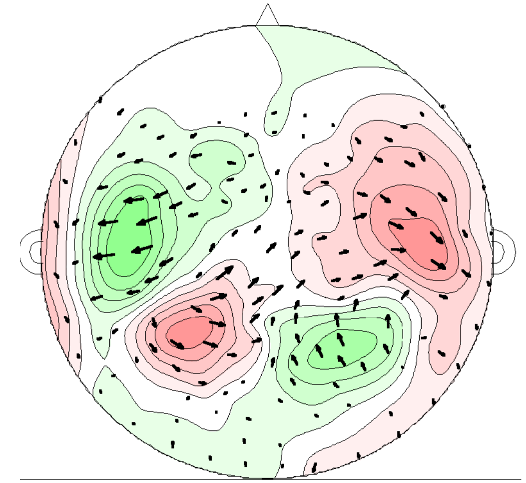
Measuring Brain Dynamics: Investigating Auditory Processing with Magnetoencephalography



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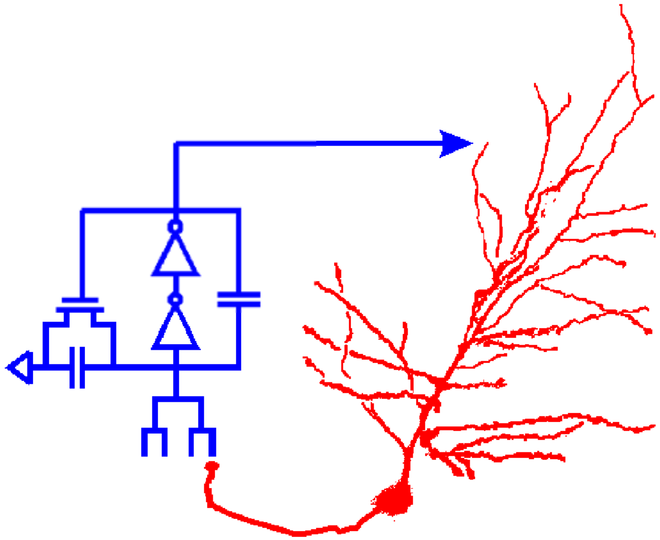

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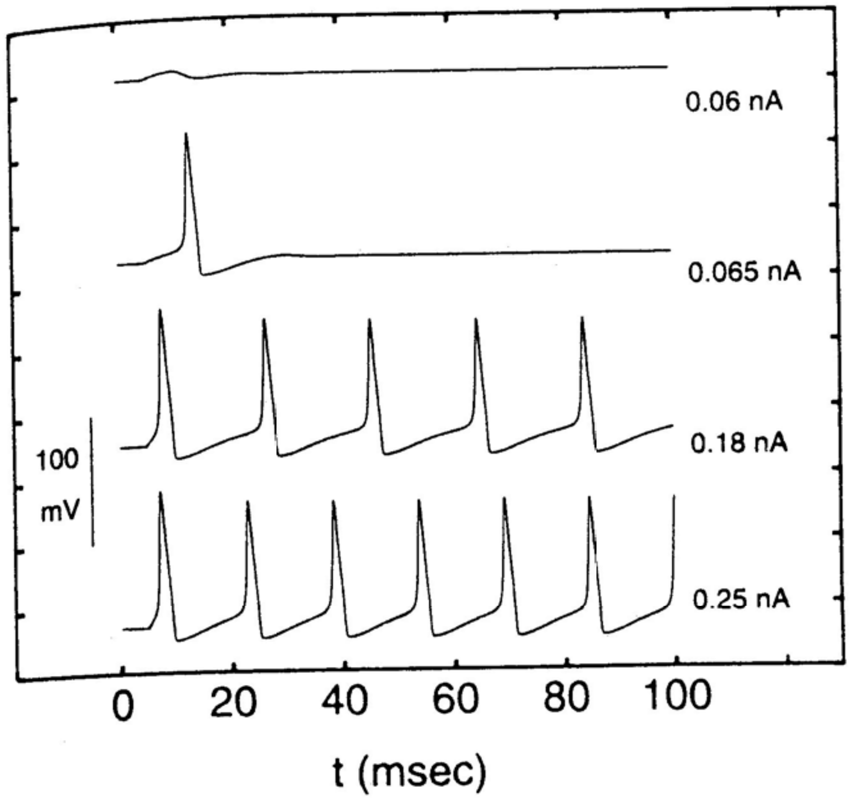
Outline

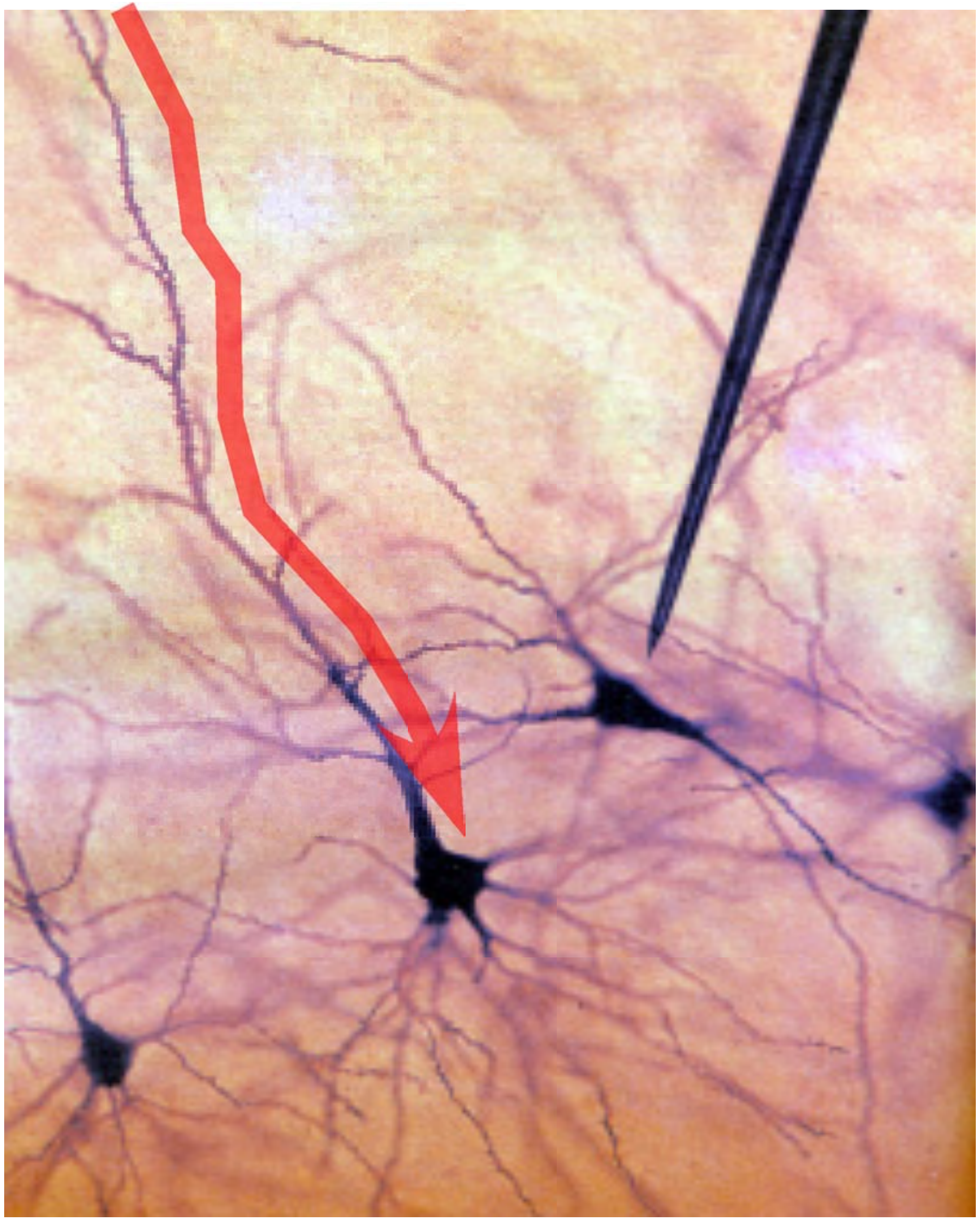
- The Brain and How It Works
- The Auditory System
- Magnetoencephalography (MEG)
- Using MEG to explore the Auditory System

Universal Neural Code

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



Primary Neural Current



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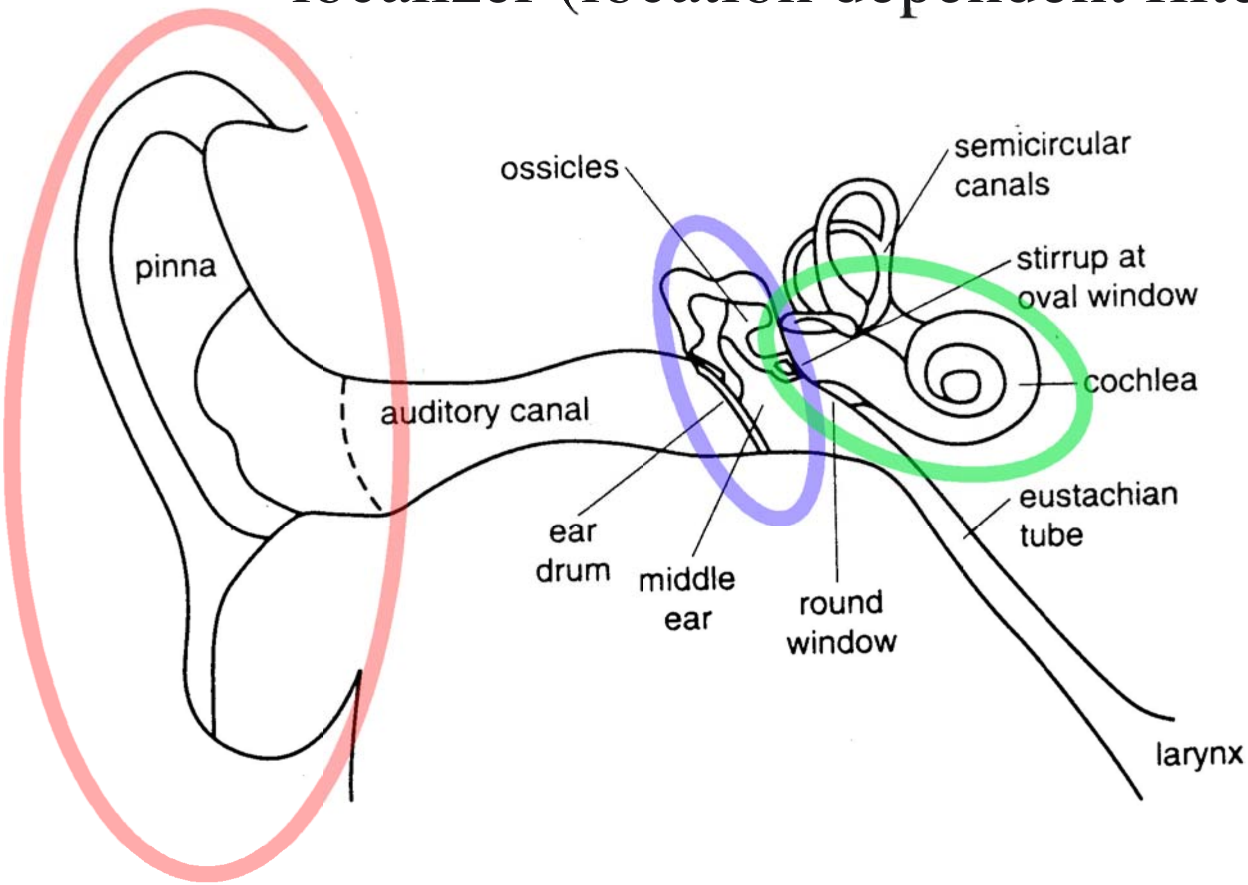
What Is Hearing?

Outer Ear (pinna) useful but not essential
- collector
- localizer (location dependent filtering)



Inner ear (cochlea)
- essential
  - neural "transducer"
  - turns *acoustic* signals into spikes

    = *auditory* signals

Only features conveyed as neural signals perceived
- e.g. masked sounds

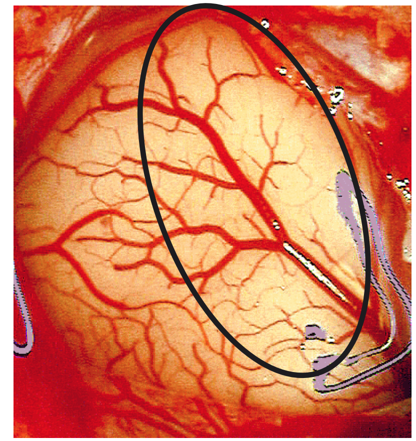
  not conveyed neurally

Middle Ear useful but not essential
- impedance matching = minimized reflection

The Auditory Pathway (oversimplified)

Parallel and serial neural processing in multiple stages

Auditory Cortex

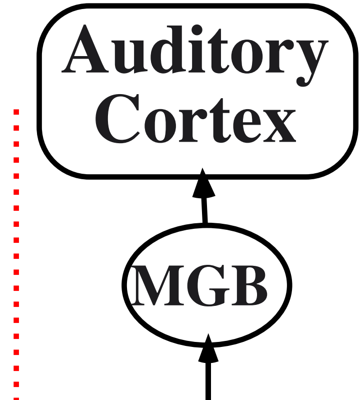


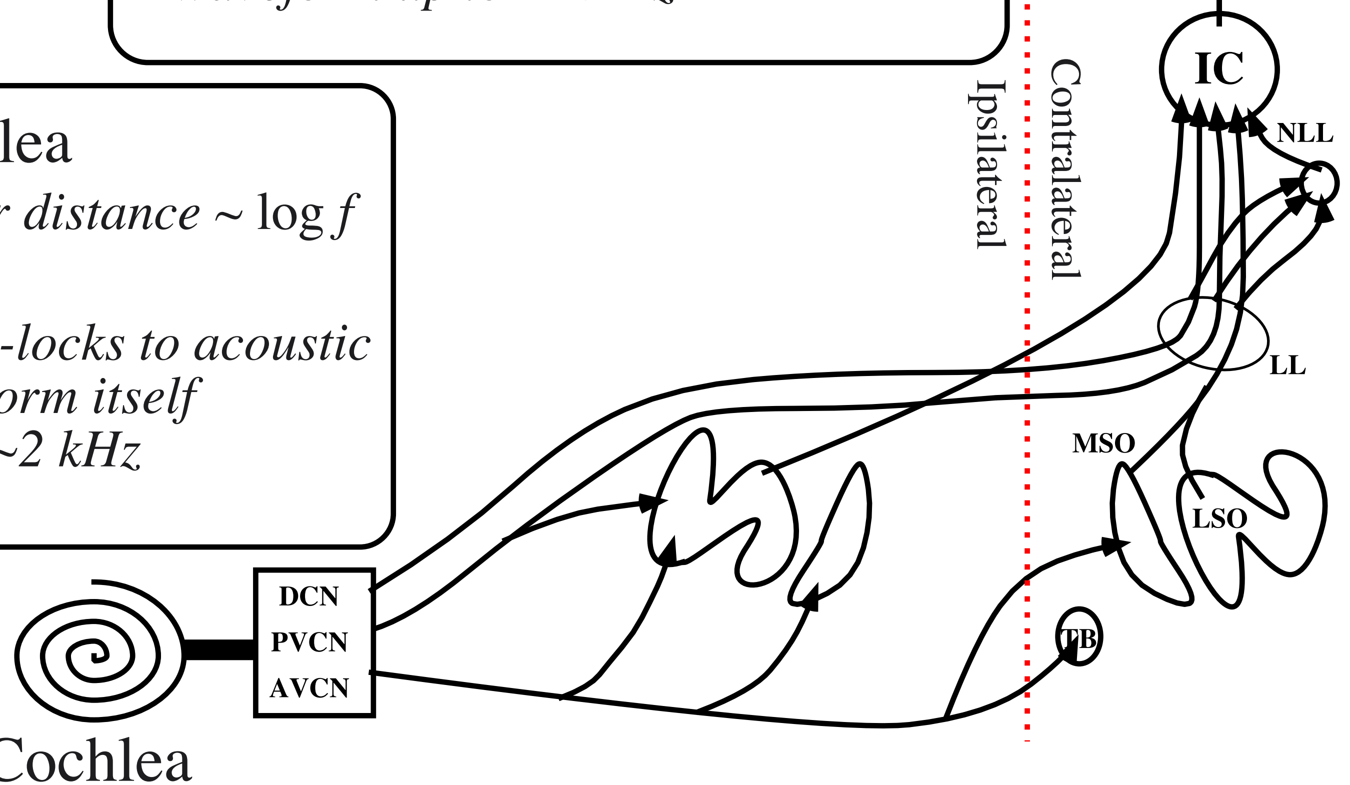
Phase-locks to envelope of acoustic waveform up to ~20 Hz

Cochlea

Linear distance ~ log *f*

Phase-locks to acoustic waveform itself up to ~2 kHz





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What Is the Auditory Neural Code?

- **Neural code is essentially unknown** for almost all auditory features
  - Especially in auditory cortex
  - Much progress in coding near periphery, especially coding of sound location

- **Most important auditory features are acoustically non-trivial**
  - e.g. speech, speaker ID, emotional content, pitch, timbre, sound location, and many, many others

What Can We Hear?

