MEG: Magnetic Source Imaging of Brain Function

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February 17th, 2011
Talking Points

MEG

• offers an advantageous combination of spatial and temporal resolution

• is well-suited to imaging functional connectivity in the brain

• challenges (opportunities?) are:
  • large data structures
  • multiple types of responses
  • source localisation in a spherical geometry
Faraday’s Law

Every current generates a magnetic field
Faraday’s Law

Every current generates a magnetic field
Faraday’s Law

Every current generates a magnetic field
From Physics to Neuroscience

**A Current Dipole**

Current flow over distance, as distance approaches zero

\[ Q \text{ [nAm]} \]

\[ B \text{ [fT]} \]

Q and B are vectors: magnitude and orientation
A Current Dipole

Current flow over distance, as distance approaches zero

\[ Q \text{ [nAm]} \]

\[ B \text{ [fT]} \]

\( Q \) and \( B \) are vectors: magnitude and orientation

(\text{Baillet et al., 2001})
Synchronous neural firing generates tiny magnetic fields

Neuroimaging With MEG

How do we detect these small fields?

(Vrba, Robinson, 2001)
Neuroimaging With MEG

Synchronous neural firing generates tiny magnetic fields.

Whole head mapping of magnetic field strength outside the head over time allows us to interpolate when and where synchronised neural activity occurs.
Neuroimaging With MEG

Synchronous neural firing generates tiny magnetic fields

Whole head mapping of magnetic field strength outside the head over time allows us to interpolate when and where synchronised neural activity occurs
Combining Flux Transformers and SQUIDs

Flux Transformers
“Transform” magnetic “flux” into current (Right Hand Rule)

Types of flux transformers:

- Magnetometer
- Axial Gradiometer
- Planar Gradiometer

Near Field + Far Field
Far Field Only

MEG field topography will be different for each gradiometer type!!!

(Hamalainen, 1993)
Neuroimaging With MEG

Combining Flux Transformers and SQUIDs

Super Conducting QUantum Interference Device

• requirement: all components are superconducting \( (T = -269 ^\circ C) \)
• energy in the SQUID sits in a “quantum well”
• flux transformer converts \( B \) field to current
• current is induced on the SQUID creating energy
• Voltage is measured as the SQUID settles
Neuroimaging With MEG

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Note: Planar gradiometer is maximal here
Neuroimaging With MEG

**MEG vs EEG**

**MEG:**
- is undistorted by intervening tissues and scalp
- is relatively insensitive to deep sources and radial sources
- has higher effective resolution
- has quicker setup
- records from 150-300 sensors
- can provide complimentary information to EEG (often recorded simultaneously)
- about 10X more expensive

**MEG vs. fMRI**

**MEG:**
- is a more direct measure of neural activity (BOLD is neurovascular)
- offers much higher temporal resolution (ms vs s)
- has poorer spatial resolution
- about the same price
- offers no structural imaging capability
Data are collected at rates up to 2500 samples/second on each sensor.

Temporal resolution: ~1 ms
Spatial resolution: ~ 1-5 mm
The magnetic fields of interest \textit{(SIGNAL)} are buried in other magnetic fields \textit{(NOISE)}:

\textbf{THE SIGNAL}
- synchronous neuronal firing (0.1 – 1 million neurons)
  \[ 10-100 \times 10^{-15} \text{ T (fT)} \]

\textbf{THE NOISE}
- environmental source of noise (i.e. power lines, elevators, cars, etc.)
  \[ 10^{-9} \text{ T (nT)} \]
- magnetic artifacts generated by the body (i.e. eye, muscle, etc.)
  \[ 10^{-12} \text{ T (pT)} \]
- brain signals in which we’re not interested (“brain noise”)
  \[ 10-100 \times 10^{-15} \text{ T (fT)} \]
- intrinsic sensor (SQUID) noise
  \[ 10^{-15} \text{ T (fT)} \]

\textbf{GOAL OF DATA ANALYSIS: Improve the Signal-to-Noise Ratio (SNR)}
The magnetic fields of interest \textit{(SIGNAL)} are buried in other magnetic fields \textit{(NOISE)}:

