Signal Processing of Auditory Responses from Magnetoencephalography (MEG)

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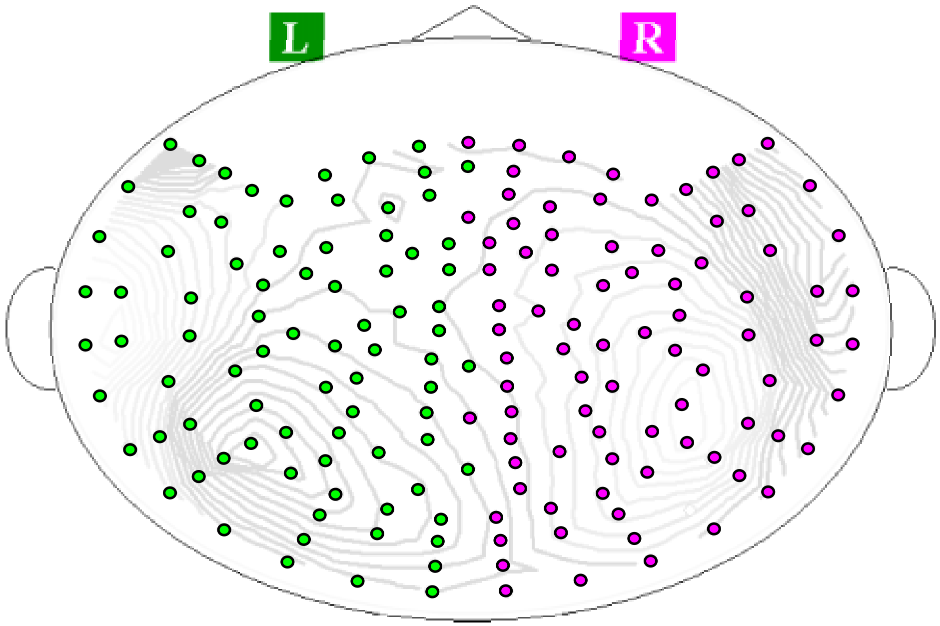

Computational Sensorimotor Systems Laboratory

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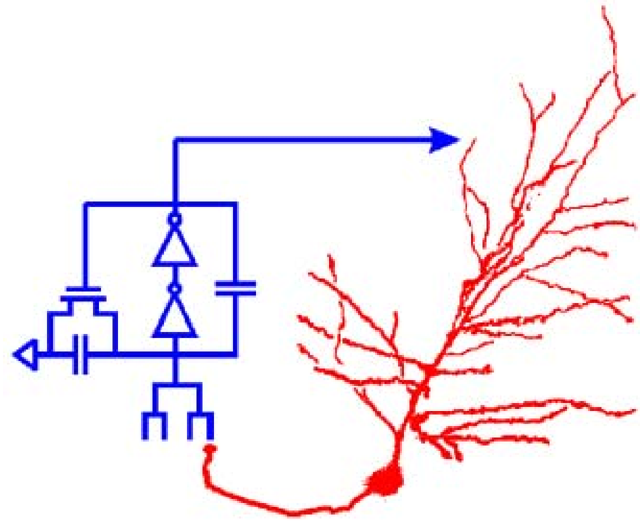

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Special Thanks
Shihab Shamma
Tony Owens

Outline

- Introduction to MEG
- Auditory MEG Signals
- Independent Component Analysis (ICA)
- Ripple Stimuli & ICA with EEG
- Spectral/Frequency Methods

Functional Imaging

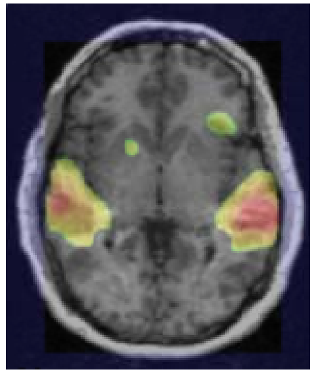
Non-invasive recording from human brain (Functional brain imaging)

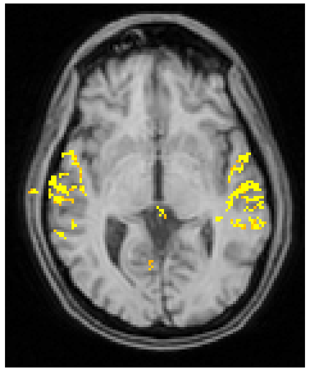
Hemodynamic techniques

Positron emission tomography
PET

Functional magnetic resonance imaging
fMRI

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



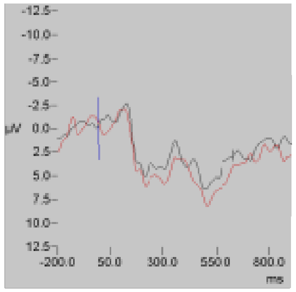


PET, EEG require across-subject averaging

fMRI and MEG can capture effects in single subjects

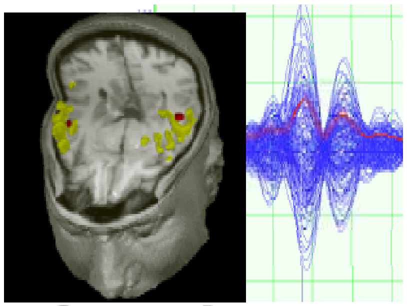
Electromagnetic techniques

Electroencephalography
EEG

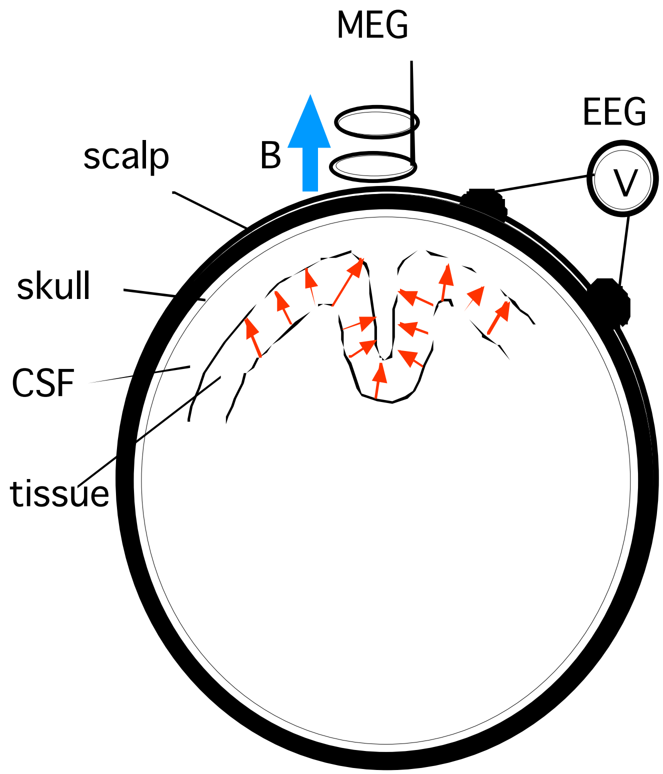


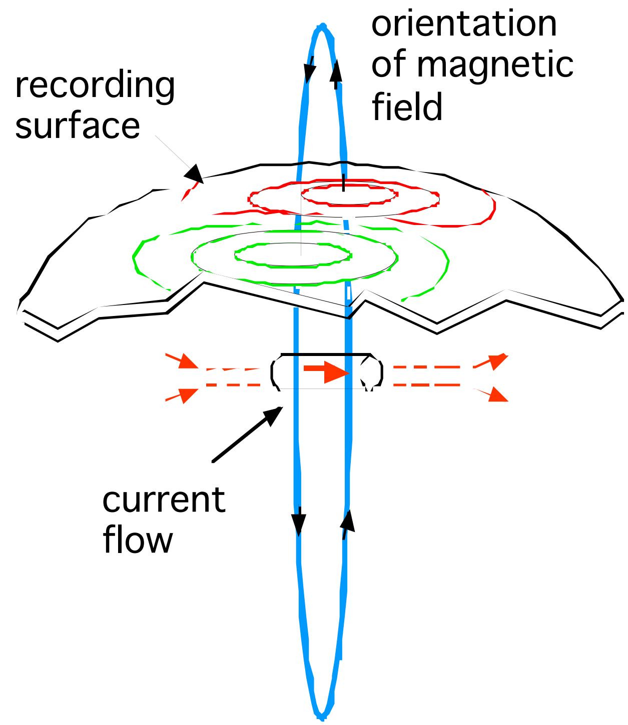
Poor spatial resolution
(~ 1 cm)
Excellent *temporal resolution*
(< 1 ms)