Table 1.6. Approximate ranges of hearing

Species	Low	High (kHz)
Human	20 Hz	20
Chimpanzee	100 Hz	20
Rhesus monkey	75 Hz	25
Squirrel monkey	75 Hz	25
Cat	30 Hz	50
Dog	50 Hz	46
Chinchilla	75 Hz	20
Rat	1 kHz	60
Mouse	1 kHz	100
Guinea pig	150 Hz	50
Rabbit	300 Hz	45
Bats	3 kHz	120
Dolphin (*Tursiops*)	1 kHz	130
Galago	250 Hz	45
Tupaia	250 Hz	45
Sparrow	250 Hz	12
Pigeon	200 Hz	10
Turtle	20 Hz	1
Frog	100 Hz	3
Goldfish	100 Hz	2
Ostariophysi	50 Hz	7
Other teleosts	50 Hz	1

Data taken from Fay 1988

Human: 20 Hz to 20 kHz

Cat: 30 Hz to 50 kHz

Mouse: 1 kHz to 20 kHz

Bat: 1 kHz to 120 kHz

What Can We Hear?

- **Spectro-Temporal Features of Any Sound**

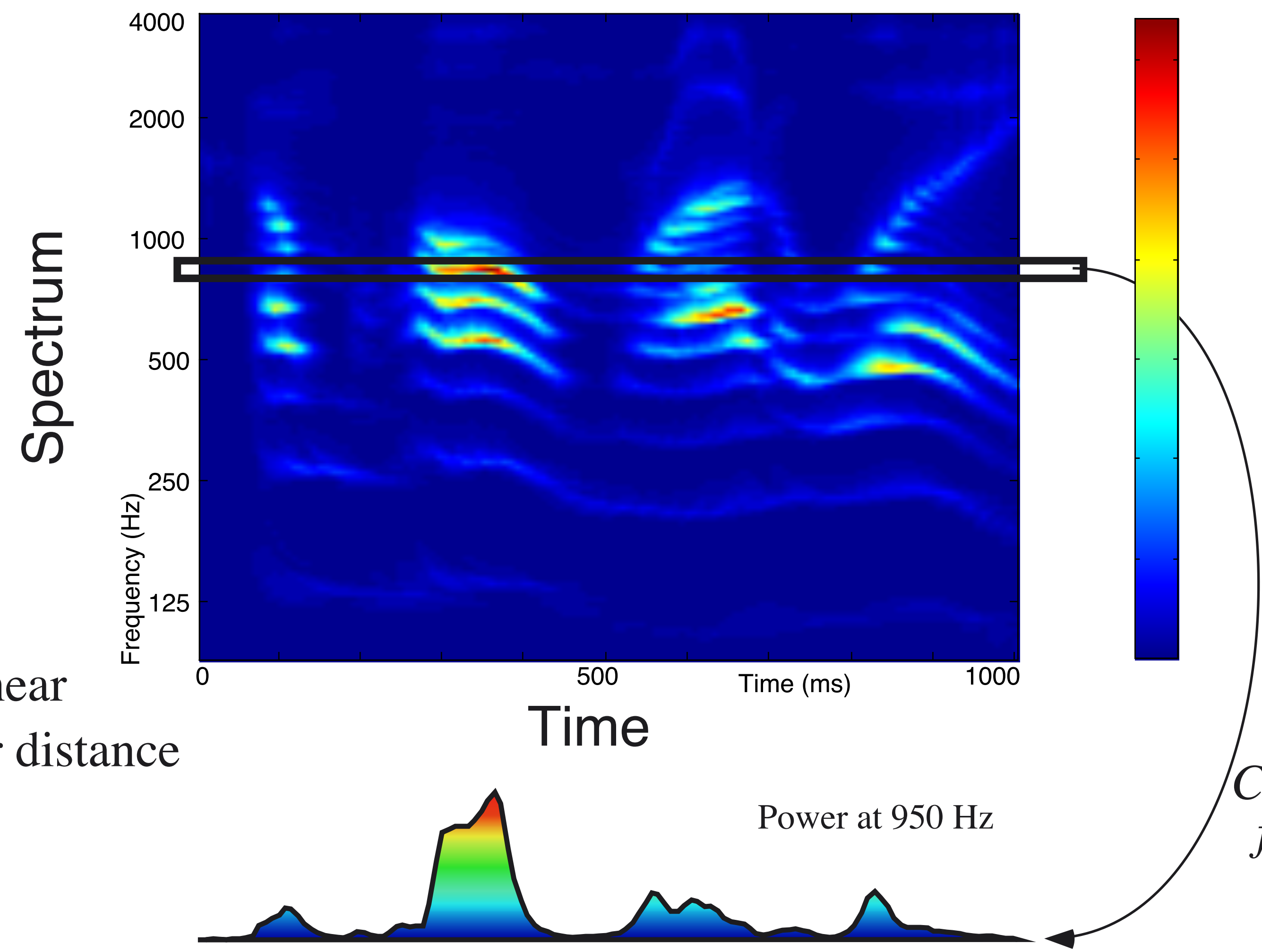
  Spectral content of sound as a function of time.

  Which spectral frequency bands have enhanced power?

  Which spectral frequency bands have diminished power?

  How do these change as a function of time?

"Come home right away."



log f = linear cochlear distance

Characterization from frequency cross-section is very limited

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MEG — Magnetoencephalography

- Simultaneous Whole Head recordings

  160 sensors (3 reference)

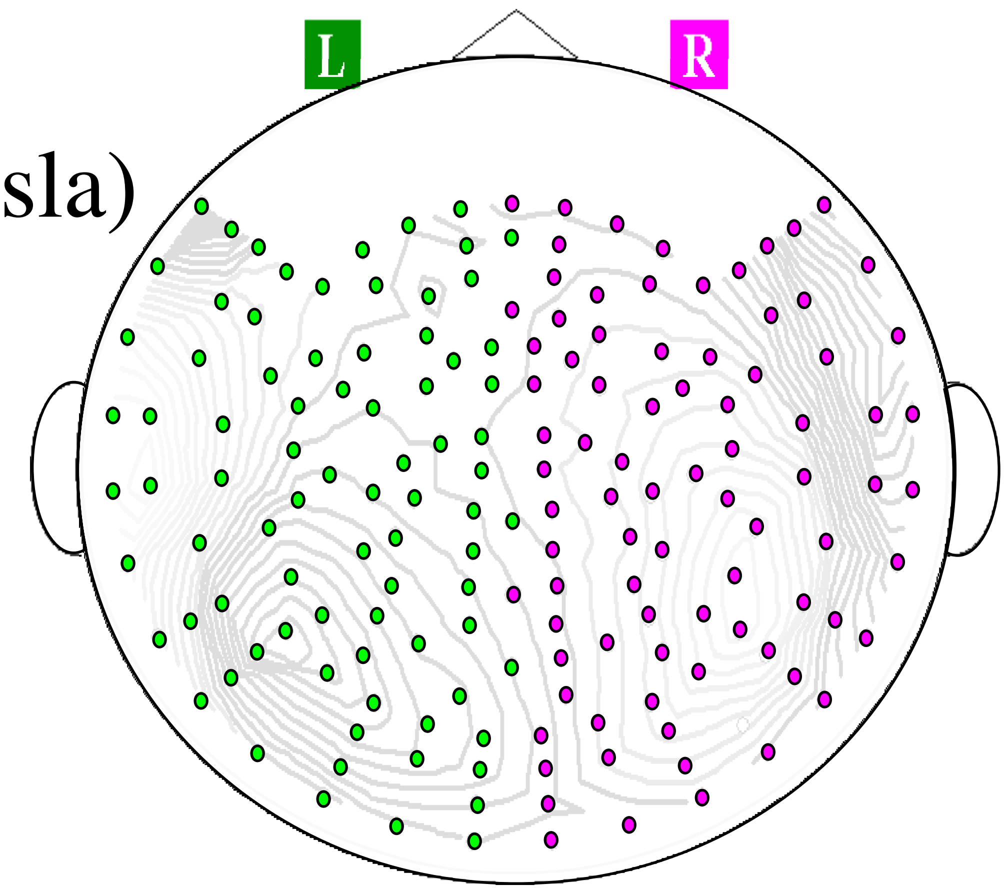
- Exquisitely Sensitive

  ~ 100 fT (10^{-13} Tesla)

  ~ 10^4 neurons

- Temporal Resolution

  ~ 1 ms

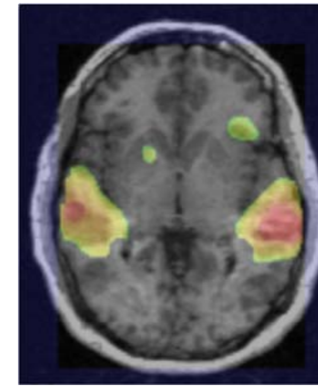


Functional Imaging

Non-invasive recording from human brain (Functional brain imaging)

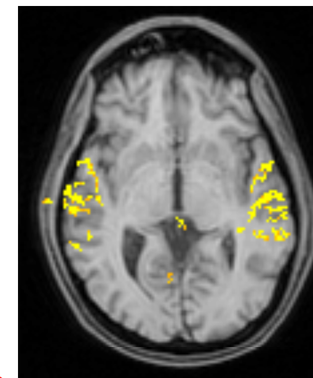
Hemodynamic techniques

Positron emission tomography
PET



Excellent *spatial resolution*
(~ 1-2 mm)
Poor temporal resolution
(~ 1 s)

Functional magnetic resonance imaging
fMRI

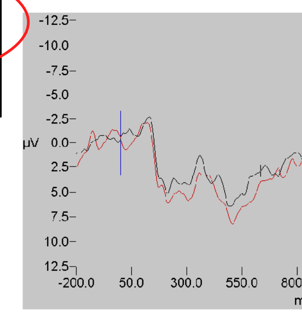


PET, EEG require across-subject averaging

fMRI and MEG can capture effects in single subjects

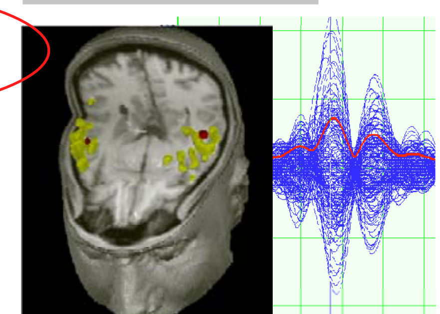
Electromagnetic techniques

Electroencephalography
EEG

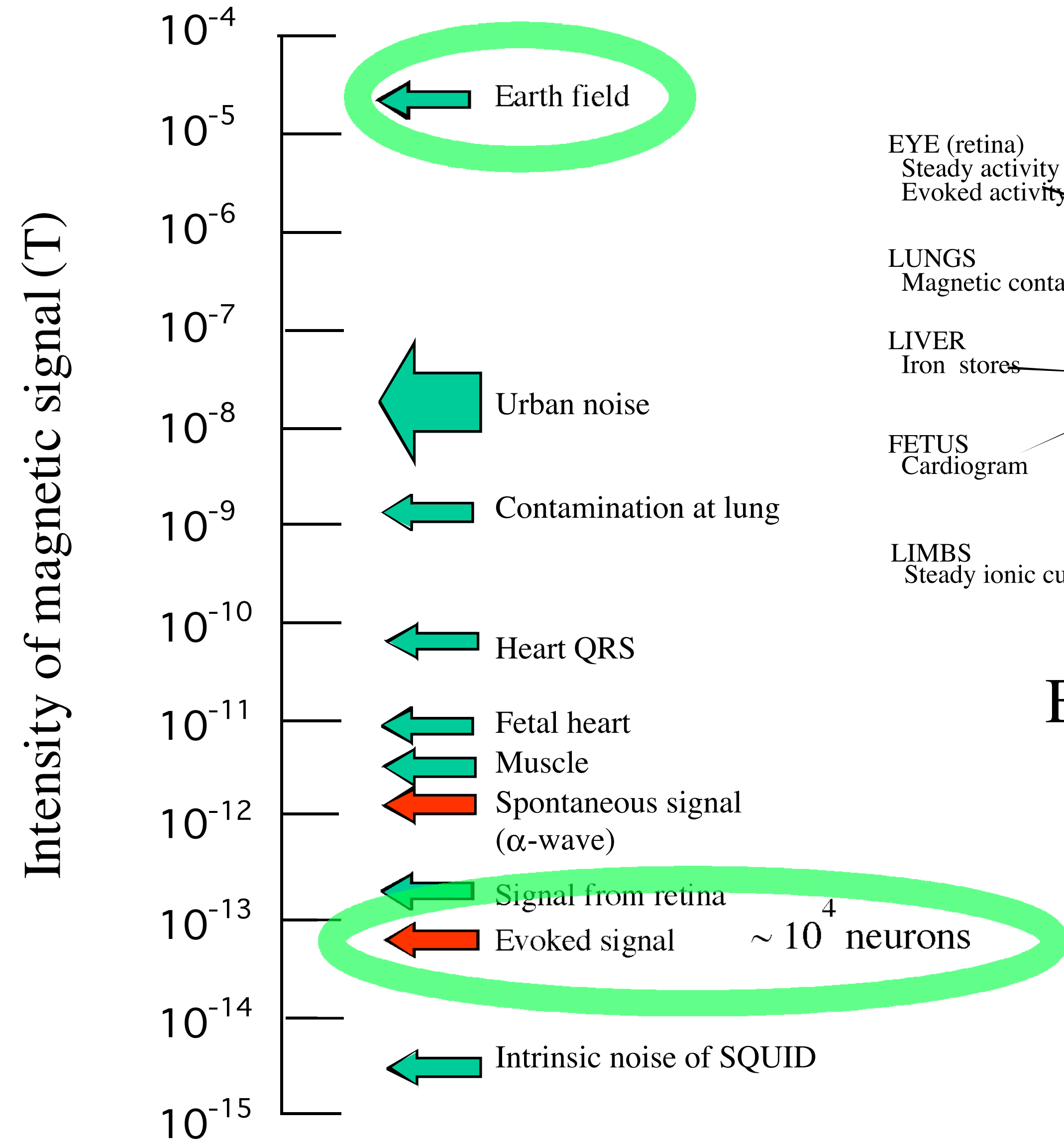


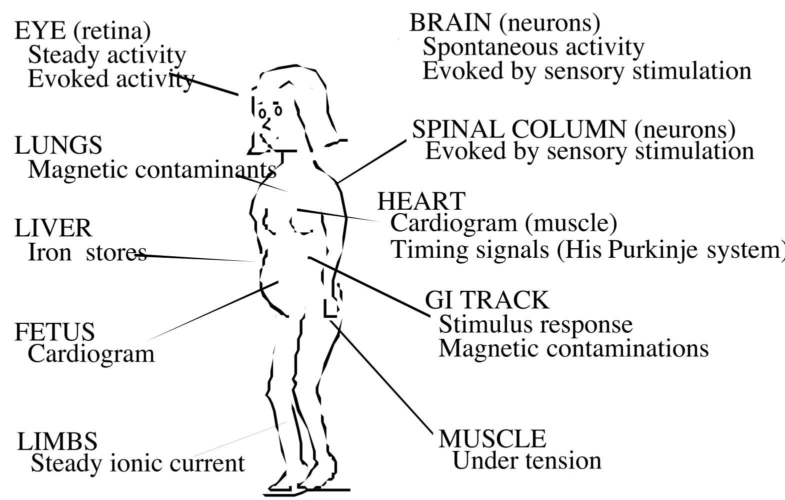
Poor spatial resolution
(~ 1 cm)
Excellent *temporal resolution*
(~ 1 ms)

