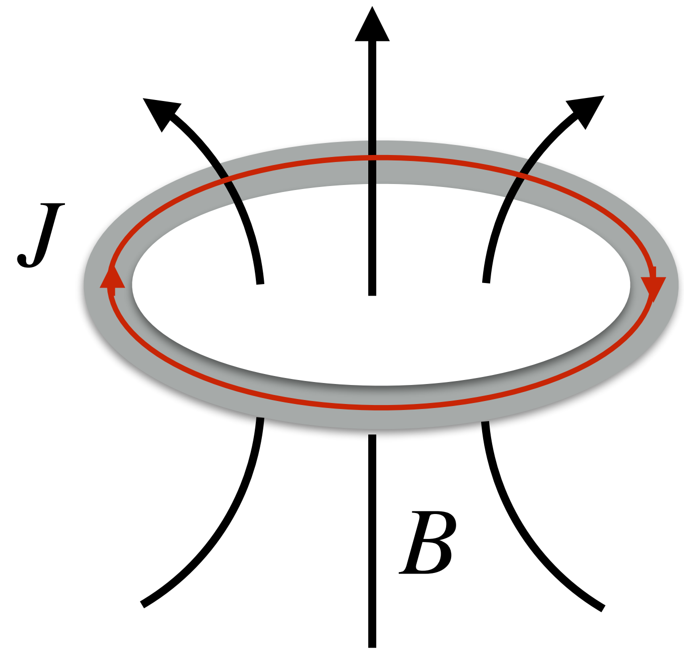


Biomagnetic Signals

SQUIDs

Superconductivity

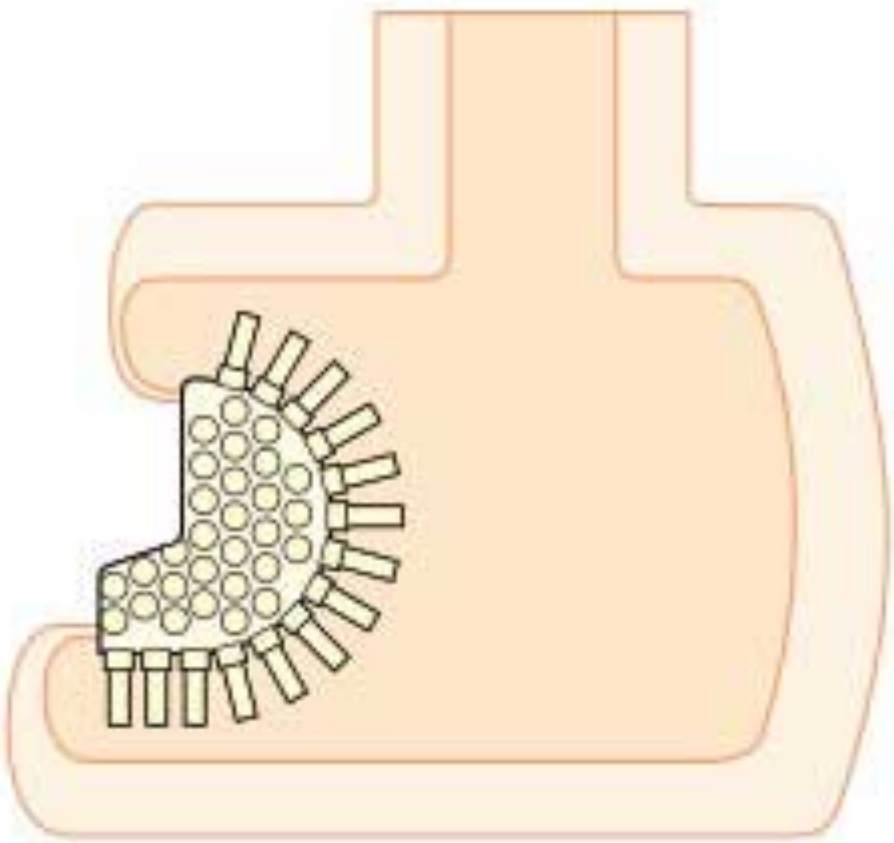
- ➔ Magnetic flux quantization
- ➔ Josephson Effect
- ➔ SQUID = Superconducting Quantum Interference Device



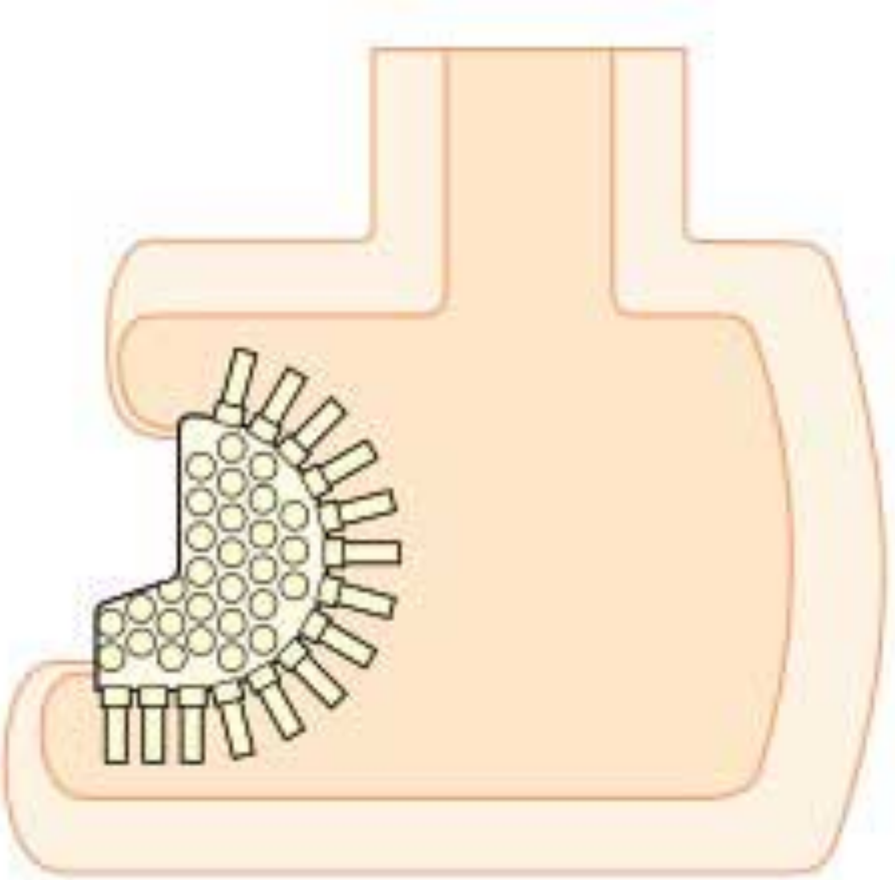
$$\Phi = n\frac{h}{2\mathrm{e}} = n\Phi_0$$

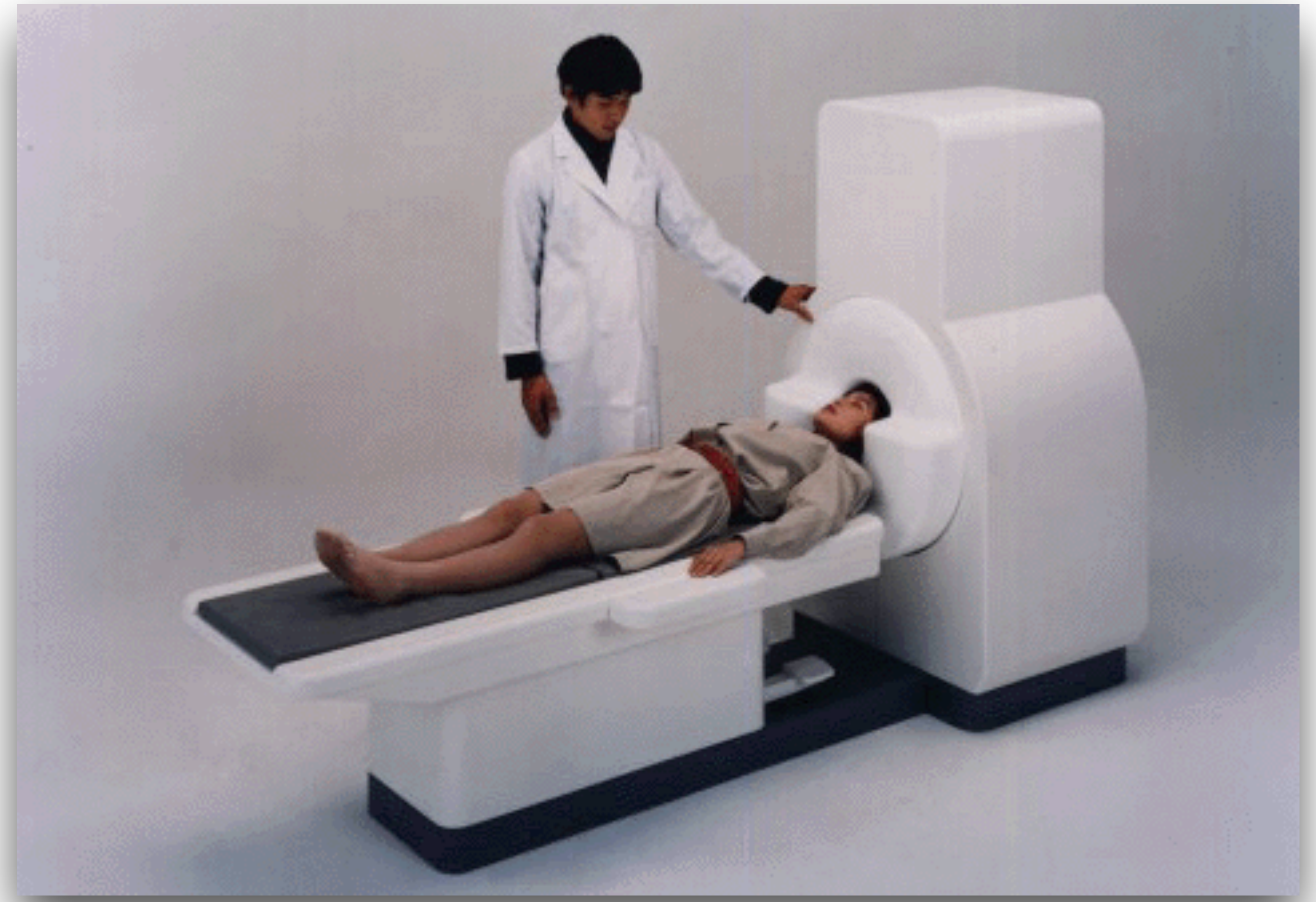
$$\Phi_0 = \frac{h}{2\mathrm{e}} = 2.07\times 10^{-15}\ \mathrm{Wb}$$

MEG Usage

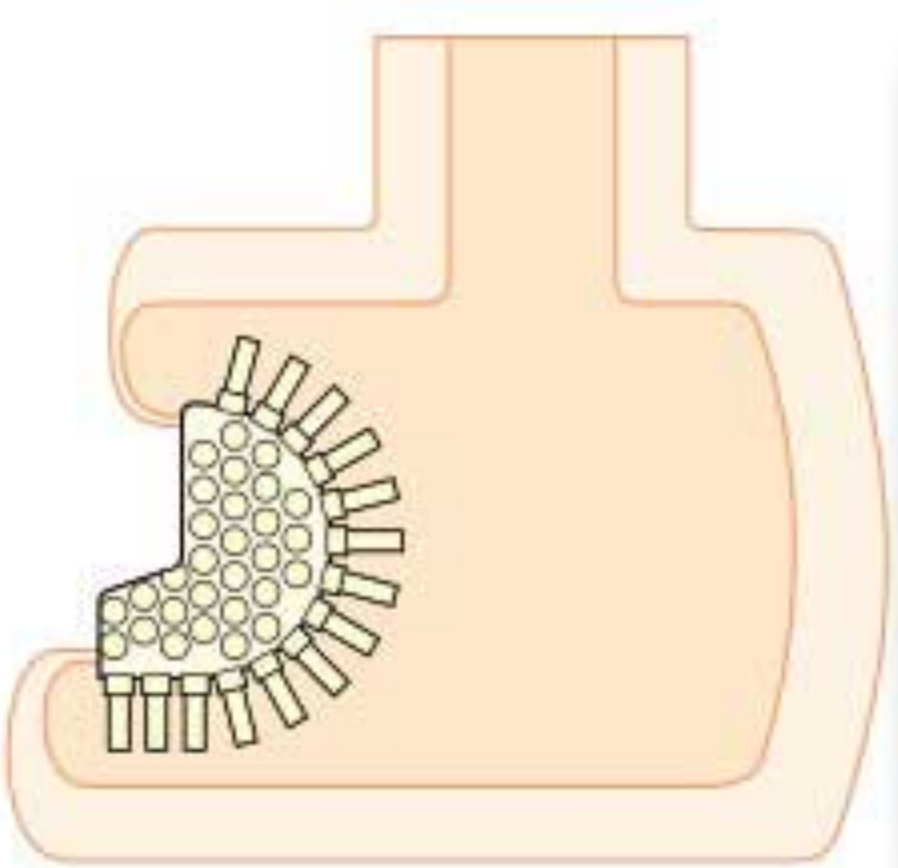


MEG Usage



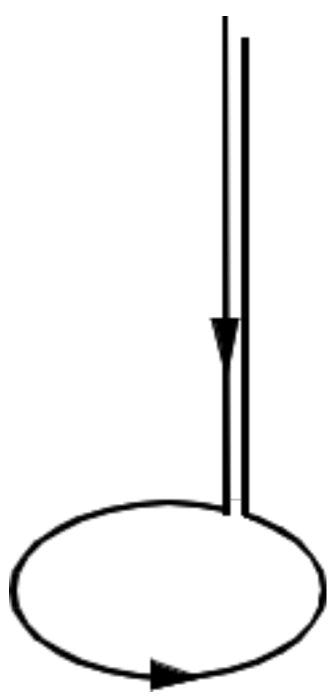


MEG Usage



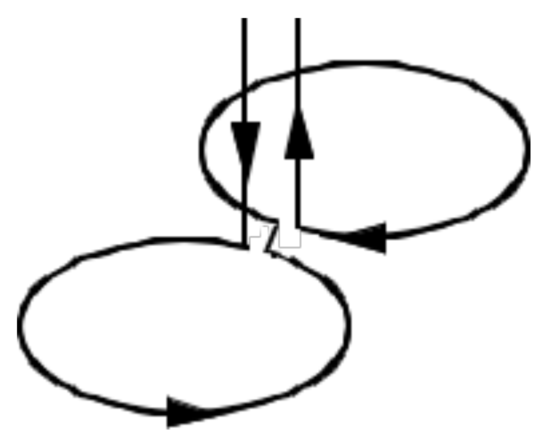
MEG SQUIDs

SQUID Magnetometer

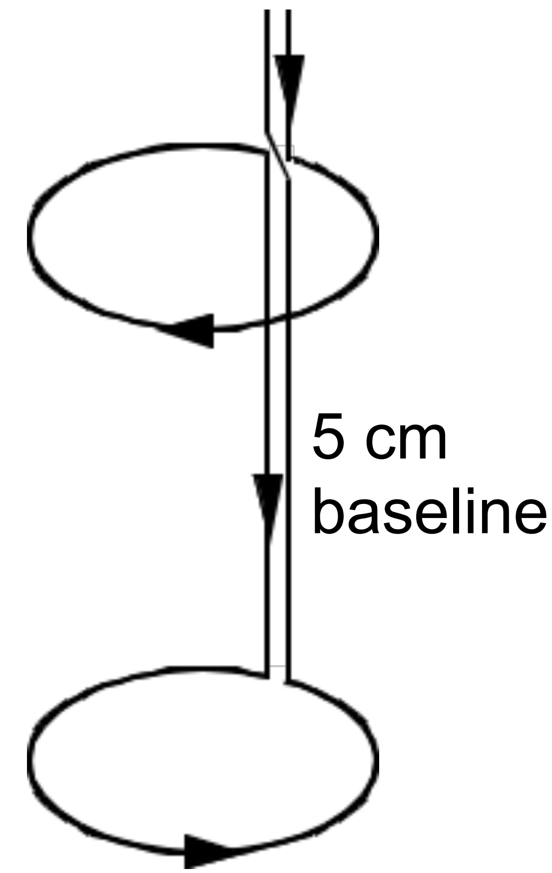


SQUID Gradiometers

Noise reduction from
Differential measurement



Planar Gradiometer



Axial Gradiometer

Neural Signals & MEG

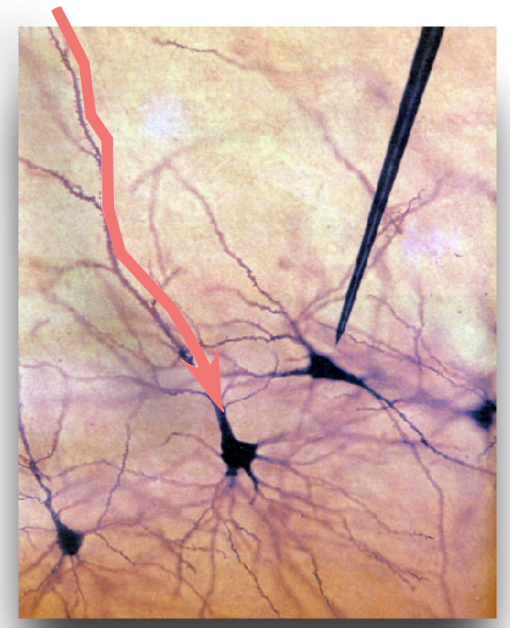
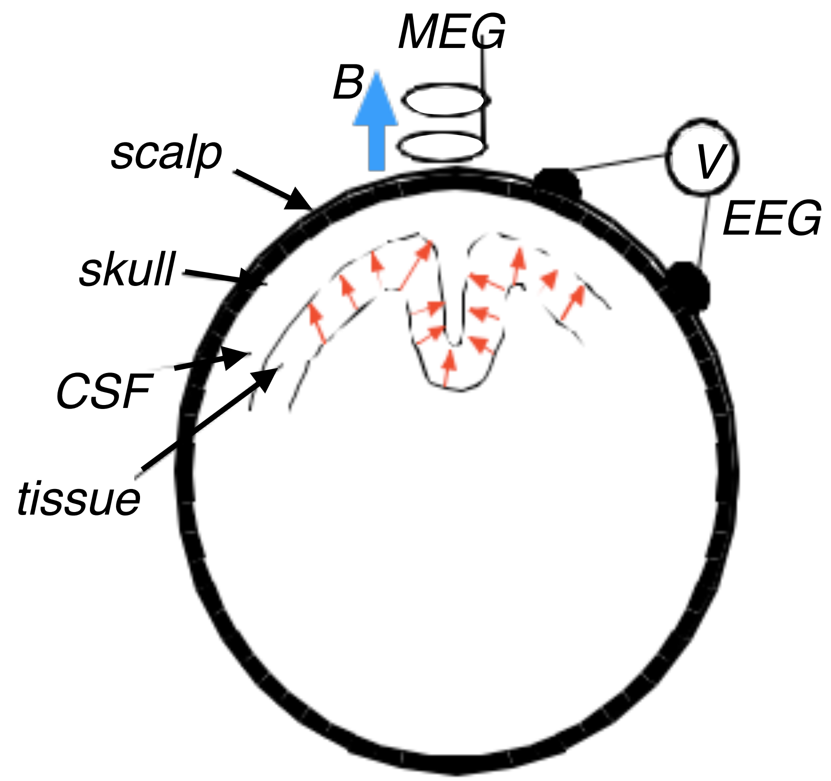
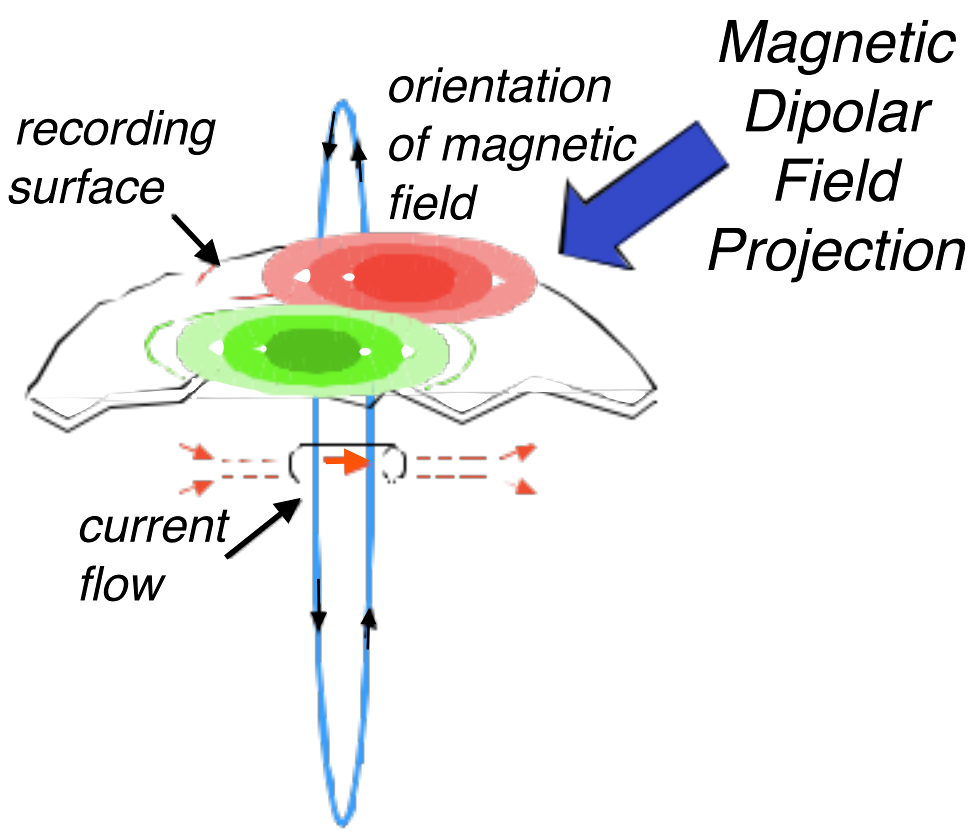


Photo by Fritz Goro

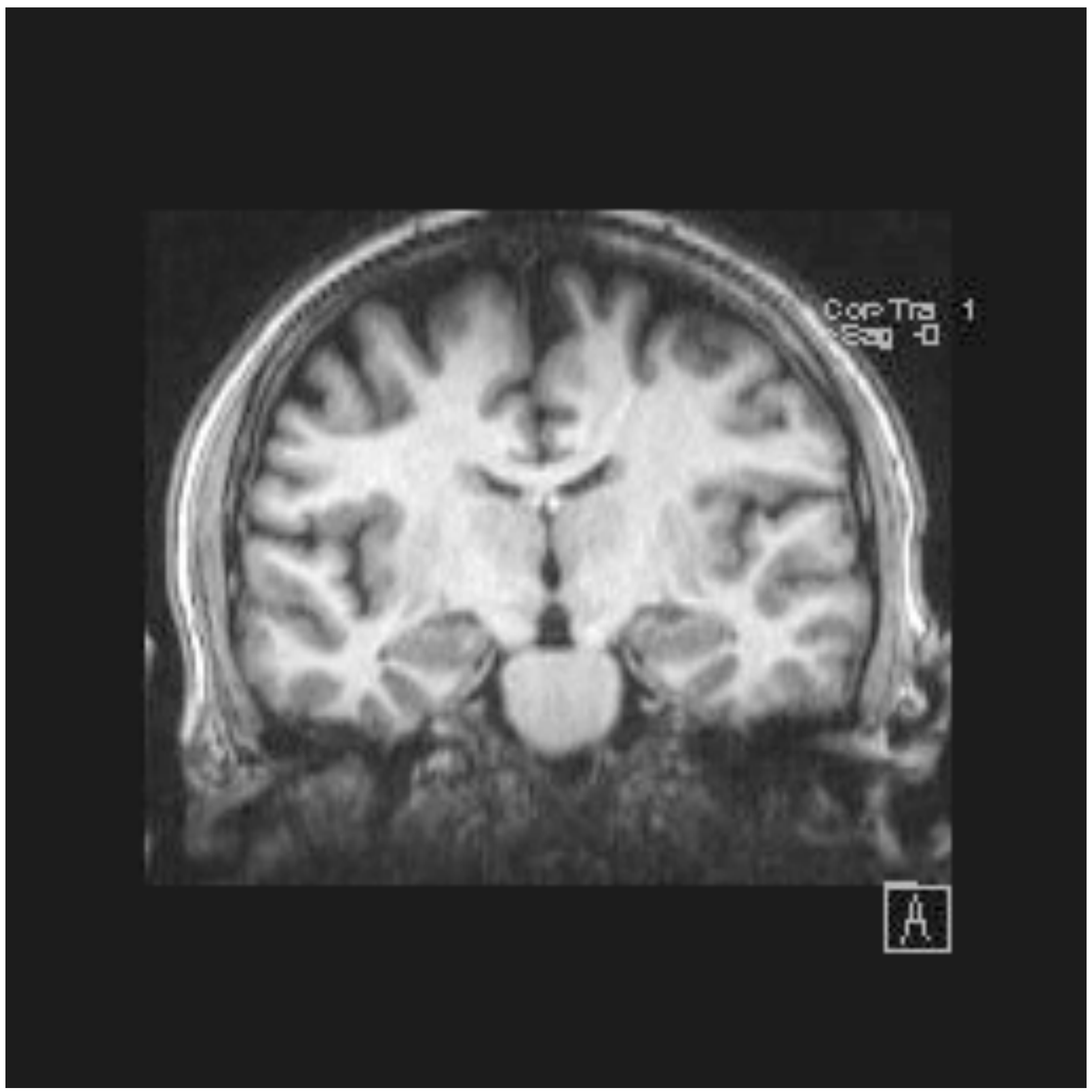


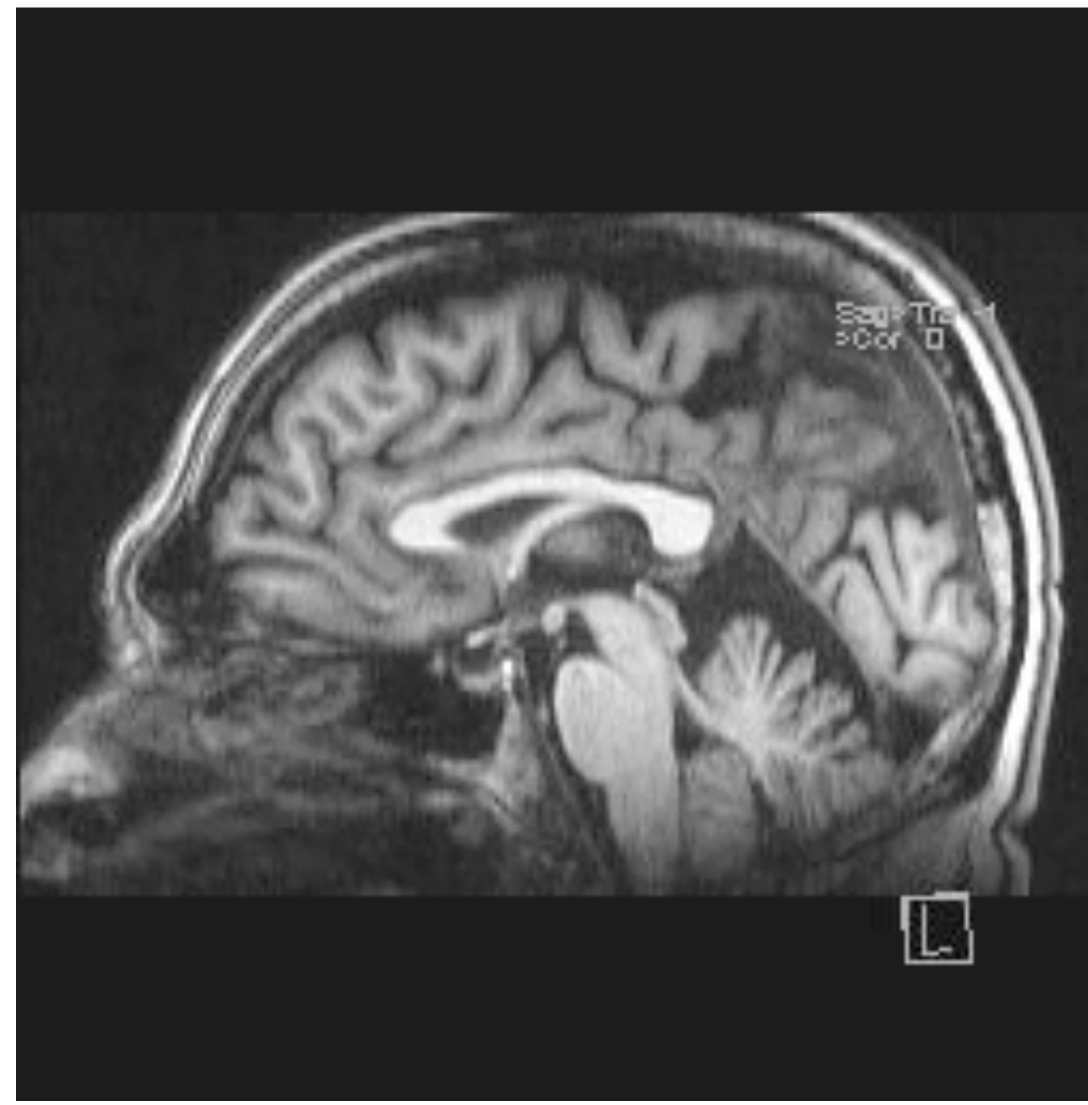


- Direct electrophysiological measurement
  - not hemodynamic
  - real-time
- No unique solution for distributed source