Magnetoencephalography
MEG



MEG Magnetic Signal

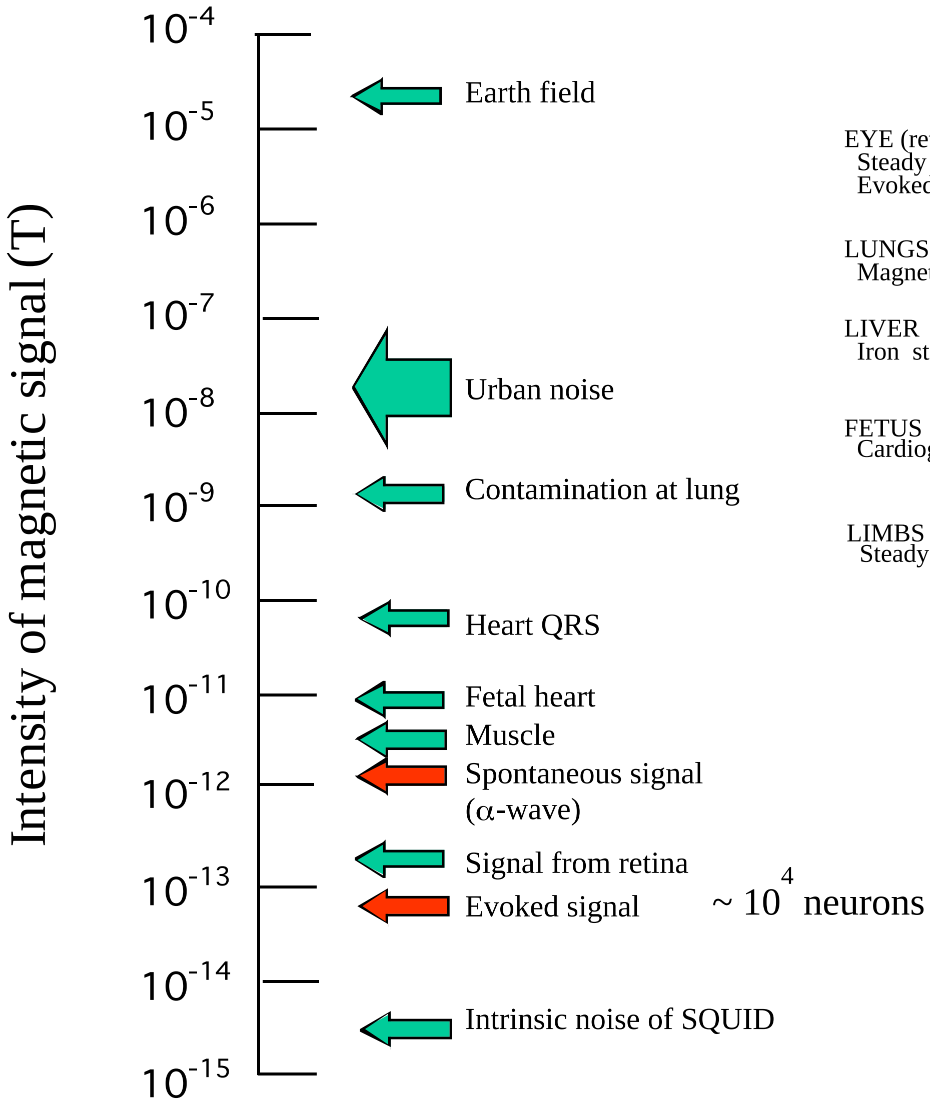


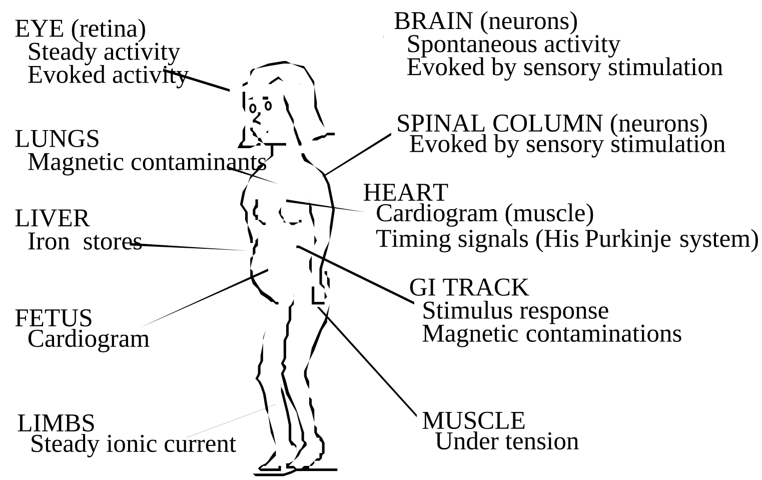


~ 10^4 neurons

Non-invasive measurement
Direct measurement

Magnetic Field Strengths





Biomagnetism

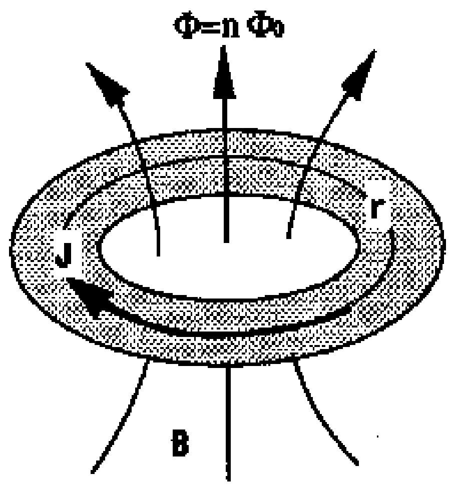
Magnetic Flux Detectors

Superconductivity →

Magnetic flux quantization →

Josephson Effect →

SQUID = Superconducting Quantum Interference Device

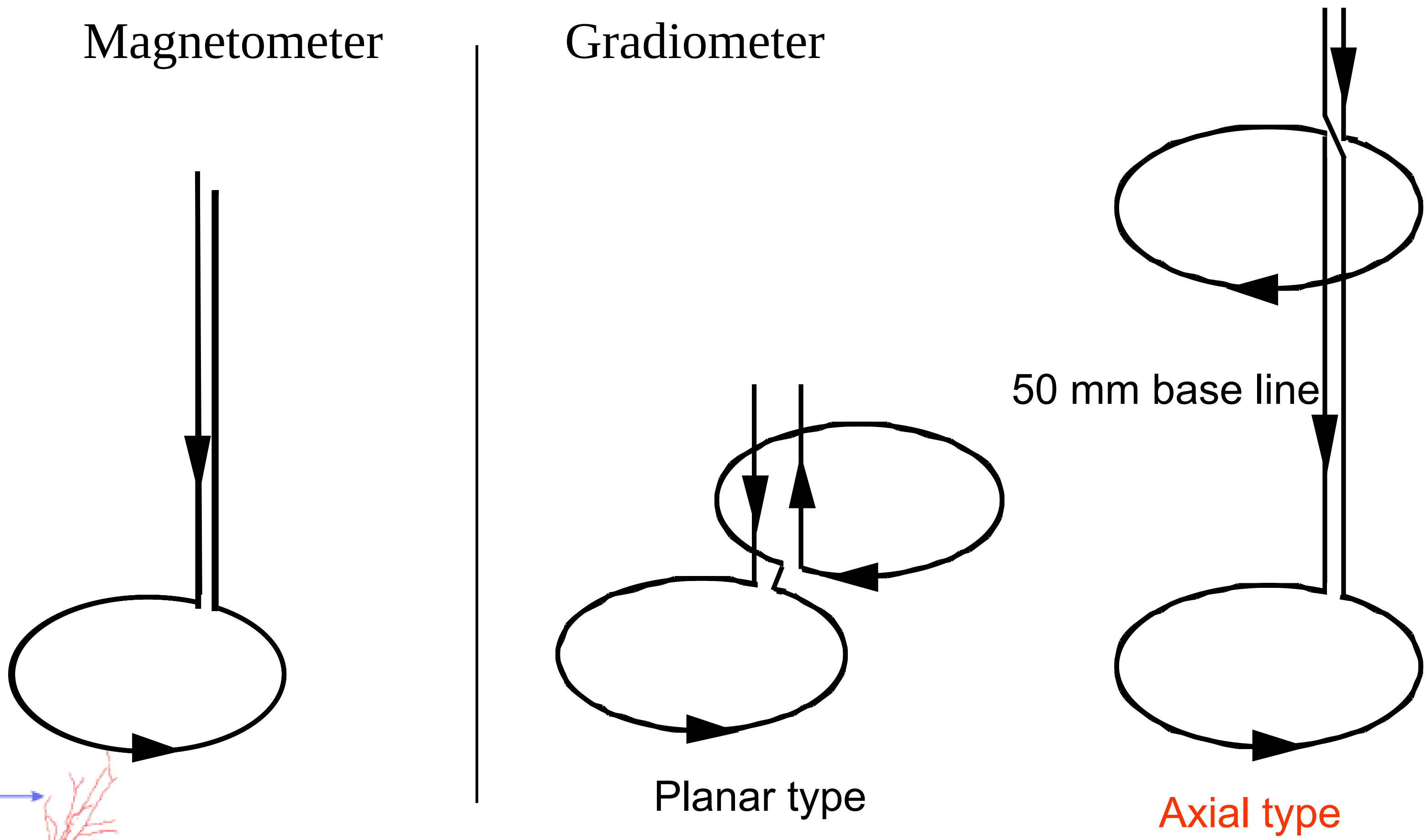


$$\Phi = n \frac{h}{2e} = n\,\Phi_0$$

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

Sensor Configurations

Noise reduction from
Differential measurement



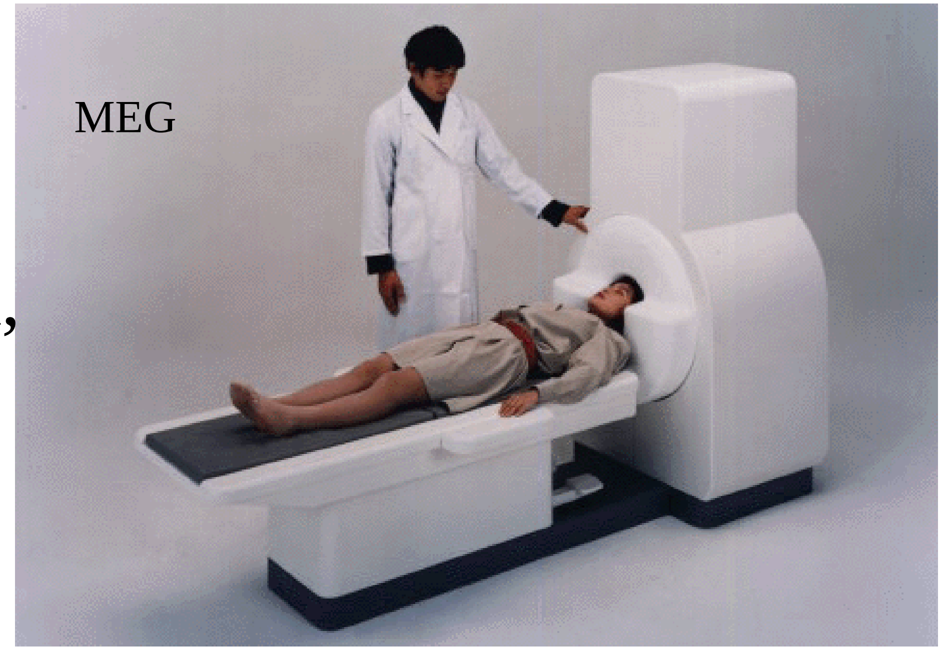
Magnetically Shielded Room

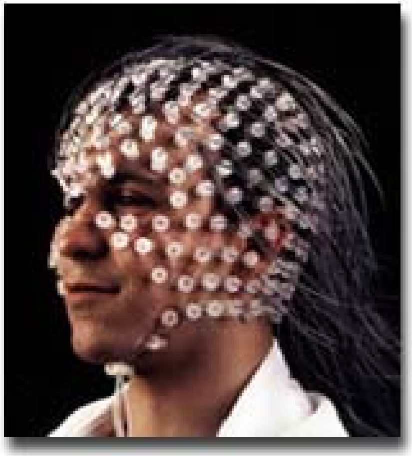
MEG (vs. EEG)

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

Expensive
Inverse problem worse(?)