Magnetoencephalography
MEG



Magnetic Field Strengths

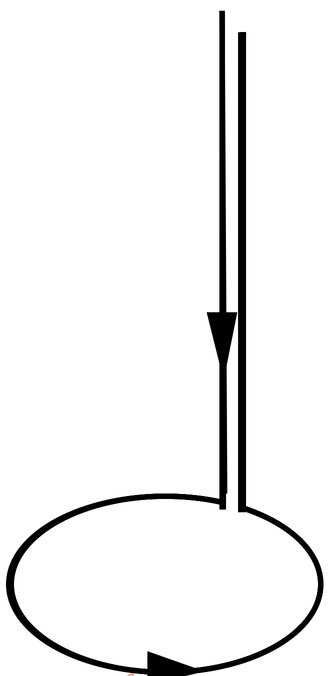




Biomagnetism

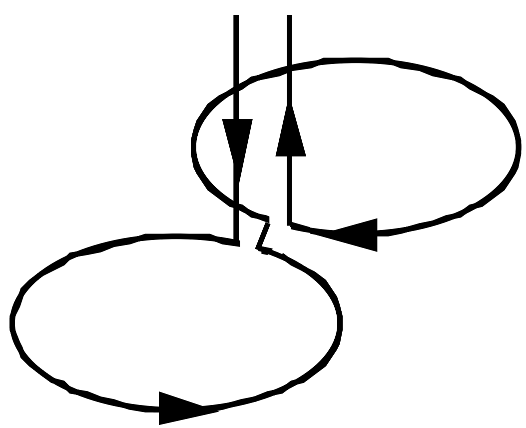
Sensor Configurations

SQUID Magnetometer



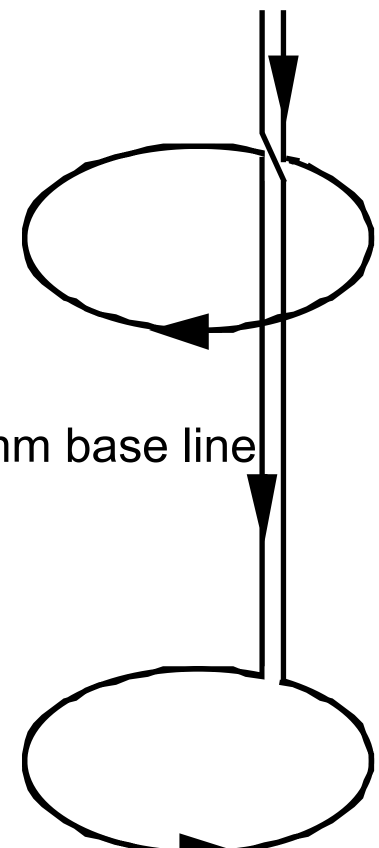
SQUID Gradiometer

Noise reduction from
Differential measurement



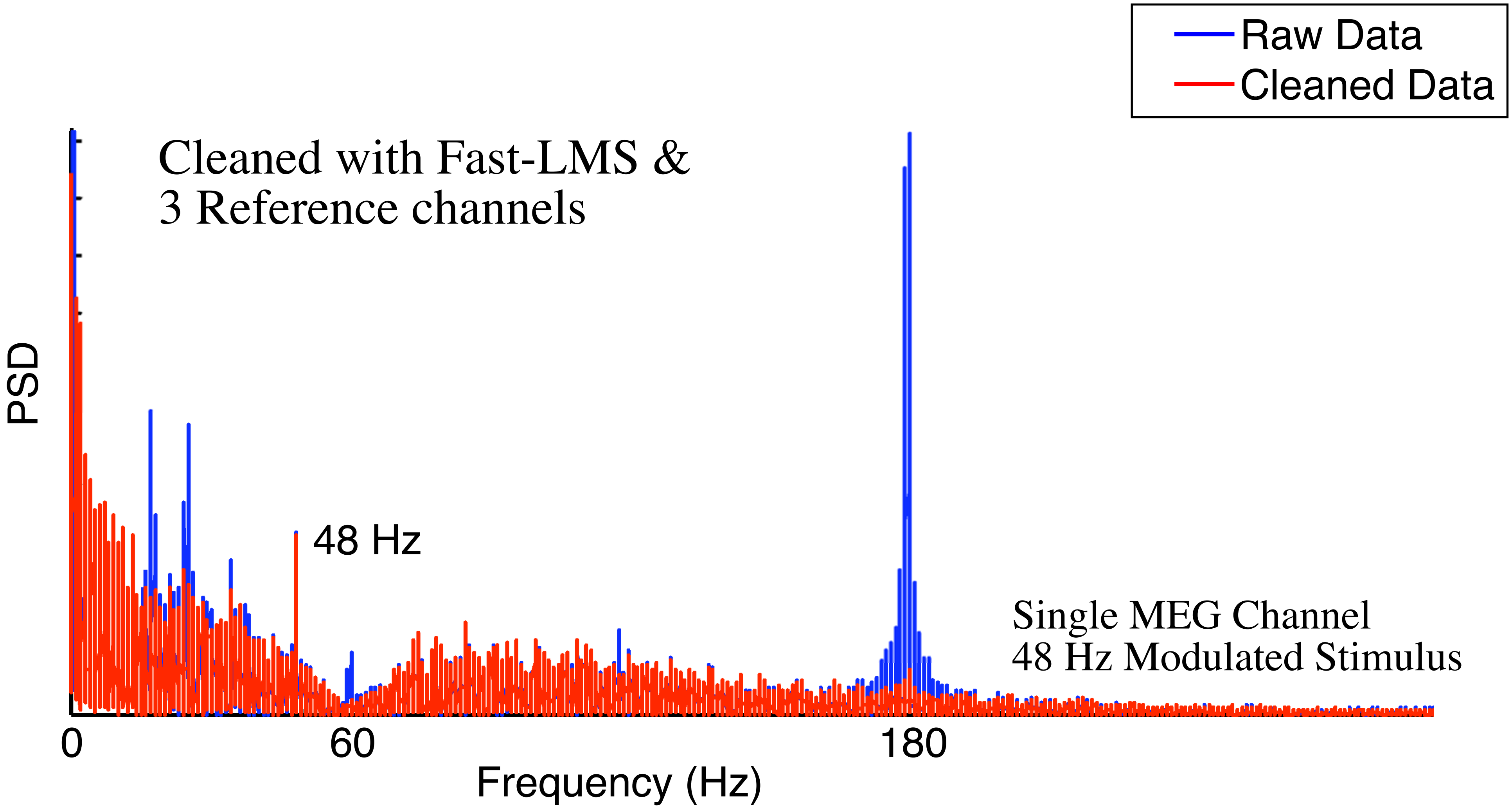
Planar type

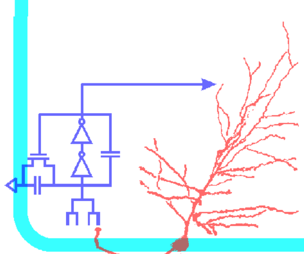
50 mm base line



Axial type

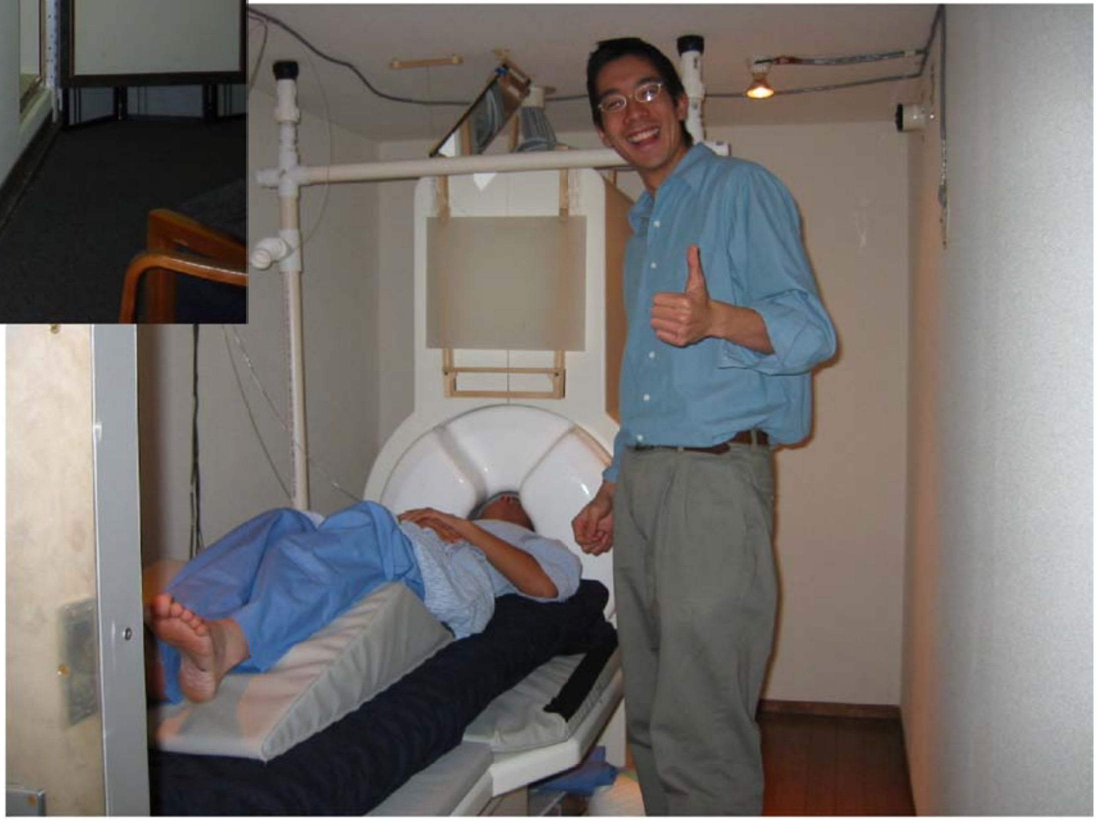
Noise Reduction in Software



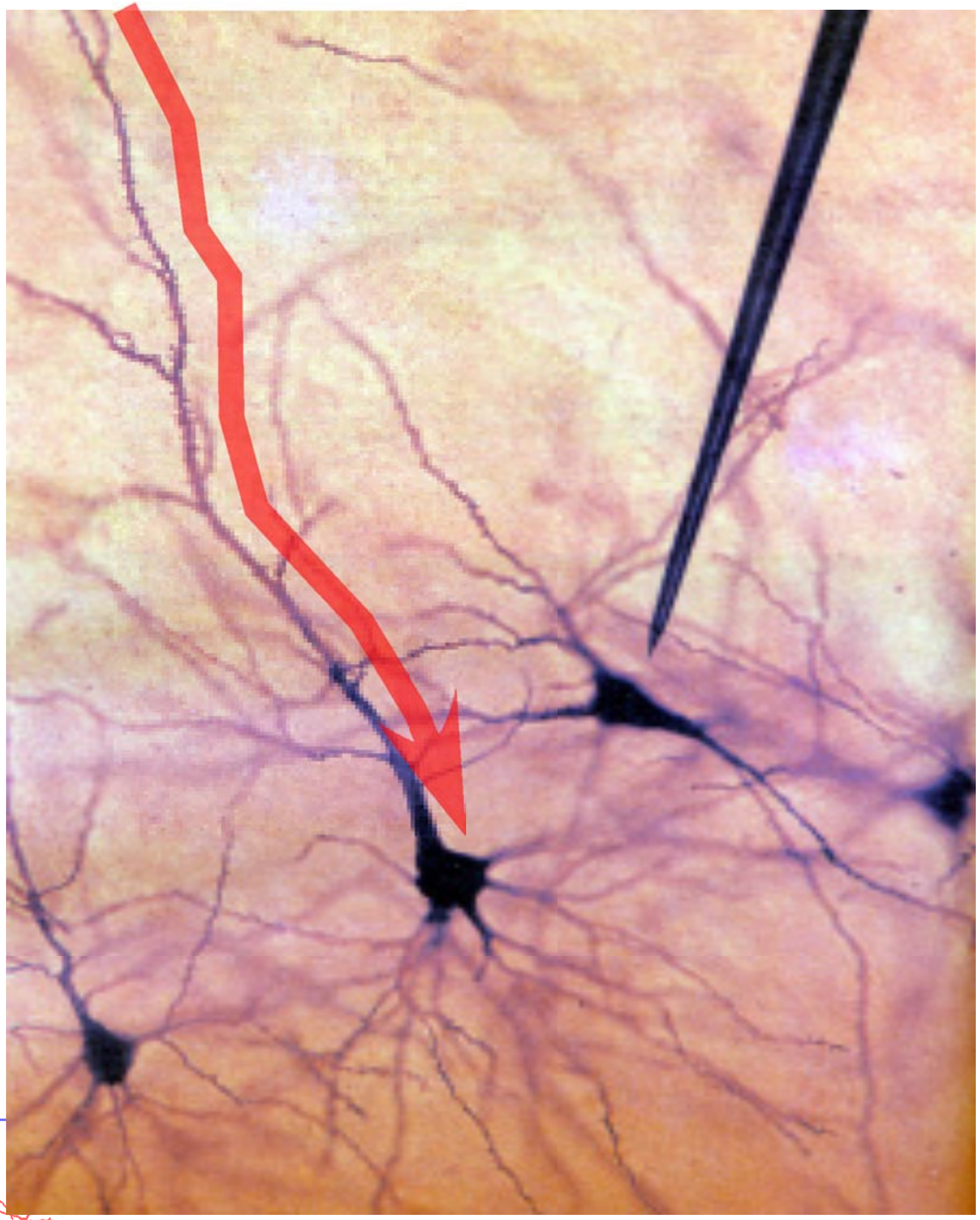


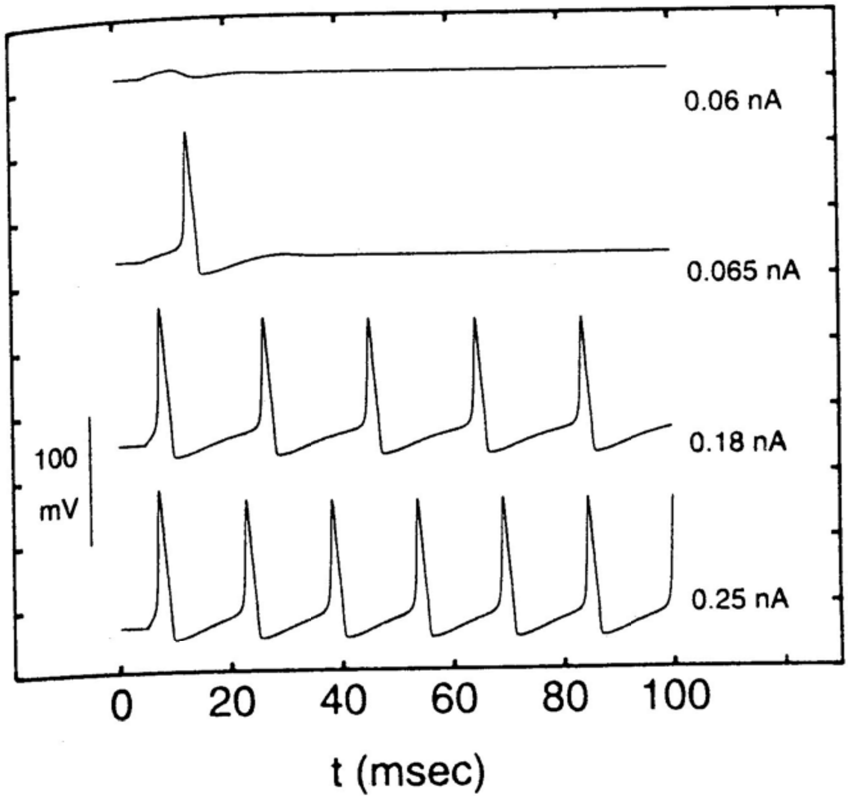
Noise Reduction in Hardware

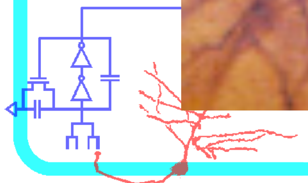
MEG at University of Maryland



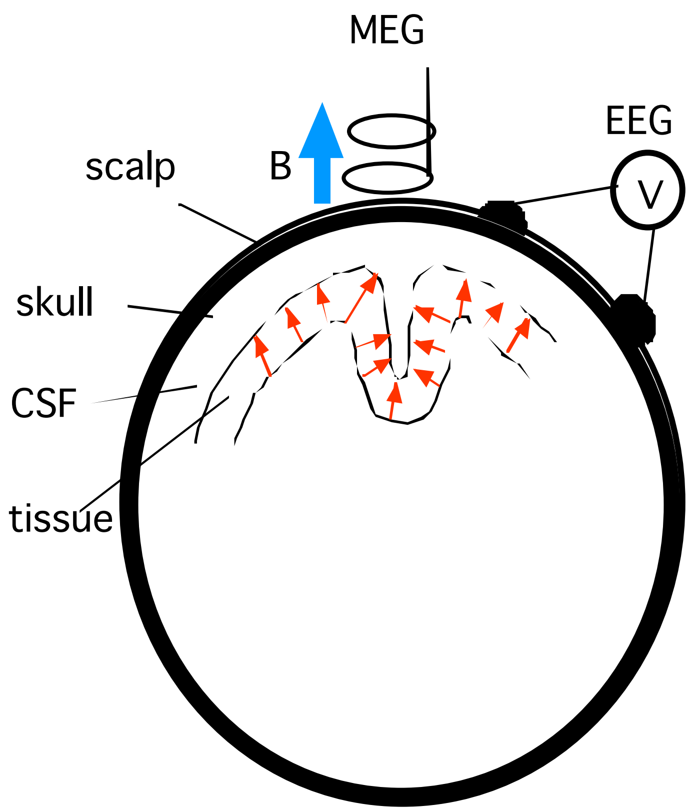