- Measures spatially synchronized cortical activity
- Fine temporal resolution (~ 1 ms)
- Moderate spatial resolution (~ 1 cm)

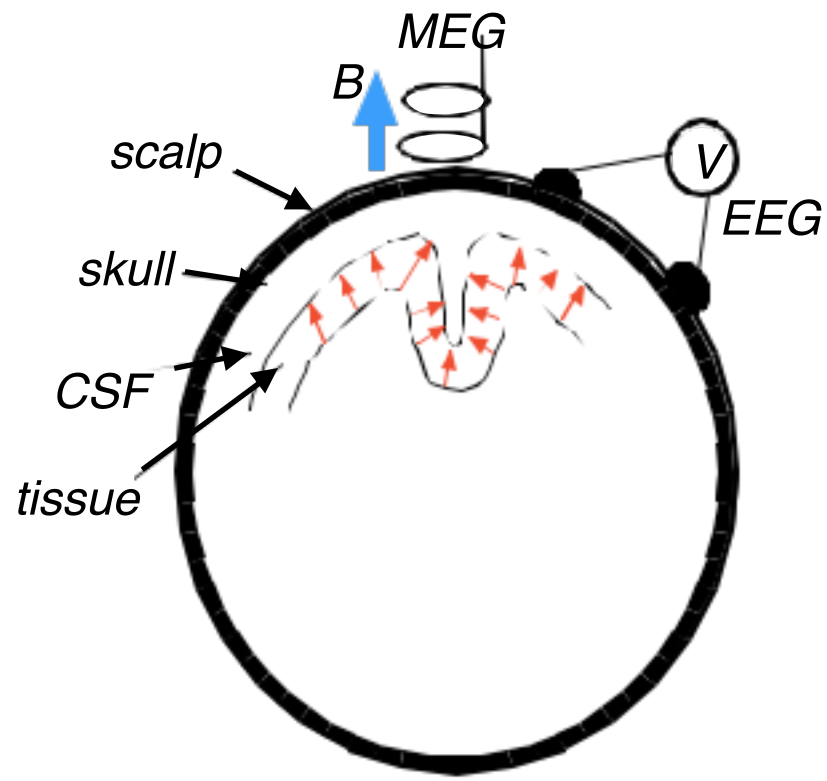
Cortex & The Brain

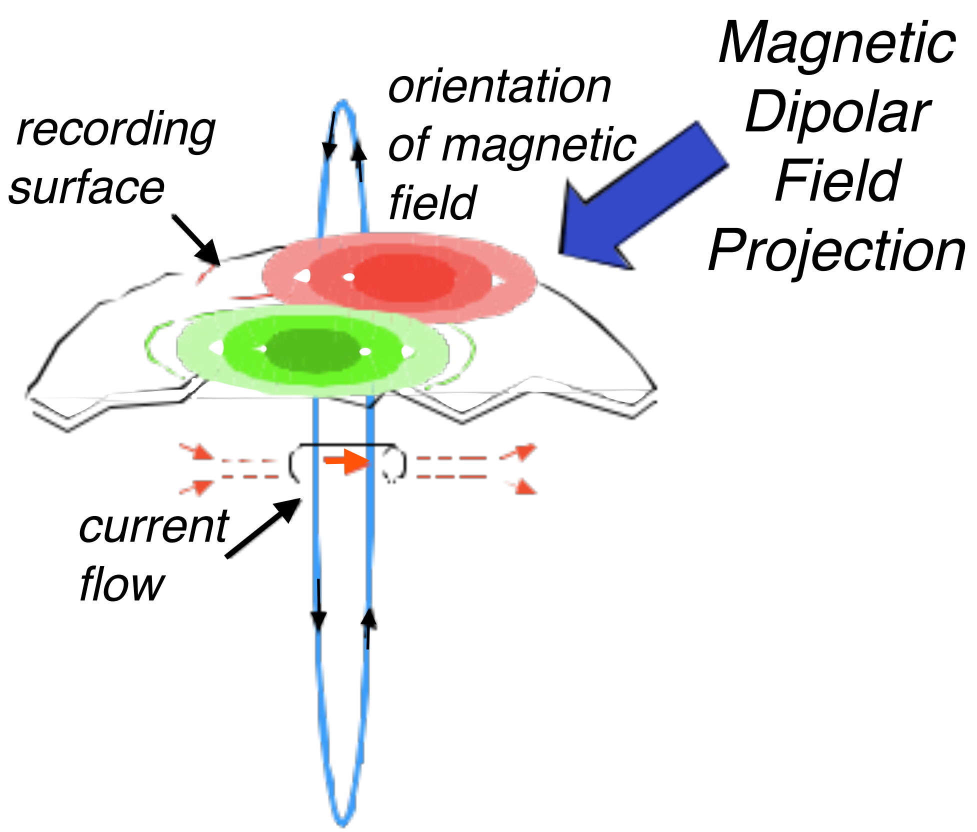




Neural Signals & MEG

Photo by Fritz Goro





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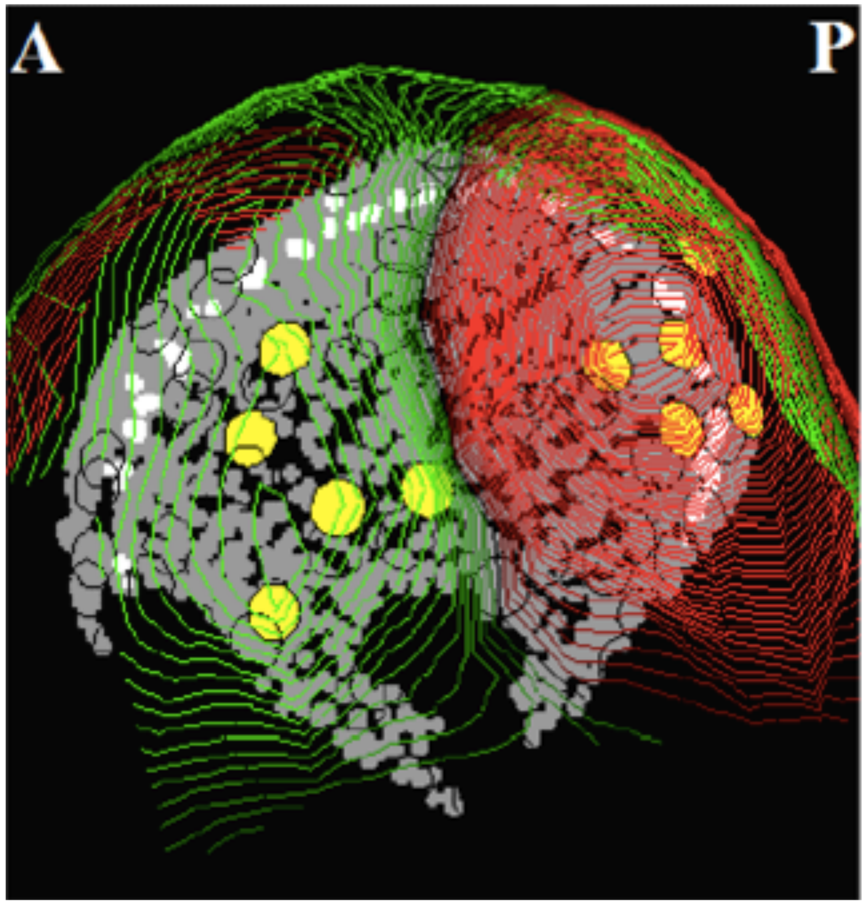
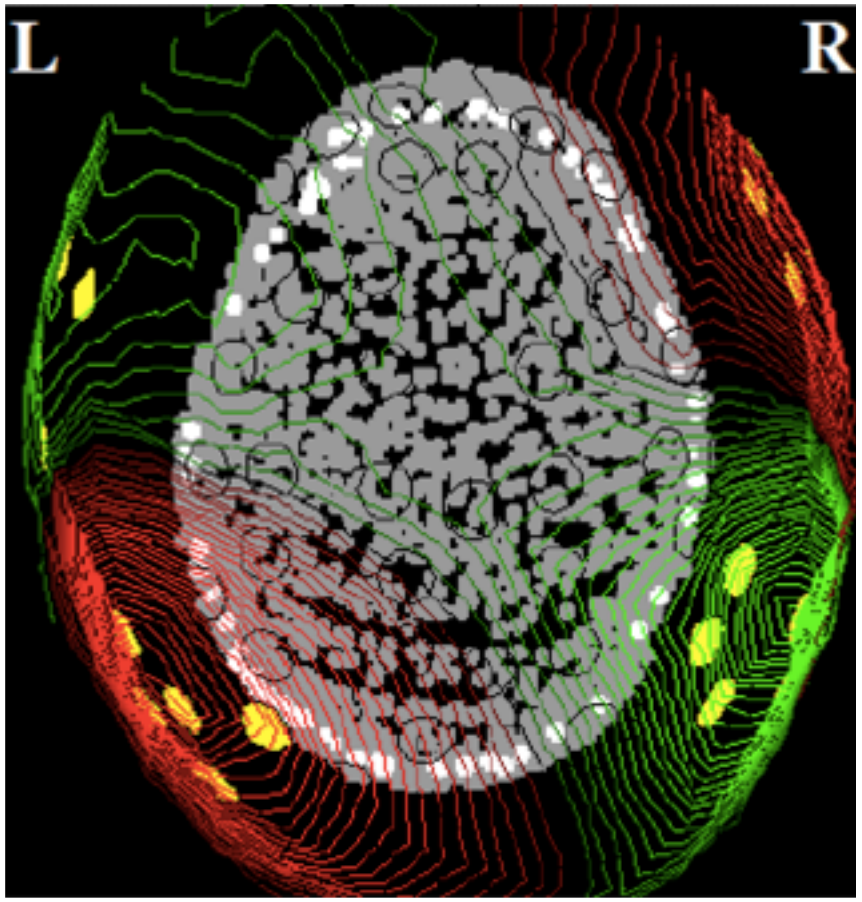
MEG Auditory Field

3-D Isofield Contour Map



Sagittal View

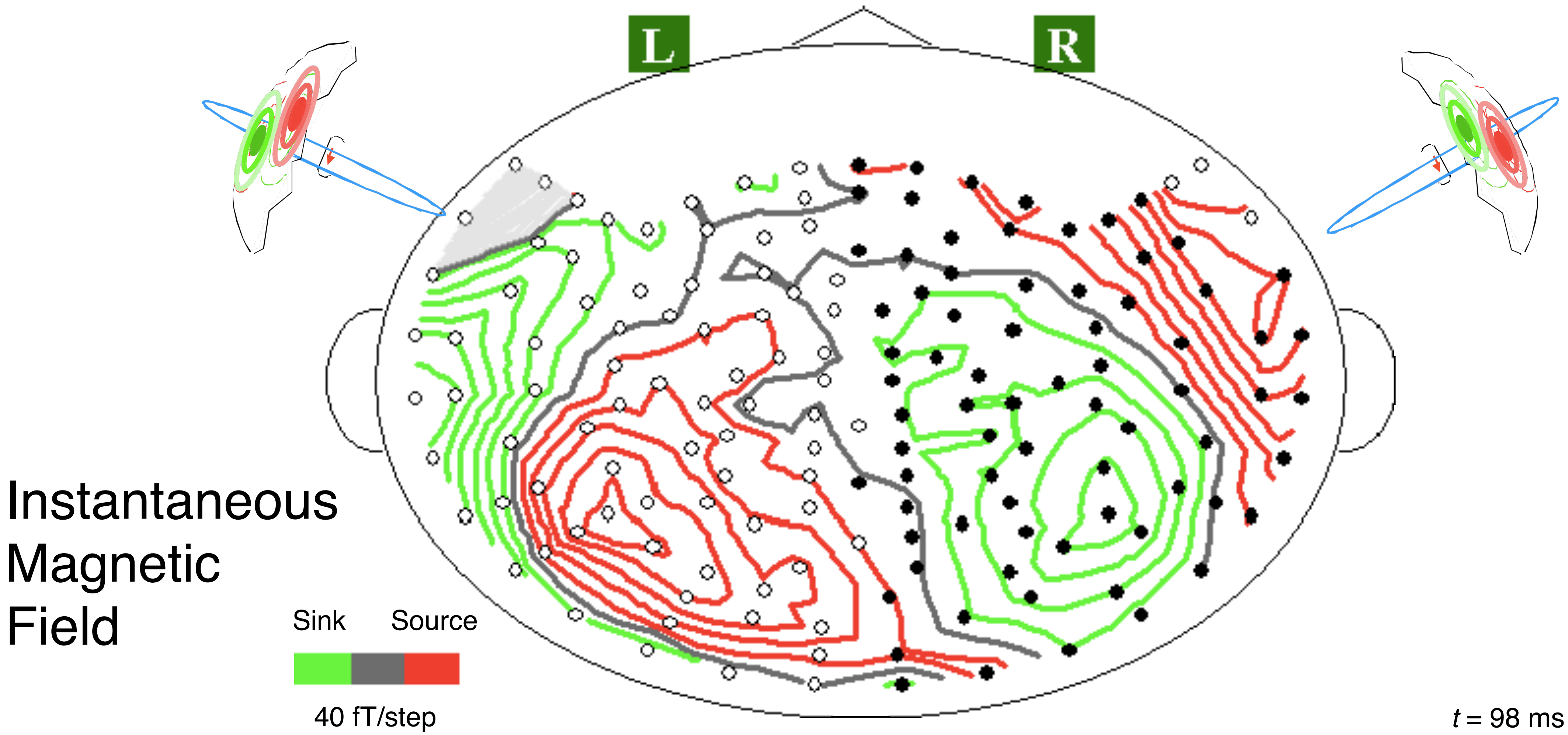


Axial View

Chait, et al., Cerebral Cortex (2006)

MEG Auditory Field

Flattened Isofield Contour Map



Neural Currents $\Rightarrow$ Magnetic Fields

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho_E \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} &= J_E \\
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0
\end{aligned}$$

Magnetic Fields $\Rightarrow$ Neural Currents

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\end{aligned}
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Magnetic Fields $\Rightarrow$ Neural Currents

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho_E \\
\nabla \cdot \mathbf{B} &= \rho_M \\
\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} &= J_E \\
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= -J_M
\end{aligned}$$

Magnetic Fields ⇒ Neural Currents

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho_E \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} &= J_E \\
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0
\end{aligned}
$$

Neural Source Localization

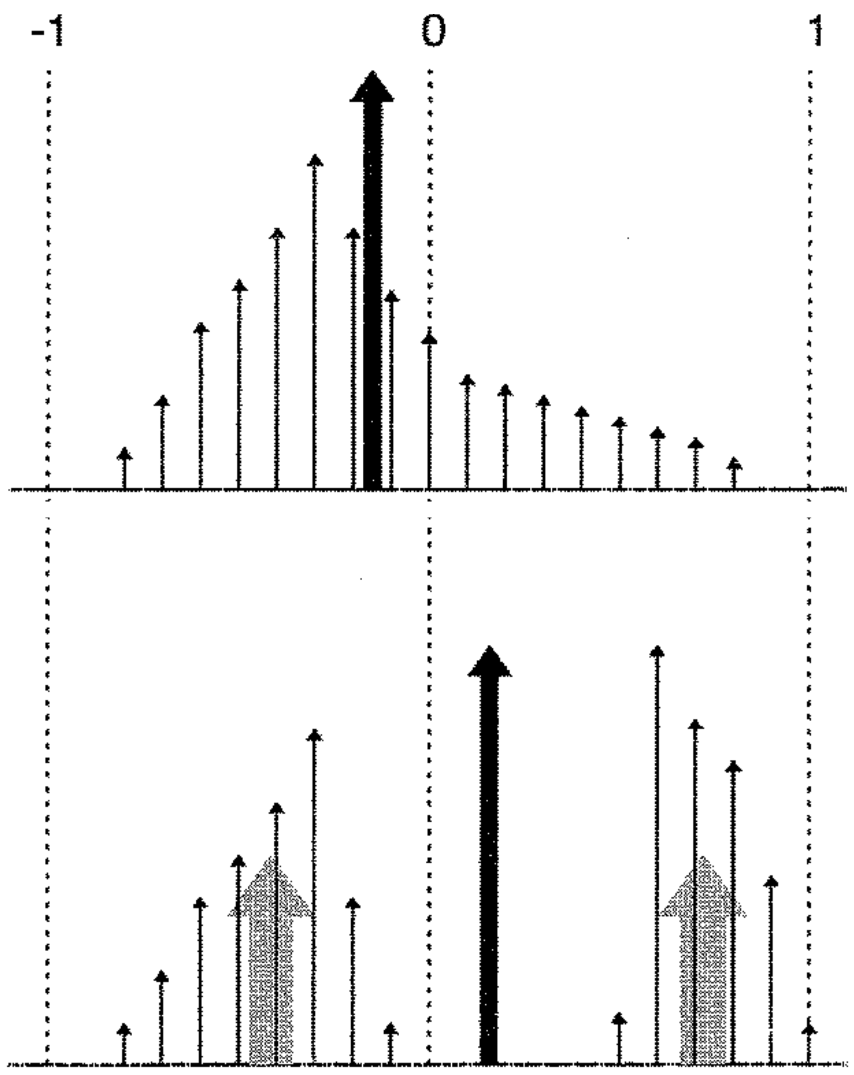
- No Unique Solution from Magnetic Field Configuration to Neural Current Distribution ("Inverse Problem")
- Several Widely Used Methods
  - Equivalent-Current Dipoles
  - Minimum Norm Estimation & variants
  - Beamforming & variants
  - Others

Neural Source Issues

- Equivalent-Current Dipoles
  - How many dipoles to use?
  - Non-intuitive side effects

Equivalent-Current Dipole

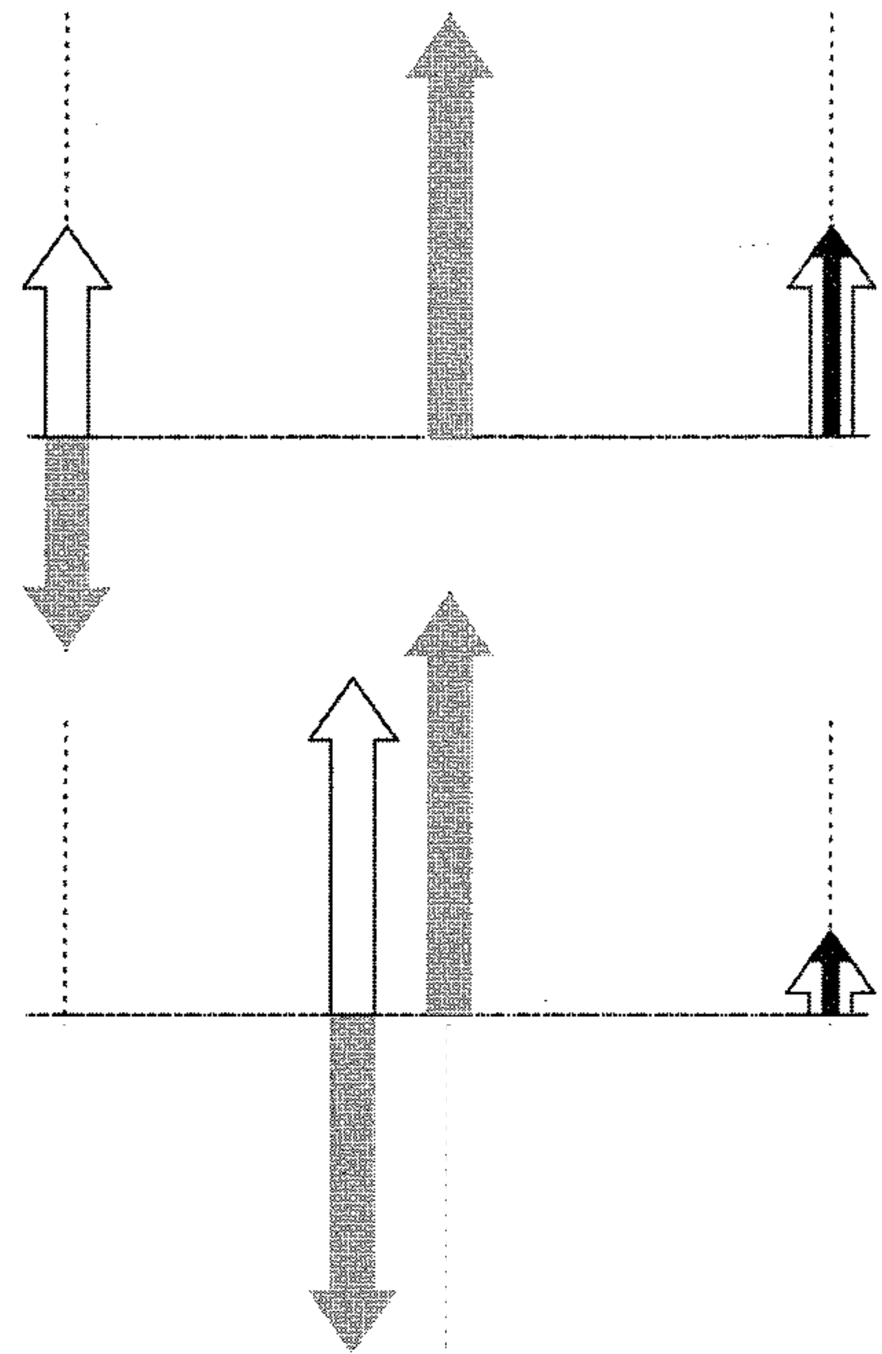
- “Center of Current” Dipole
- c.f. “Center of Mass”



Lükenhöner & Mosher (2007)

Equivalent-Current Dipole

- "Center of Current" Dipole
- c.f. "Center of Mass"
- ***BUT***
  for Center of Mass, $m_i > 0$
- ***NOT*** so
  for Center of Current, $I_i \gtrless 0$



Lükenhöner & Mosher (2007)

Neural Source Issues

- Equivalent-Current Dipoles
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  - Non-intuitive side effects (nonetheless still valid)

Neural Source Issues

- Equivalent-Current Dipoles
  - How many dipoles to use?
  - Non-intuitive side effects (nonetheless still valid)
- *Minimum Norm* vs. *Beamforming*
  - Advocates for each can produce datasets that show misleading results from the other method
- Recommended Reading
  - Lütkenhöner & Mosher (2007)

Neural Source Solutions?