Complementary Techniques





EEG

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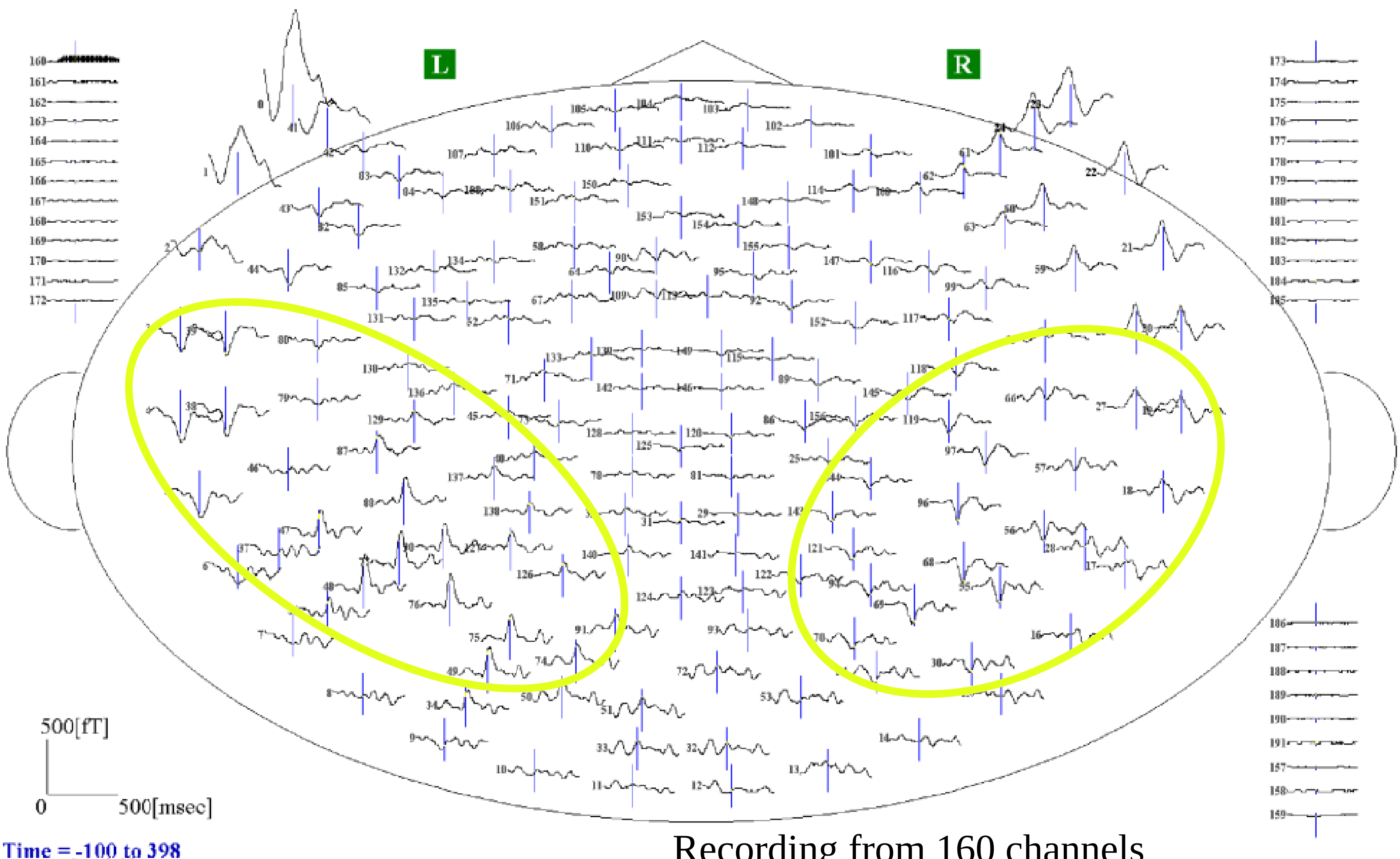
Sensor Layout

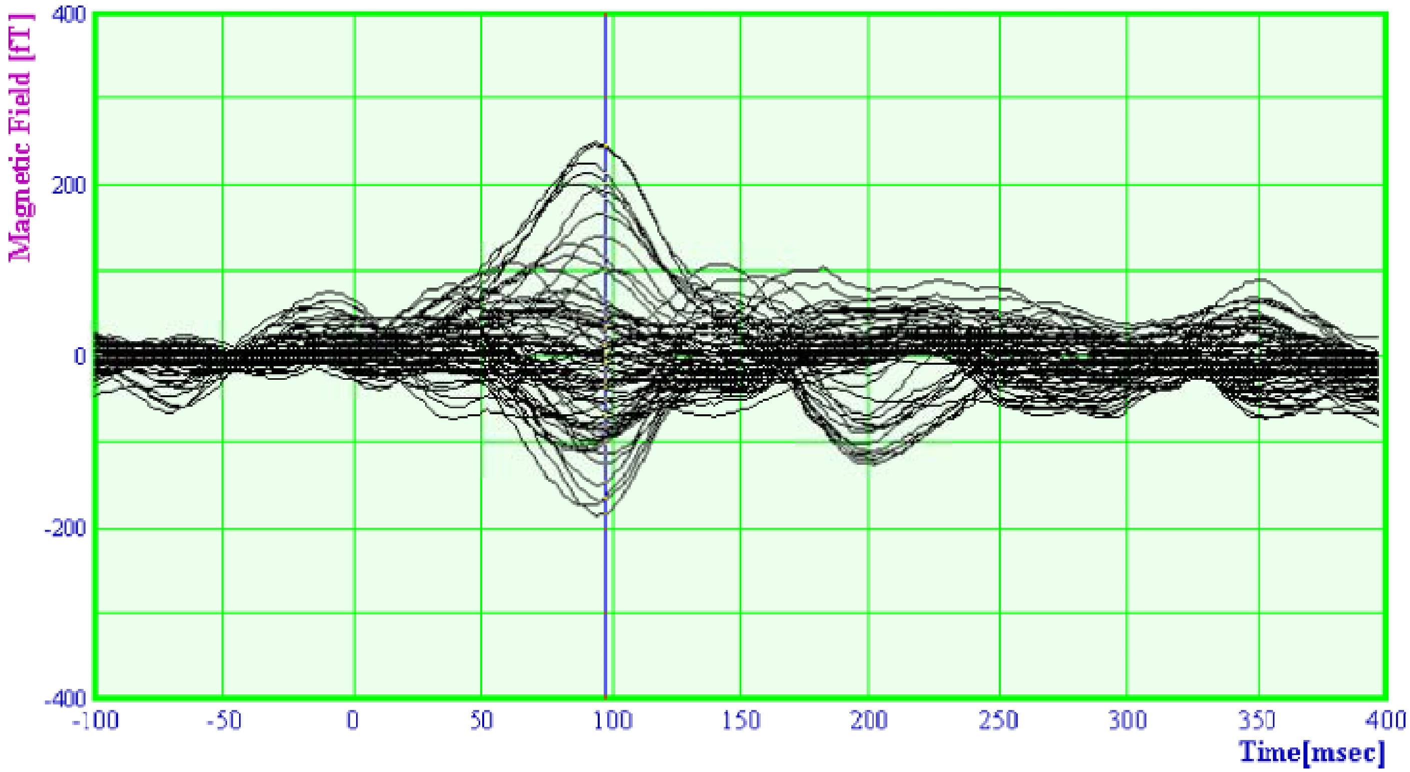


Recording from 160 channels

Response peak at 98 ms after onset of an auditory stimulus, in the left and right temporal lobes.

Butterfly Plot

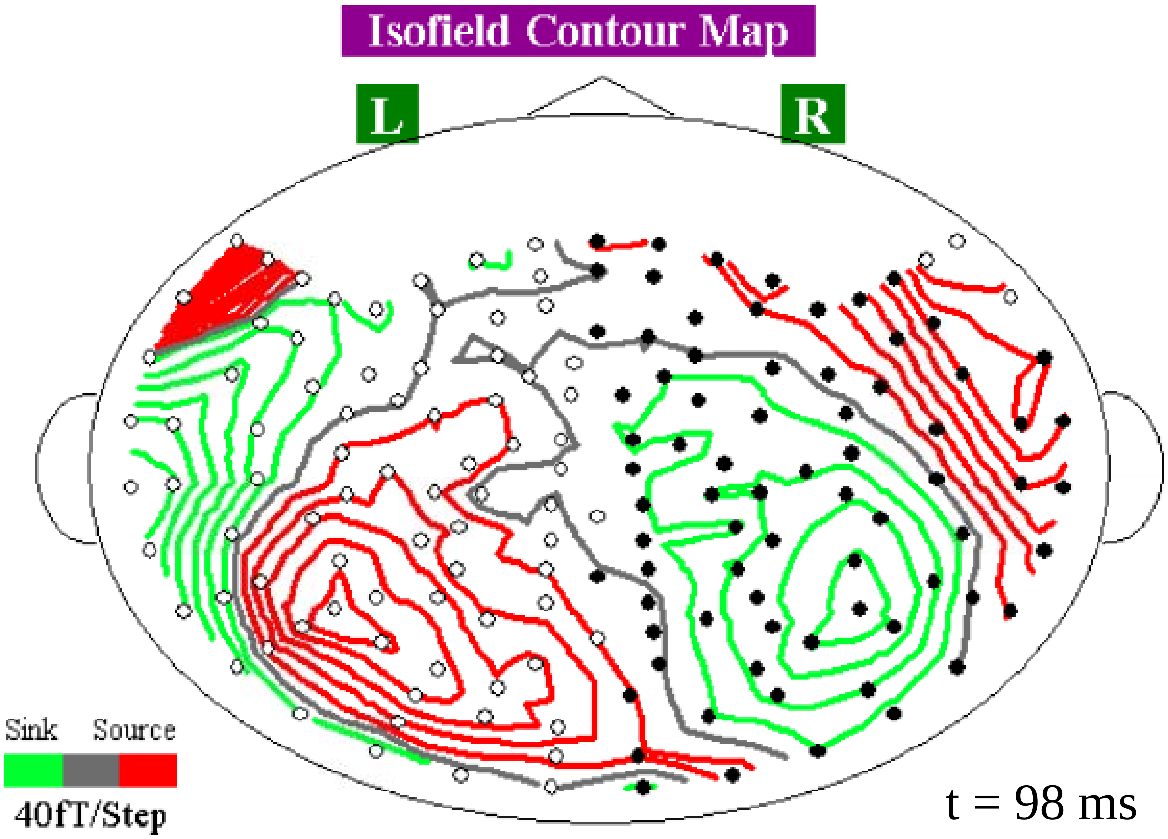
Overlay of all channels above right temporal lobe



Response peak at 98 ms after onset of an auditory stimulus

Contour Plot

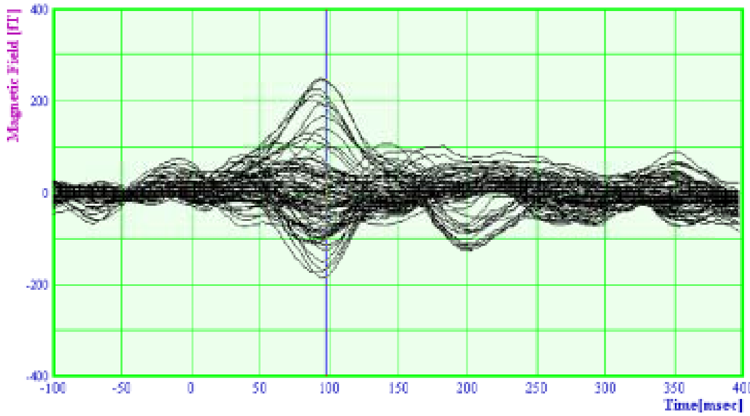
Distribution of magnetic field at peak response