\textbf{Properties of Magnetic Noise}

- environmental noise occurs far from the MEG
  - so ... use a magnetically shielded room (MSR)
  - or ... model it out (SSS)
The magnetic fields of interest (*SIGNAL*) are buried in other magnetic fields (*NOISE*):

**Properties of Magnetic Noise**

- covers the entire frequency spectrum while neuromagnetic activity is 0-100 Hz
  - so ... filter it out
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A Needle In A Haystack

The magnetic fields of interest (SIGNAL) are buried in other magnetic fields (NOISE):

**Properties of Magnetic Noise**

- covers the entire frequency spectrum while neuromagnetic activity is 0-100 Hz
  - so ... filter it out

- generally **not temporally correlated** with stimulation or behaviour
  - so ... correlate it out
  - This is event-related analysis

- generally **not temporally correlated** with other neural populations
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  - This is functional connectivity analysis
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What types of brain signals do we measure with MEG?

“Evoked” activity
  • synchronous neural firing that occurs at a consistent latency with respect to a stimulus or event

“Induced” activity
  • changes in the strength of ongoing neural rhythms

“Connectivity”
  • synchrony between neural rhythms in spatially separated neuronal populations
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Characteristics of an Evoked Neuromagnetic Signal

- occur inside the helmet
- relatively slow (< 100 Hz, usually < 40 Hz)
- strong temporal correlation with stimulation or behaviour

Characteristics of a Magnetic Noise

- generally occur outside the helmet
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Finding Evoked Responses

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MEG Activity

- Evoked Responses
- Induced Responses
- Connectivity

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 Parsing/ Averaging
Finding Evoked Responses

MEG Data are Synchronised to Events, then Averaged

parse data based on Event

average across N trials to attenuate “noise”

Plot average MEG signal over time

\[ \text{SNR} \propto \sqrt{N} \]
Example: Language Lateralisaton

Where and When Does Language-Related Processing Occur in the Cortex?

• subjects see a list of 3 intact (“nameable”) or scrambled images
• after a wait interval (3-4 s), an image is presented
• subject responds to indicate if fourth image is “new” or “old”
• condition order is random
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Example: Language Laterisation

Data Analysis: Language-Related Evoked Response

1. Parse data based on list items (-0.1 < t < 1.0s)
2. Retain only correct trials
3. Baseline correct and low-pass (55Hz), re-sample to 250Hz
4. Artifact Removal
5. Cleaned Epoched MEG Data

Correct Trial Numbers

1. Divide trials into nameable/scrambled
2. Nameable MEG Data (Trials) → Average → Nameable Average MEG Data → Difference
3. Scrambled MEG Data (Trials) → Average → Scrambled Average MEG Data → Difference

Event latencies

1. Correct Trial Numbers
2. Nameable Trial Numbers
Example: Language Lateralisisation

Averaged MEG Data for Nameable List Objects Shows Left Lateralized Activation
Example: Language Laterisation

Language-Related Differences are Consistently Evident in the Left Hemisphere

List Item Evoked Field Data
Subject 6070910 (Patient)

----- Nameable
----- Scrambled

$t = -100$ to 1000 ms
BP = 0.1-40 Hz
Language-Related Differences are Consistently Evident in the Left Hemisphere
Example: Language Lateralisatation

Language-Related Differences are Consistently Evident in the Left Hemisphere

List Item Evoked Field Data
Subject 8070910 (Patient)
- Nameable
- Scrambled

$t = -100$ to $1000$ ms
$BP = 0.1$-$40$ Hz

360 ms
Example: Language Lateralisaiton

Source Modelling with Minimum Norm Estimation (MNE) shows Left Lateralised Language-Related Evoked Responses (360 ms)
Inter-Trial Coherence (ITC)
• a normalised (0...1) measure of synchronisation of phase across trials for a given signal
• How consistent is the signal phase across trials?
• Evoked responses, by definition, have high ITC

\[ \bar{R} = \frac{1}{N} \left( C^2 + iS^2 \right) \]

where
\[ C = \sum_{n=1}^{N} \cos \varphi_n, S = \sum_{n=1}^{N} \sin \varphi_n \]
\[ |\bar{R}| = \text{magnitude of "phase locking"} \]
\[ \varphi(\bar{R}) = \text{mean phase of evoked response} \]
\[ p(\bar{R}, N) \]