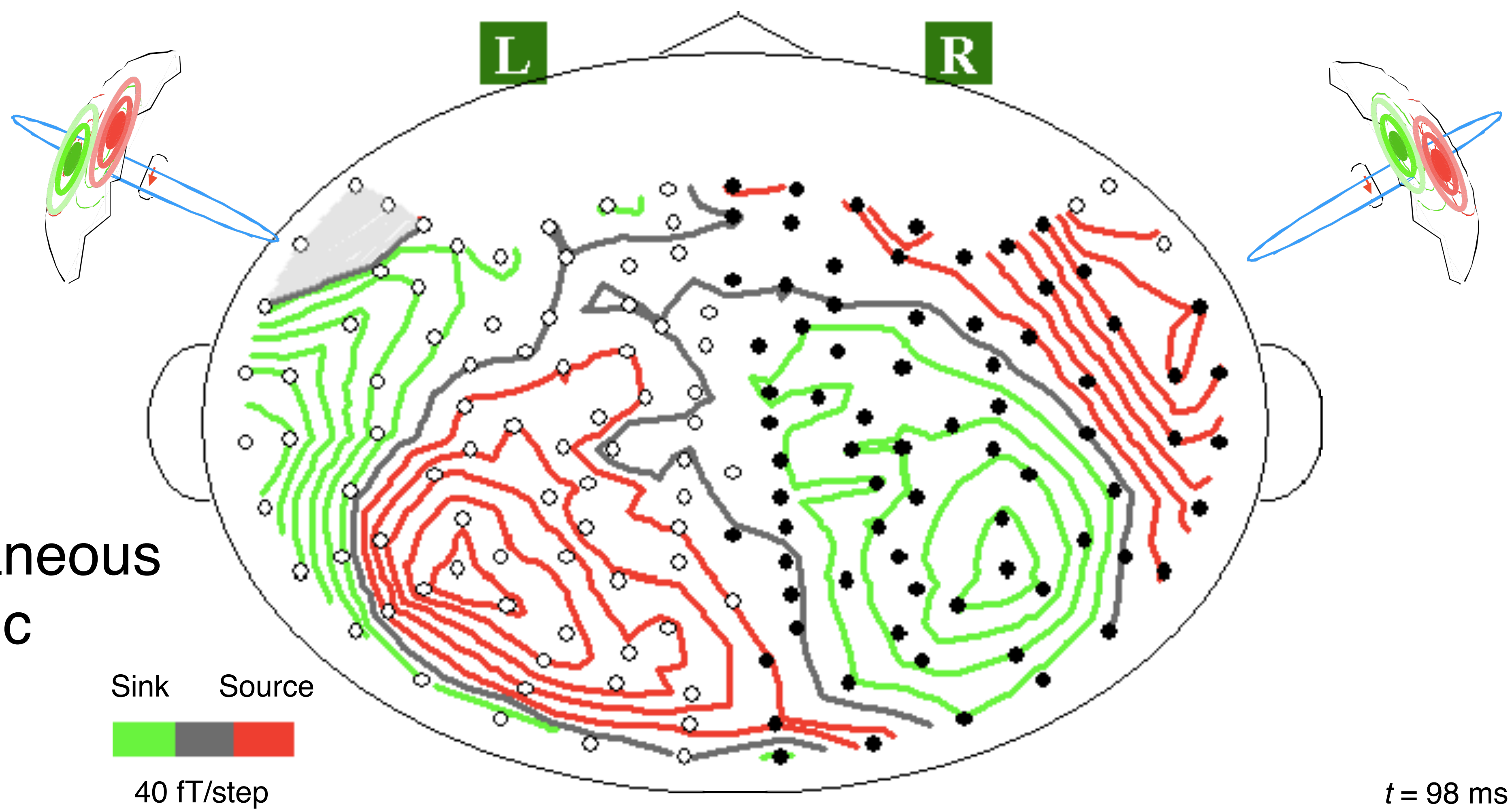
- All major methods are workable in practice
  - Can give physiologically plausible result
  - Can give "correct/true" result
- Any might also get you into trouble
  - Each has weaknesses & blind spots

Comparison with EEG

- High temporal resolution
- Inexpensive, Room temperature
- Slow, careful set-up
- Electric fields strongly distorted
  - Brain = *inhomogeneous*, *anisotropic*, dielectric
  - Poor spatial neural reconstruction unless very carefully modeling of currents and entire head
  - Inverse problem: worse? better?
- Many more neural sources
- Complementary with MEG

MEG Auditory Field

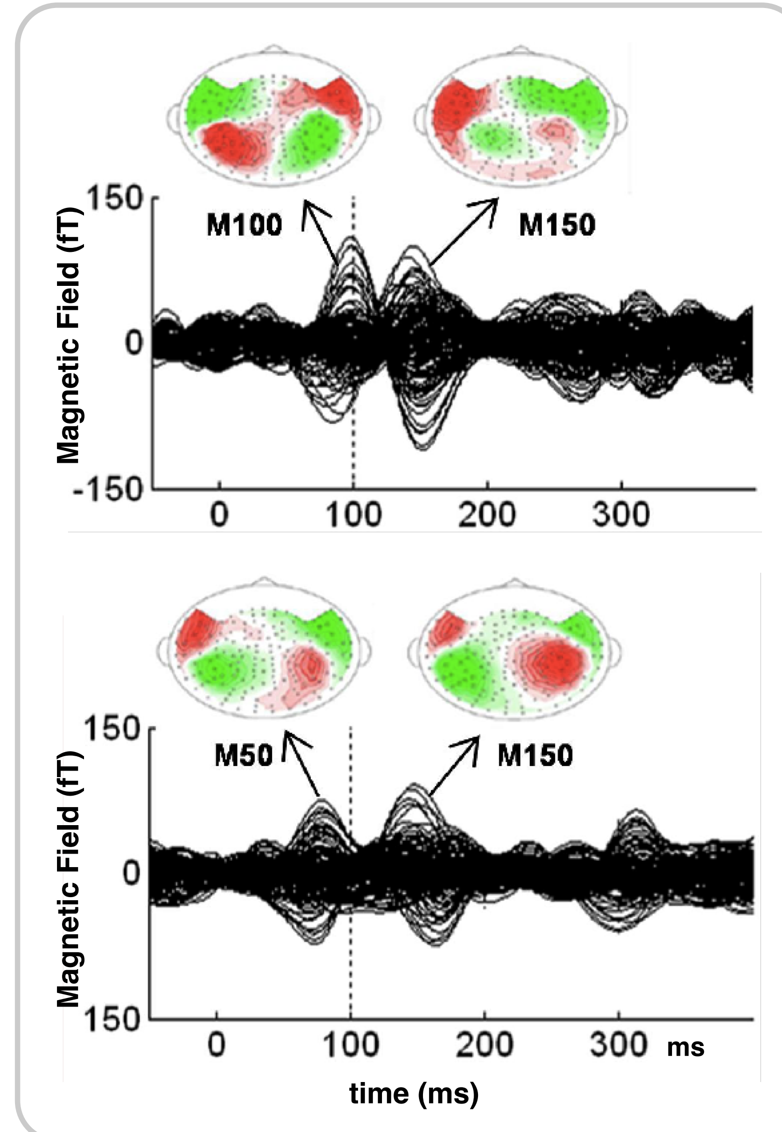
Flattened Isofield Contour Map



Instantaneous Magnetic Field

Time Course of MEG Responses

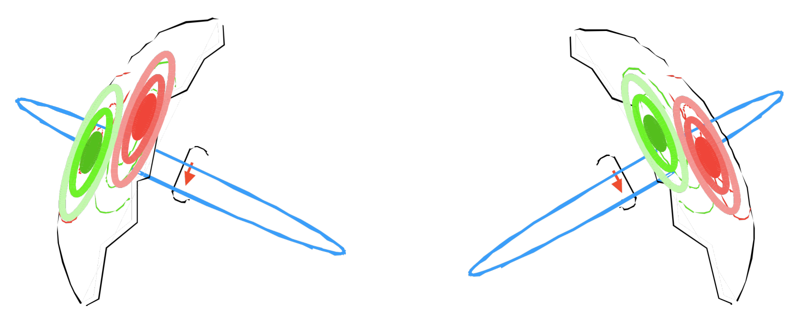
Pure Tone



Broadband Noise

Auditory Evoked Responses

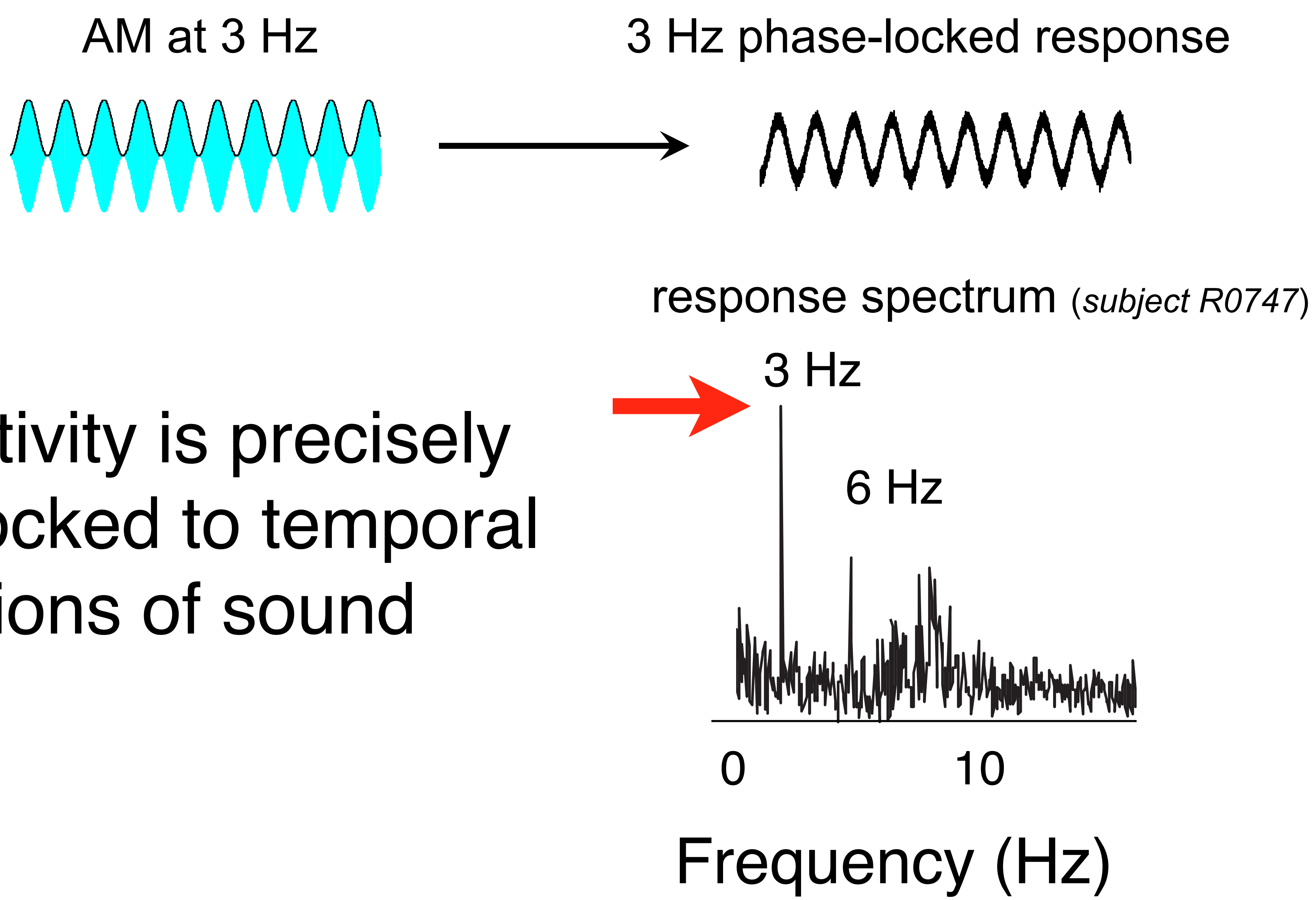
- MEG Response Patterns Time-Locked to Stimulus Events
- Robust
- Strongly Lateralized



- **Auditory Induced Responses**

- MEG Response Patterns not Time-Locked to Stimulus Events
- Can be larger than Evoked Responses but cannot be averaged directly

Phase-Locking in MEG to Acoustic Modulations

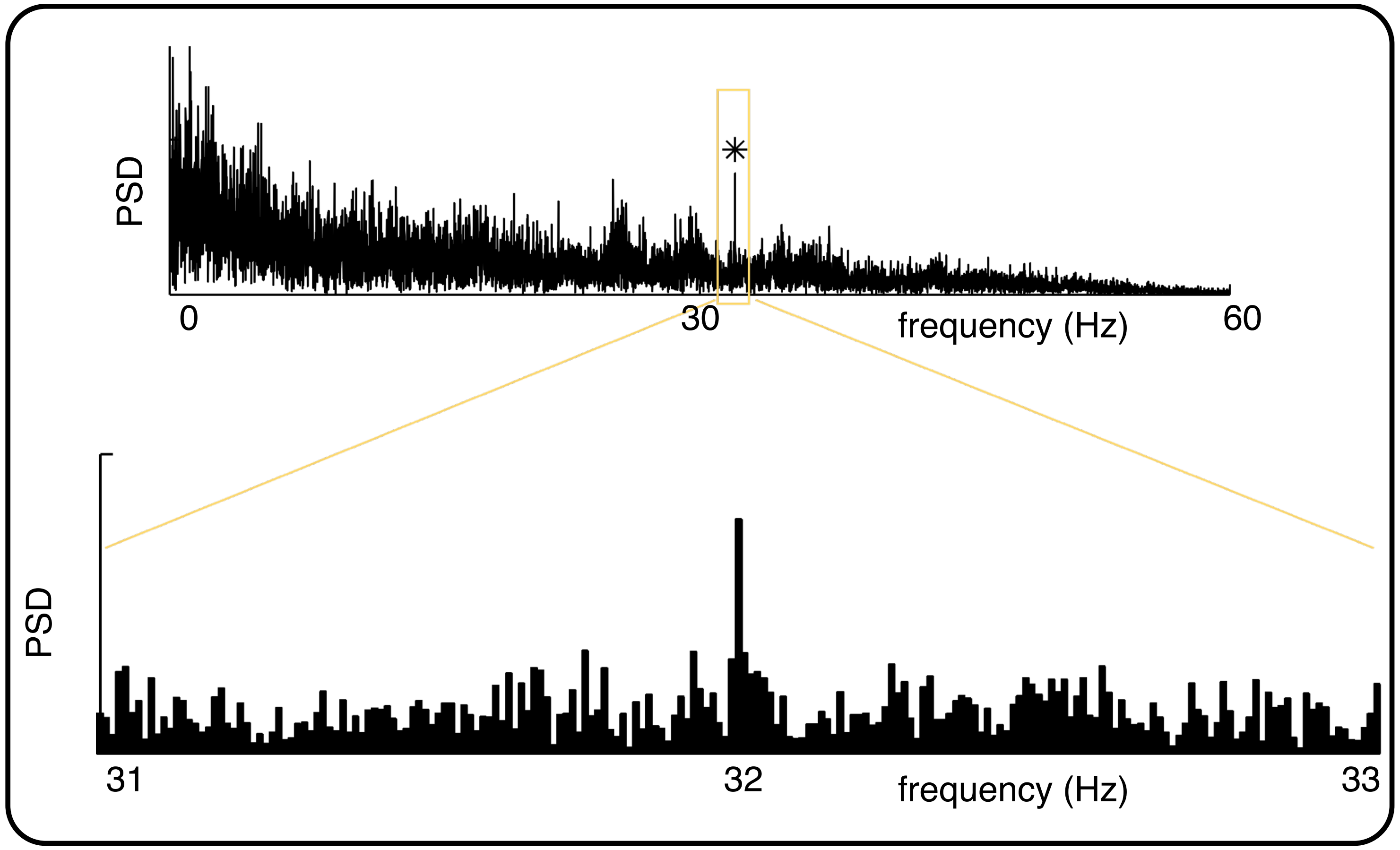


MEG activity is precisely phase-locked to temporal modulations of sound

Ding & Simon, J Neurophysiol (2009)
Wang et al., J Neurophysiol (2012)

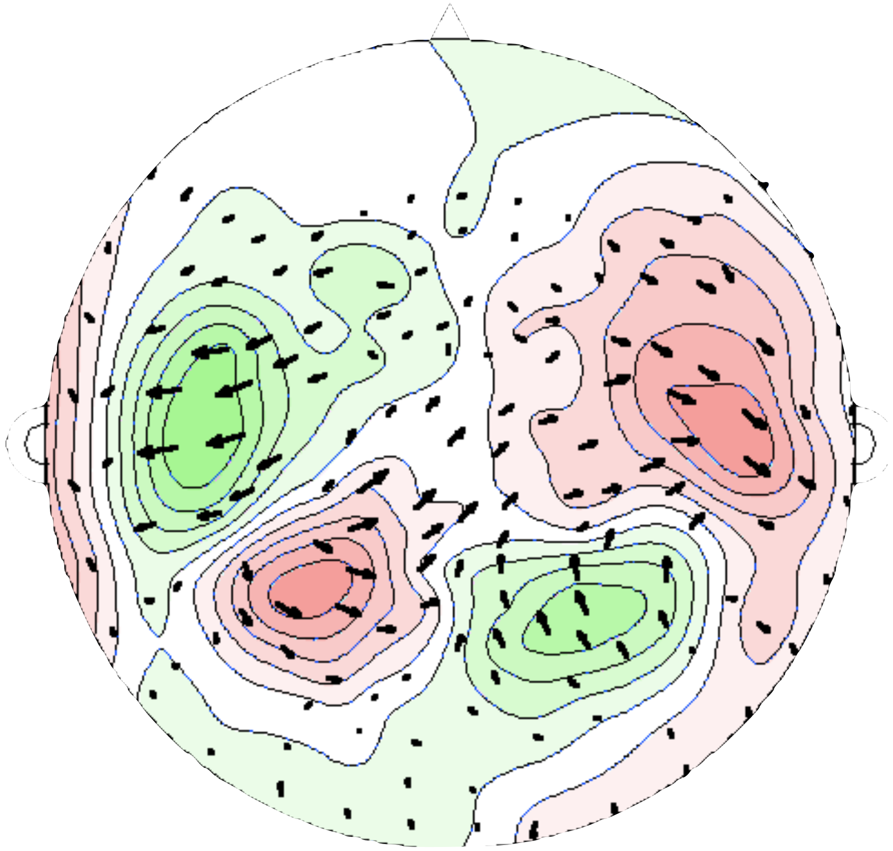
MEG Fourier Phase Analysis

Frequency Response to 32 Hz Amplitude Modulation



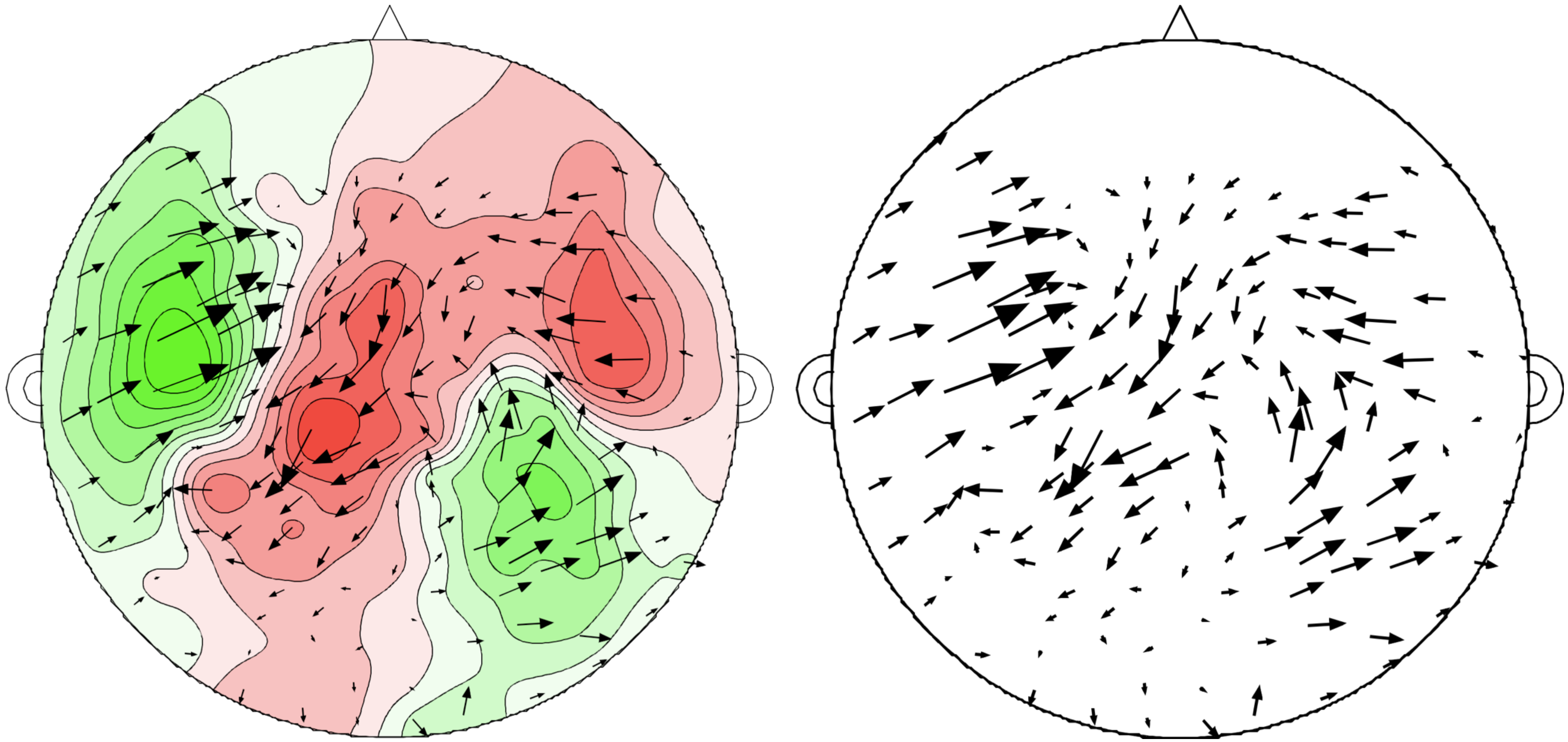
400 Hz tone carrier
100 trials @ 1 s
(concatenated)

Phasor Isofield Contour Map

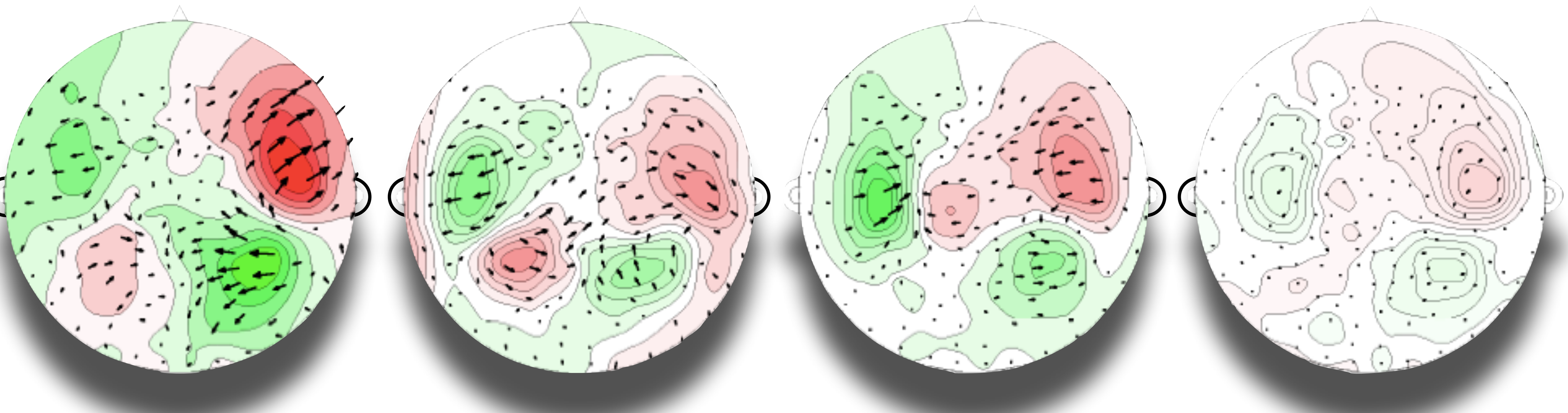


f = 32 Hz

Complex Magnetic Field with / without generated contours

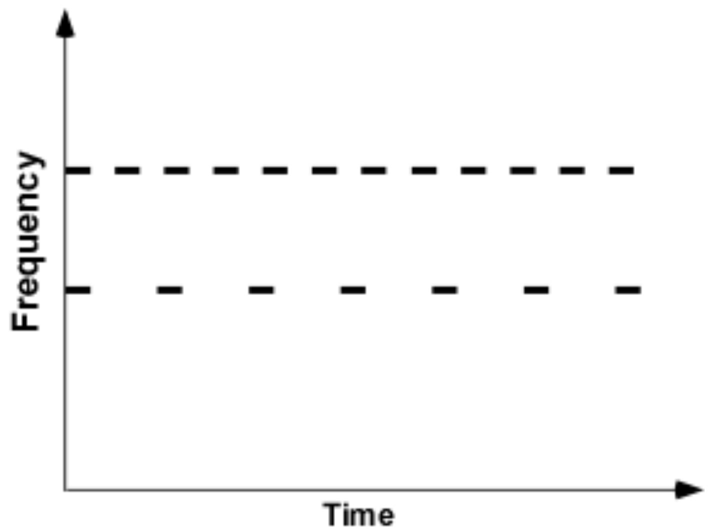


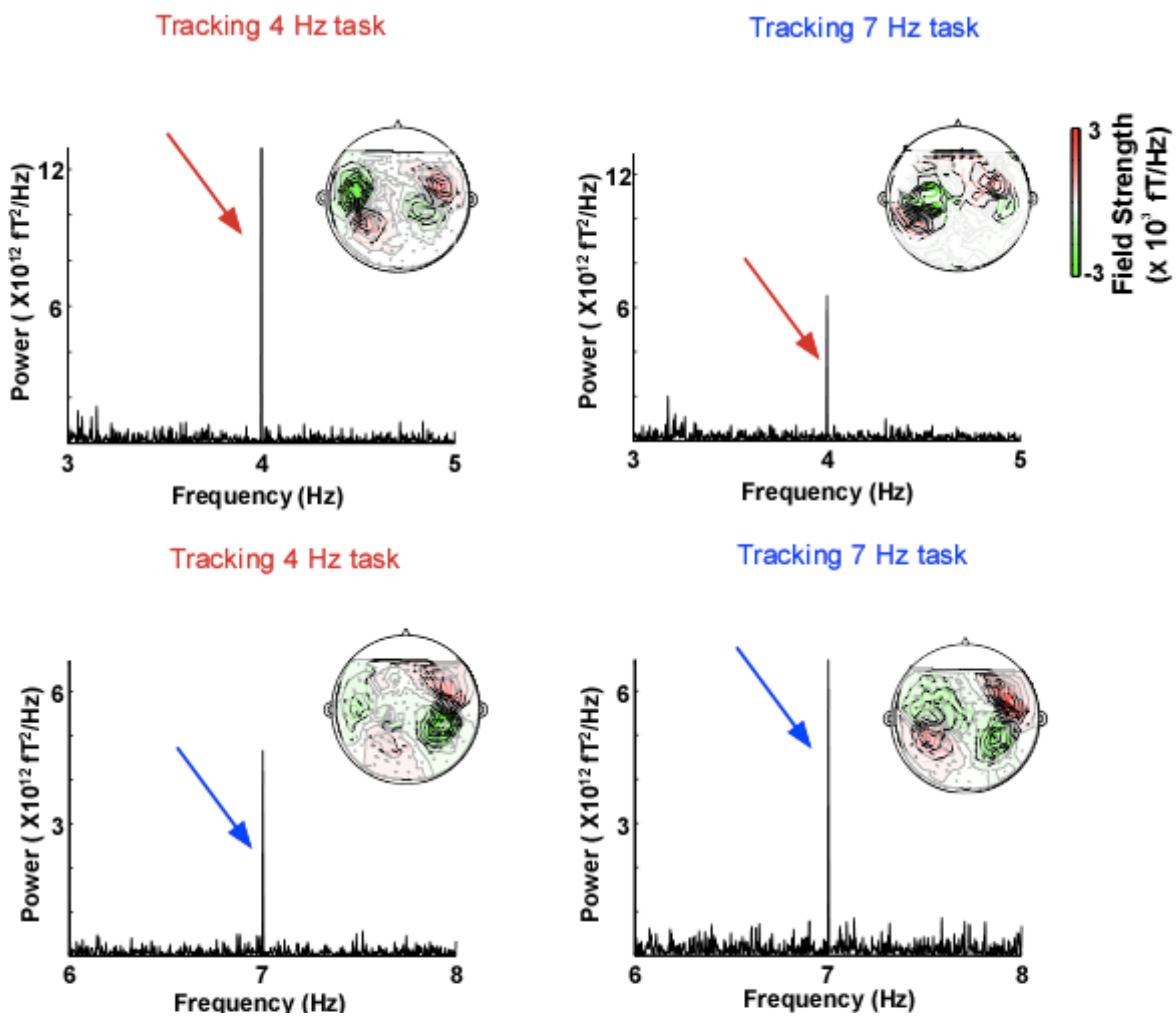
Example: Whole Head Transfer Function



16 Hz 32 Hz 48 Hz 64 Hz

Example: Auditory Streaming

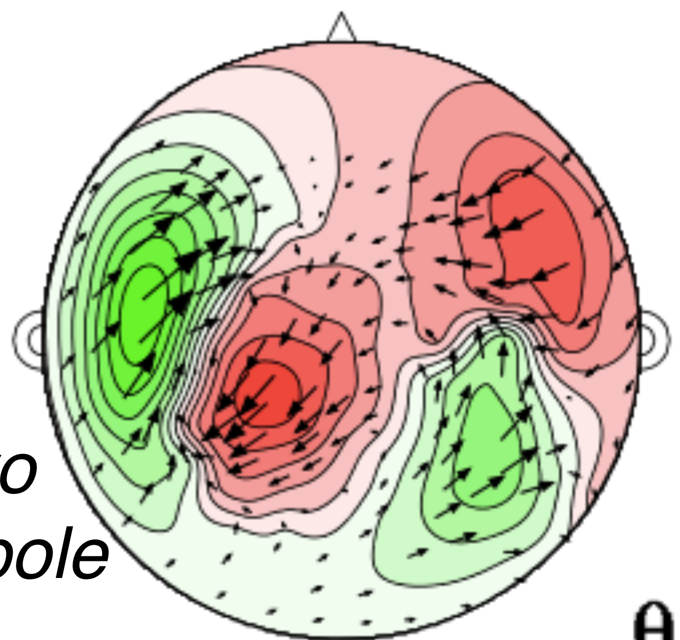




- Stream Segregation with Competing Foregrounds
- Attentional Modulation of Neural Representation