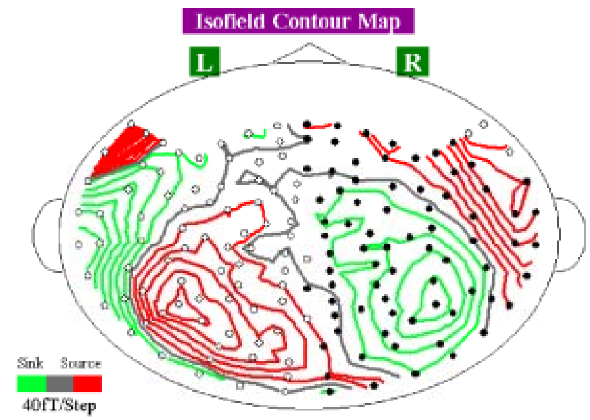


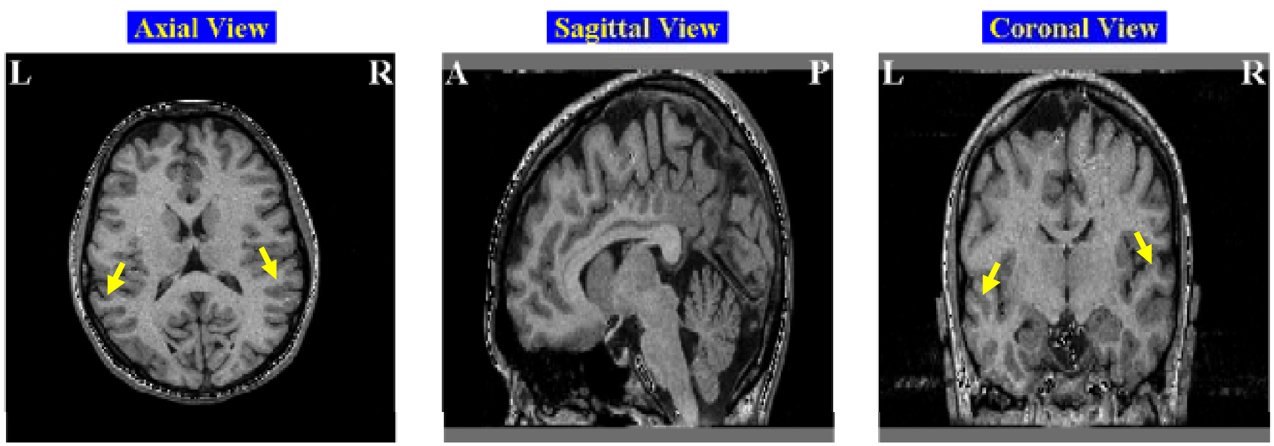
Magnetic Source Imaging

MEG + MRI

Dipole fit at response peak, 98ms after onset of stimulus



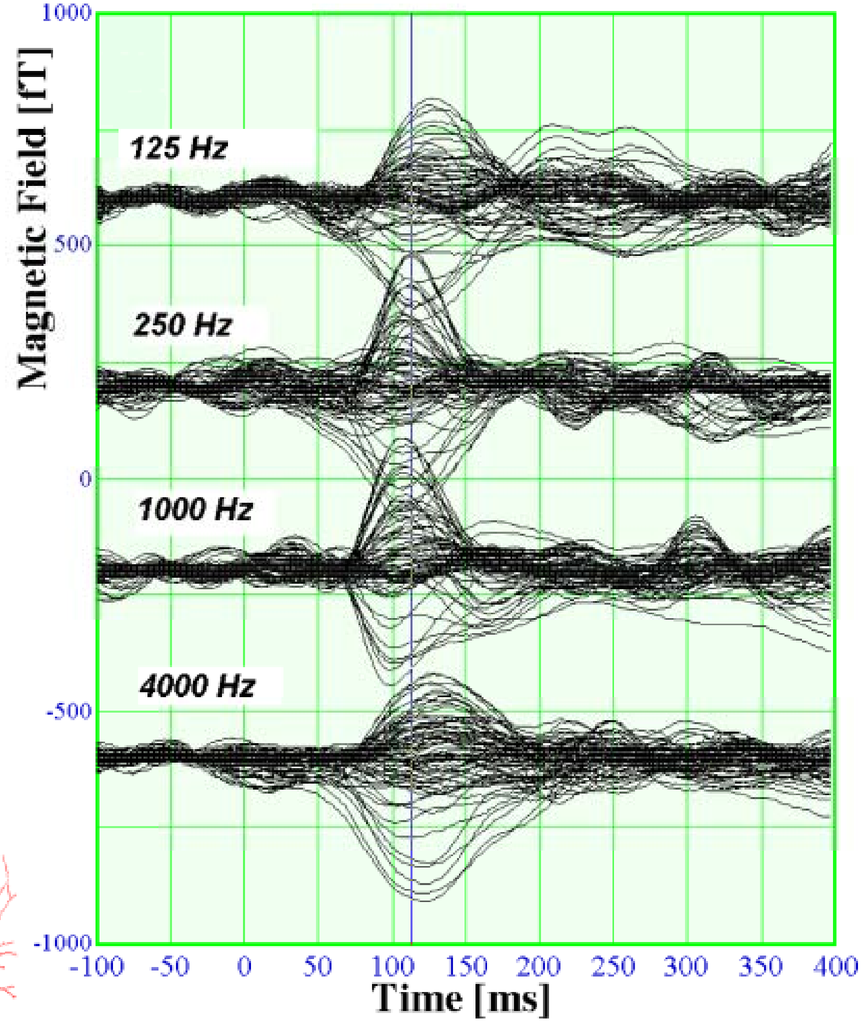




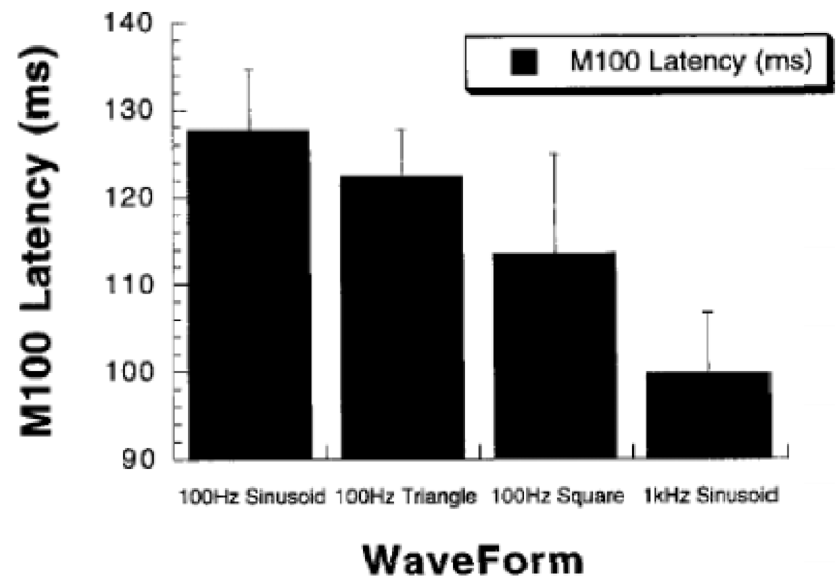
M100 Latency

M100 Peak

Latency decreases with increasing frequency



Latency decreases with increasing harmonics



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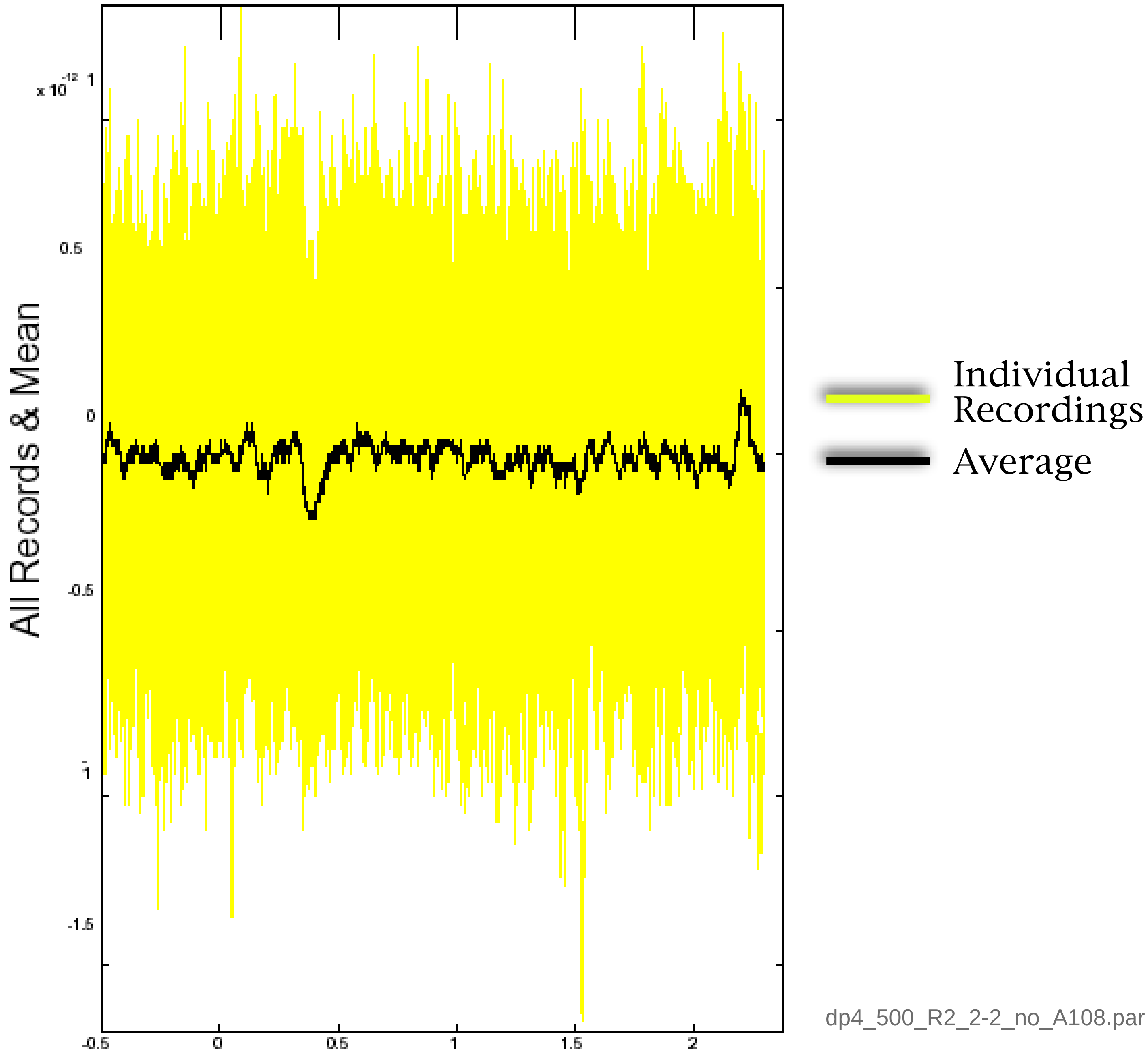
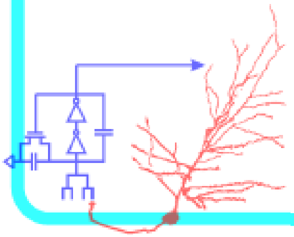
MEG Variability





Beyond Averaging

We should be able to do better
than mean and variance of responses to multiple presentations of one stimulus

Jitter across responses cancel
so we lose variance of latencies

Coherence across channels ignored

Blind Source Separation (BSS)? ICA…

Independent Component Analysis

Independent Component Analysis (ICA)
(1) unmixes the separate sources' activity, and
(2) reduces the information overlap between components