(Stapells et al., EEG Clin Neurophysiol, 1987)
Steady-State Somatosensory Stimulation

- steady-state stimulation of the right index finger pad at 23 Hz
- MEG, EMG (right 1DI) and somatosensory stimulator driving signal will be recorded
- 23 Hz pulse trains will be applied for 3 seconds with a randomised inter-stimulus interval (ISI) of 3-5 seconds
- the subject watches a movie with subtitles

Onset asynchrony = 6-8 seconds / onset
10 minute data collection => 600 s / 7.5 s/onset = 80 epochs
Example: Somatosensory Steady-State Response

Steady-state evoked field is strongest at contralateral MEG sensors

(Bardouille, Ross, NeuroImage, 2008)
Inter-trial coherence is also strongest at contralateral MEG sensors. Mean phase varies from a single value.
Inter-trial coherence identifies multiple brain areas activated by finger vibration at different phases. This suggests a network involved in somatosensation.

Example: Somatosensory Steady-State Response

(Bardouille, Ross, NeuroImage, 2008)
Connectivity and Schizophrenia

Evaluating Emotional Faces

(Ioannides et al.. NeuroImage 2004)
Connectivity and Schizophrenia

Mutual Information Identifies Connectivity Between V1/V2 – Fusiform Gyrus – Inferior Frontal Cortex – Amygdala During Emotion Recognition

(Ioannides et al. NeuroImage 2004)
Connectivity and Schizophrenia

Connectivity Is Reduced During Emotion Recognition in Persons with Schizophrenia

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Neural Oscillations and Functional Connectivity

Cortical Oscillations (Rhythms)

- bursts of oscillatory activity found in neuroelectric/magnetic recordings
- indicative of rhythmic firing in the underlying population of neurons
- likely caused by sub-threshold oscillations of neuronal membrane potentials

(Murthy, Fetz, 1992)
Neural Oscillations and Functional Connectivity

Cortical Oscillations (Rhythms)

- bursts of oscillatory activity found in neuroelectric/magnetic recordings
- indicative of rhythmic firing in the underlying population of neurons
- likely caused by sub-threshold oscillations of neuronal membrane potentials

Why is this interesting?

- cortical rhythms are a major component of brain activity in general
- changes in cortical rhythms have functional significance
- synchrony in rhythms between neuronal groups may facilitate communication

(Womelsdorf et al., Science, 2007)
Finding Induced Responses

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Finding Induced Responses

Evoked and Induced Activity

10 x 2 second trials @ 1250 Hz sample rate
1 cycle of 10 Hz at t = 0 s
ongoing 20 Hz signal (from 0.1 to 0.2 fT at t = 0 s)
Neuroimaging With MEG

Evoked and Induced Activity

1. Calculate power spectrum for each segment
2. Average power spectra across trials
3. Plot average power spectrum over time

Induced Response

- 1 cycle of 10 Hz at t = 0 s
- Ongoing 20 Hz signal (from 0.1 to 0.2 fT at t = 0 s)

10 x 2 second trials @ 1250 Hz sample rate
Finding Induced Responses

Evoked and Induced Activity

10 x 2 second trials @ 1250 Hz sample rate
1 cycle of 10 Hz at t = 0 s
ongoing 20 Hz signal (from 0.1 to 0.2 fT at t = 0 s)

Single Trial Time-Frequency Response

Trials

Signal Strength [fT]

Average (Evoked Response)

Time

Signal Power [fT]

Evoked

Induced
Finding Induced Responses

Evoked and Induced Activity

10 x 2 second trials @ 1250 Hz sample rate
1 cycle of 10 Hz at t = 0 s
ongoing 20 Hz signal (from 0.1 to 0.2 fT at t = 0 s)

Average Time-Frequency Response

Trials

Average (Evoked Response)

Signal Strength [fT]

Time

Signal Power [fT]

Frequency [Hz]

Time [s]
Finding Induced Responses

Evoked and Induced Activity

10 x 2 second trials @ 1250 Hz sample rate
1 cycle of 10 Hz at t = 0 s
ongoing 20 Hz signal (from 0.1 to 0.2 fT at t = 0 s)

Induced Time-Frequency Response
Finding Induced Responses

Characteristics of an Induced Neuromagnetic Signal

• occur inside the helmet

• occurs in a specific frequency band (α, β, θ, δ, γ, …)