Xiang et al, J Neurosci (2010)

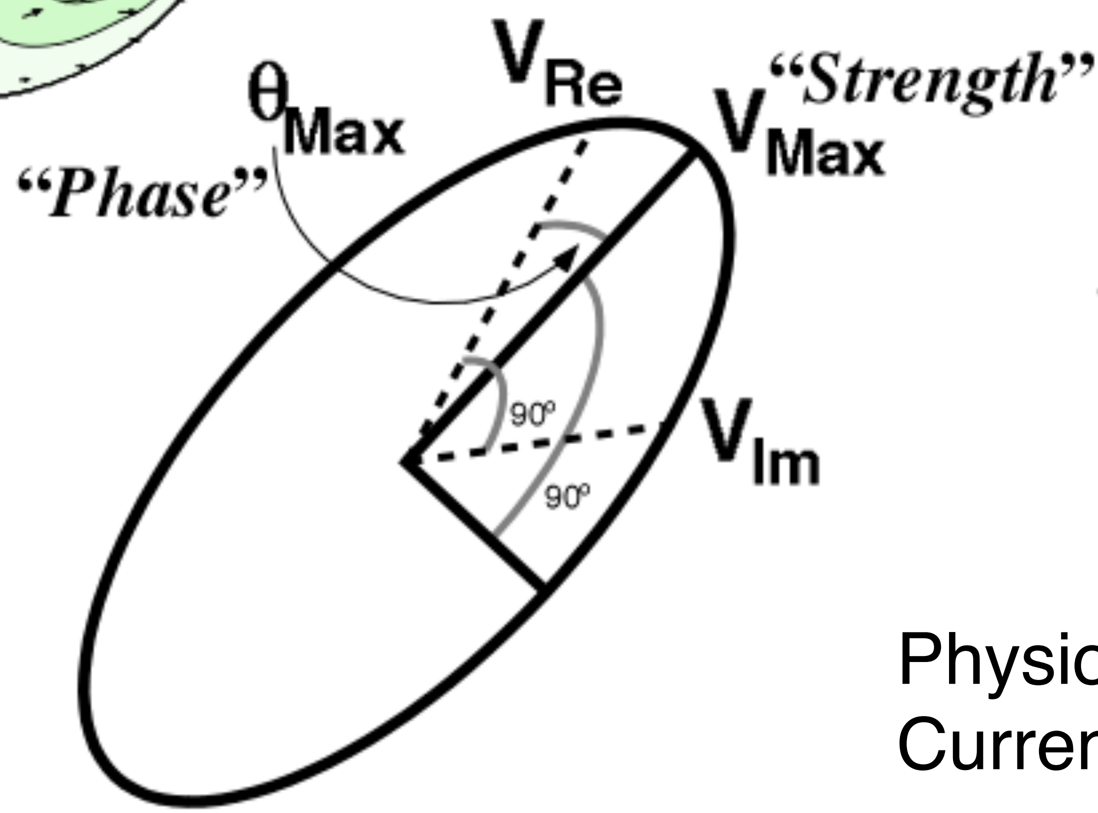
Complex Neural Current Sources



Two Dipole Fit

$$\vec{V} = \vec{V}_{Re} + i\,\vec{V}_{Im}$$

$$\vec{V}(\theta) = \vec{V}_{Re}\cos(\theta) + \vec{V}_{Im}\sin(\theta)$$



“Sharpness”

$$\eta = \frac{|V_{Min}|}{|V_{Max}|}$$

$$0 < \eta < 1$$

$\hat{V}_{Max}, \hat{V}_{Min}$

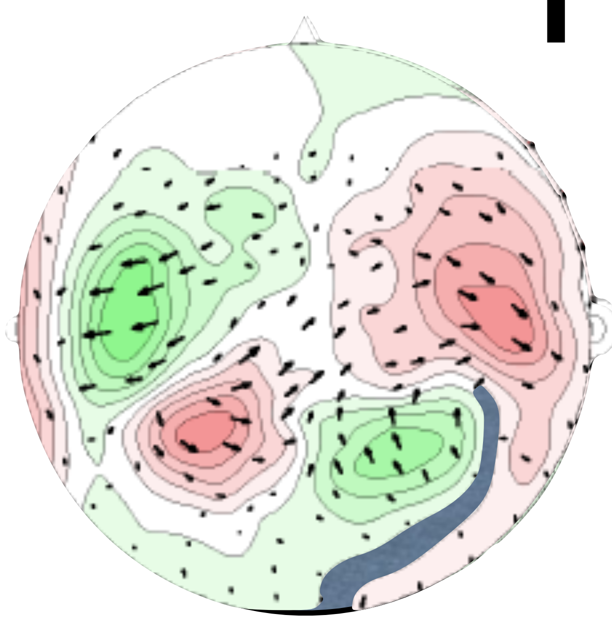
Orientations

Physiologically Simple Current Sources: $\eta = 0$

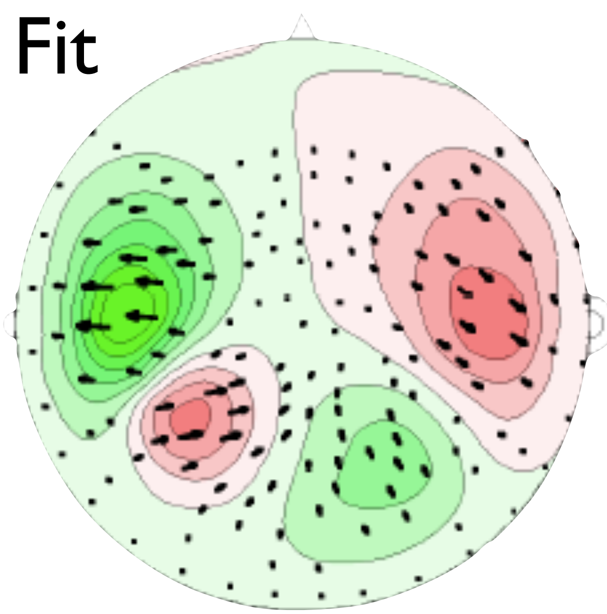
Simon and Wang, J. Neurosci. Methods (2005)

Complex Equivalent-Current Dipoles

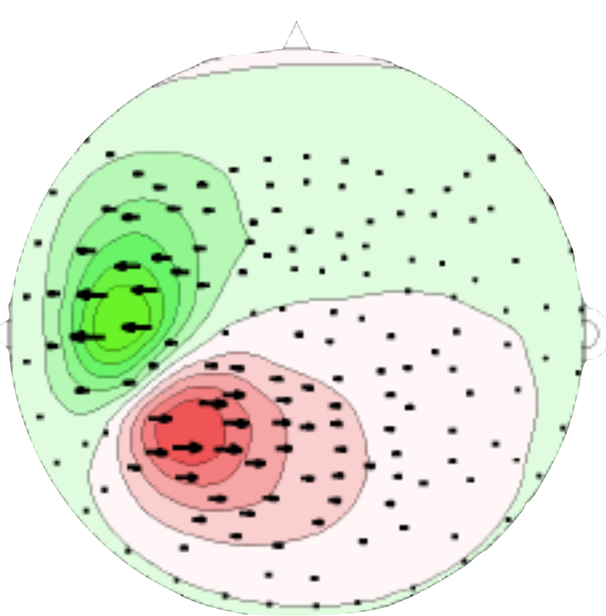
Raw Magnetic Field Data

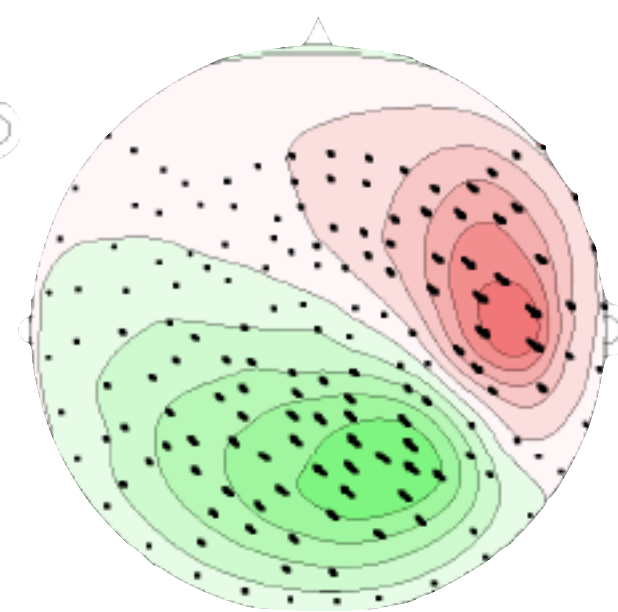


Two Dipole Fit



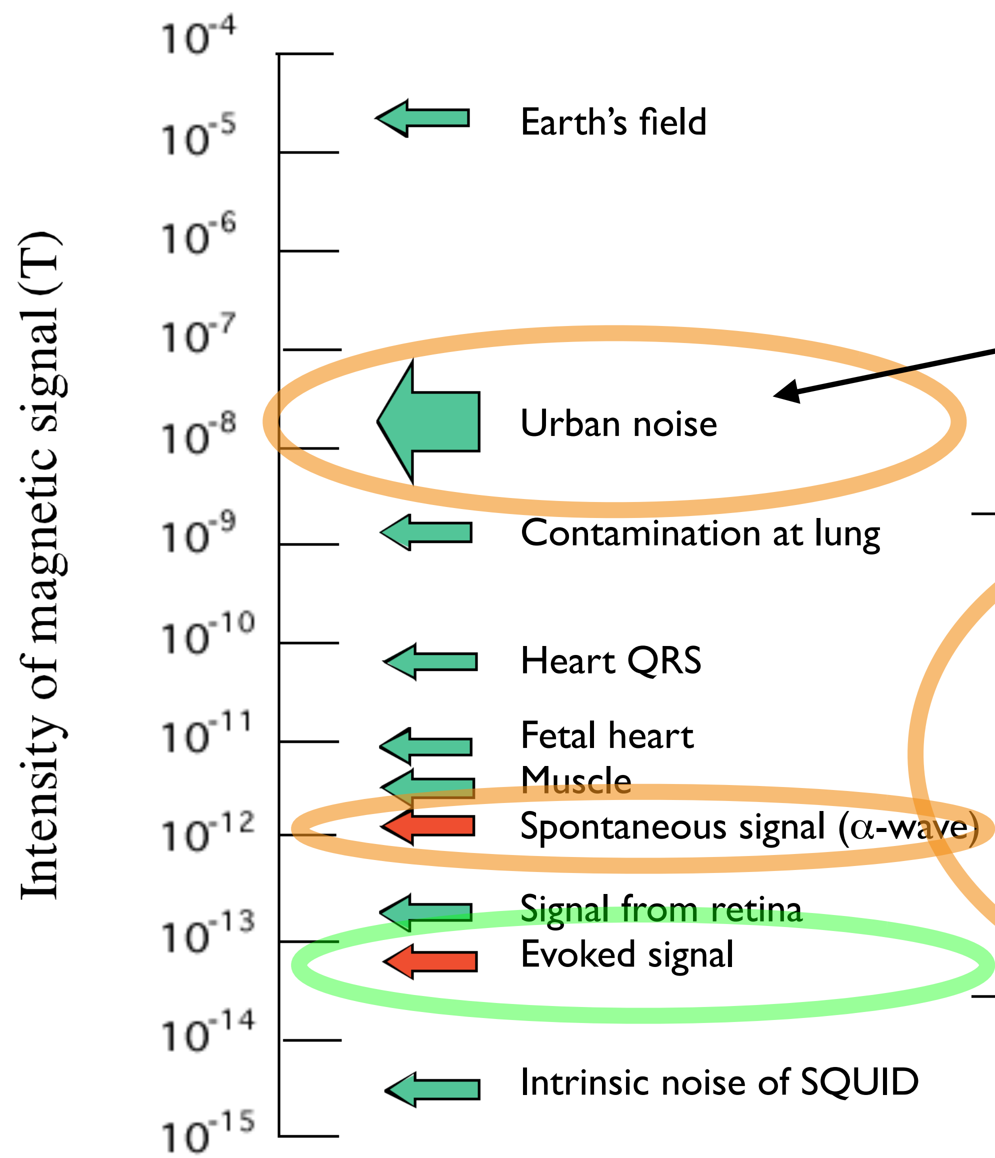
Left Hemisphere Current Equivalent Dipole

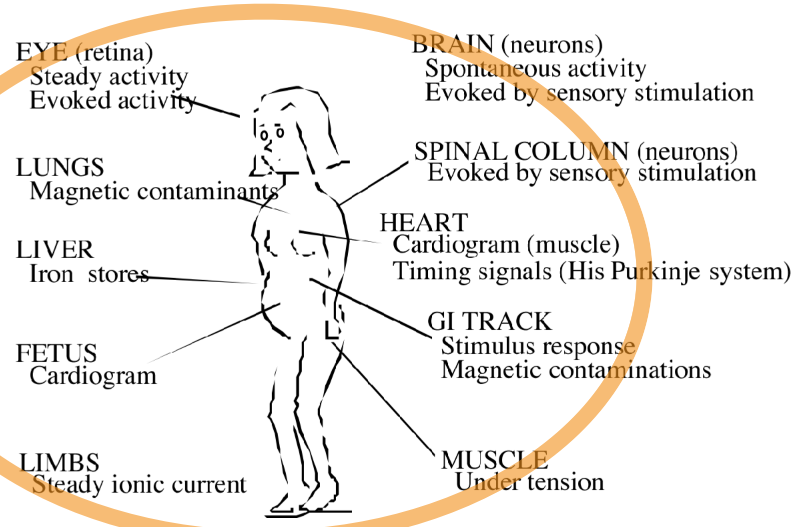




Right Hemisphere Current Equivalent Dipole

Magnetic Field Strengths

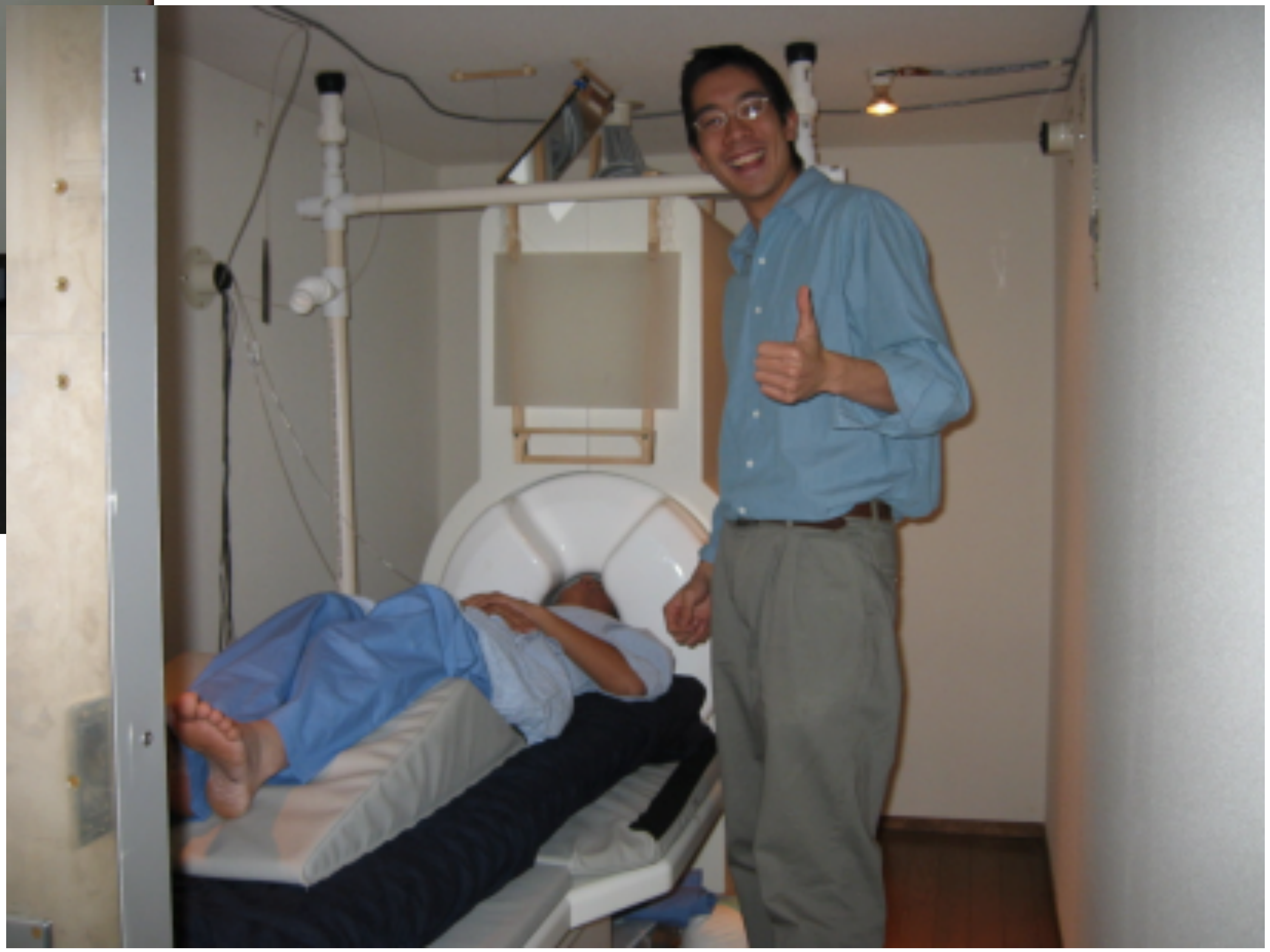




Biomagnetic Signals

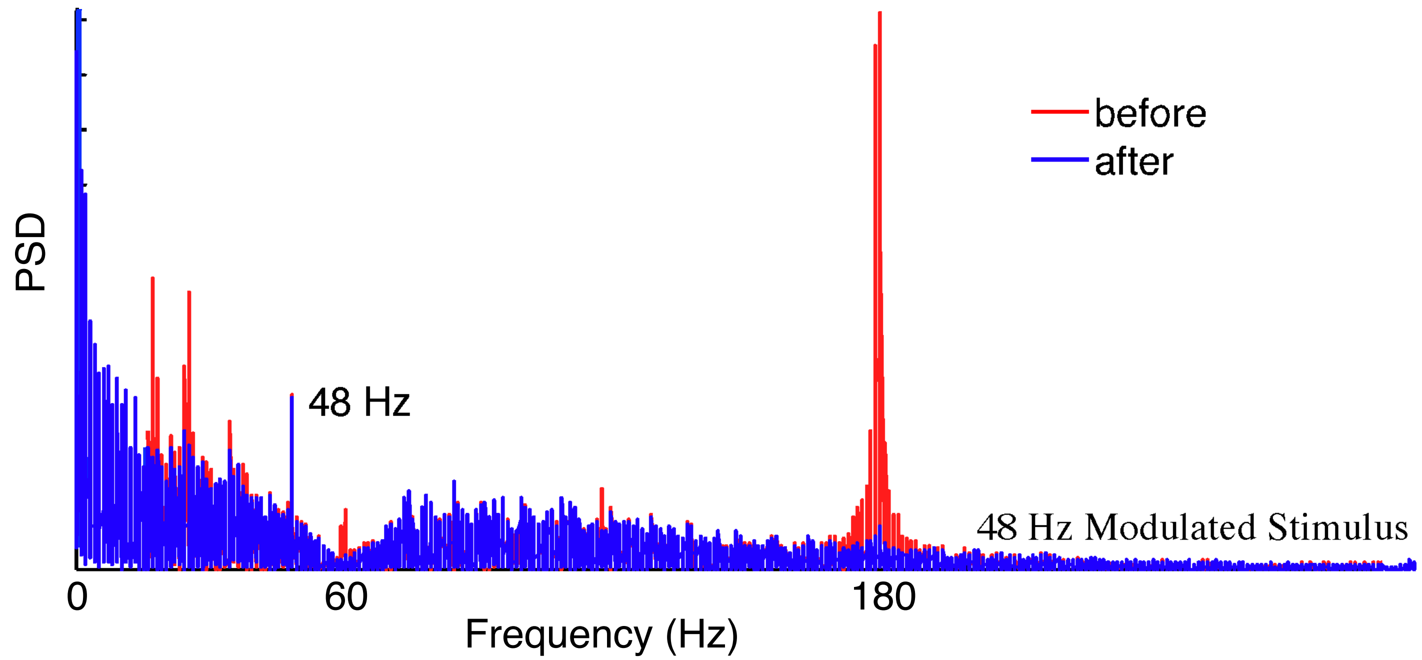
Hardware Noise Reduction: External Noise