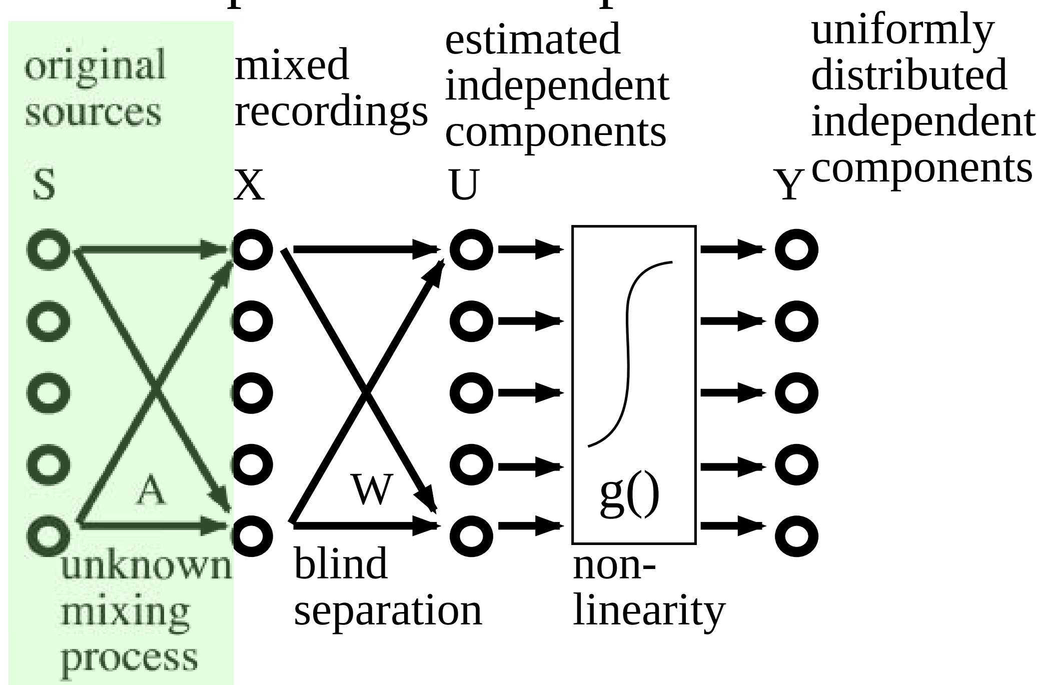
- **Model:**

Instantaneous Linear Mixing

X(t) = A*S(t)

A*W = P*D*I

P: Permutation Matrix
D: Diagonal Scaling Matrix
I: Identity Matrix



- **Method:**

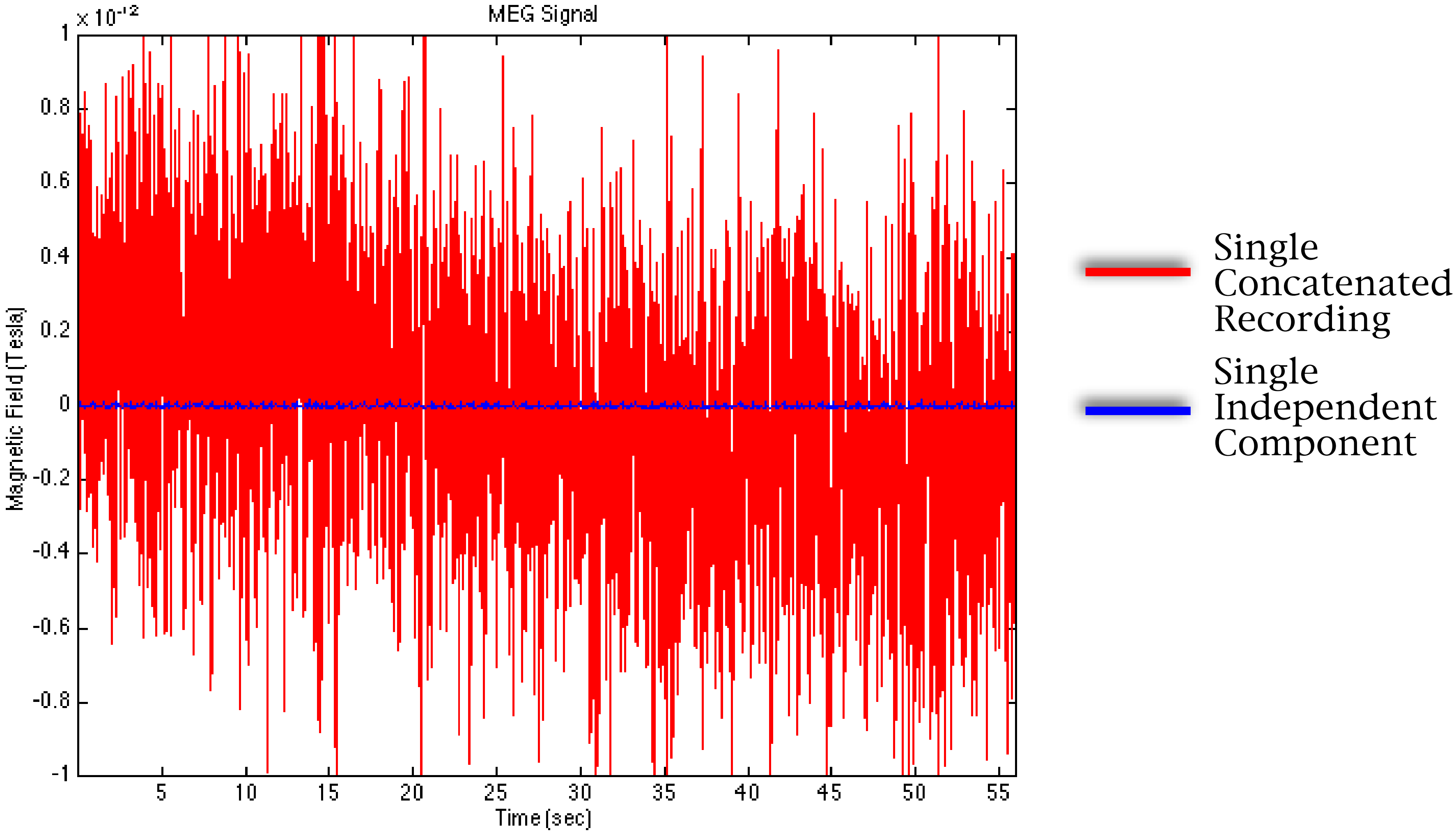
Estimate weights so to maximize output entropy **H(y)** => minimize mutual information **I(y)**

- **Goal:**

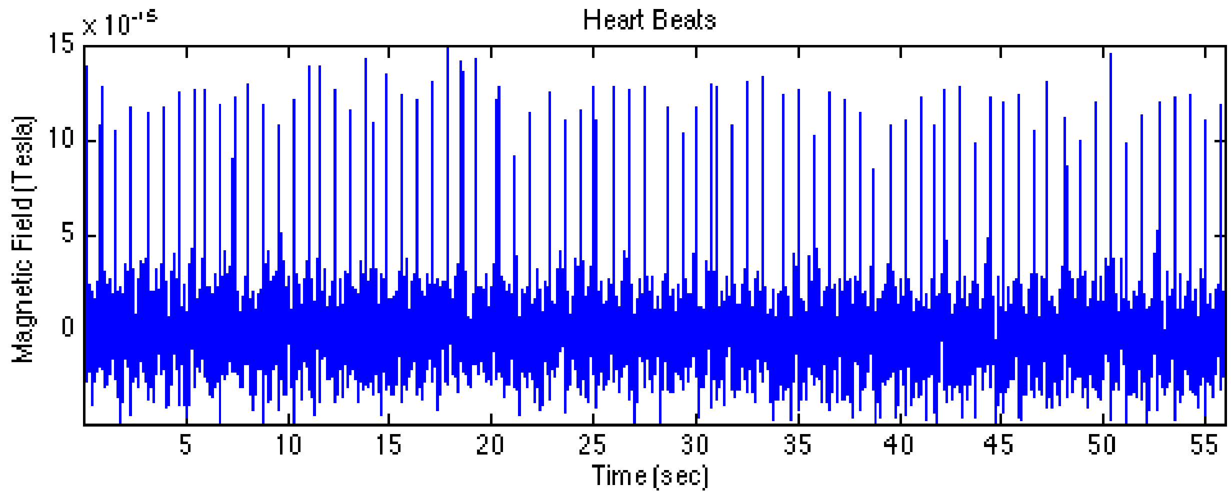
Learned weights approximate inverse of mixing matrix