Neural Activity = Neural Current

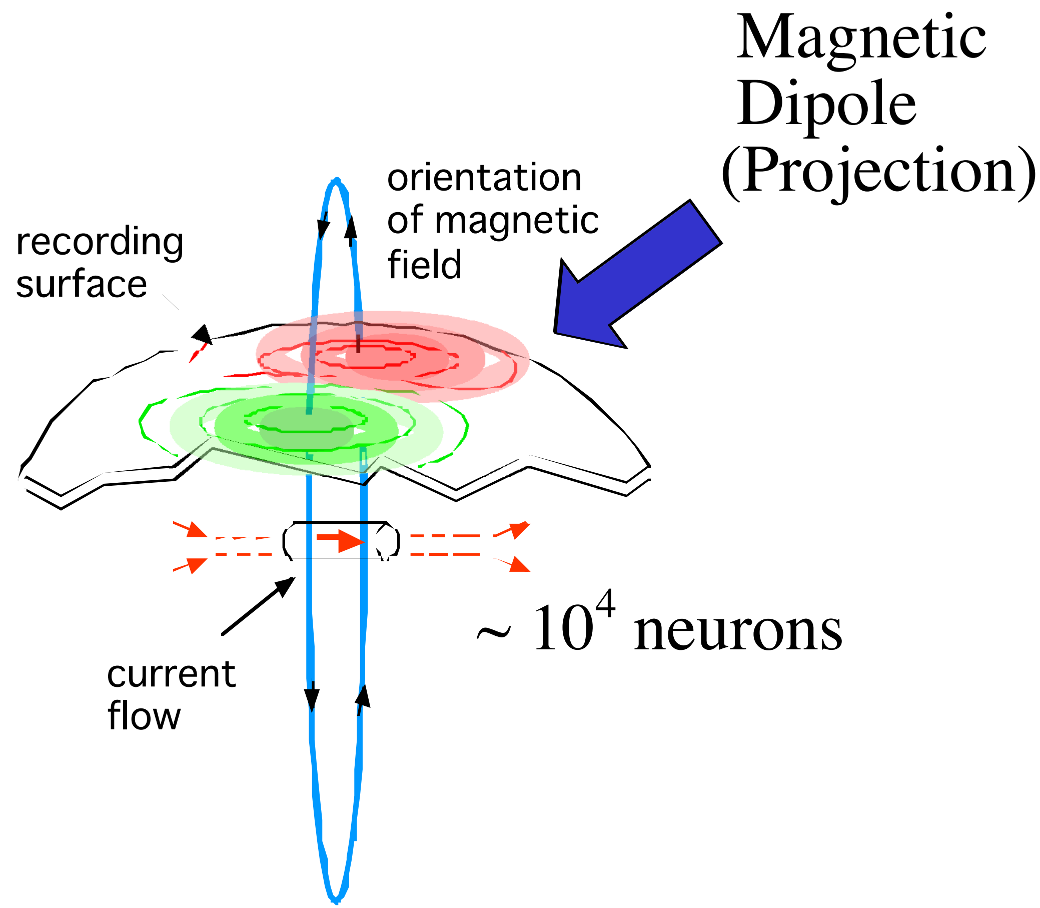






MEG Magnetic Signal





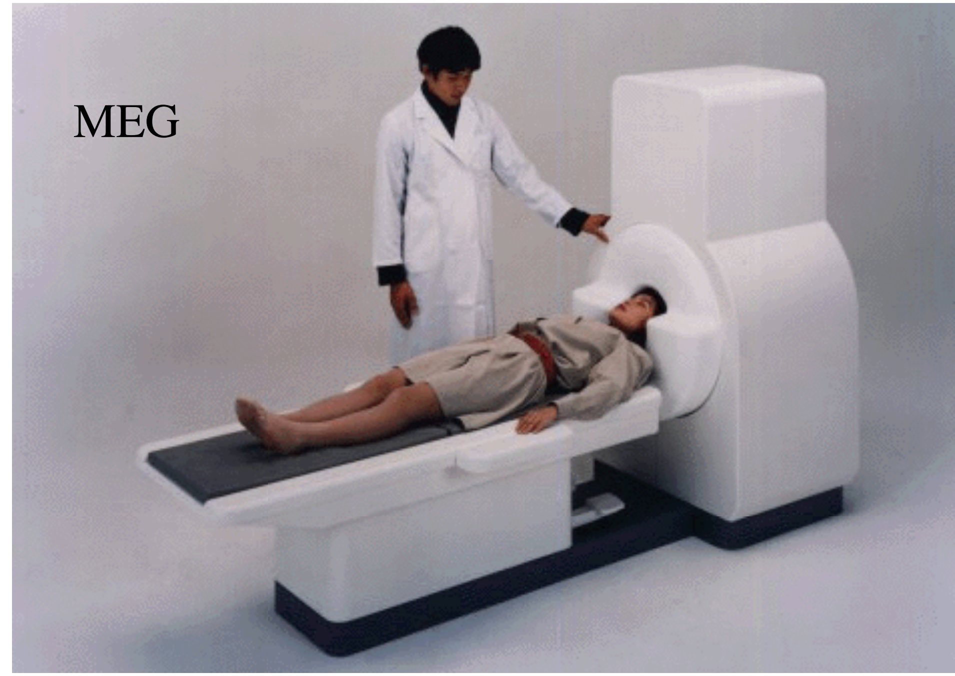
Non-invasive measurement
Direct measurement of Neural Activity

MEG compared to EEG

Temporal resolution high as EEG
Fast, easy set-up
Magnetic fields are not attenuated or distorted, unlike electric fields
Higher spatial resolution

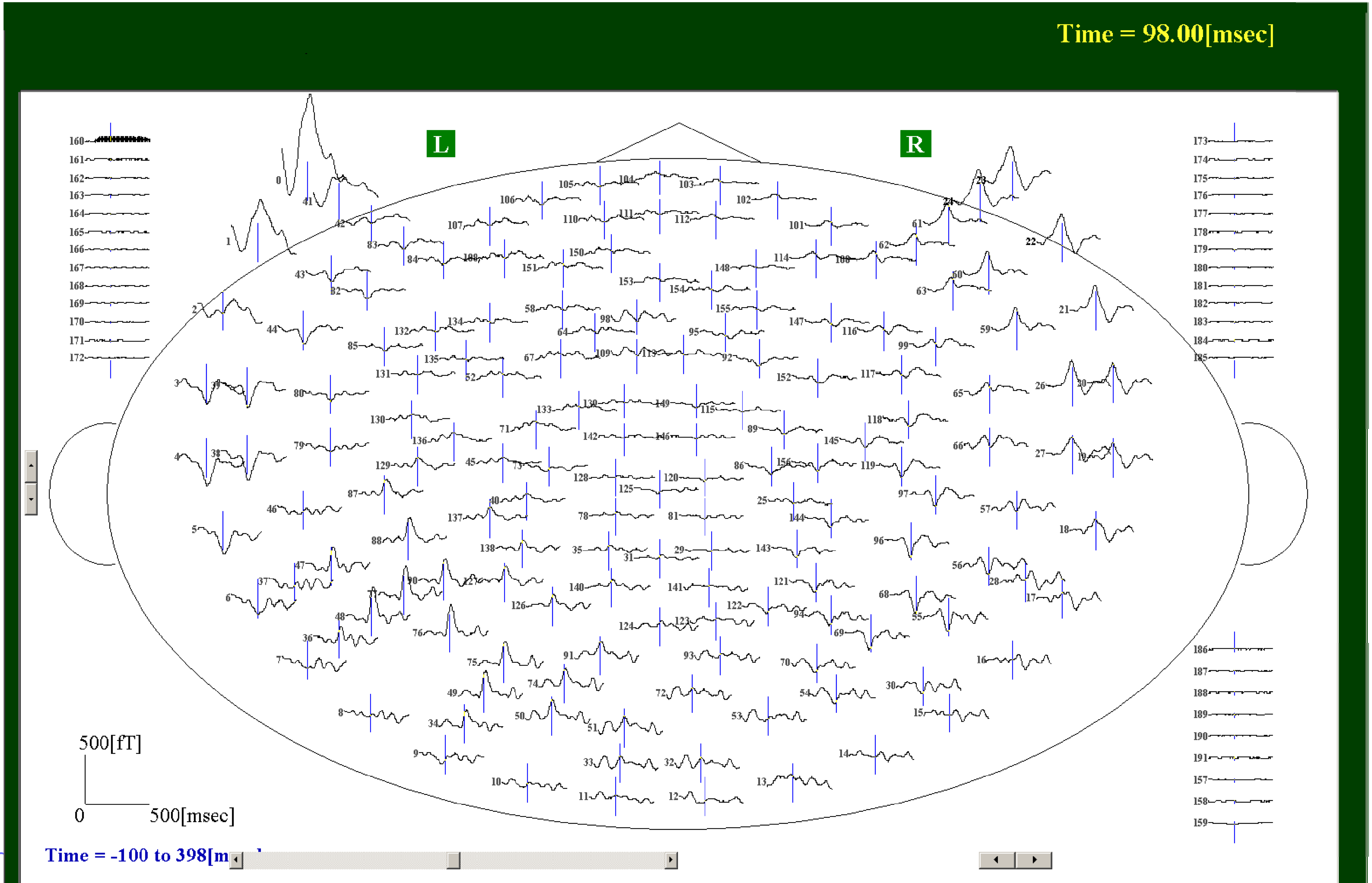
Expensive
Inverse problem worse? better?

Complementary Techniques

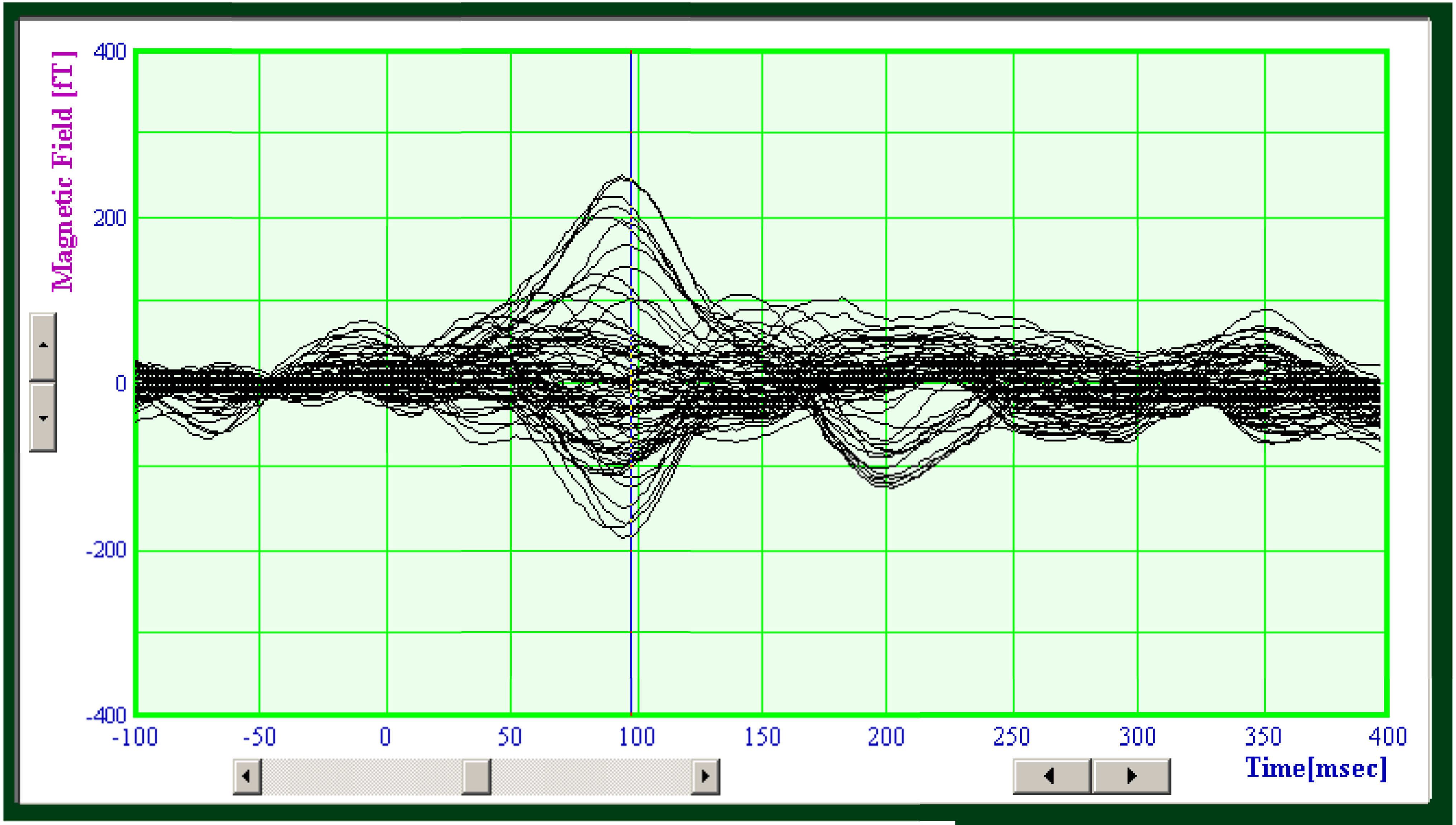


EEG

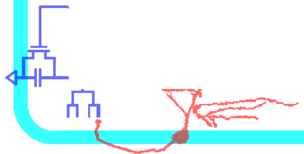
MEG Response



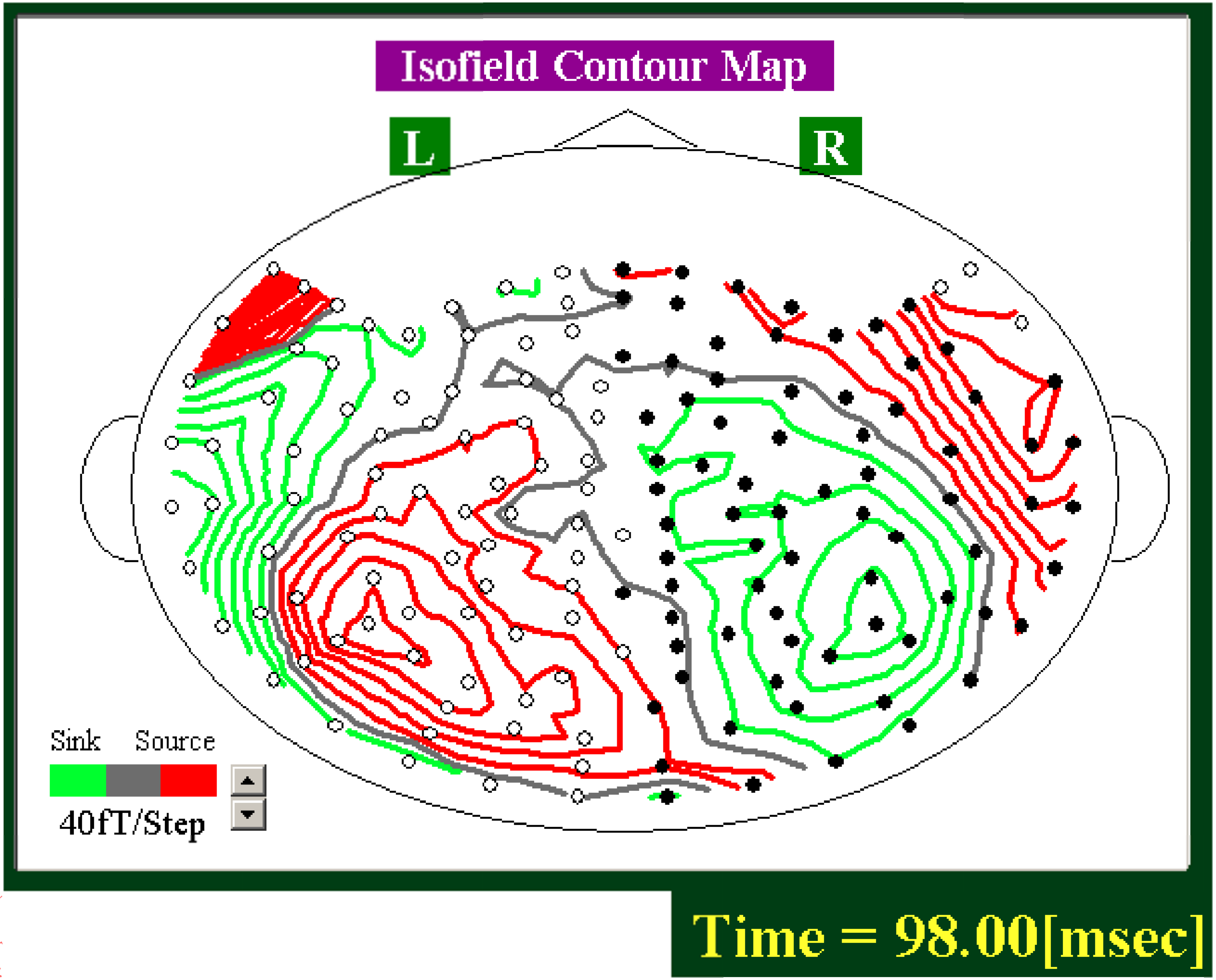
MEG Response

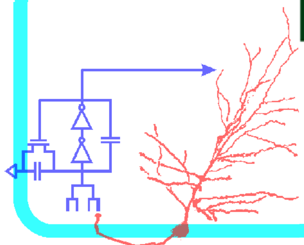


Time = 98.00[msec]