Hardware Noise Reduction: External Noise

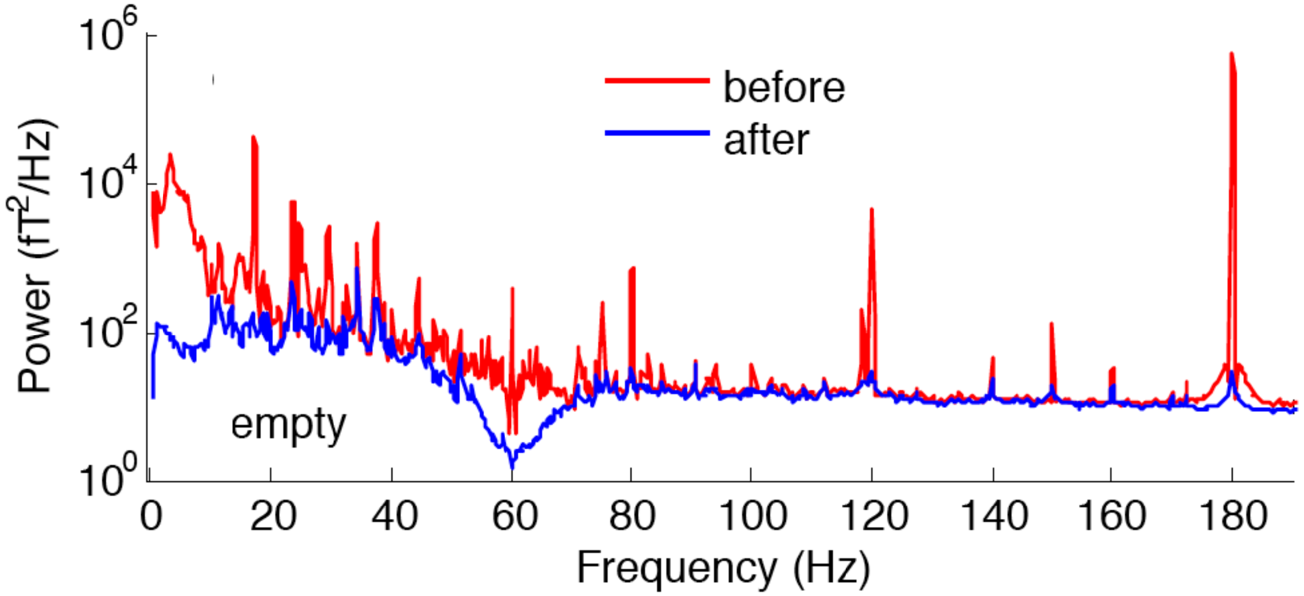


Software Noise Reduction: External Noise

Cleaned with Fast-LMS + 3 Reference channels



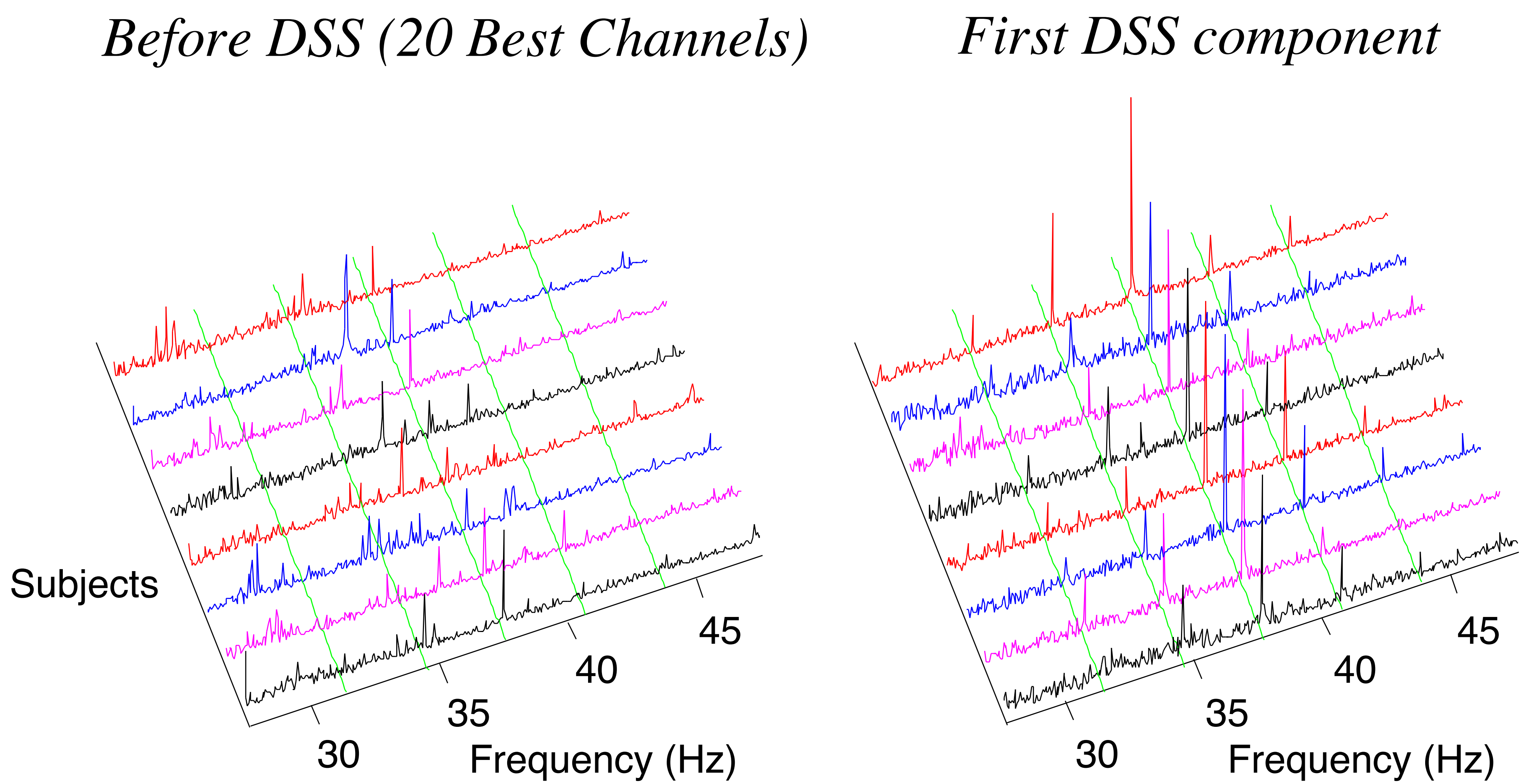
Cleaned with TSPCA + 3 Reference channels



Ahmar & Simon, Neural Engineering (2005)
de Cheveigné and Simon, J. Neurosci. Methods (2007)

Software Noise Reduction: Neural Noise

Spectra of MEG Steady State Response (to dual modulation)

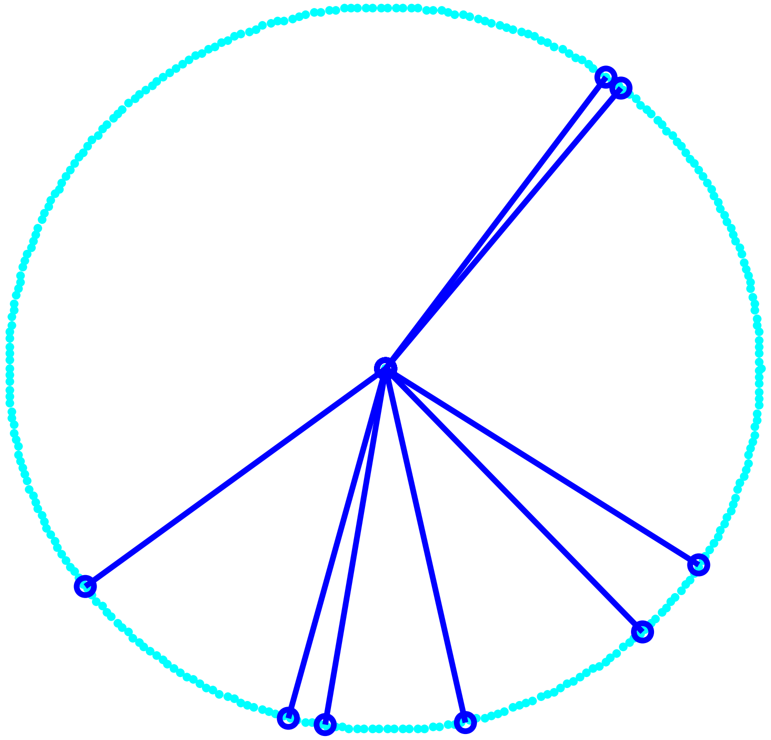


DSS = Denoising Source Separation

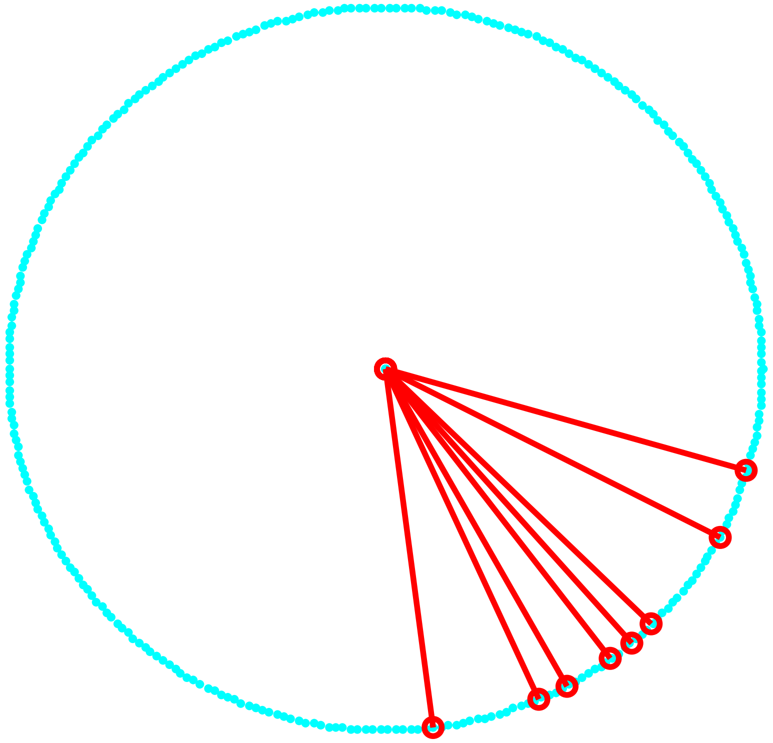
de Cheveigné and Simon, J. Neurosci. Methods (2008b)

Software Noise Reduction: Neural Noise

Phase coding parameter α (by subject)



Before DSS (20 Best Channels)



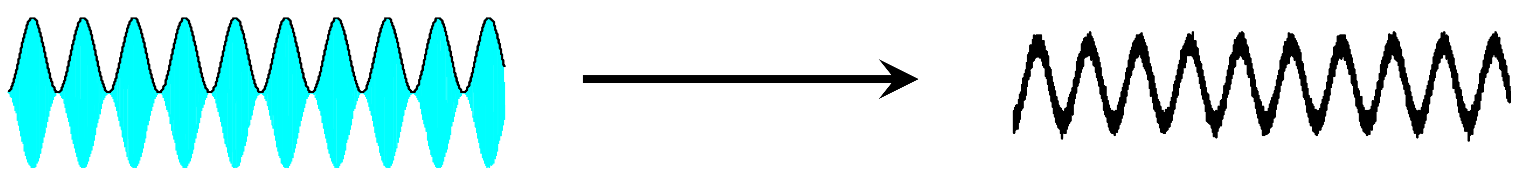
First DSS component

de Cheveigné and Simon, J. Neurosci. Methods (2008b)

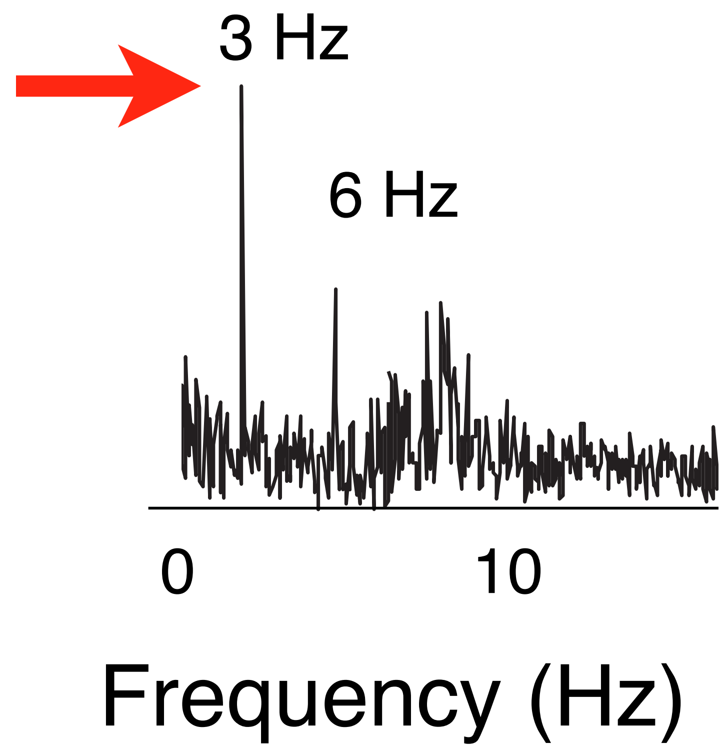
Phase-Locking in MEG to Slow Acoustic Modulations

AM at 3 Hz

3 Hz phase-locked response



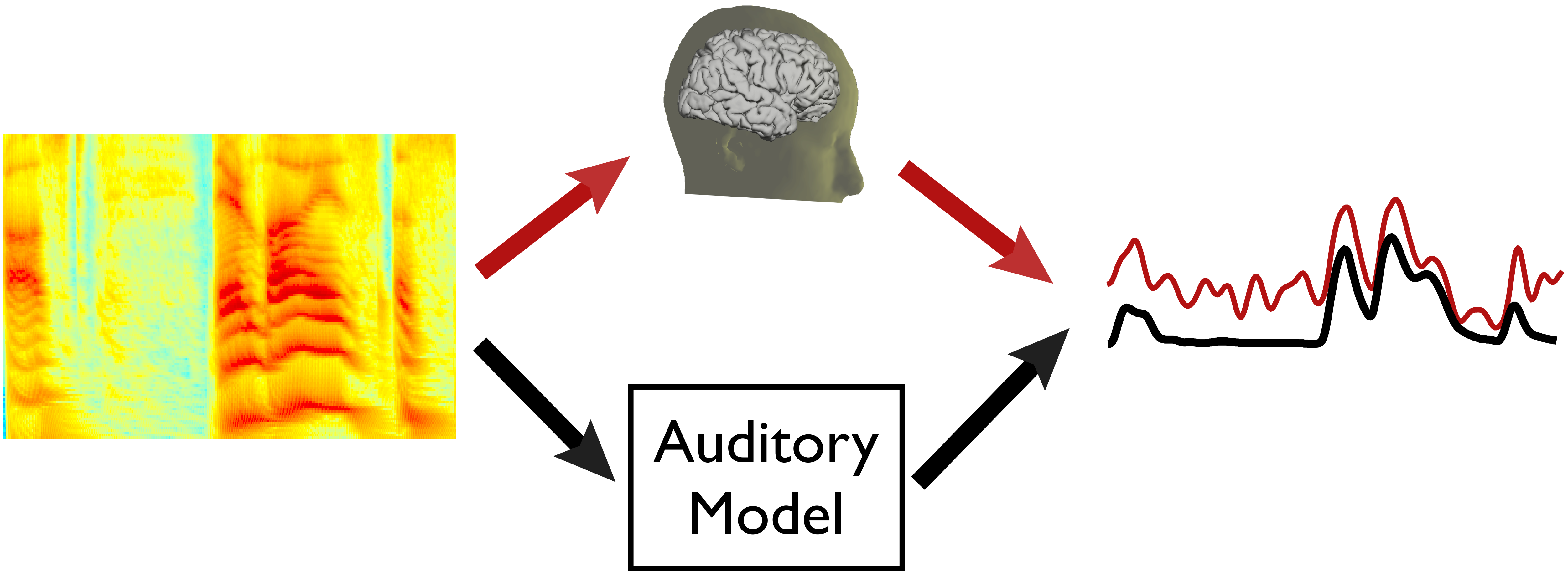
response spectrum (*subject R0747*)



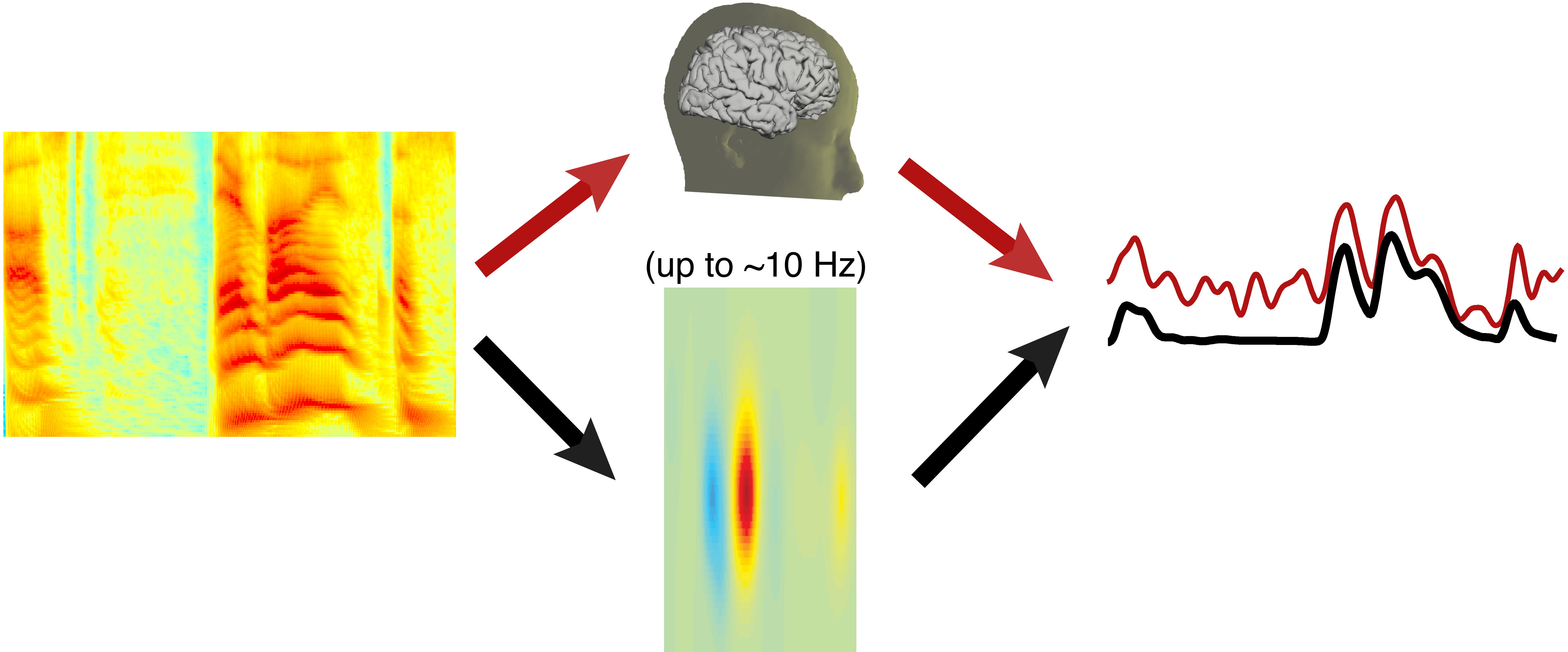
MEG activity is precisely phase-locked to temporal modulations of sound

Ding & Simon, J Neurophysiol (2009)
Wang et al., J Neurophysiol (2012)

MEG Responses to Speech Modulations



MEG Responses Predicted by STRF Model

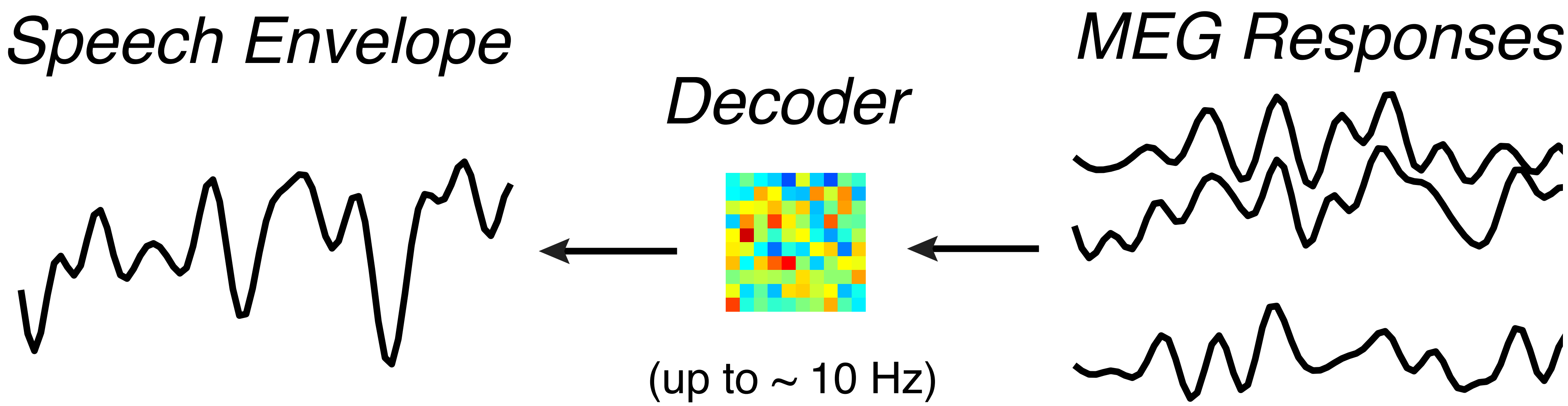


Linear Kernel = STRF

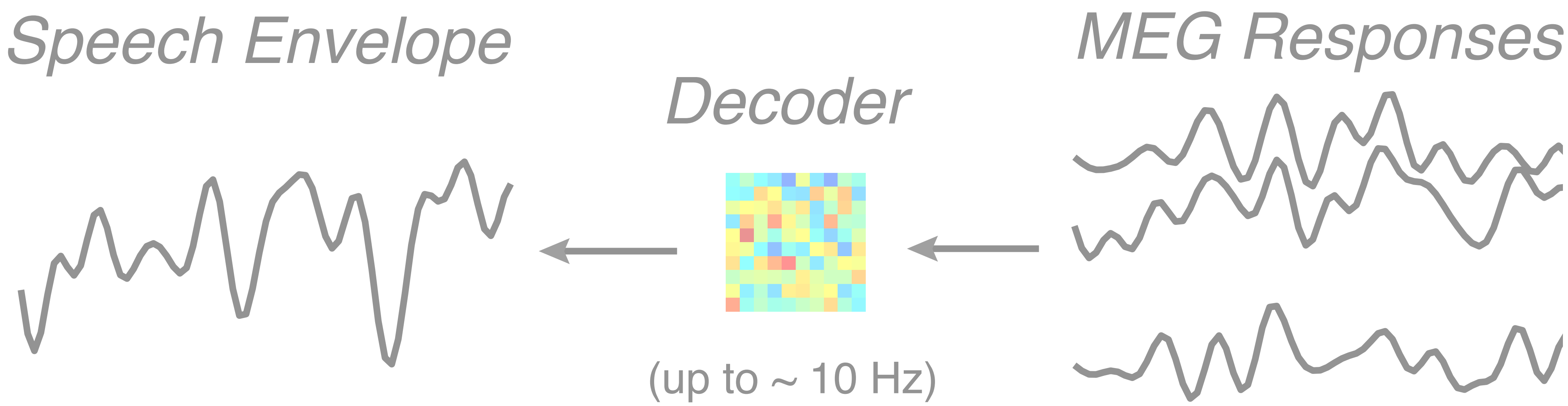
"Spectro-Temporal Response Function"

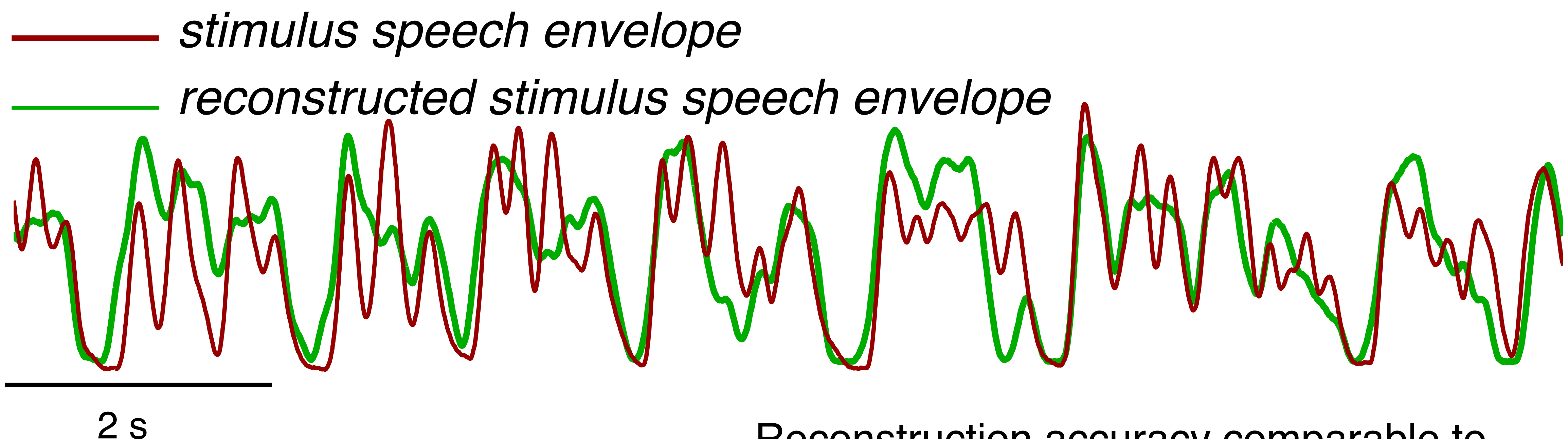
Ding & Simon, J Neurophysiol (2012)

Neural Reconstruction of Speech Envelope



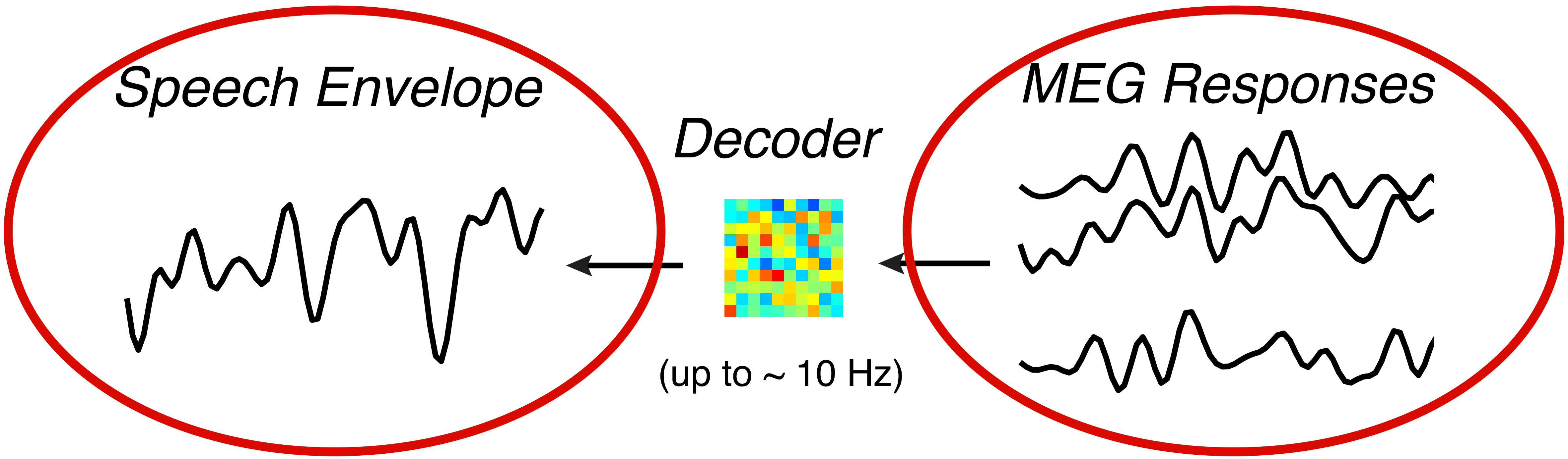
Neural Reconstruction of Speech Envelope





Reconstruction accuracy comparable to single unit & ECoG recordings

Ding & Simon, J Neurophysiol (2012)
Zion-Golumbic et al., Neuron (2013)