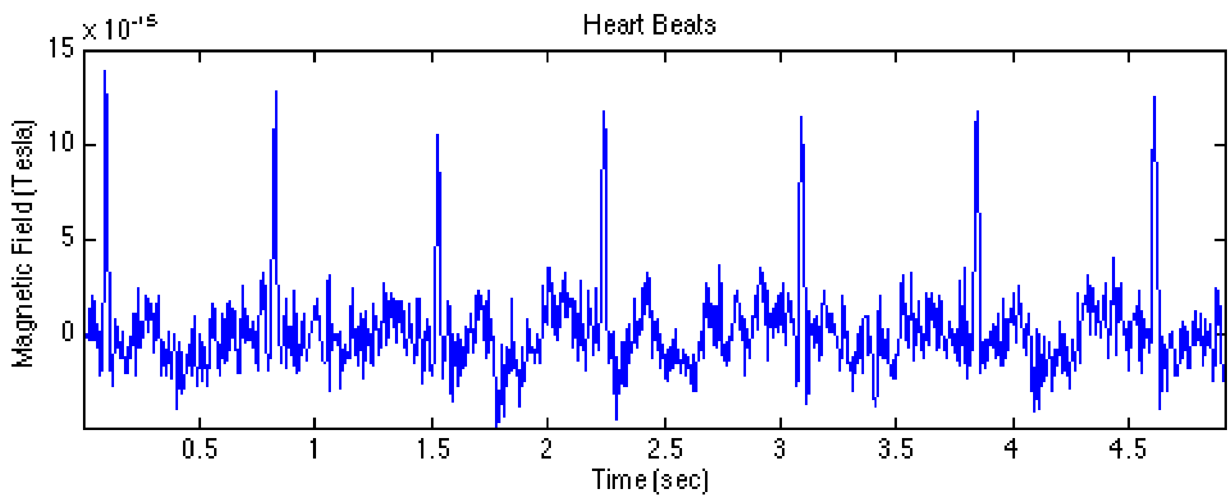
MEG Waveform & ICA

Independent Component Analysis



Independent Component Analysis





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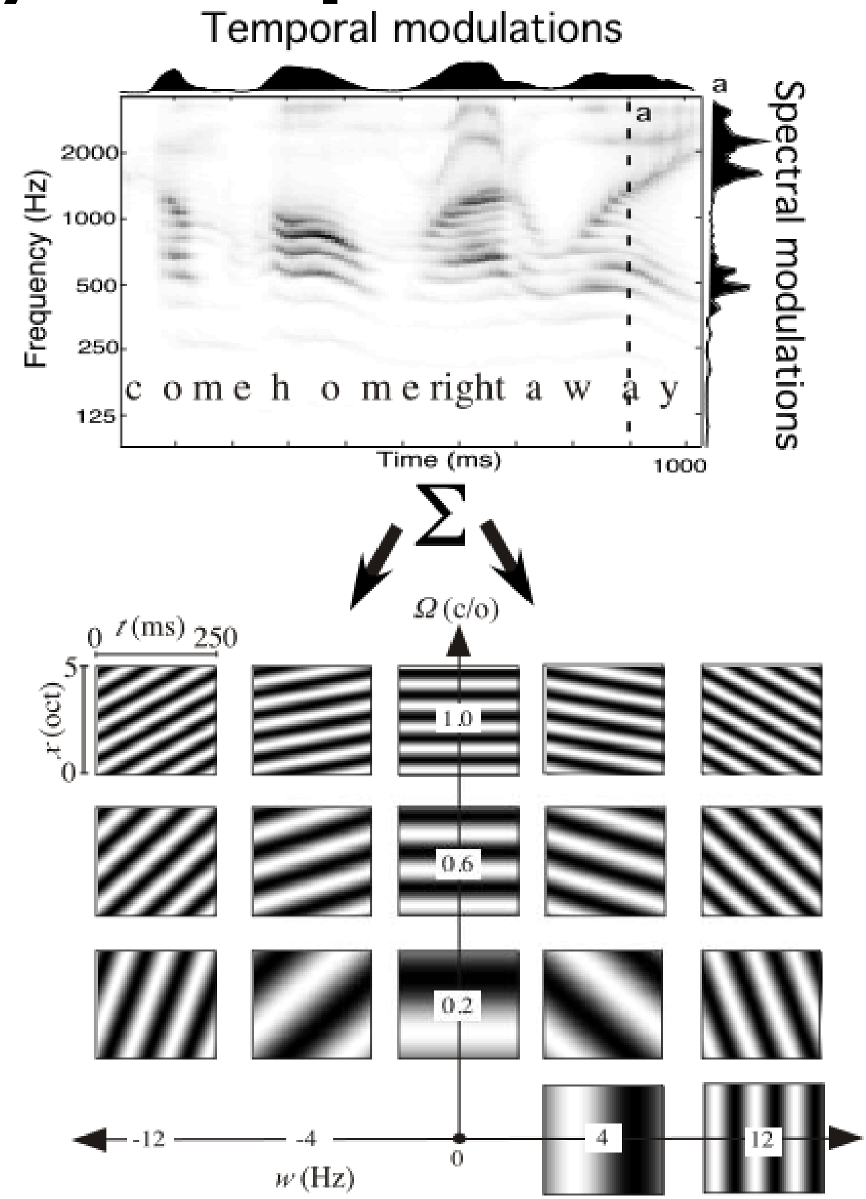
Systems Theory and Speech

- Speech
  - Broadband, Dynamic
  - Spectrotemporally rich
  - Algorithmically complex
- Systems Theory
  - Complex objects can be expressed as sum of simpler objects
- Dynamic Ripples
  - Broadband, Dynamic
  - Spectrotemporally rich
  - Algorithmically *Simple*



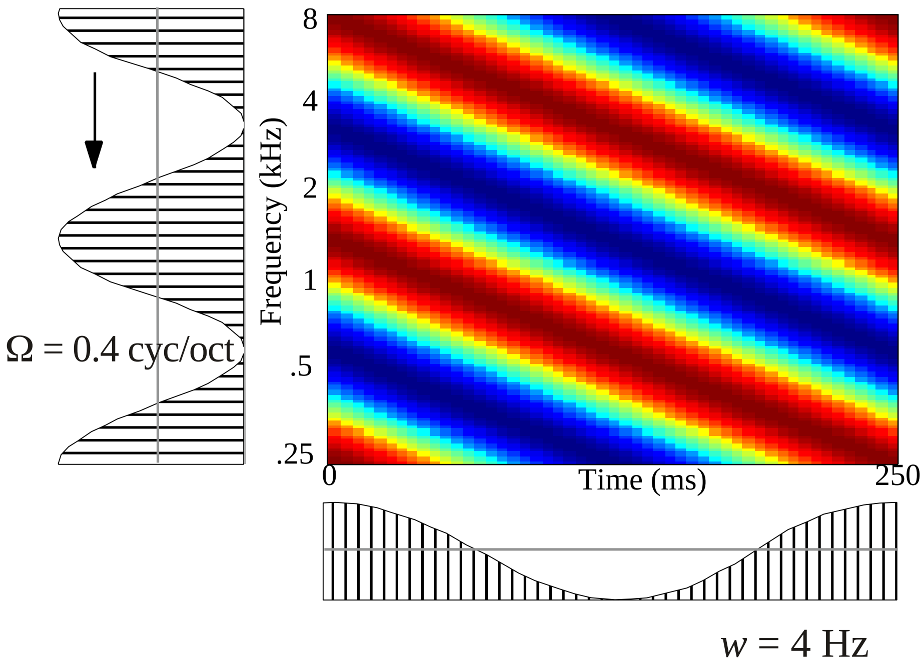
Single Moving Ripple

Simple Spectrally Dynamic Stimulus

$$S(t,x) = \sin(2\pi w t + 2\pi \Omega x + \phi)$$

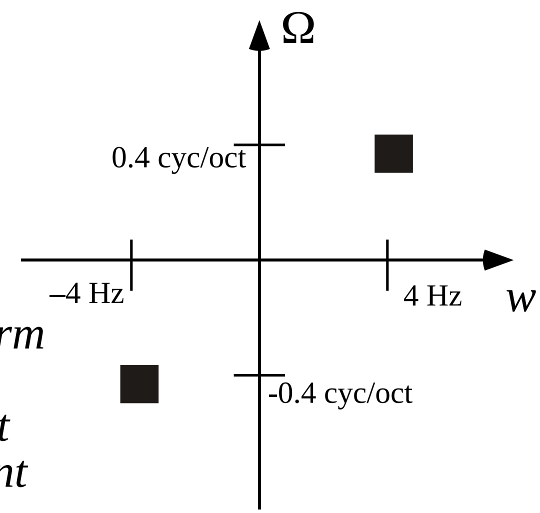
$x = \log_2(f / f_0)$
w = ripple velocity,
e.g. 4 Hz = 4 cycles/s
Ω = ripple density,
e.g. 0.4 cycles/octave
= 2 cycles/5 octaves

Spectro-Temporal representation
(*Spectrogram*)