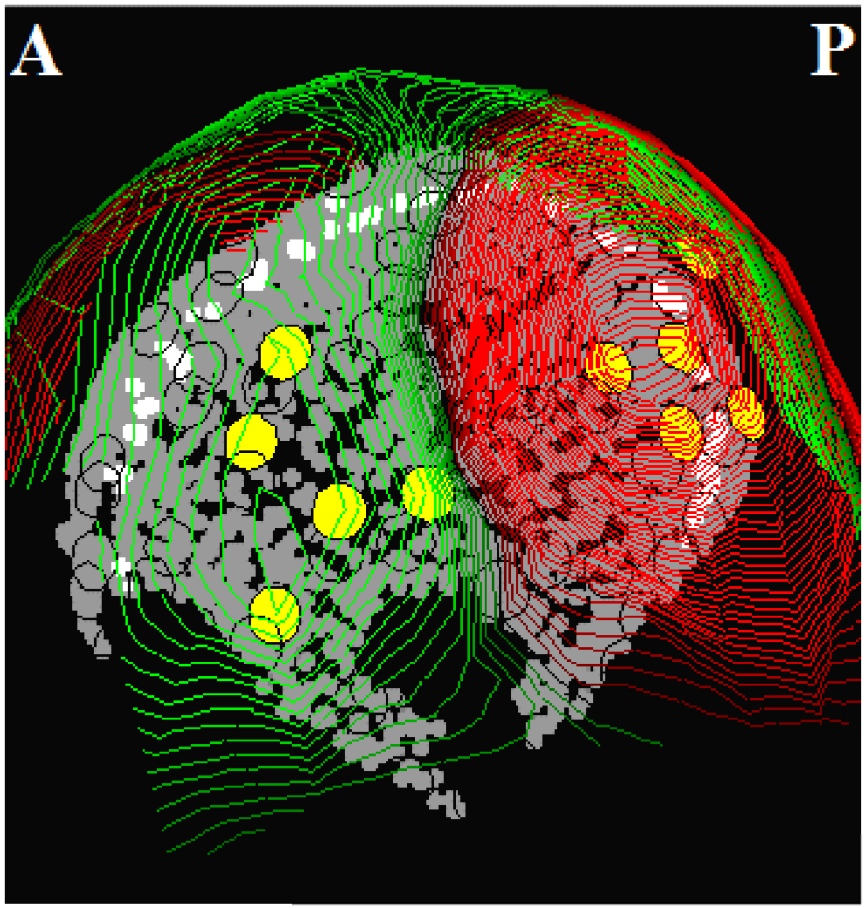
MEG Response



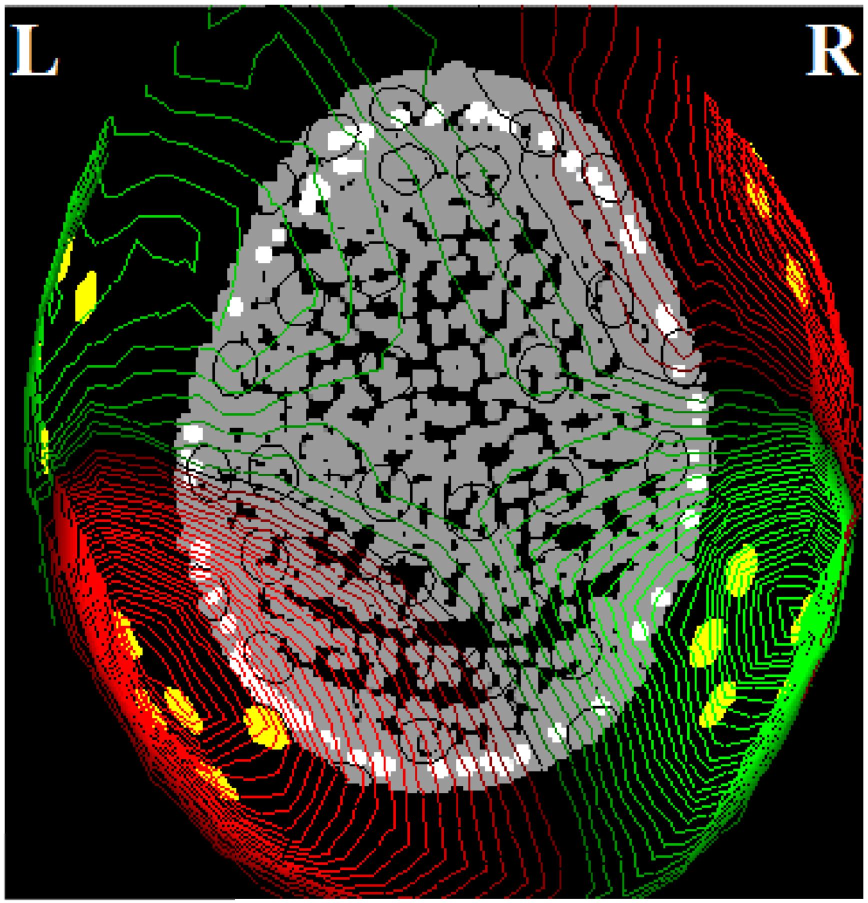


MEG Response

Sagittal View



Axial View



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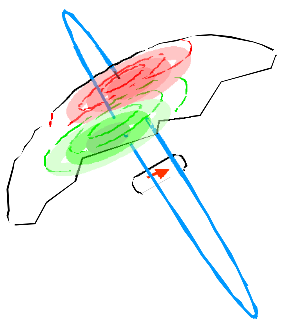
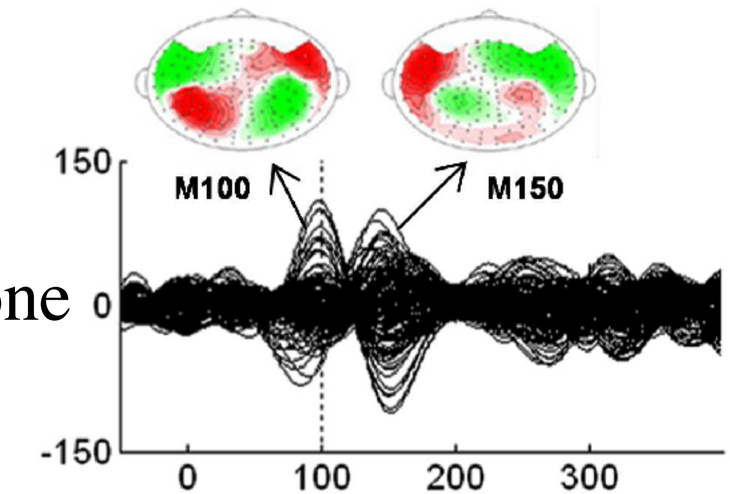
Time Course of MEG Responses

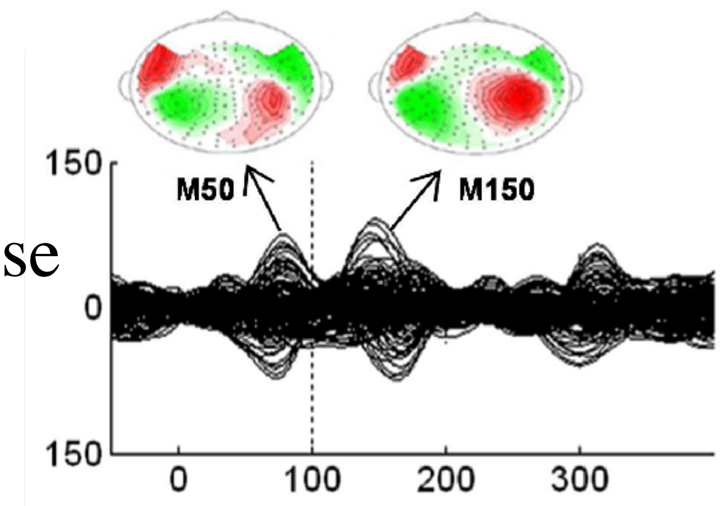
Evoked Responses
MEG Events Time-Locked
to Stimulus Event



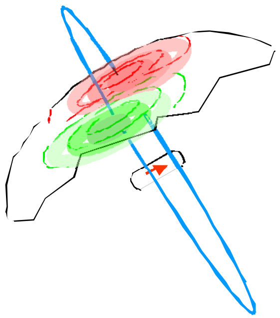
Pure Tone



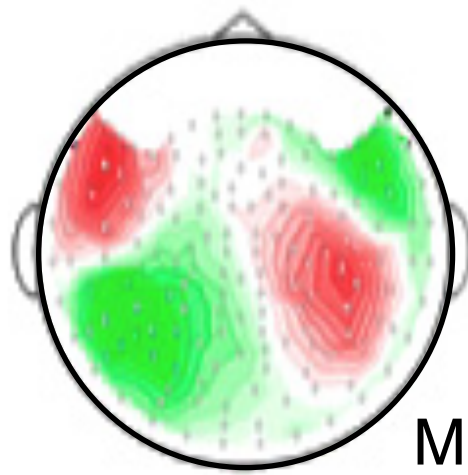
Broadband Noise



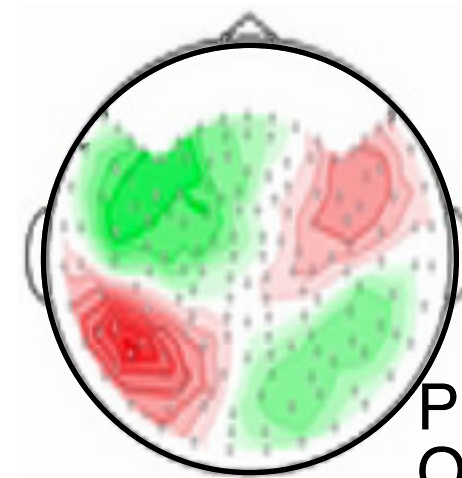
Spatial Auditory MEG Responses



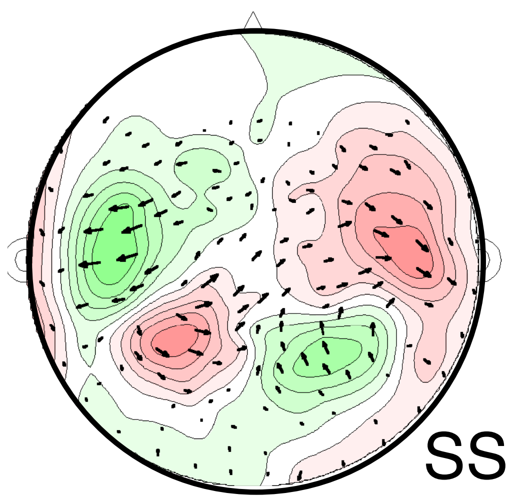
Auditory Responses
Robust
Strongly Lateralized



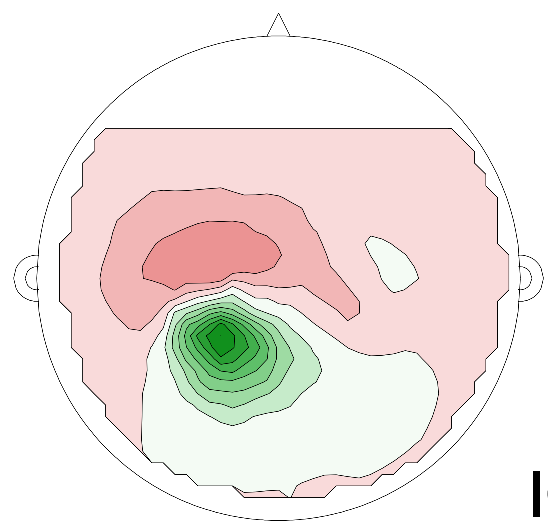
M50

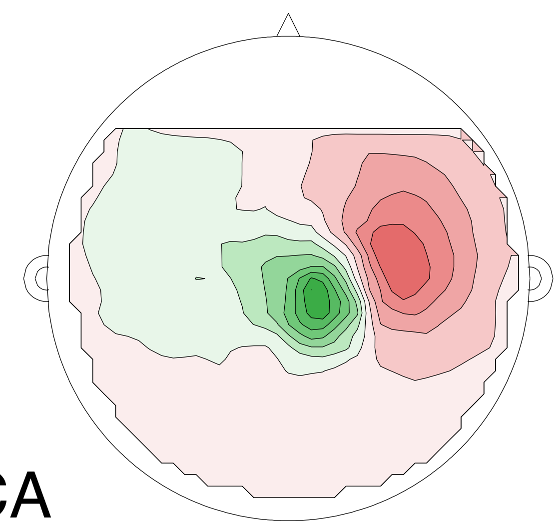


Pitch Onset



SSR





ICA

An Alternative to Time: Frequency

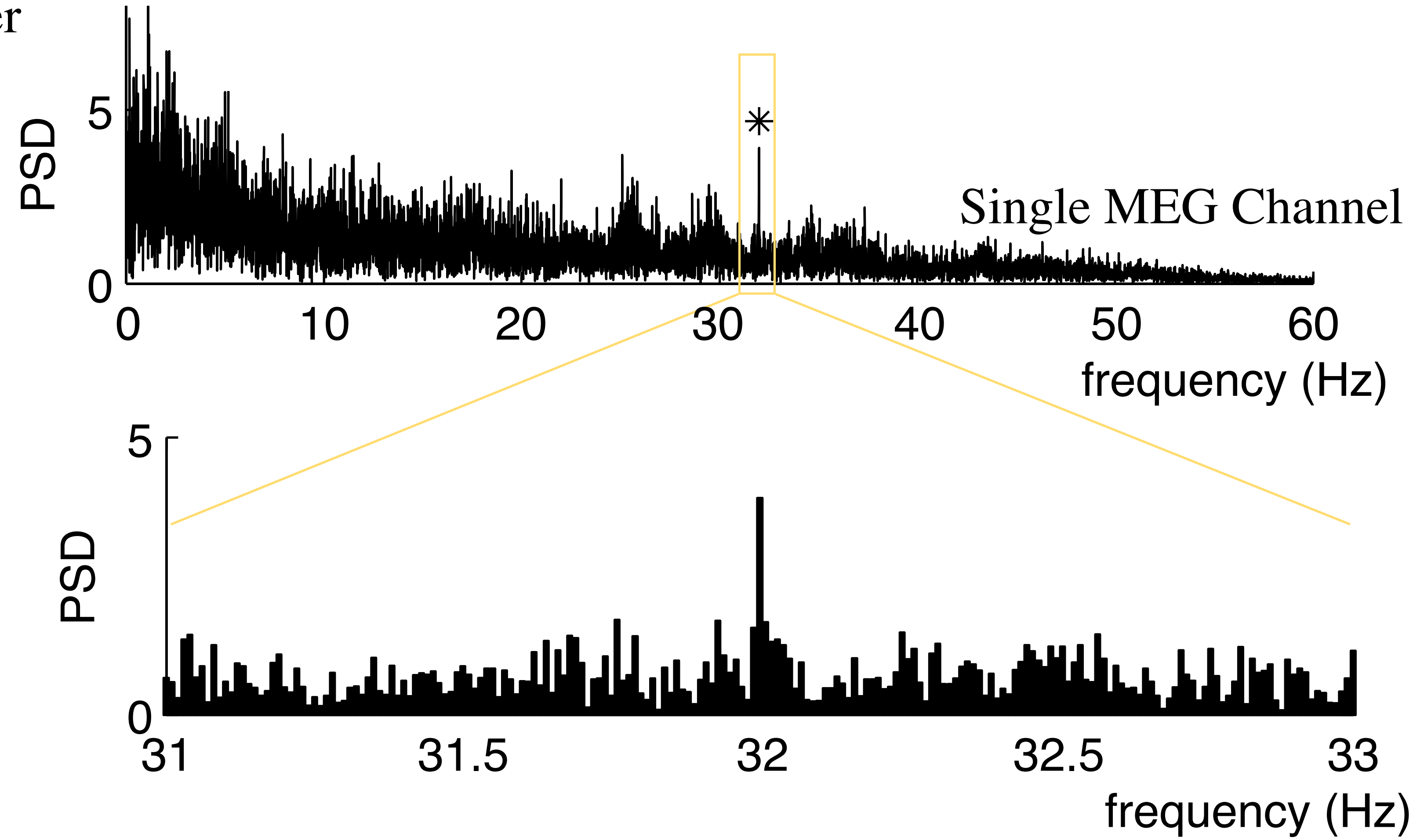
- Use Stimuli localized in Frequency rather than time
- Examine Response at Same Frequency
- Well Established Method:

  Frequency Response or ***Transfer Function***
- Stimulus Modulated at Single Frequency:

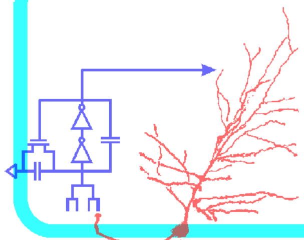
  Steady State Response (SSR)

Frequency Response

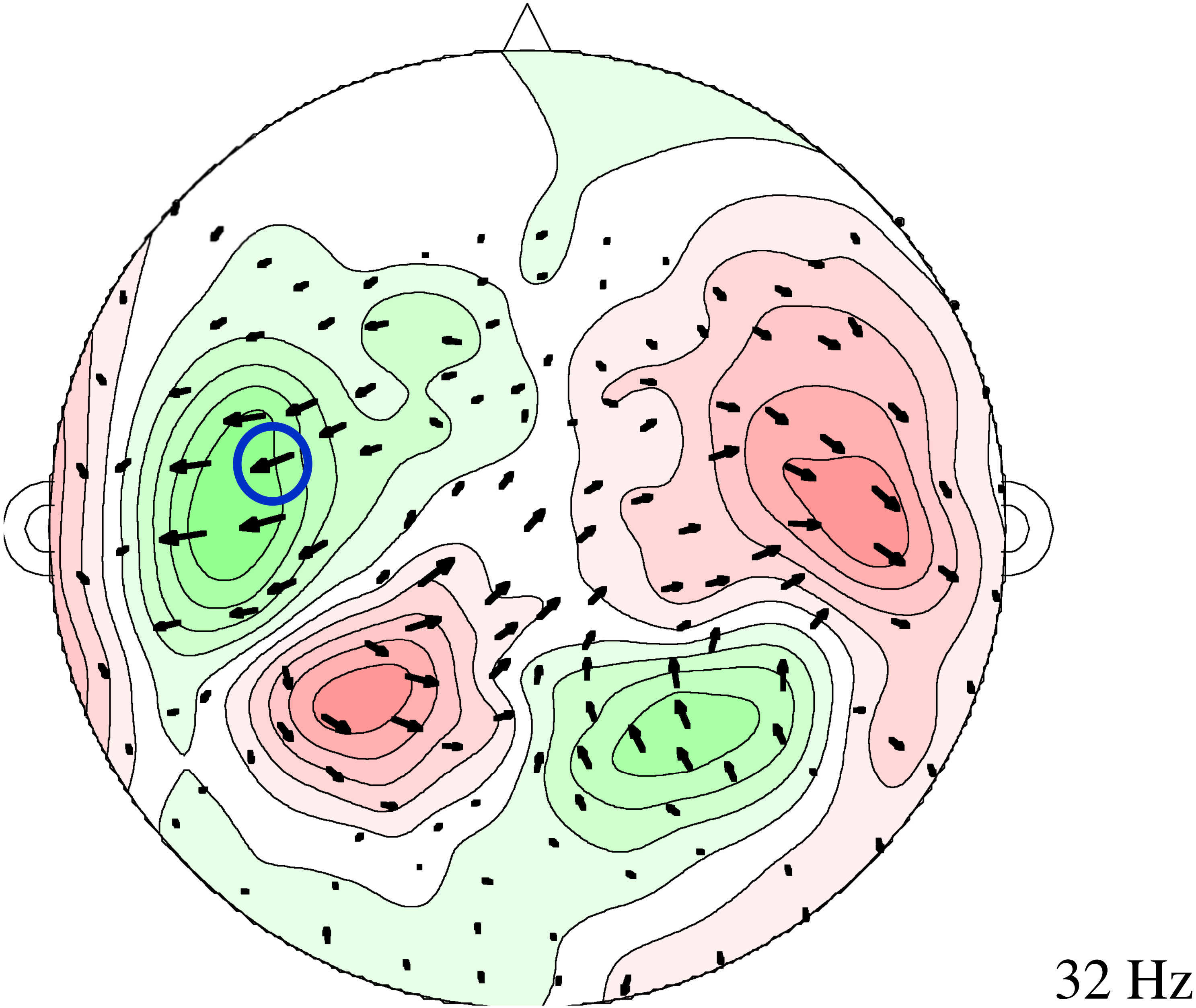
32 Hz Modulation
400 Hz tone carrier
100 trials @ 1 s
(concatenated)