Speech Envelope
Decoder
(up to ~ 10 Hz)
MEG Responses

Listening to Speech at the Cocktail Party

Alex Katz,
The Cocktail Party

Listening to Speech at the Cocktail Party

Alex Katz,
The Cocktail Party

Listening to Speech at the Cocktail Party

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The Cocktail Party

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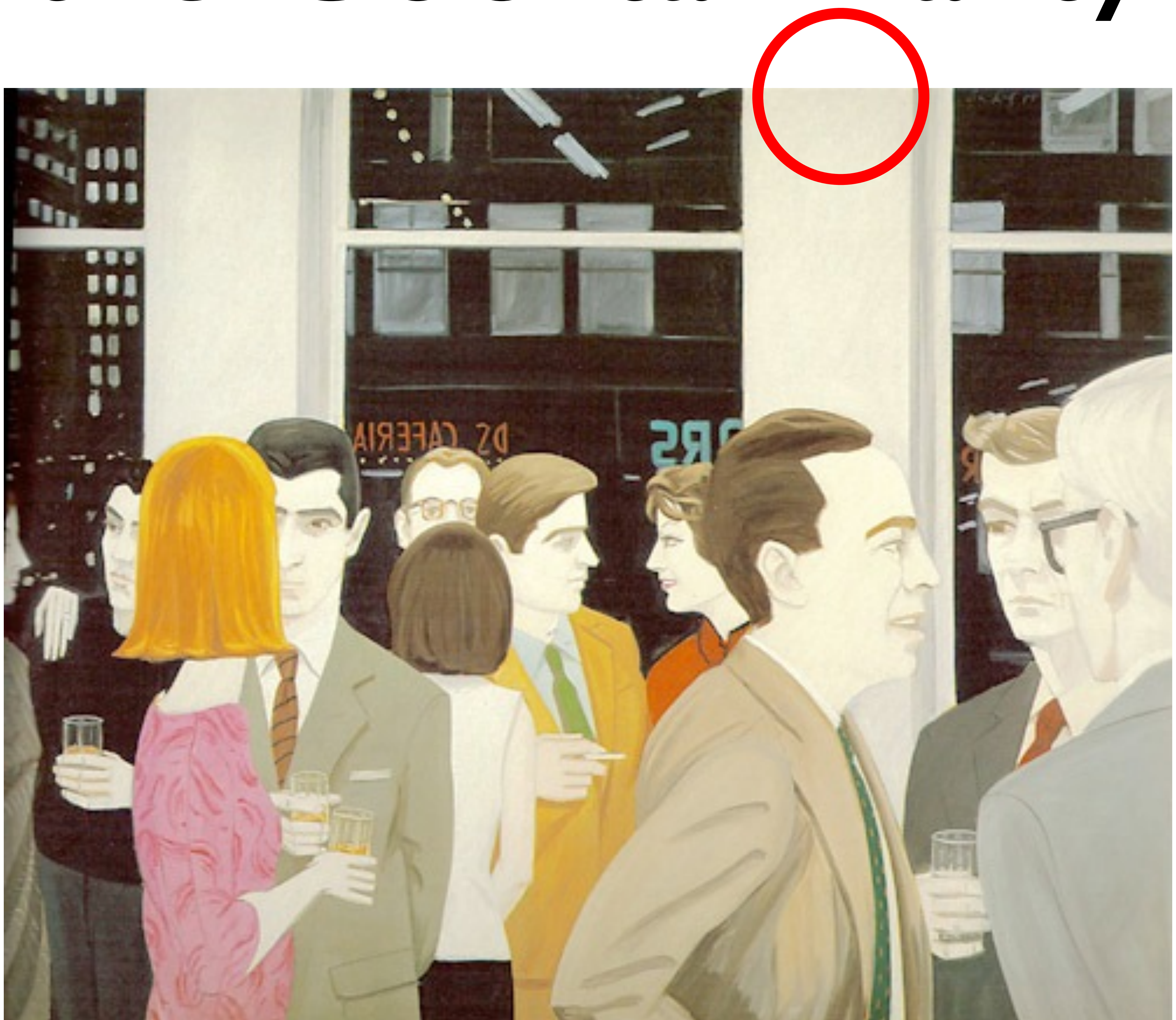
Listening to Speech at the Cocktail Party

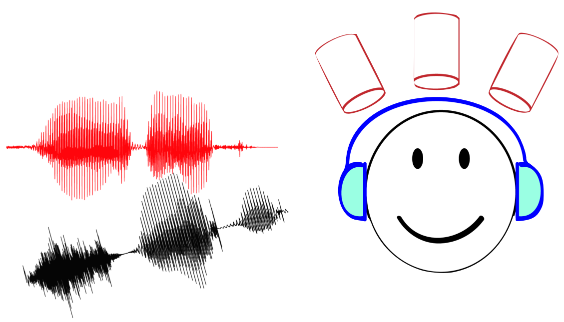


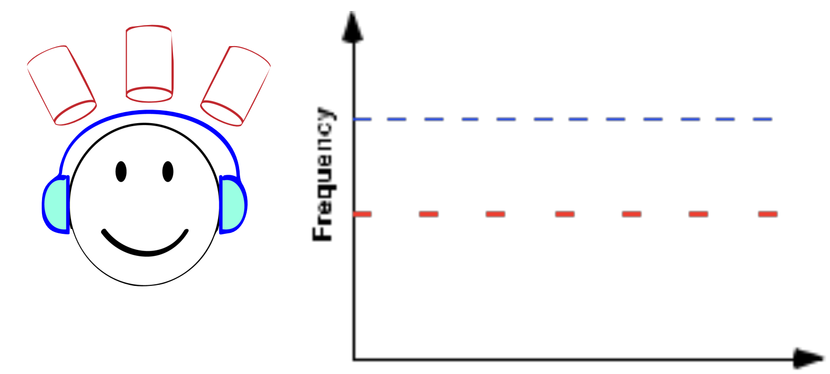
Alex Katz,
The Cocktail Party

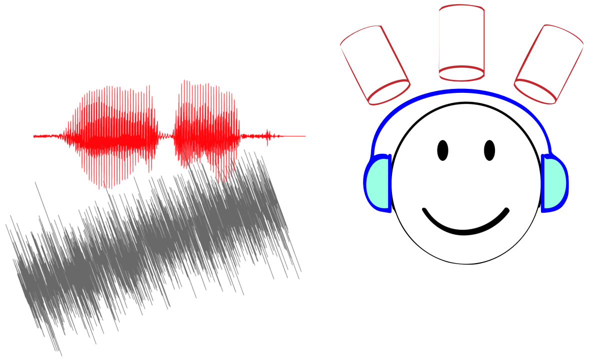
Listening to Speech at the Cocktail Party

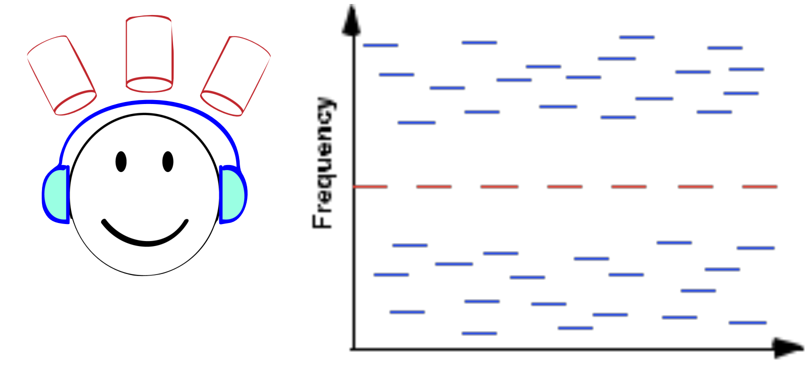
Alex Katz,
The Cocktail Party

Experiments

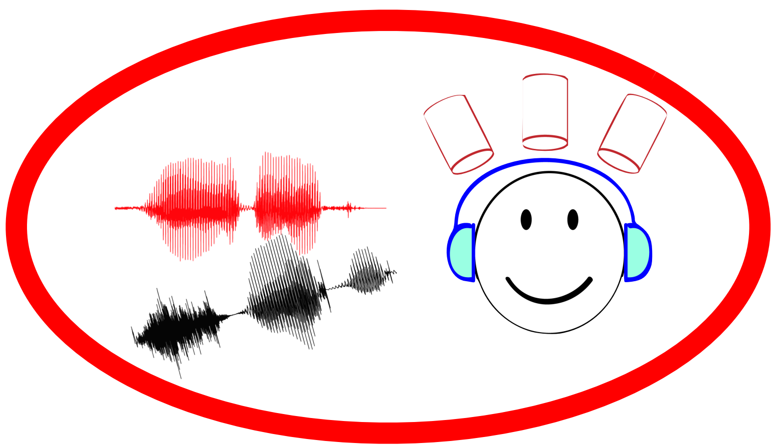


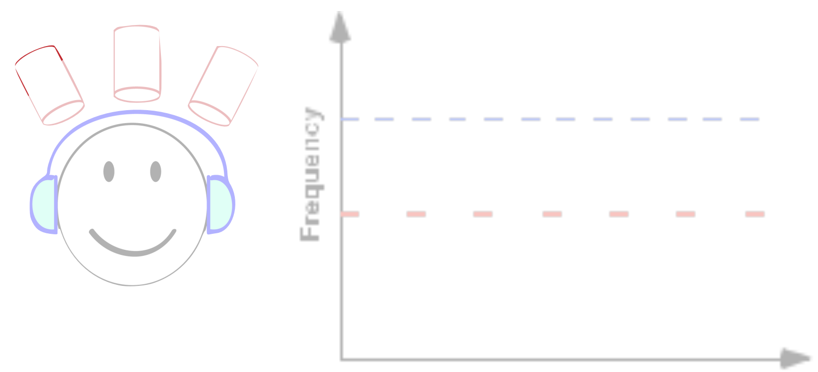


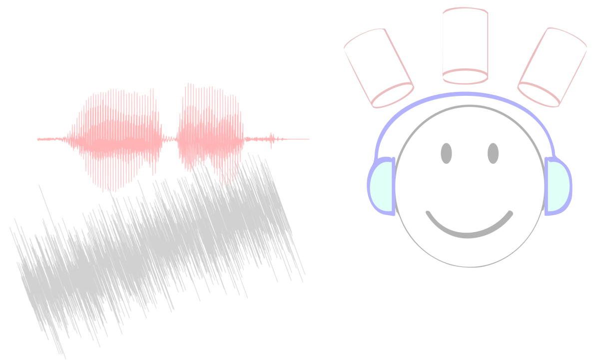


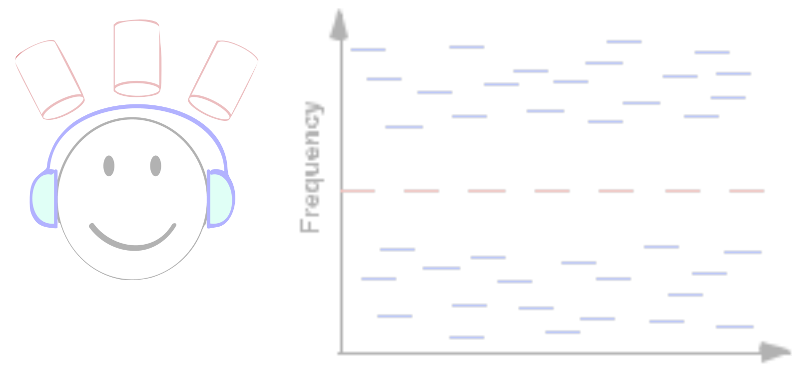


Experiments



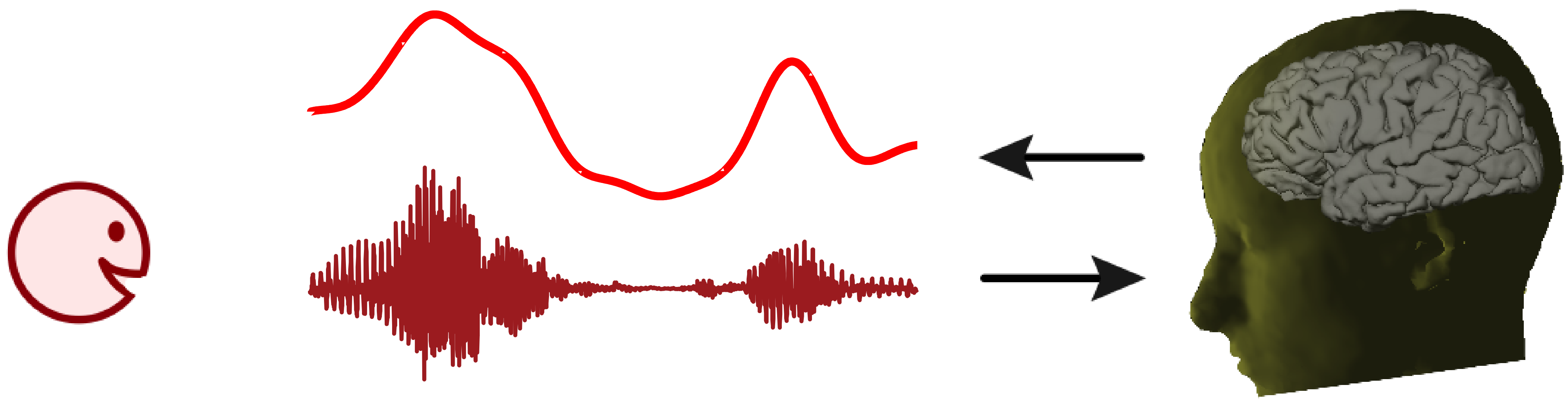




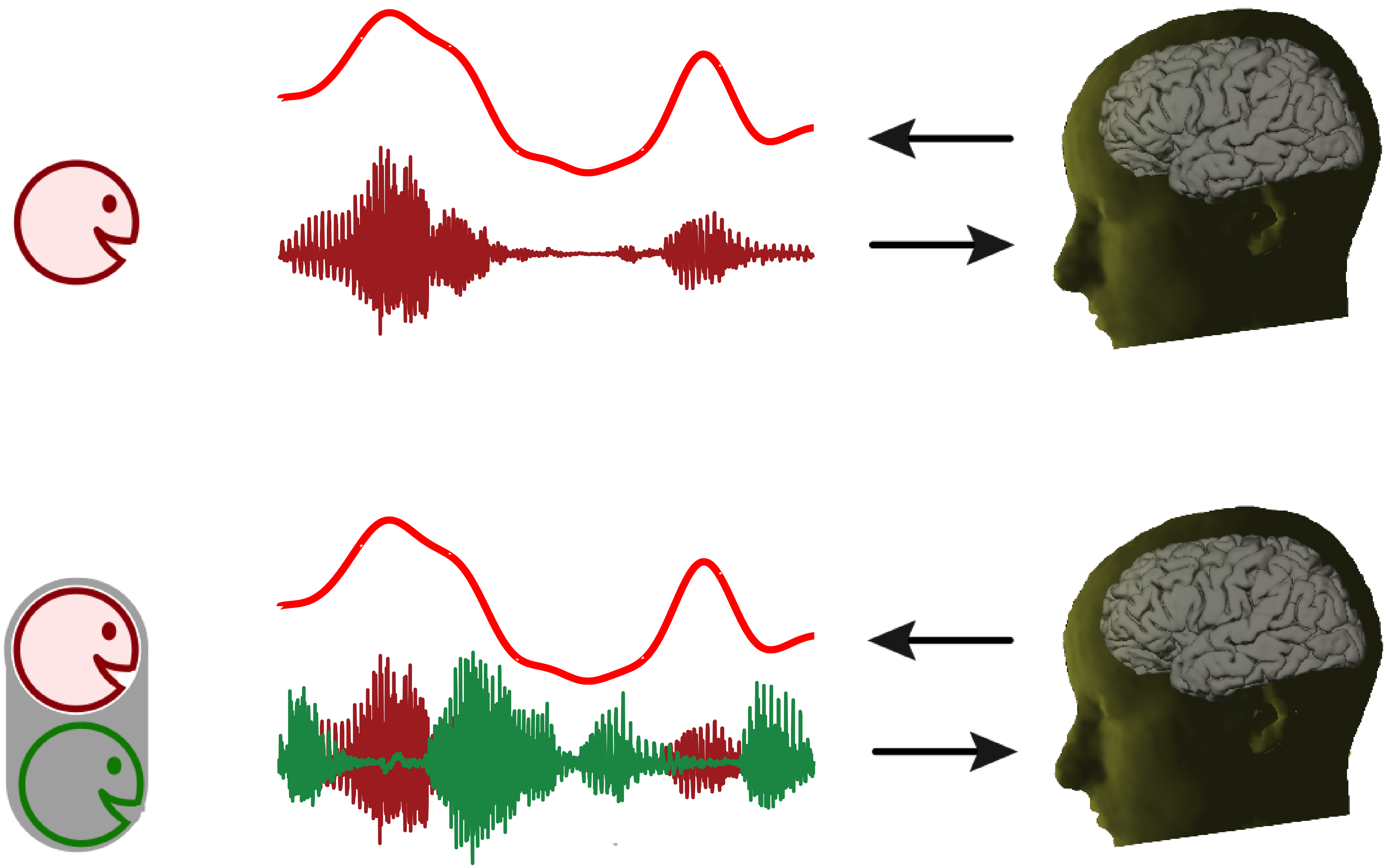


Ding & Simon, PNAS (2012)

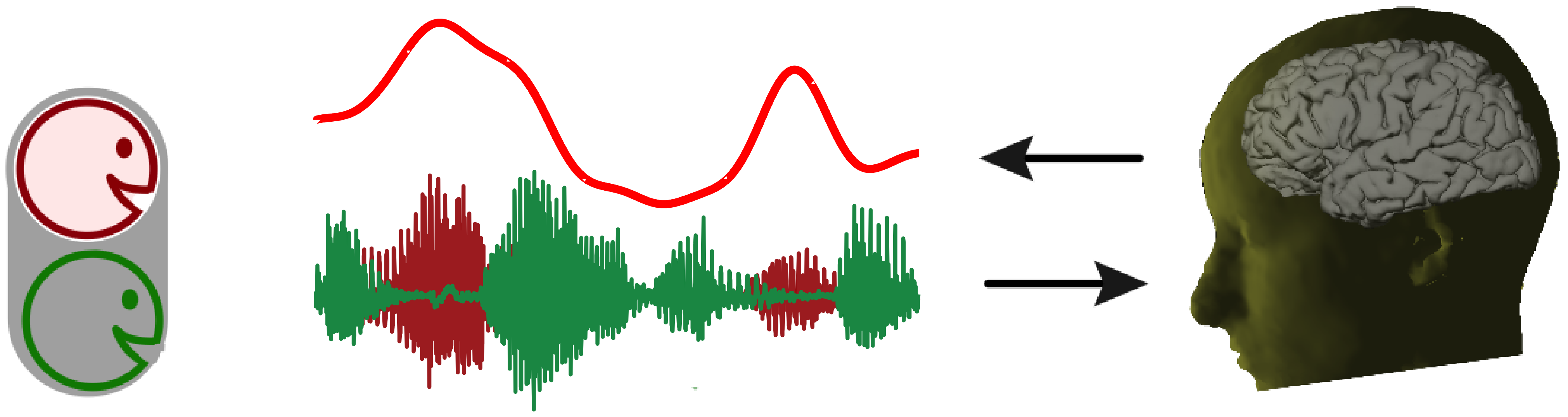
Selective Neural Encoding



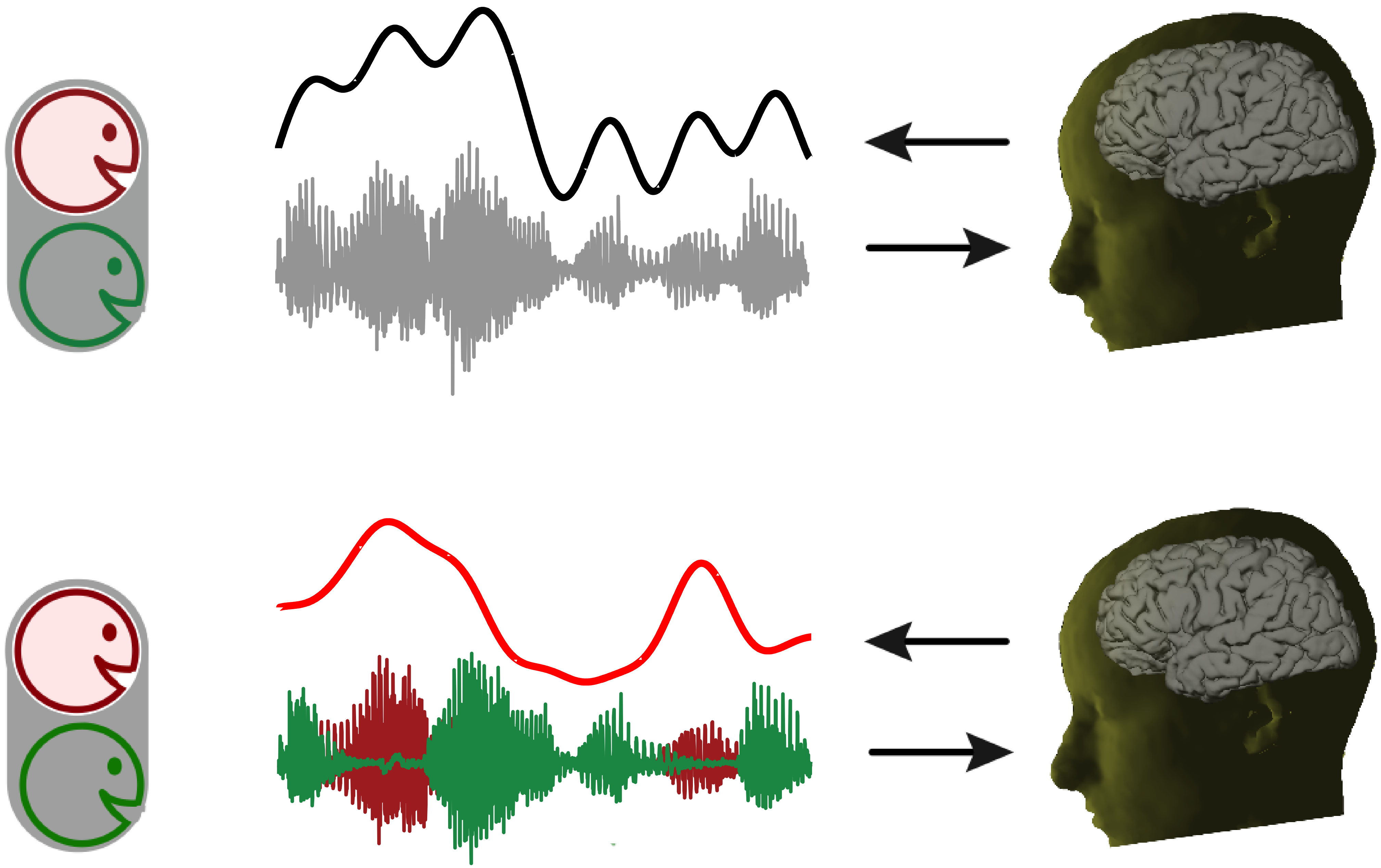
Selective Neural Encoding



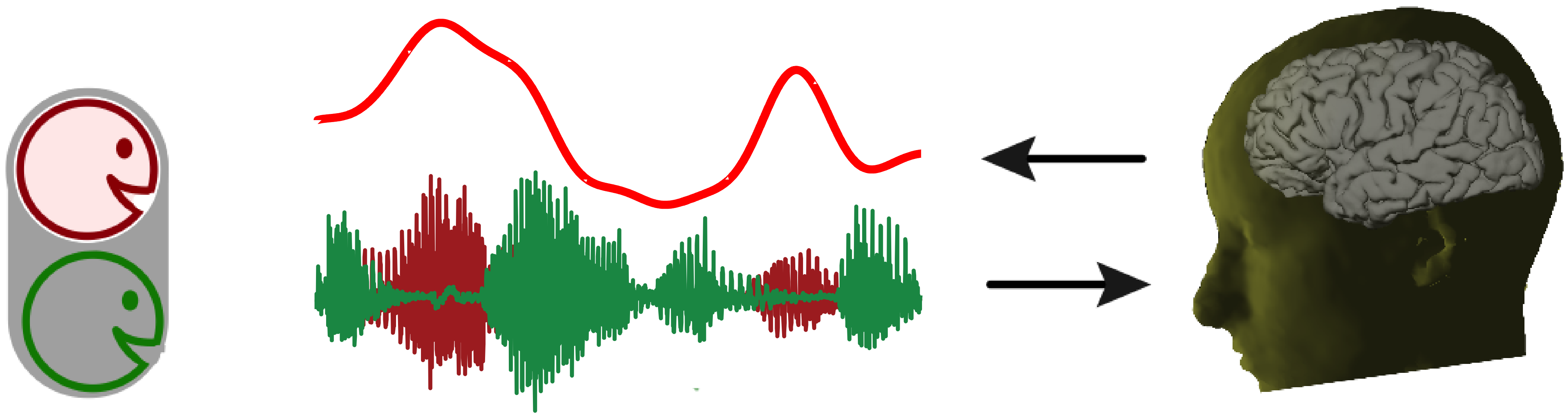
Selective Neural Encoding



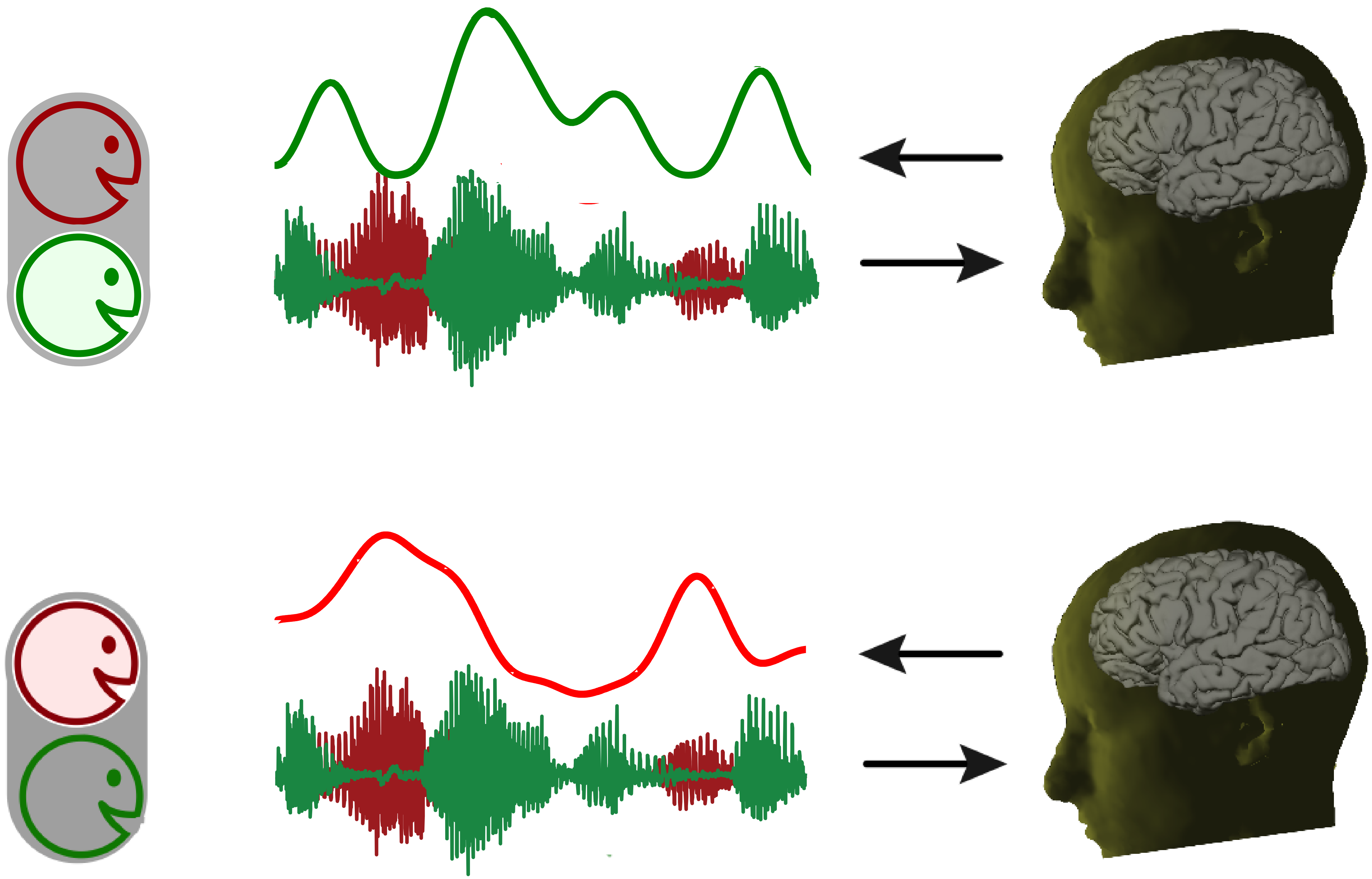
Unselective vs. Selective Neural Encoding