$\int [.] \exp(\pm 2\pi j \Omega x \pm 2\pi j w t)$

Fourier Space
representation

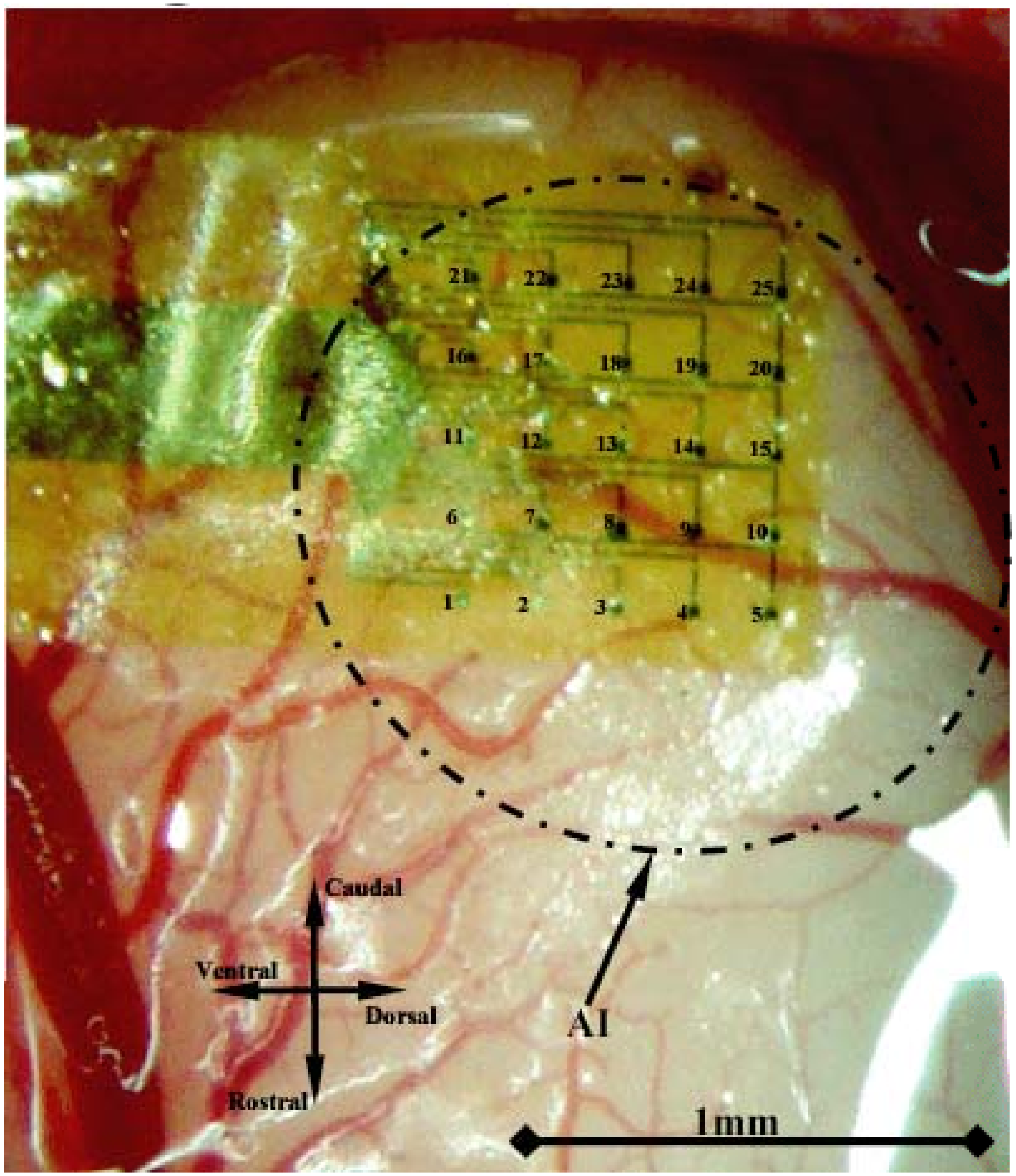


c.f. visual
contrast gratings

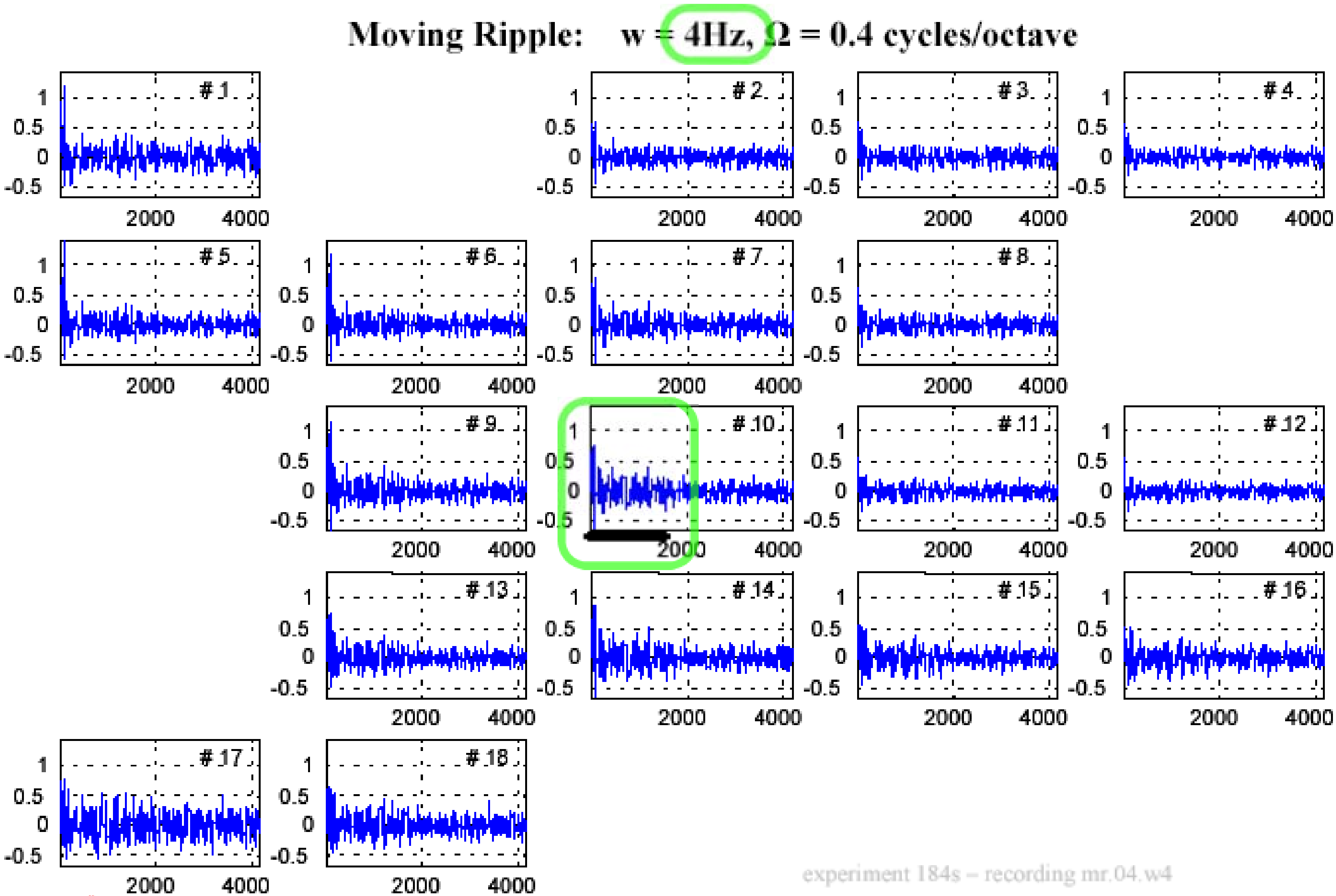
The Fourier transform of a single moving sinusoid has support only on a single point (and its complex conjugate).

Miniature EEG

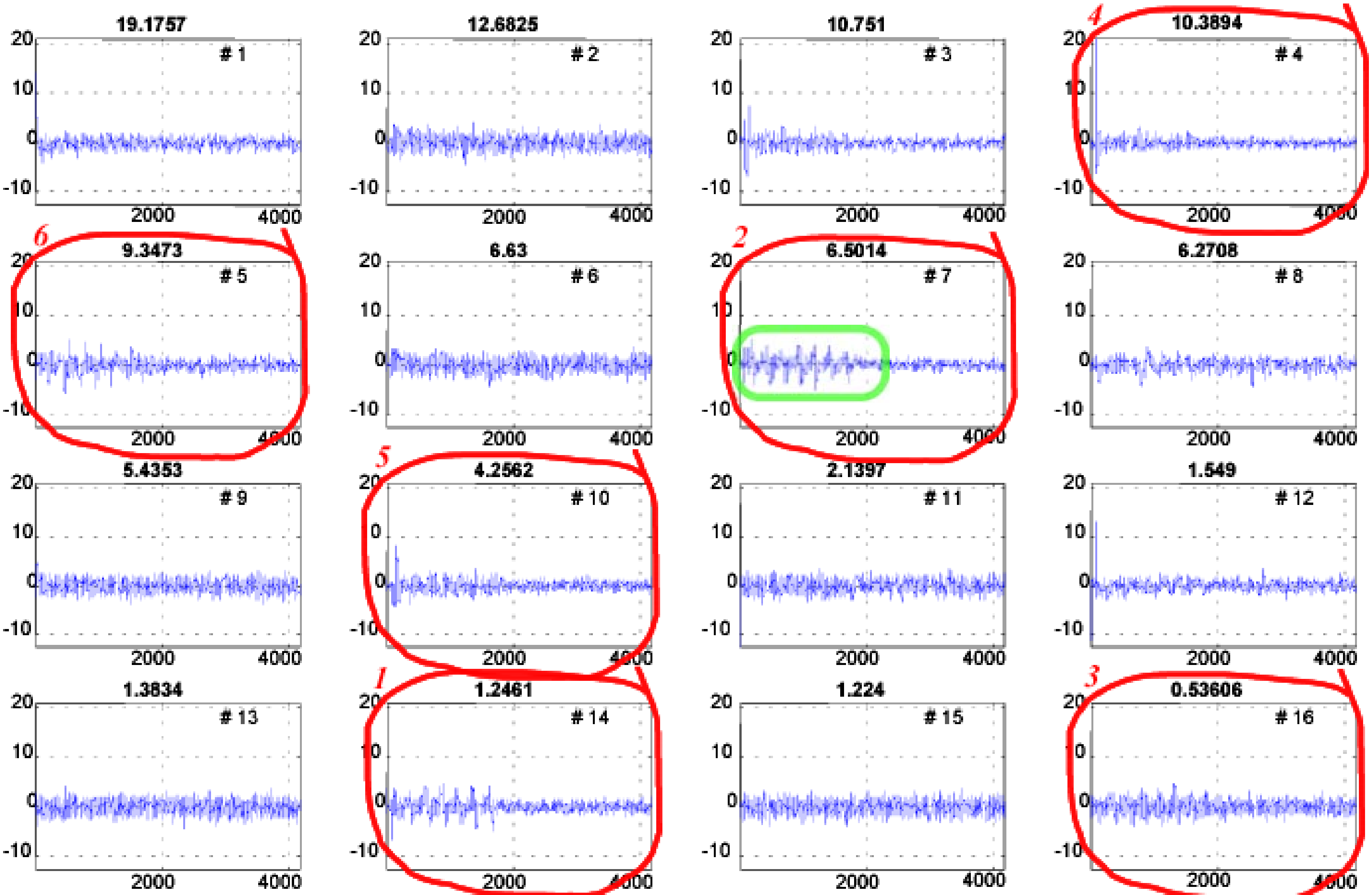
- Thin-film micro-electrode array, developed by Anthony Owens and Shihab Shamma recording Evoked Potentials (EPs).
- 24 gold electrodes ($40x40\mu m^2$) sandwiched between two layers of biocompatible polyimide.
- Rests directly on cortex surface
- Flexible enough to conform to the shape of the cortex
- Simultaneous recording, independent of the state of the animal and the level of anesthesia.