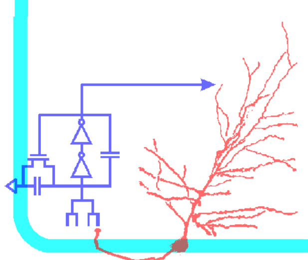


Extremely Precise Phase-Locking: 0.01 Hz
No trial-to-trial jitter

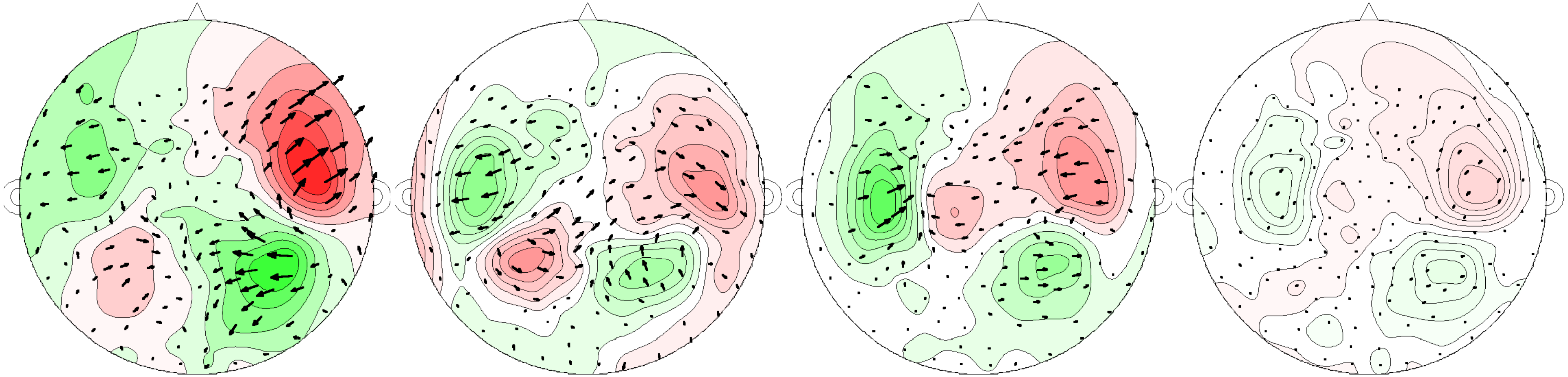


Whole Head Steady State Response



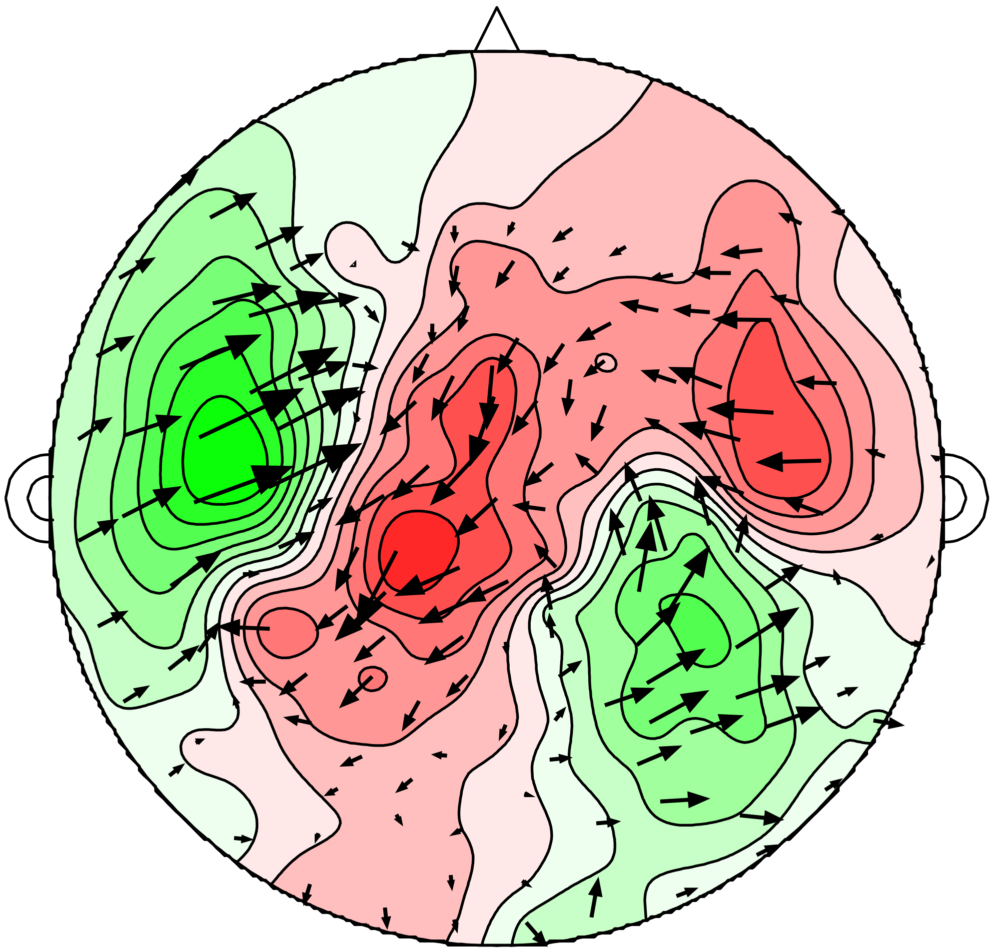


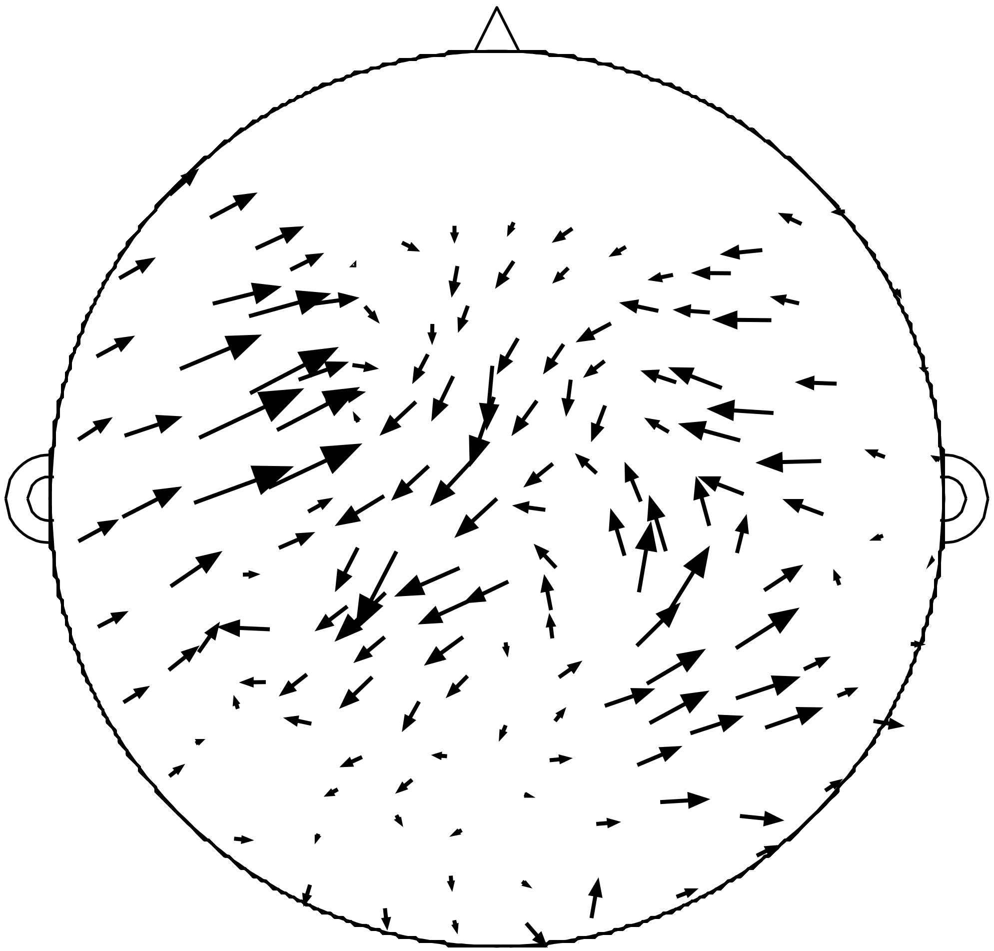
Whole Head Transfer Function

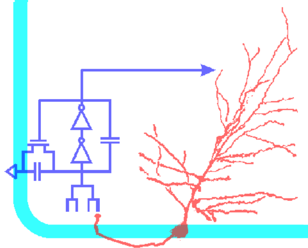


16 Hz 32 Hz 48 Hz 64 Hz

Complex Magnetic Field



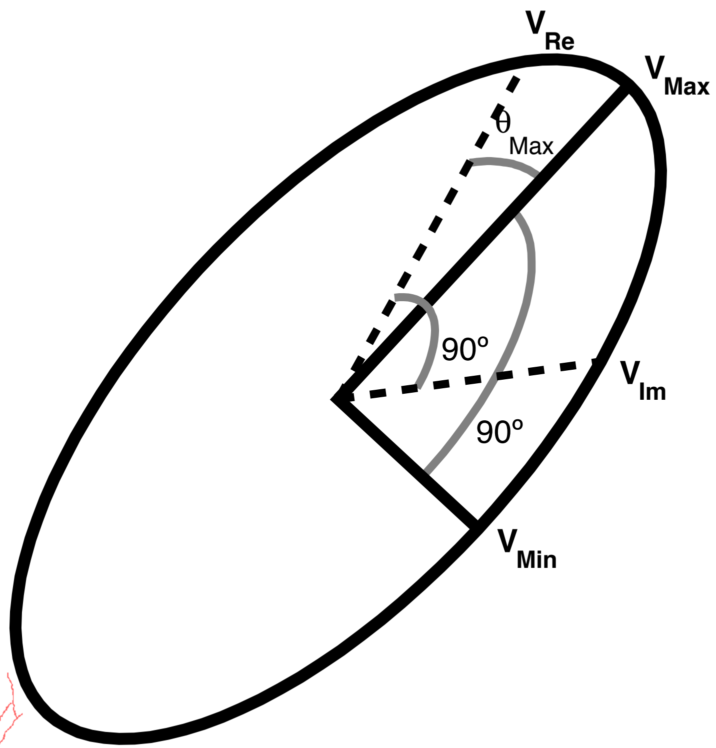


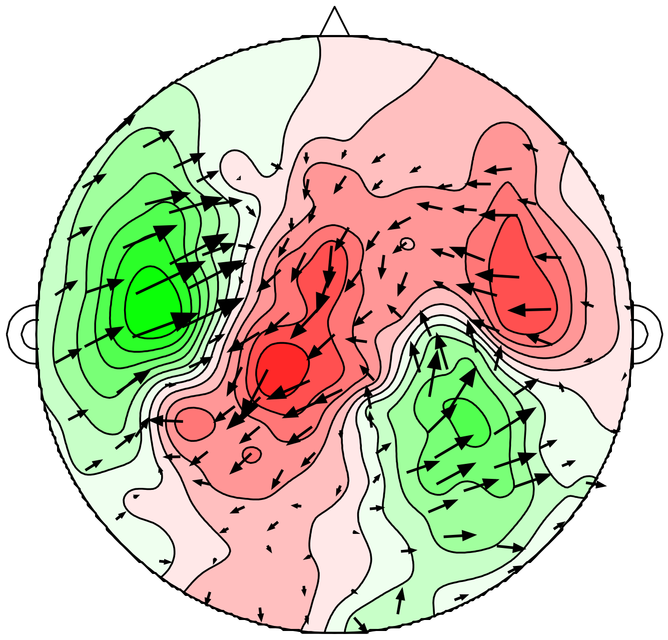


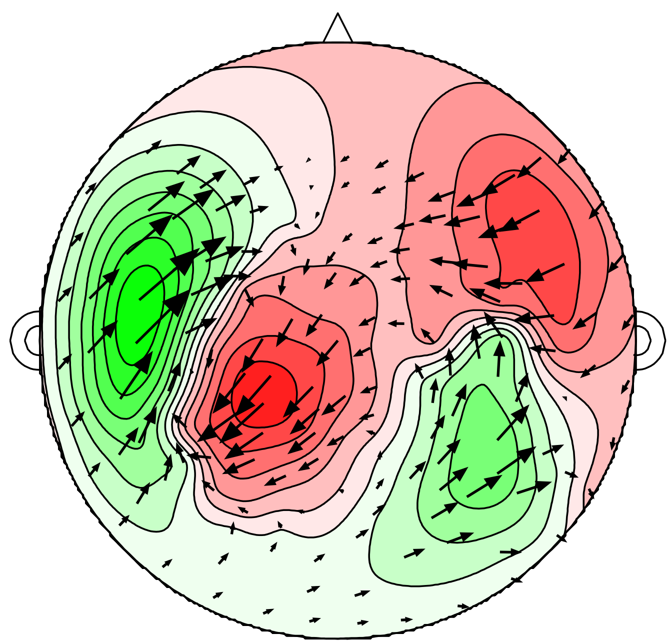
Complex Neural Current Sources

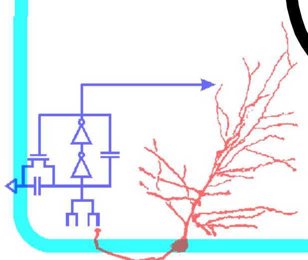
$$\vec{V} = \vec{V}_{Re} + j\,\vec{V}_{Im}$$