Unselective vs. Selective Neural Encoding



Selective Neural Encoding

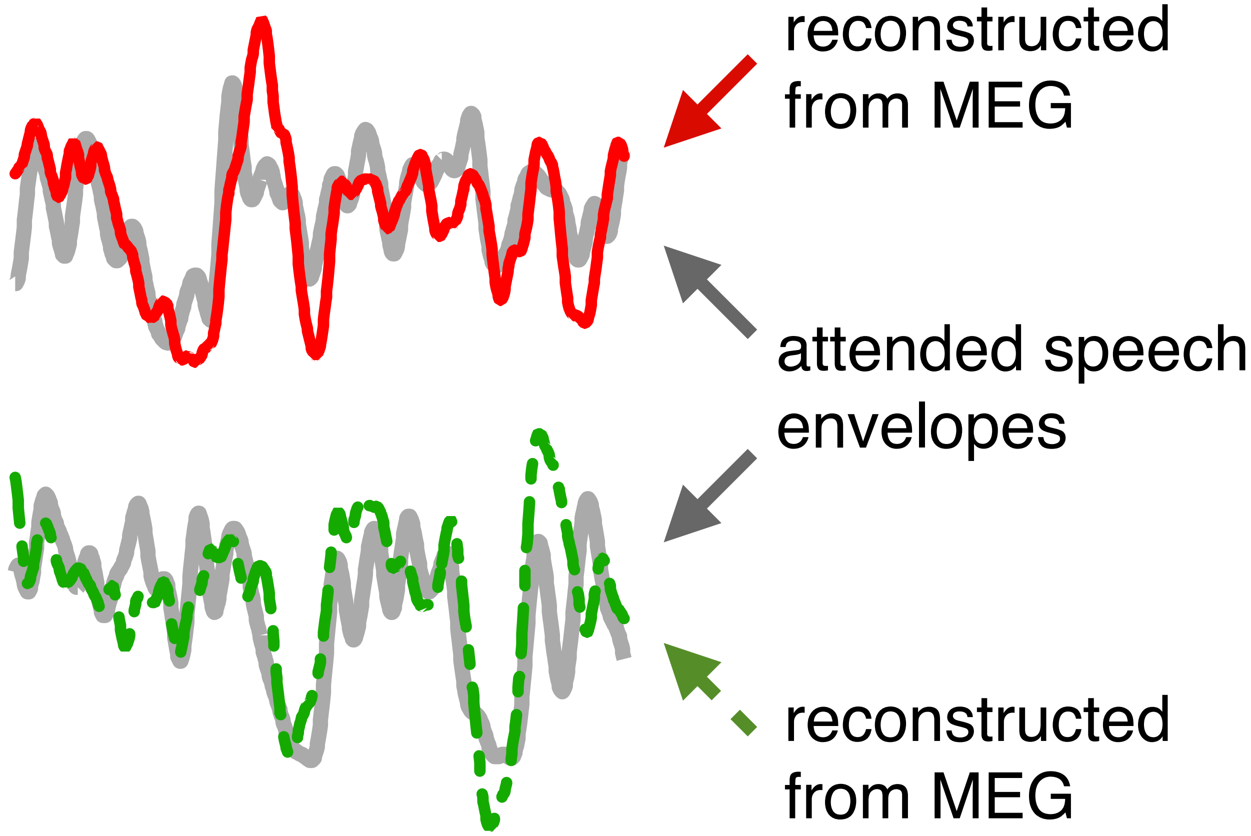


Stream-Specific Representation

grand average over subjects

attending to speaker 1

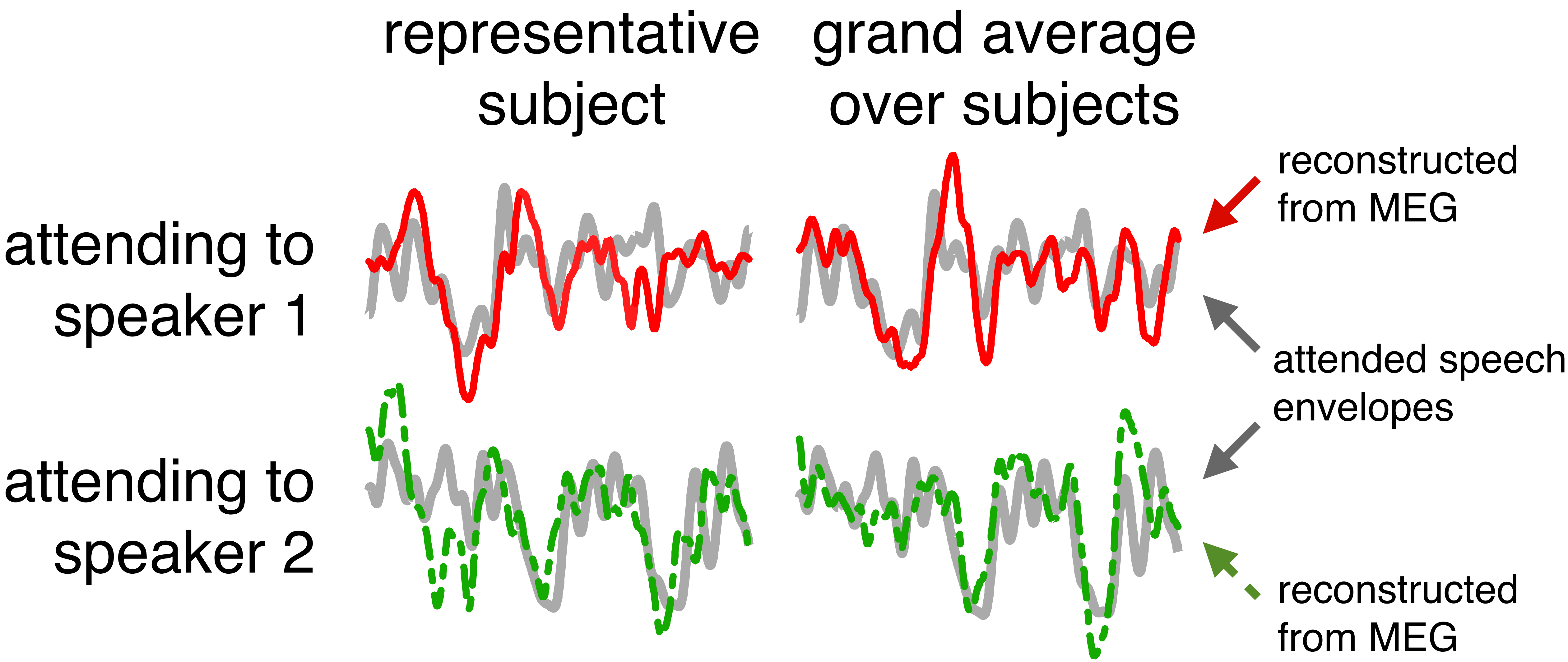
attending to speaker 2



Identical Stimuli!

Ding & Simon, PNAS (2012)

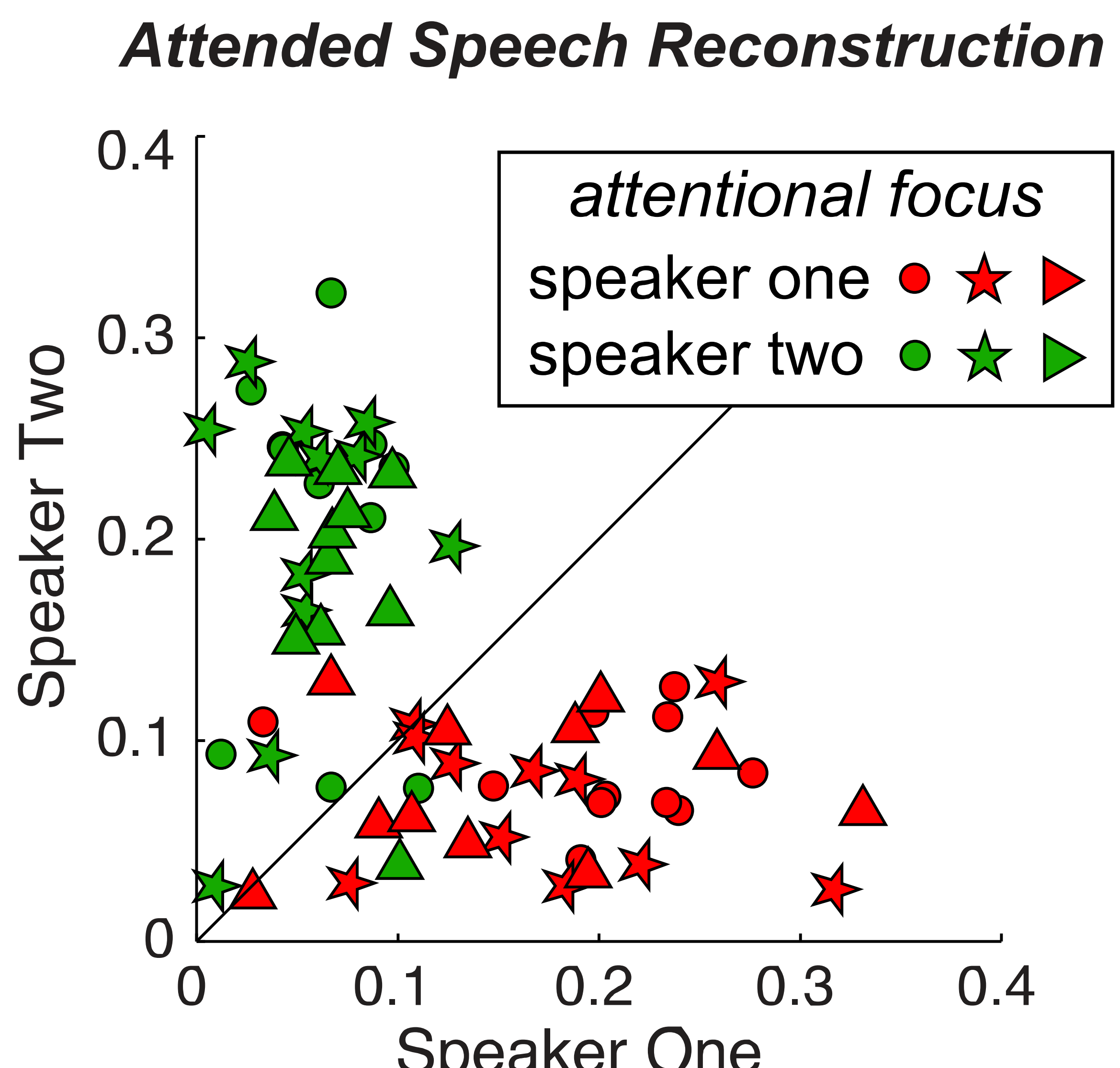
Stream-Specific Representation



Identical Stimuli!

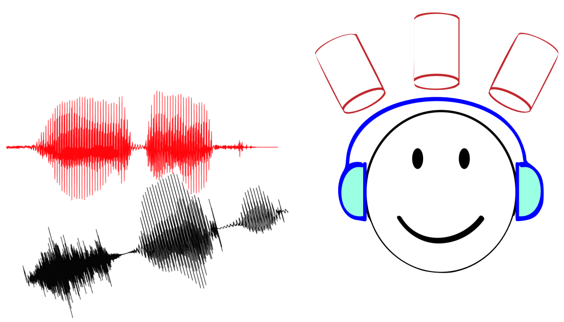
Ding & Simon, PNAS (2012)

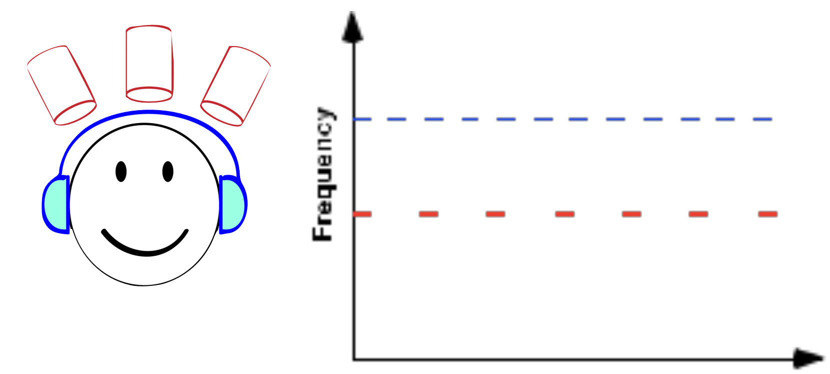
Single Trial Speech Reconstruction

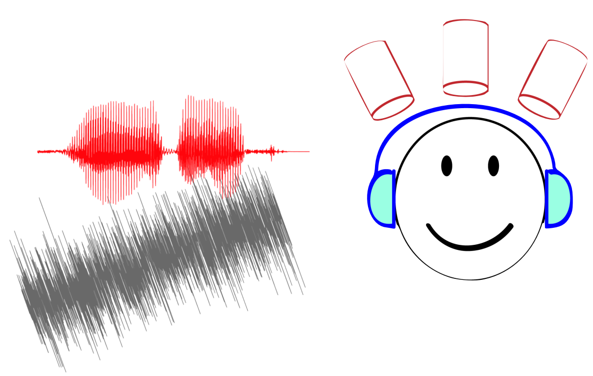


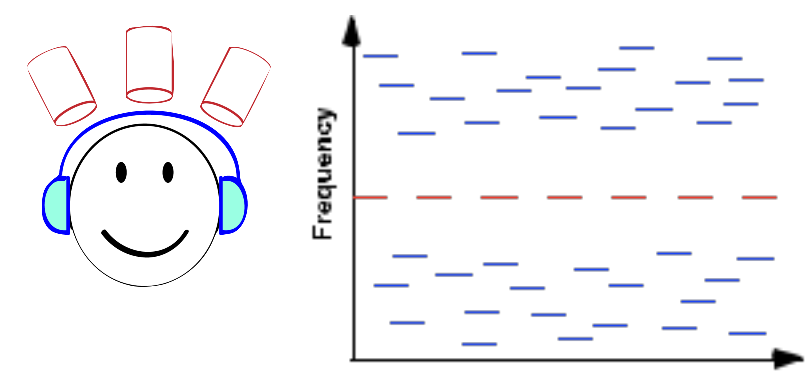
Ding & Simon, PNAS (2012)

Experiments

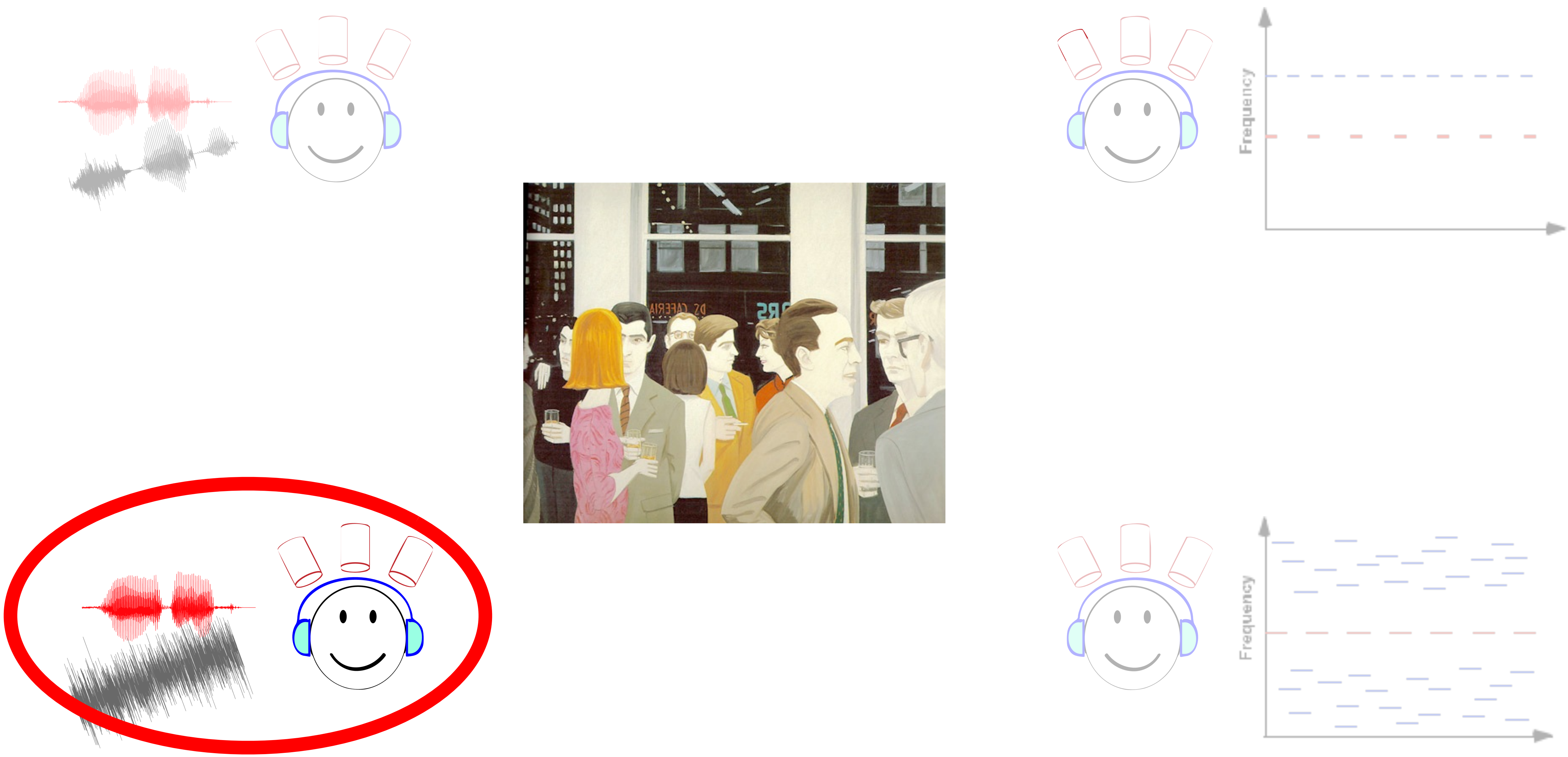






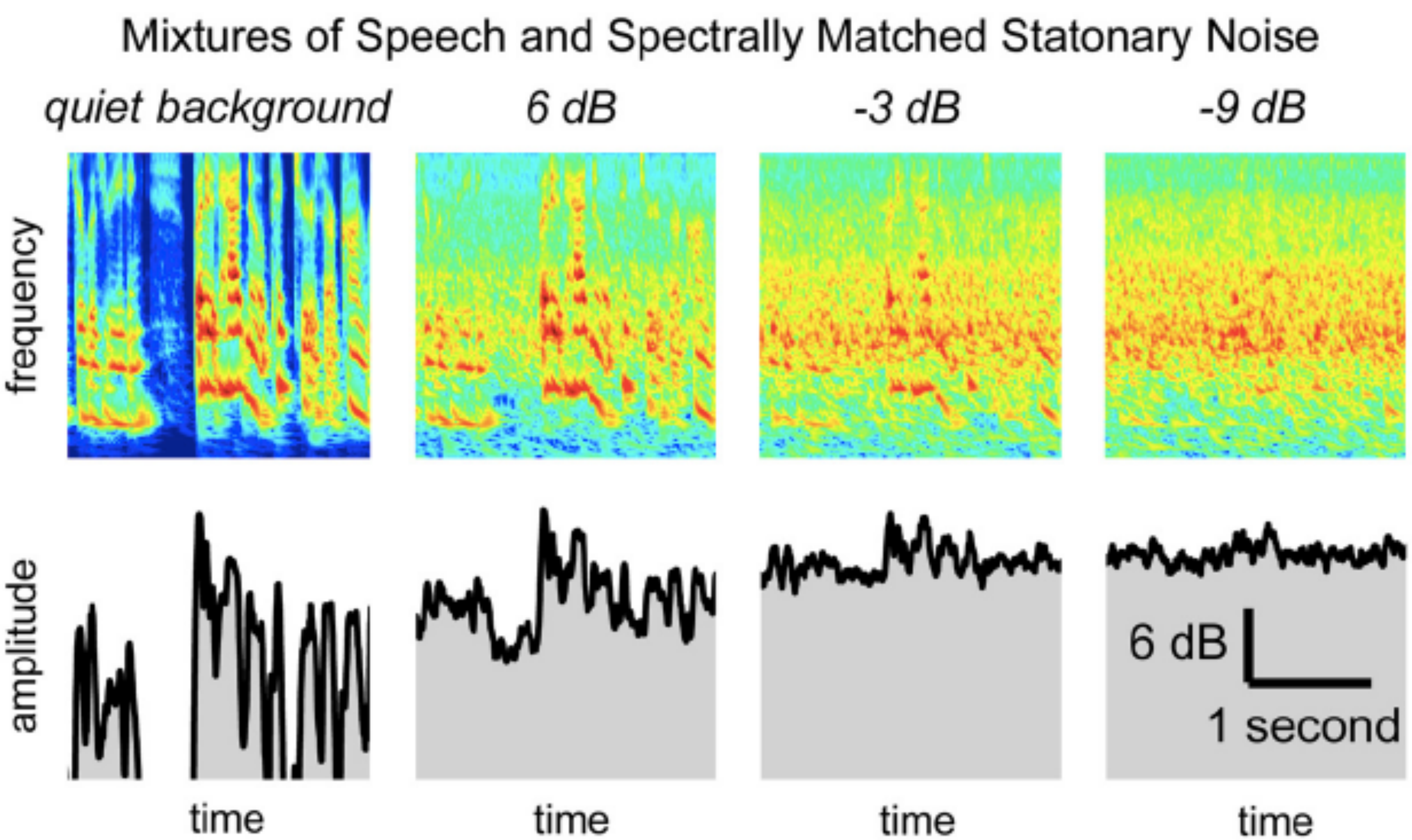


Experiments



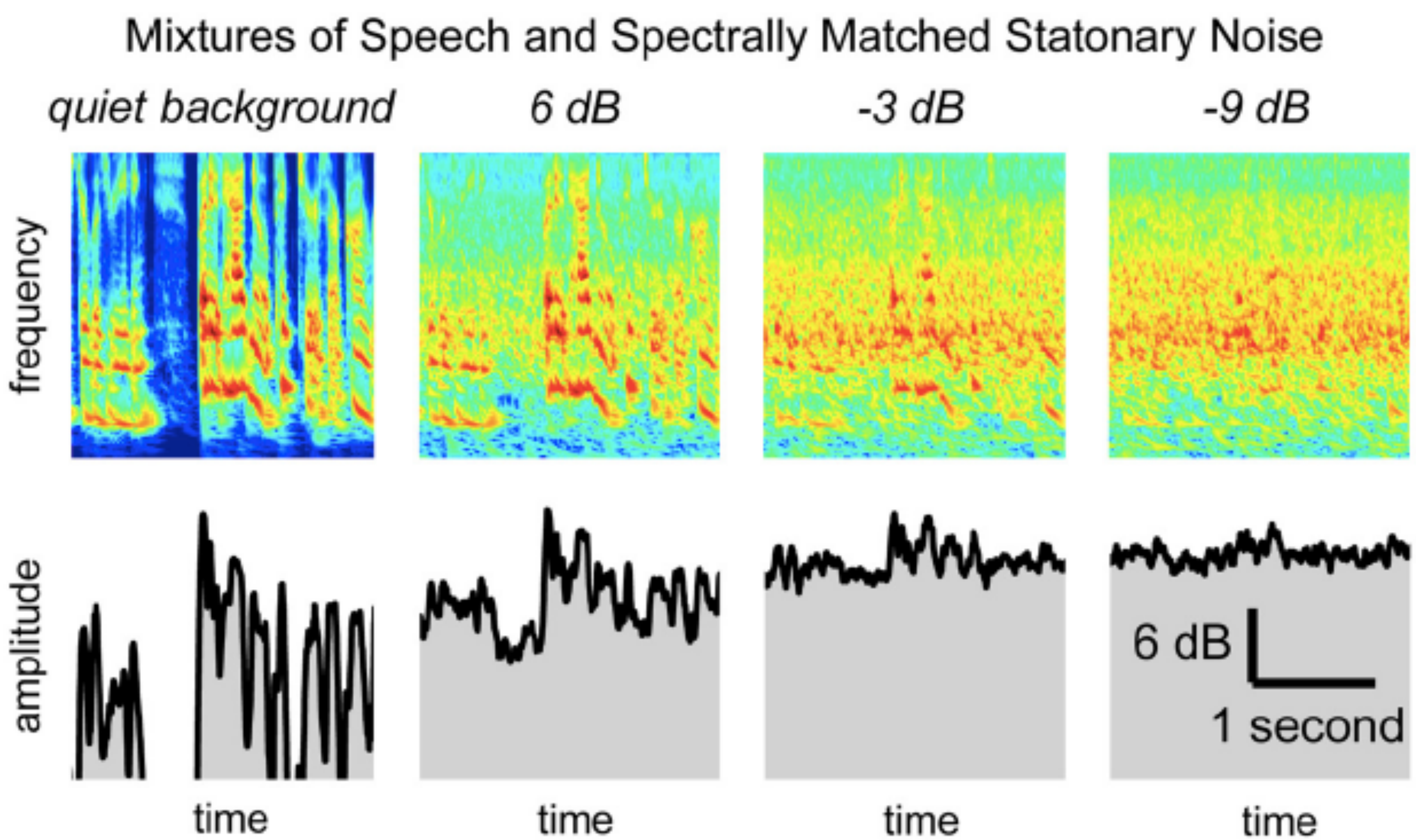
Ding & Simon, J Neurosci (2013)