• weak temporal correlation with stimulation or behaviour

Characteristics of a Magnetic Noise

• generally occur outside the helmet

• covers the entire noise spectrum

• generally no temporally correlation with stimulation or behaviour
Finding Induced Responses

MEG Data are Synchronised to Events, then Averaged

- Parse data based on Event
- (306 channels continuous)
- (306 channels x 100 trials)
- Generate average TFRs
- \[ \Delta P(t, f) = \frac{P(t, f) - \bar{P}(t_{\text{baseline}}, f)}{\bar{P}(t_{\text{baseline}}, f)} \cdot 100\% \]
- Baseline Correction
- (306 channels x 1 trials
  x 32 frequency bin)
Finger Vibration and Attention

How Does Focused Attention Change Responses to Finger Vibration?

- Finger Vibration
- 3 sec. 3 sec. 4 sec. 3 sec.

**ATTEND Condition**
- "Count the number of long duration stimuli"
- INSTRUCTIONS

**IGNORE Condition**
- VIDEO
- Seems logical to me captain.
- "Enjoy the movie"
Finger Vibration and Attention

How Does Focused Attention Change Responses to Finger Vibration?

The steady-state response in contralateral SI gets 10% bigger.

(Bardouille et al., Eur J Neurosci, 2010)
Finger Vibration and Attention

How Does Focused Attention Change Responses to Finger Vibration?

In the attend condition, changes in beta (15-30 Hz) power occur bilaterally in SI and MI.

(Bardouille et al., Eur J Neurosci, 2010)
How Does Focused Attention Change Responses to Finger Vibration?

In the attend condition, changes in beta (15-30 Hz) power occur bilaterally in SI and MI

(*Bardouille et al., Eur J Neurosci, 2010*).
Concurrent changes in cortical oscillations occur even at rest

(De Pasquale et al., PNAS, 2010)
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Coherence is:

- a normalised measure of the phase consistency between two signals as a function of frequency
- bound between 0 and 1
- high for synchronized oscillators (i.e. communicating neural populations)
- phase of coherence defines the mean phase difference (i.e. lag)
- measured with respect to another signal (not an event)

Cross-Spectral Density
\[ G_{nx}^{xy}(f) = \mathcal{F}_n(x(t), f) \cdot \mathcal{F}^*_n(y(t), f) \]
where \( \mathcal{F} = \text{Fourier transform} \)

Mean Cross-Spectral Density
\[ \overline{G}_{nx}^{xy}(f) = \frac{1}{N} \sum_{n=1}^{N} G_{nx}^{xy}(f) \]

Coherence
\[ C_{nx}^{xy}(f) = \frac{\overline{G}_{nx}^{xy}(f)}{\sqrt{\overline{G}_{nx}^{xx}(f) \overline{G}_{nx}^{yy}(f)}} \]
Coherence and Functional Connectivity

Example
- 450 1-second epochs
- 2 signals containing 3 sinusoids plus white noise

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Δφ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate amplitude and synchrony</td>
<td>5 Hz</td>
<td>5 fT</td>
<td>± 18</td>
</tr>
<tr>
<td>Large amplitude, no synchrony</td>
<td>12 Hz</td>
<td>12 fT</td>
<td>± 180</td>
</tr>
<tr>
<td>Small amplitude, complete synchrony</td>
<td>20 Hz</td>
<td>1 fT</td>
<td>± 0</td>
</tr>
</tbody>
</table>

![Graph showing coherence and amplitude vs frequency.](image-url)
Coherence and Functional Connectivity

Coherence can identify a cerebello-thalamo-cortical network associated with slow, precise finger movements

Synchronized with Muscle (6-9 Hz)

Synchronized with Motor cortex (6-9 Hz)

(Gross et al, PNAS, 2001)
Neuromagnetic Activity

Tells us about:

- synchronization of neural activity that is phase-locked to an event
  - neural firing temporally correlated to an event
- changes in ongoing neural activity related to an event
  - neural inhibition or excitation depending on the frequency
- synchronization between the neuromagnetic activity and the muscle
  - functional connectivity / binding

✓ Is a powerful method for imaging the brain as a dynamic system