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

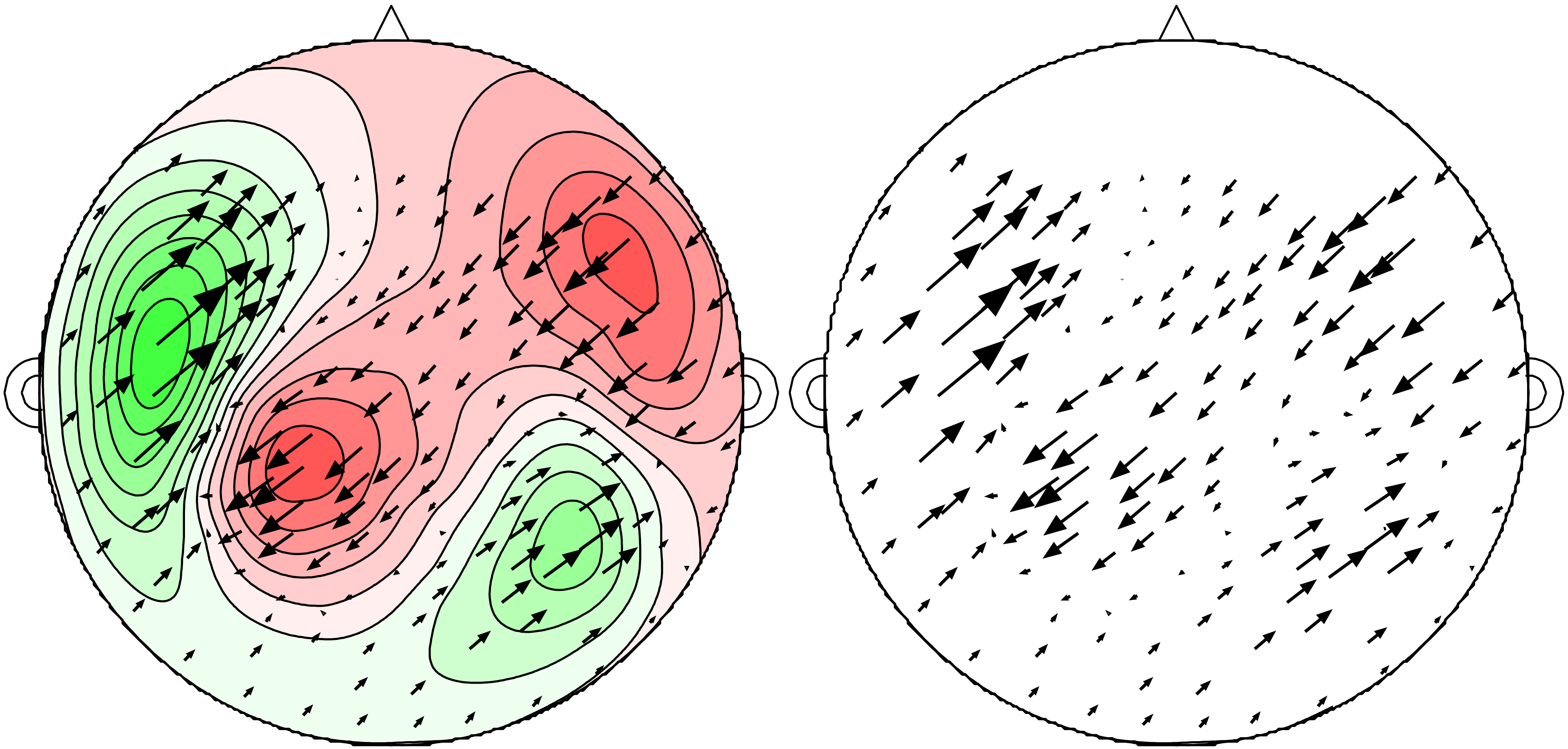


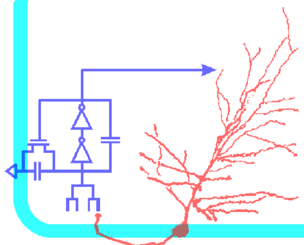






Single Orientation Current Sources





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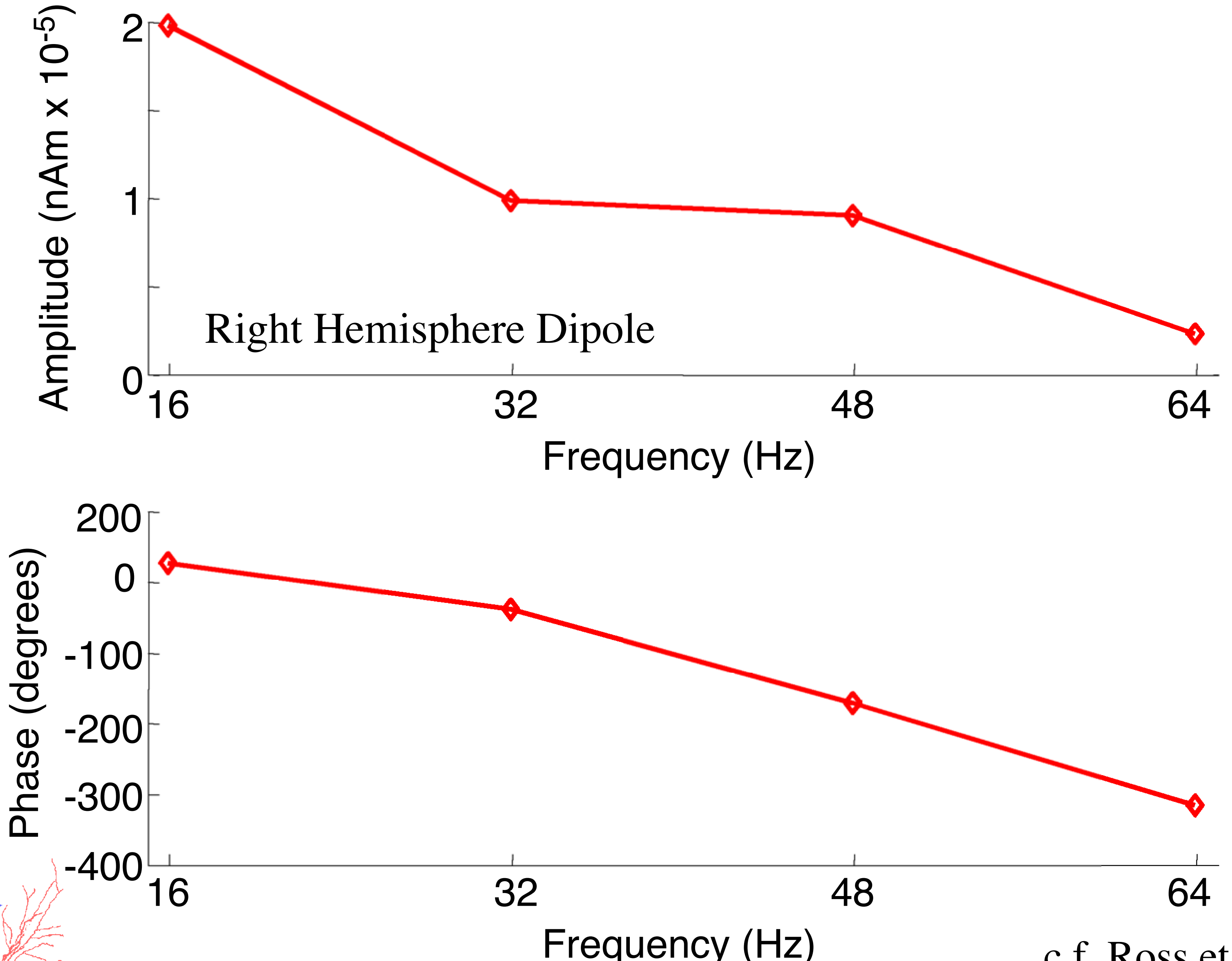
Neural Modulation Transfer Function



c.f. Ross et al. (2000)

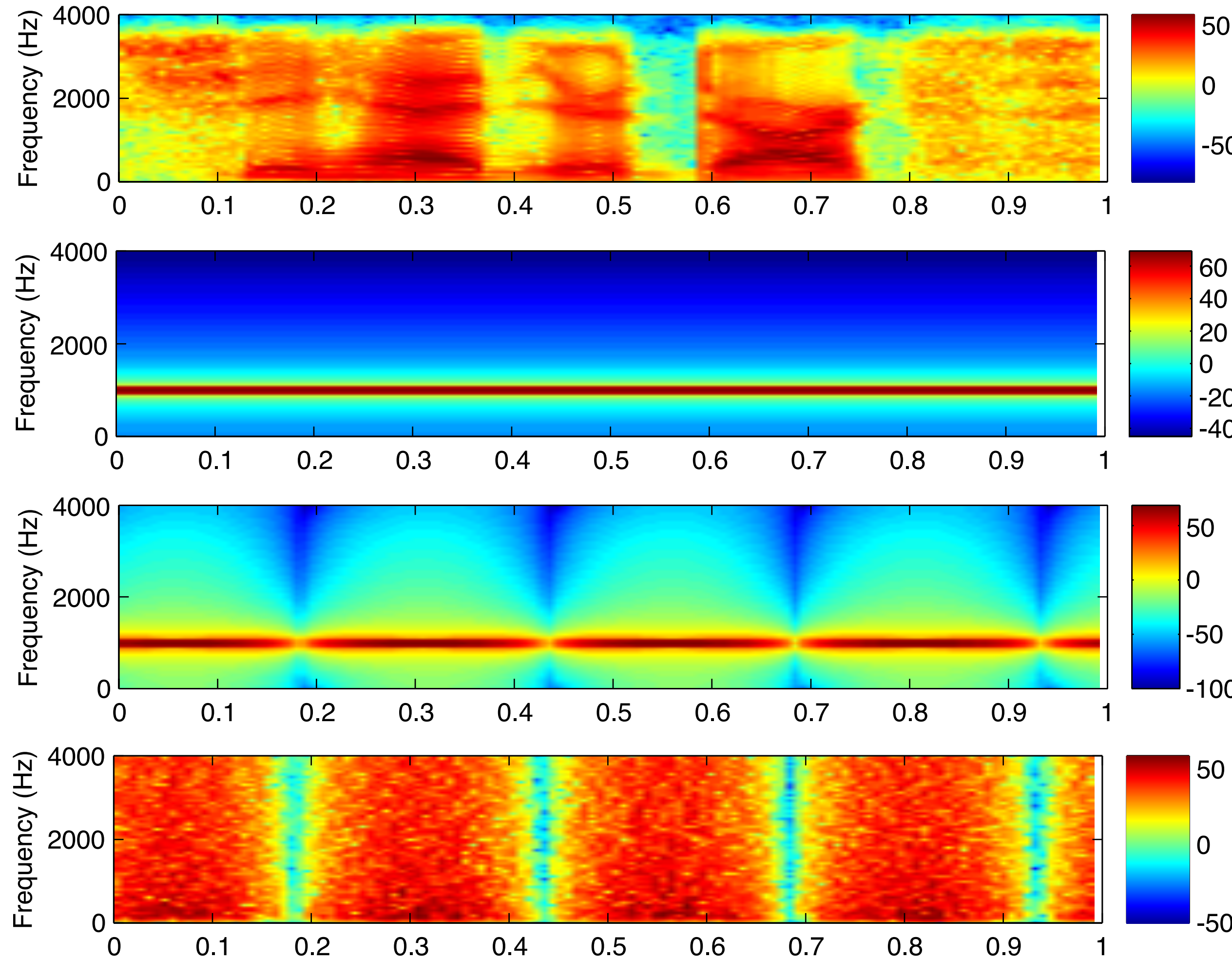
The Dilemma of Complex Stimuli

Speech

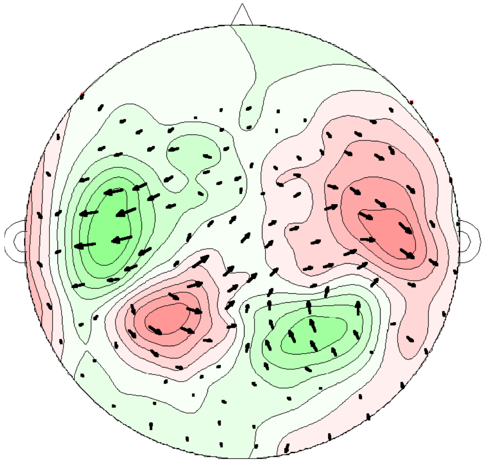
Pure Tone

Modulated Pure Tone

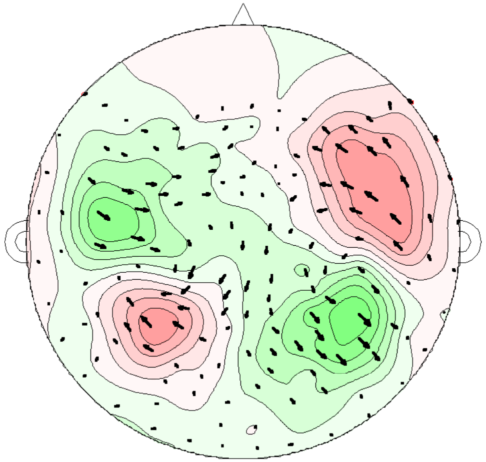
Modulated Broadband Noise



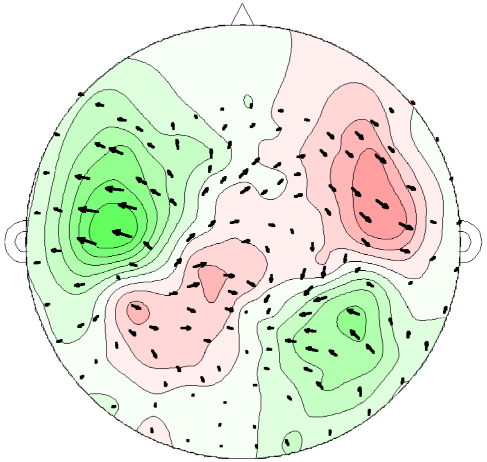
SSR as Function of Bandwidth



Tone



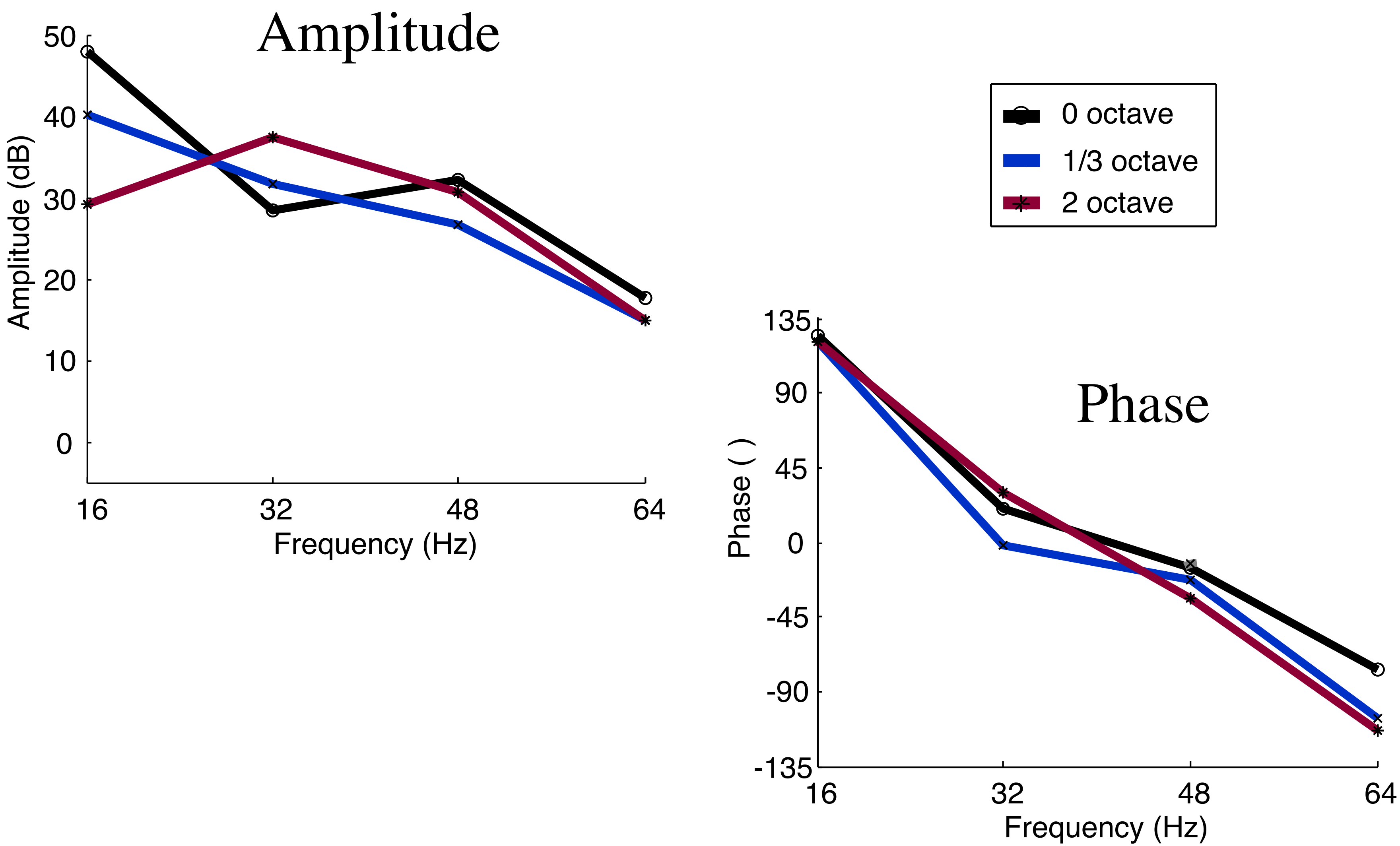
1/3 Octave Noise



2 Octave Noise

32 Hz Modulation

Multiple Transfer Functions



Stimuli Revisited

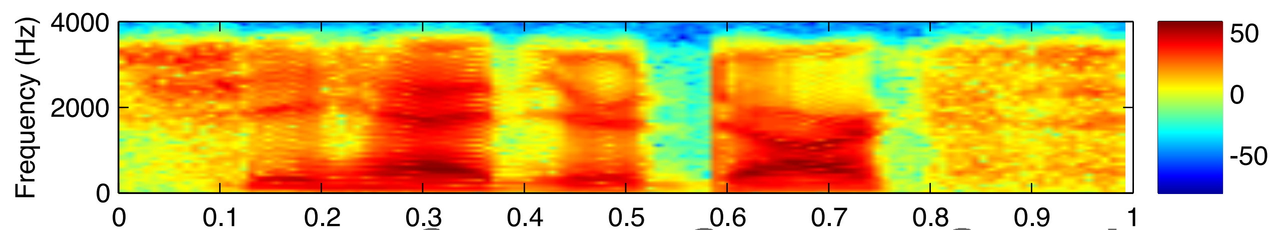
- Multiple Bandwidths: 0 to 5 octaves
- Low Modulation Frequencies: 2 to 32 Hz

  Natural Sounds (e.g. speech)