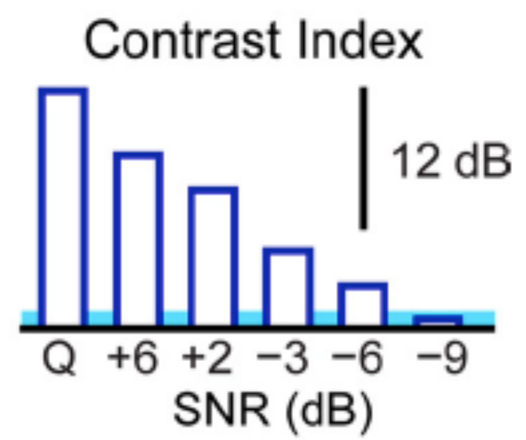
Speech in Noise: Stimuli



Ding & Simon, J Neurosci (2013)

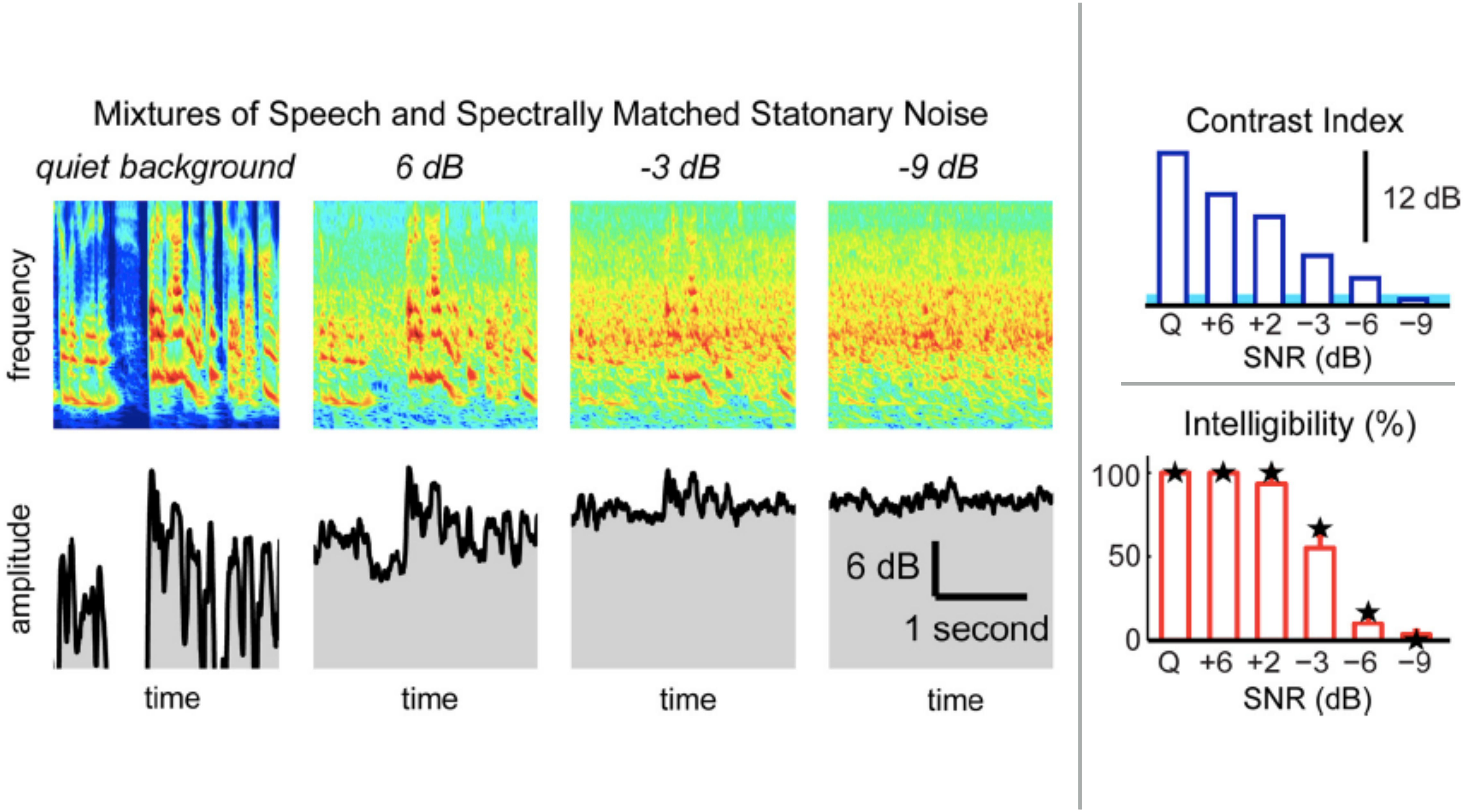
Speech in Noise: Stimuli





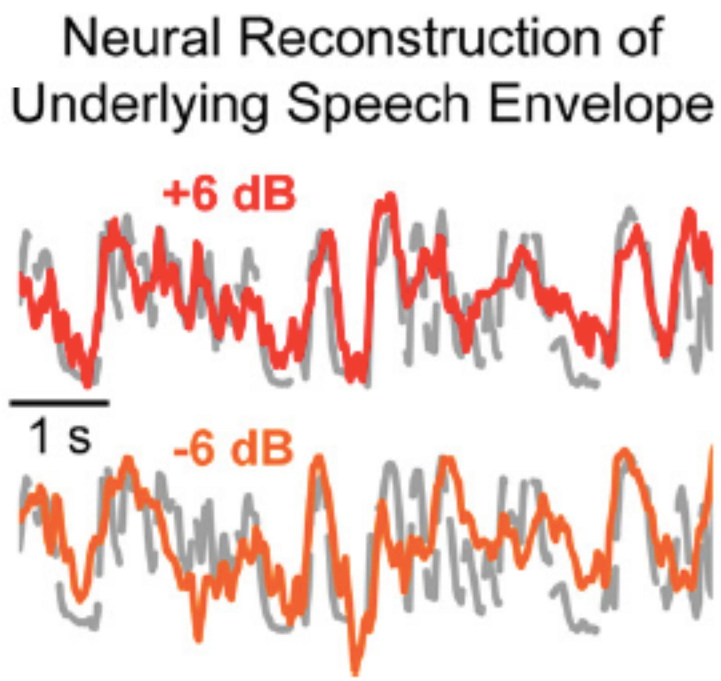
Ding & Simon, J Neurosci (2013)

Speech in Noise: Stimuli



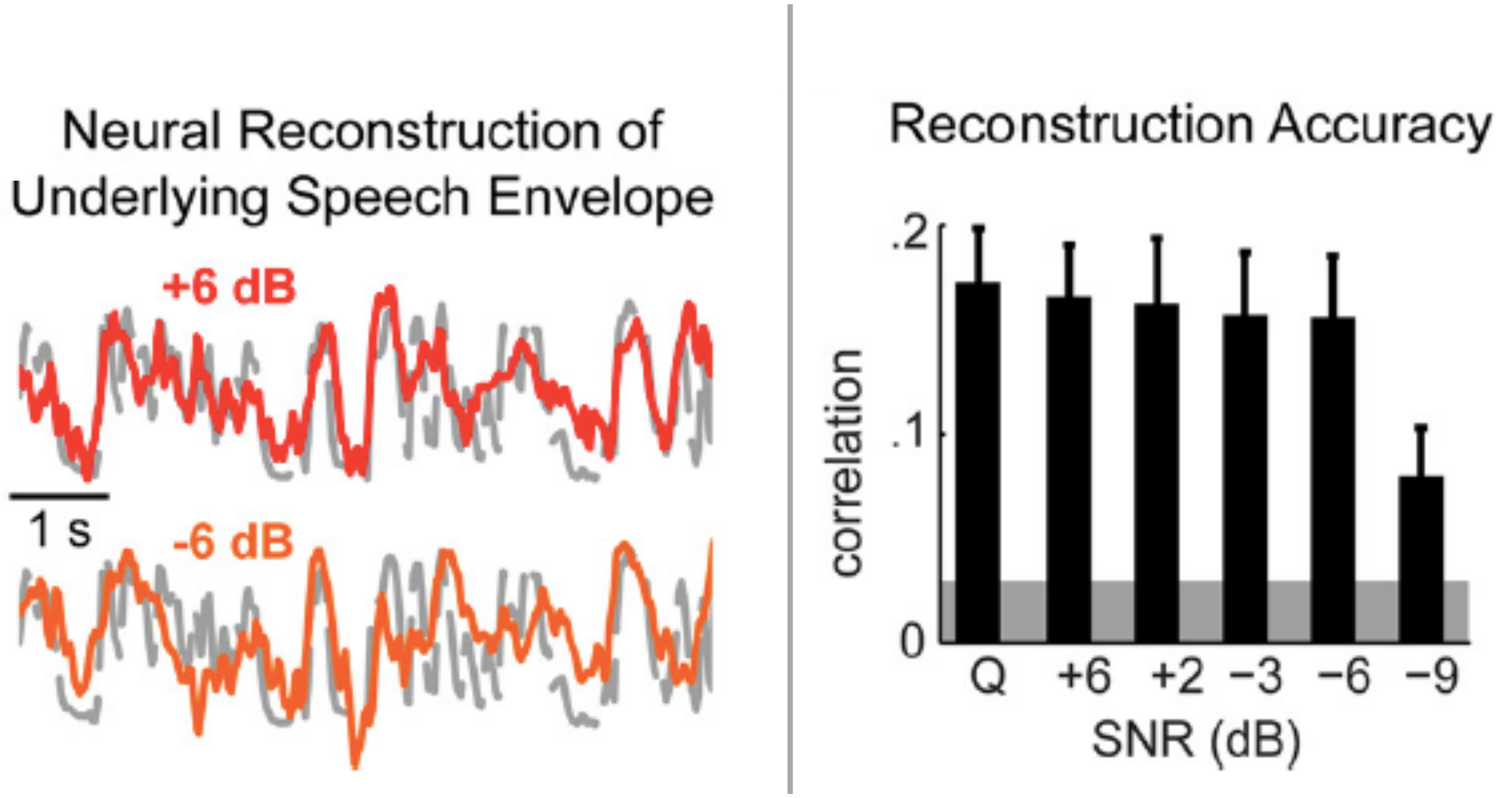
Ding & Simon, J Neurosci (2013)

Speech in Noise: Results



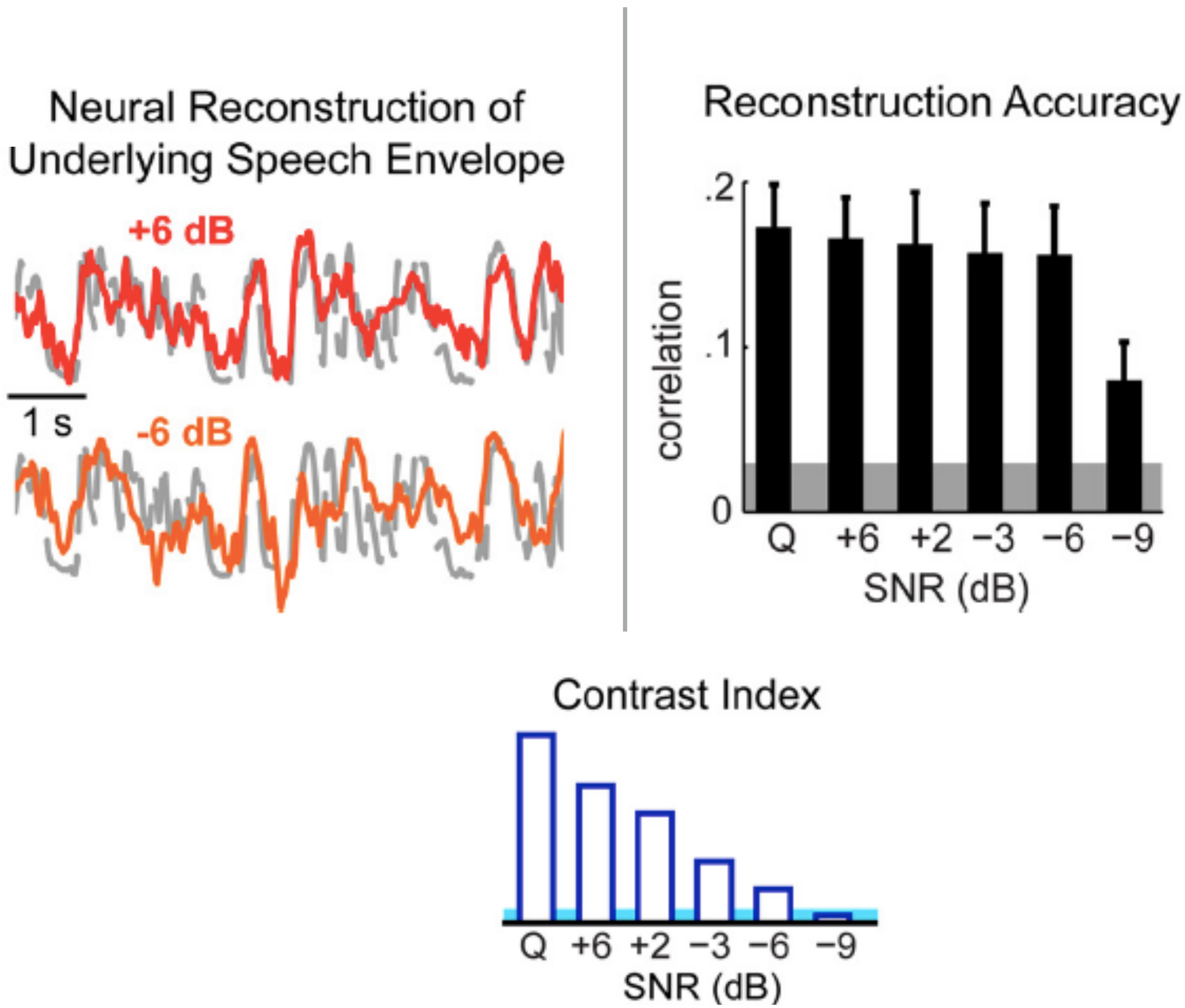
Ding & Simon, J Neurosci (2013)

Speech in Noise: Results



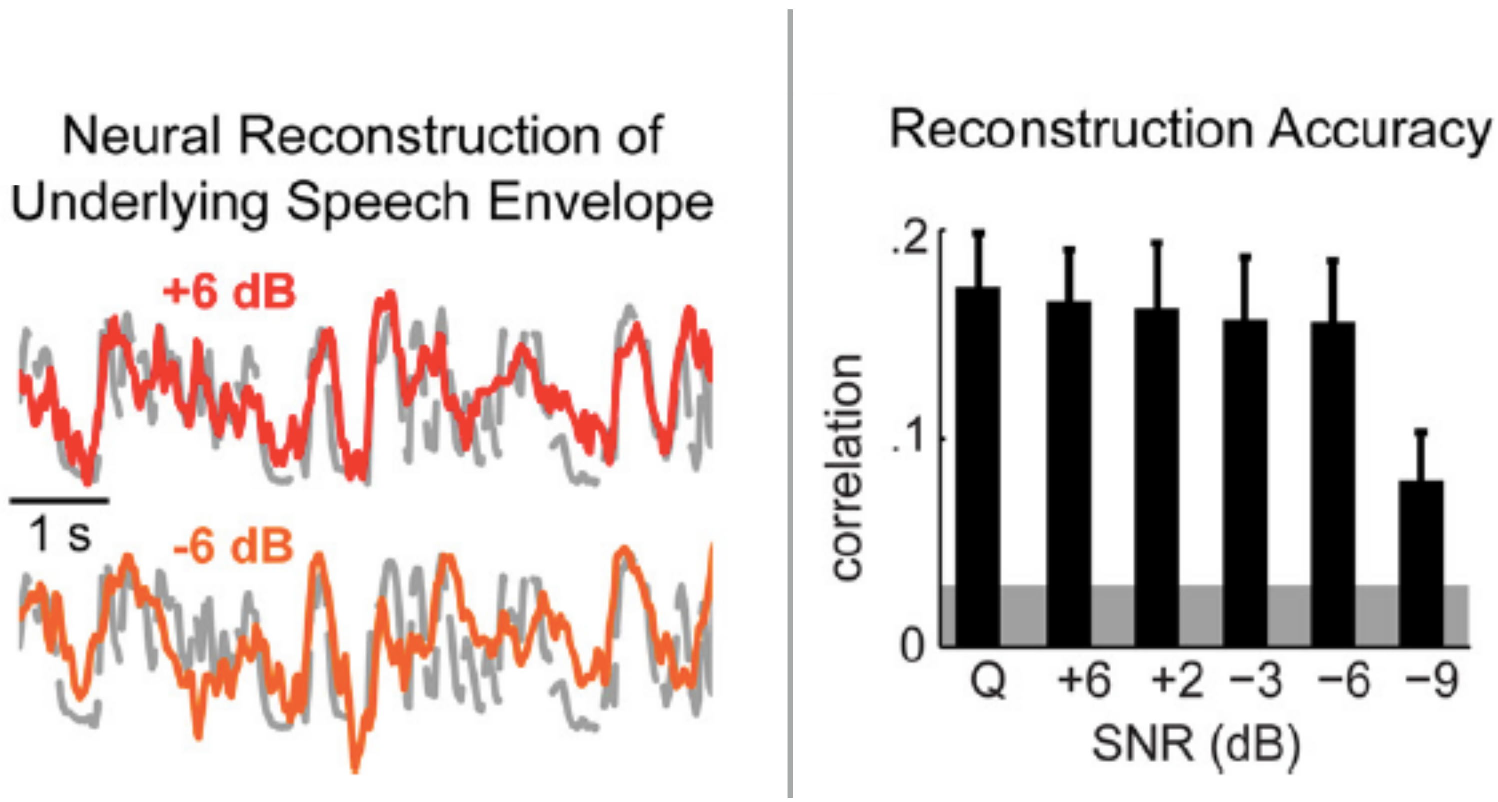
Ding & Simon, J Neurosci (2013)

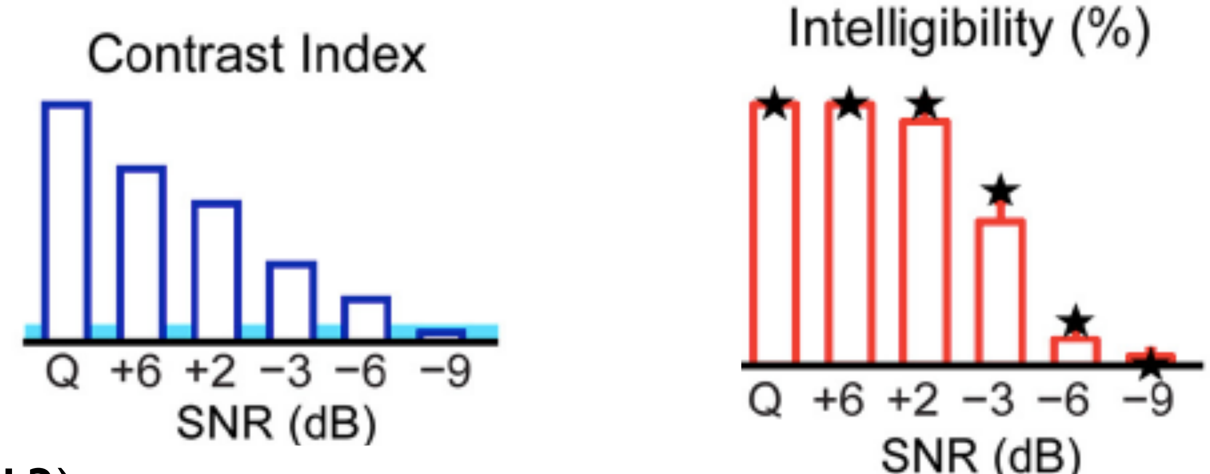
Speech in Noise: Results



Ding & Simon, J Neurosci (2013)

Speech in Noise: Results





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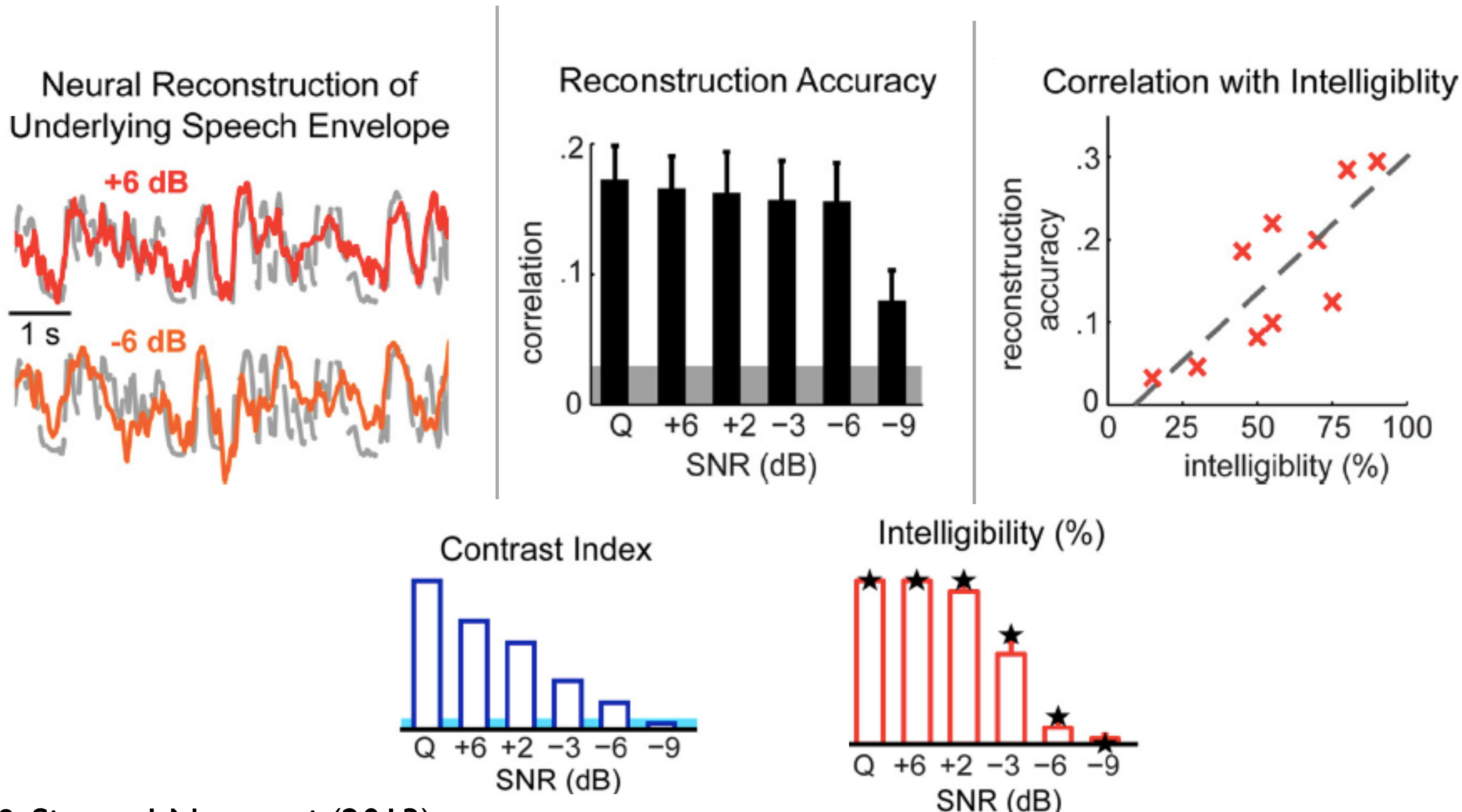
Speech in Noise: Results



Ding & Simon, J Neurosci (2013)

Summary

- Magnetoencephalography = powerful tool
- Useful for Neuroimaging but Especially Useful in the Time (and Frequency) Domain
- In auditory cortex, separates ***Acoustic*** neural processing from ***Auditory*** neural processing

Acknowledgements

Grad Students

Francisco Cervantes
Alex Presacco
Krishna Puvvada

Past Grad Students

Nayef Ahmar
Claudia Bonin
Maria Chait
Marisel Villafane Delgado
Kim Drnec
Nai Ding
Victor Grau-Serrat
Ling Ma
Raul Rodriguez
Juanjuan Xiang
Kai Sum Li
Jiachen Zhuo

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Ben Walsh

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Murat Aytekin
Julian Jenkins
David Klein
Huan Luo

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Yadong Wang

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Catherine Carr
Monita Chatterjee
Alain de Cheveigné
Didier Depireux
Mounya Elhilali
Jonathan Fritz
Cindy Moss
David Poeppel
Shihab Shamma

Funding

NIH R01 DC 008342
NIH R01 DC 007657
NIH R01 DC 005660
NIH R01 DC 000436
NIH R01 AG 036424
NIH R01 AG 027573
NIH R01 EB 004750
NIH R03 DC 004382
USDA 20096512005791

Thank You

At the monthly meeting of
Squidheads Anonymous