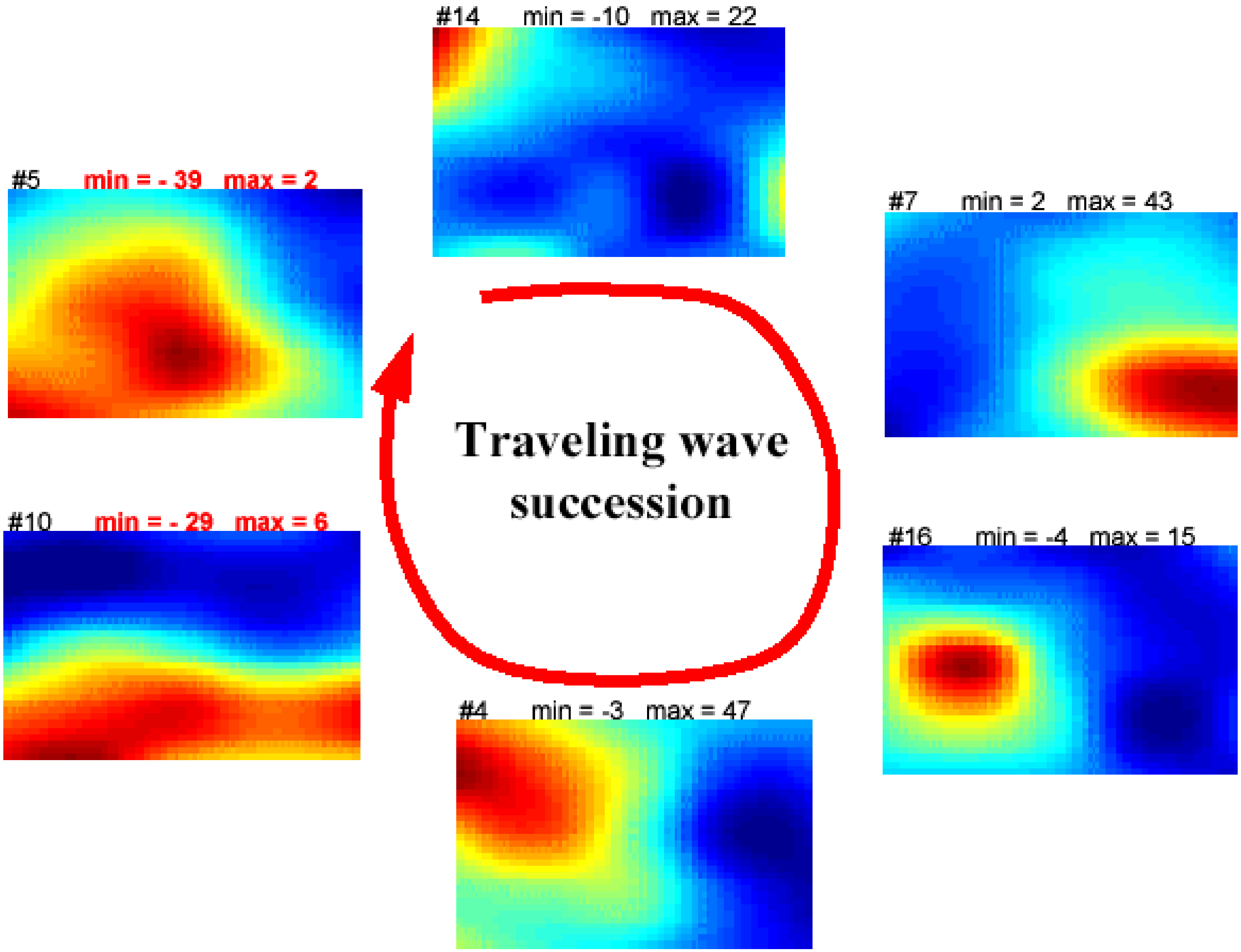
Cortical Surface EEG Before ICA



ICA & Cortical Surface EEG



ICA Reveals Cortical Traveling Wave



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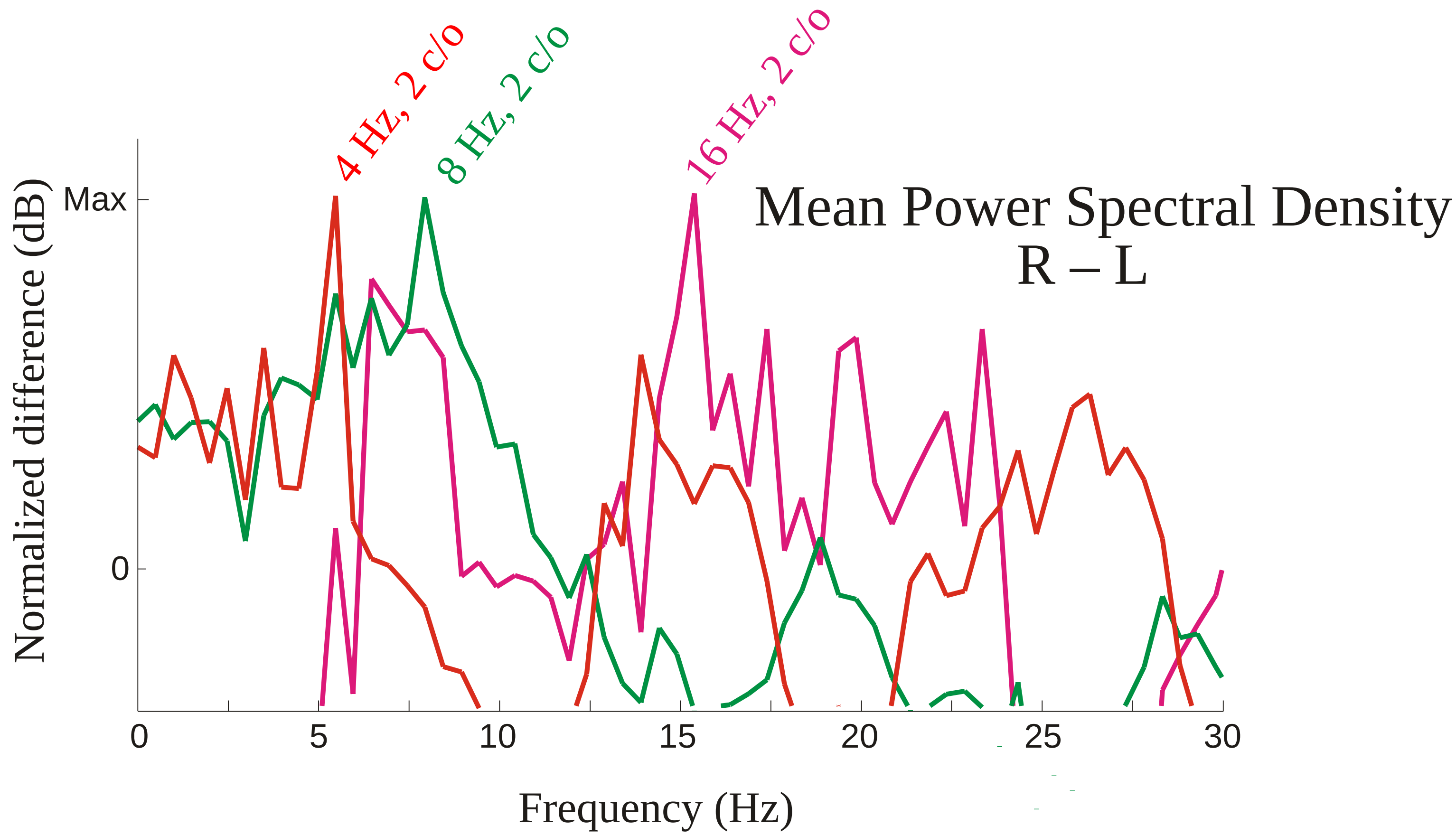
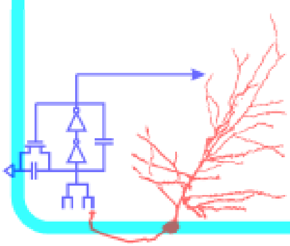
Power Spectral Density Follows Ripple Speed



- Power Spectral Density Peaks (of response) correspond to stimulus Ripple velocity
- Left-Right Processing Asymmetry (MEG required)

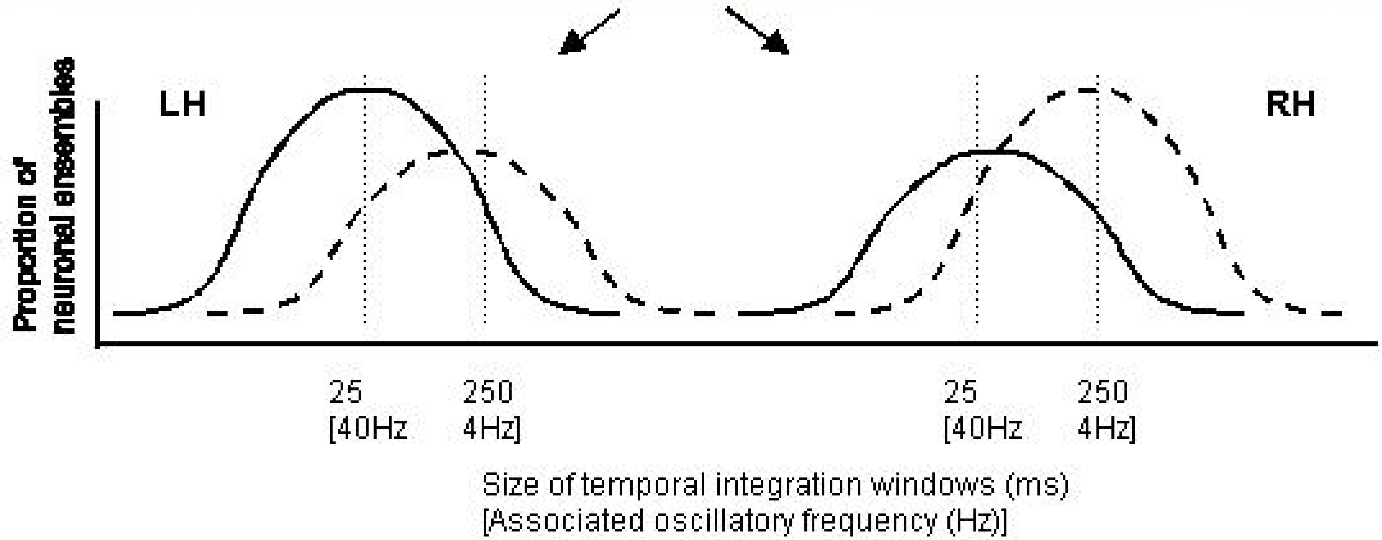


Asymmetric Sampling in Time (AST)

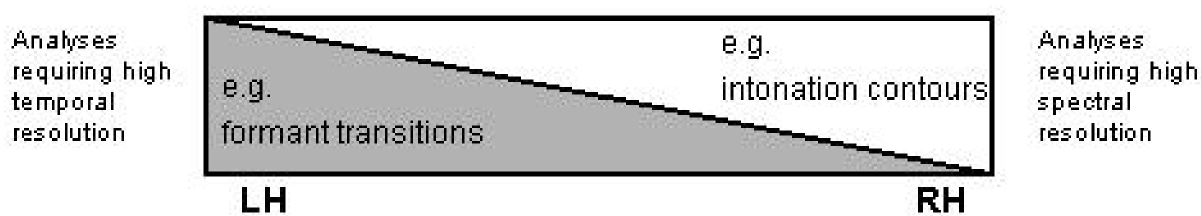
a. Physiologicallateralization

Symmetric representation ofspectro-temporal receptive fields in primary auditory cortex

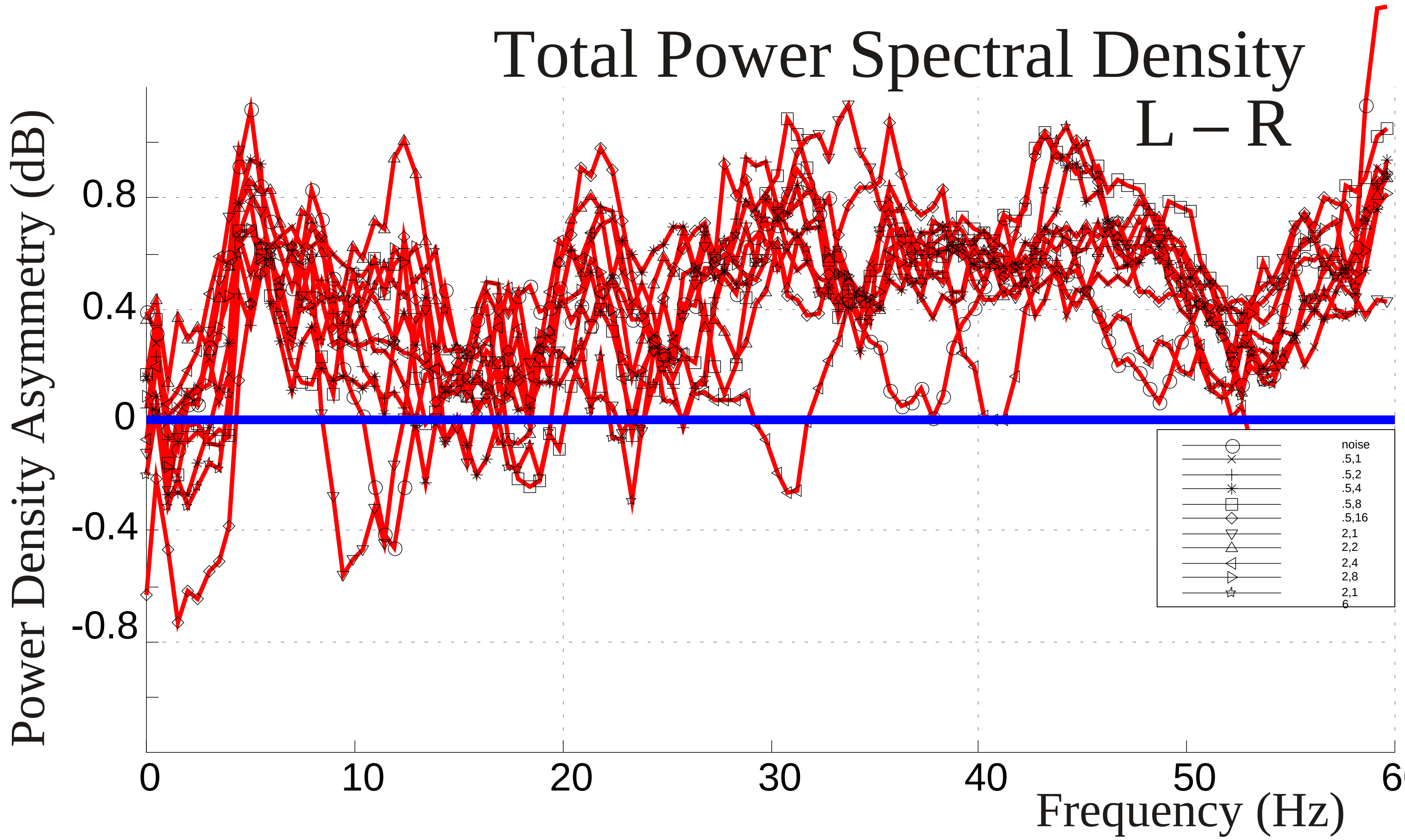
Temporally asymmetric elaboration of perceptual representations in non-primary cortex



b. Functionallateralization



Total Power Spectra: Hemispheric Asymmetry



- Enhanced Processing in Left Hemisphere for higher frequencies (above ~ 30 Hz).
- Left-Right Processing Asymmetry (MEG required)

Conclusions

- High Temporal Resolution
- Especially Suitable for Human Auditory Cortex
- Potentially Poor Signal to Noise Ratio (Neural Variability)

BUT...

✔ Independent Component Analysis:
  Artifact Rejection & Signal Enhancement

✔ Spectral and Spectro-Temporal Methods

✔ Systems Theory informs choice of stimuli

✔ Spatial Distribution of Signal Separates across hemi-spheres

✔ Other methods still, e.g. phase correlational methods

[redacted]