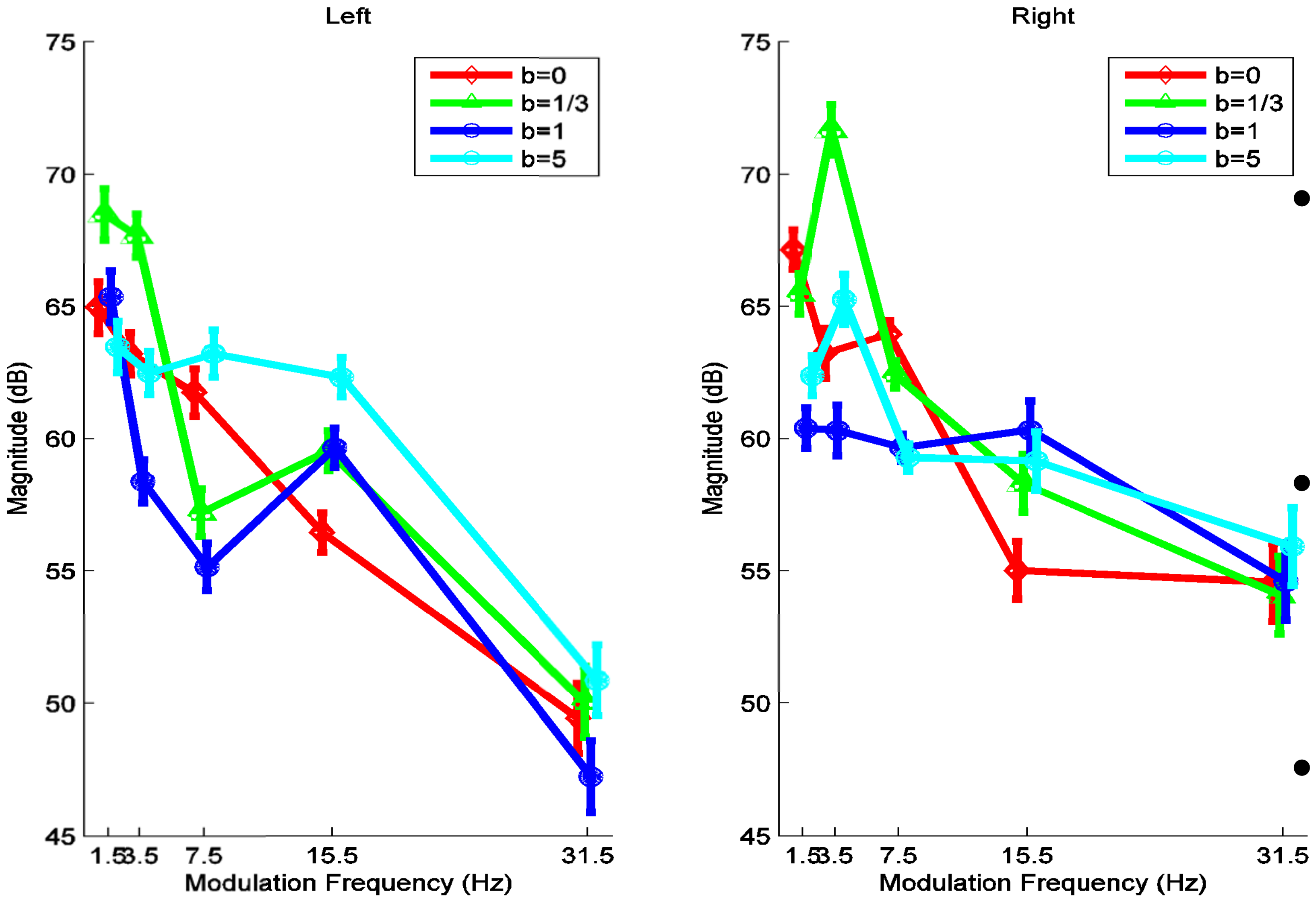
  Intracranial Recordings from Human Auditory Cortex find peaks at 4-8 Hz in Liégeois-Chauvel et al. (2004).

- SSR vs. "Continuous Onsets"?

  Evidence of significant (~30%) linearity to ***envelope of speech*** from Ahissar et al. (2001).



Low Frequency Transfer Functions



- Differences between Bandwidths Not Significant
- Increasing Response at Decreasing Frequencies
- Hemispheric Differences

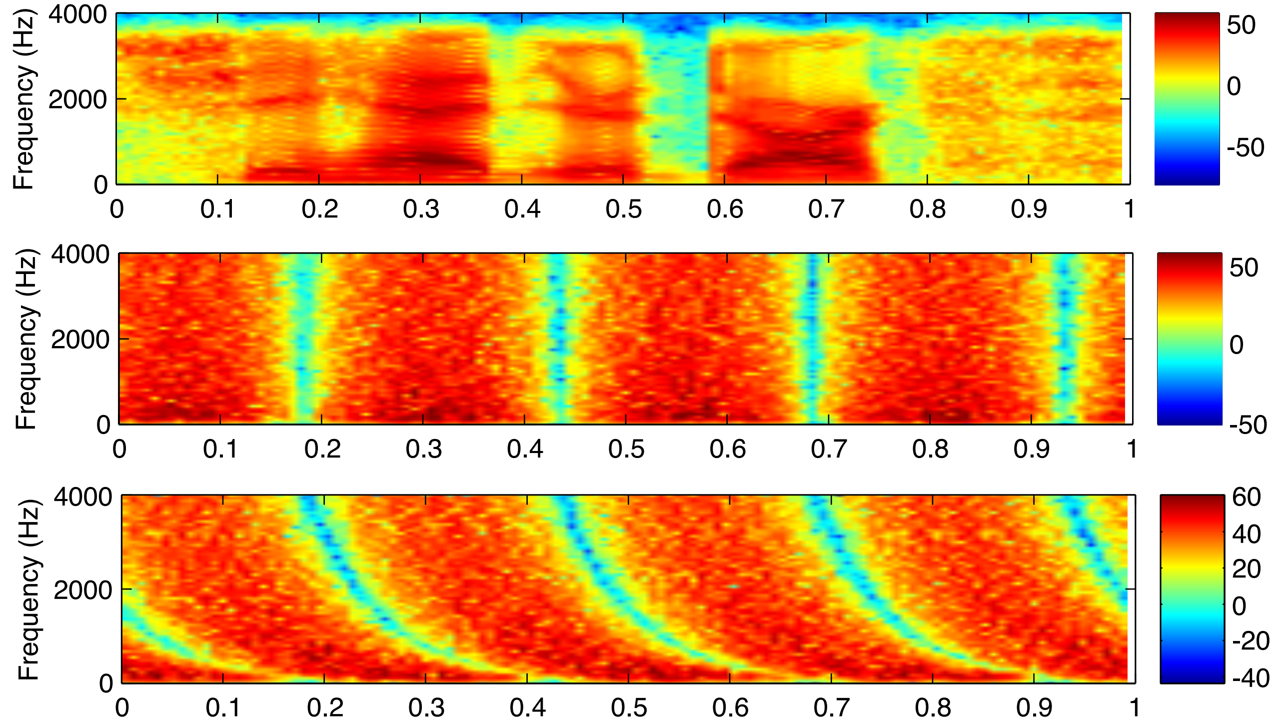
12 Subjects

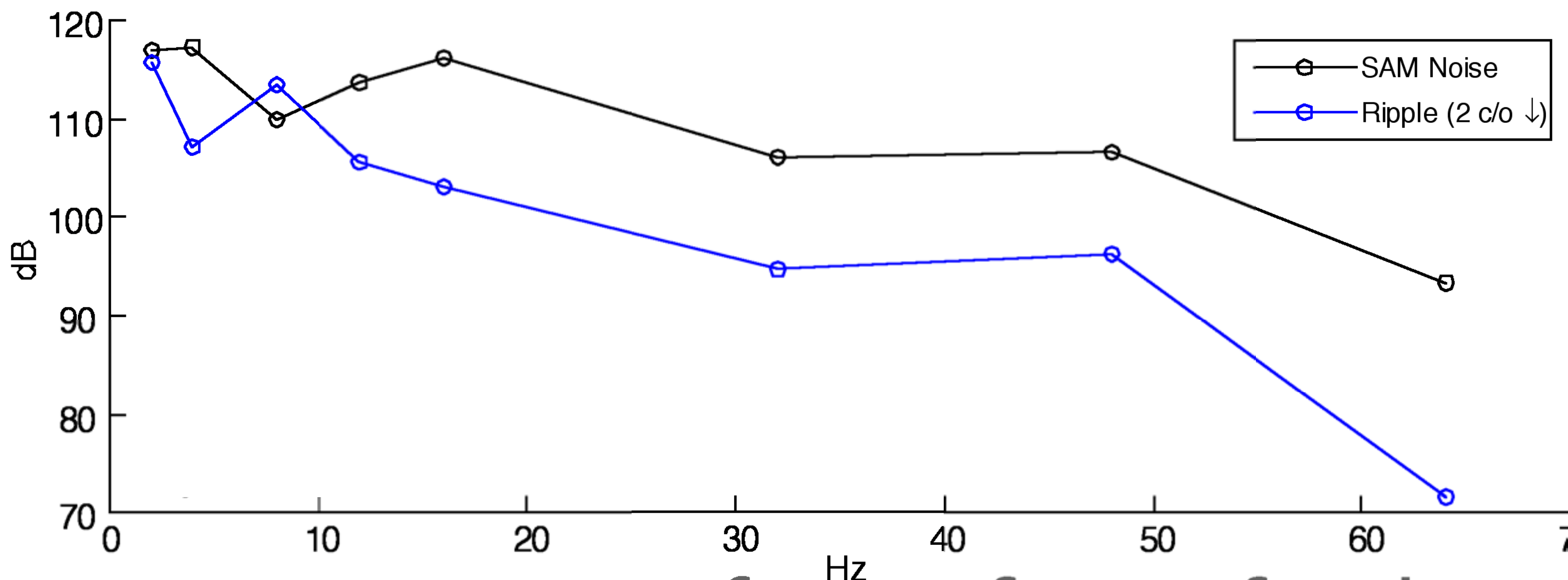
Next on "To Do" List

Speech

Modulated Broadband Noise

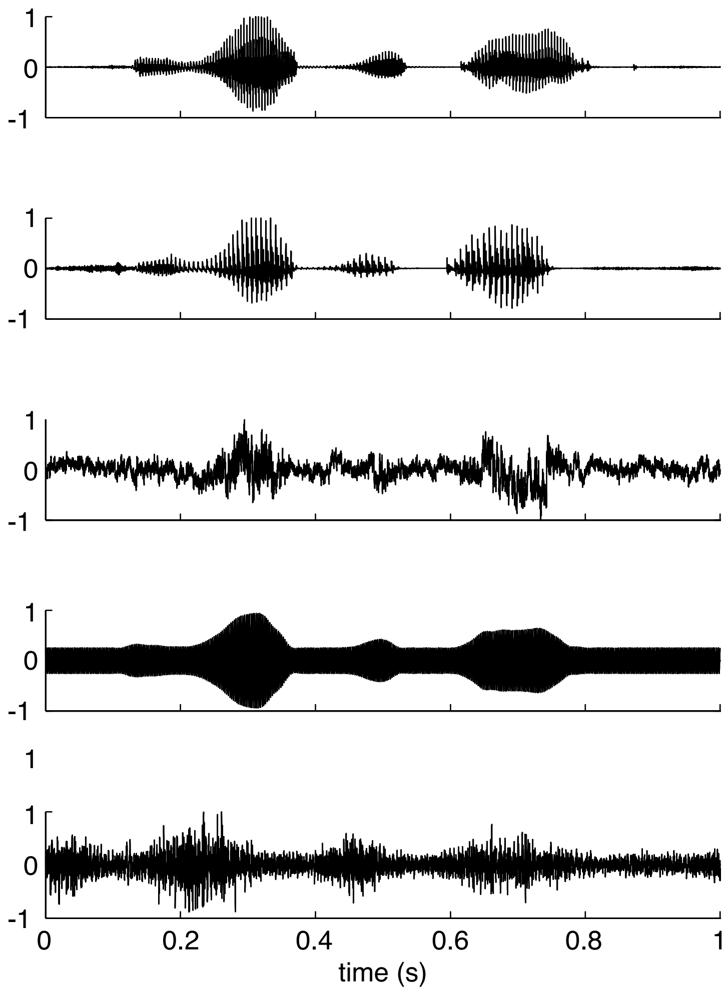
Auditory Ripple



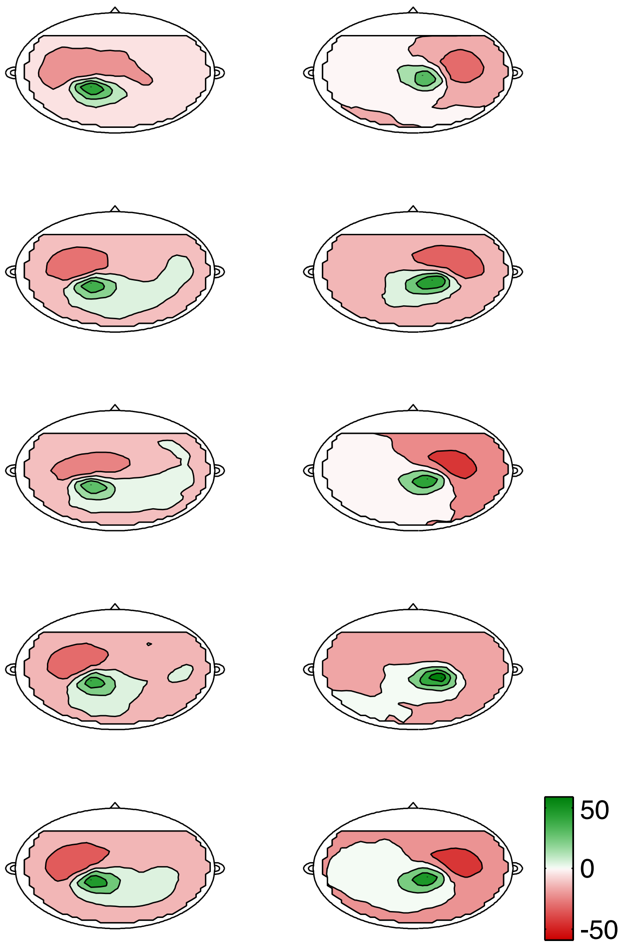


Related Project: Speech + ICA

Speech & Speech-like Stimuli

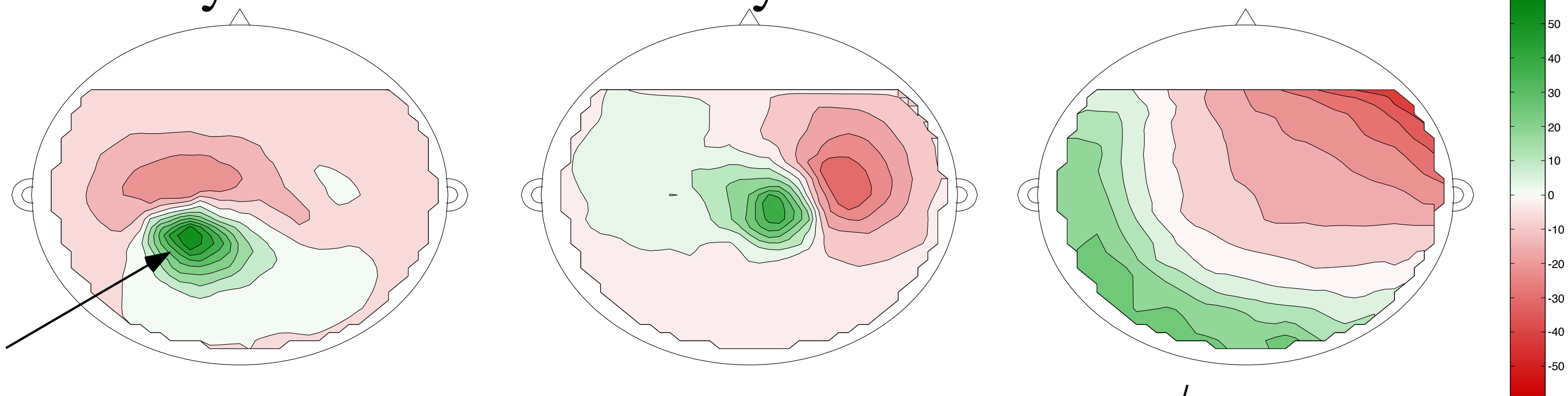


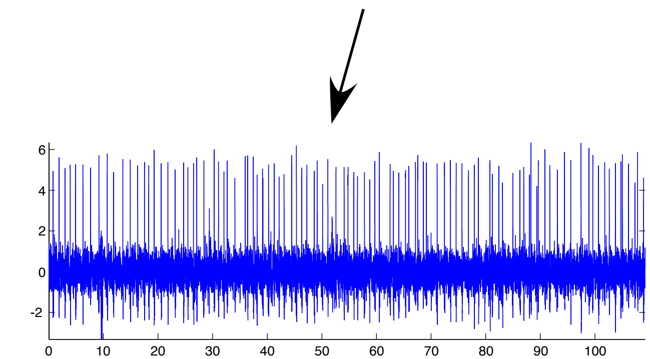
Auditory Independent Component Responses

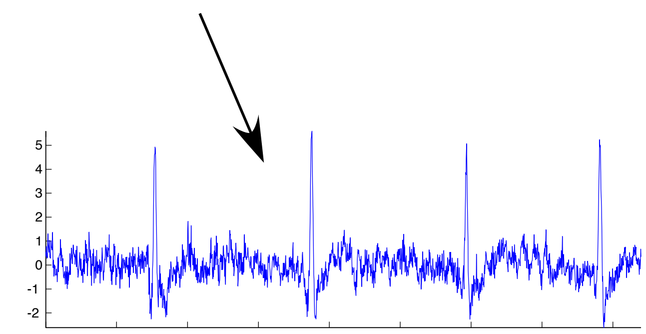


Independent Component Analysis

Left Auditory Cortex | Right Auditory Cortex | Heartbeat







ICA finds:

Independent Neural Sources in *Auditory* areas

Independent Neural Sources in *non-Auditory* areas

Independent non-Neural Sources

Summary

- Magnetoencephalography (MEG)
  - Directly generated by neural currents
  - Excellent time/frequency resolution
  - Spatial Localizability an open question
- Whole Head SSR
  - Spatial Phase Coherence
  - Complex Dipoles
  - Dipole Modulation Transfer Functions
  - Complementary to Time Based Methods (e.g. Speech with ICA)

Thank You