Neural Coding of Multiple Stimulus Features in Auditory Cortex

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Introduction

- Magnetoencephalography (MEG) as a tool of Non-Invasive Auditory Physiology
- Neural Encoding of Simple Modulations
- Neural Encoding of Independent Modulation Pairs (AM & FM)
Magnetoencephalography (MEG)

• Non-invasive, Passive, Silent
• Simultaneous Whole-Head Recording (~200 sensors)
• Sensitivity
  high: $\sim 100 \text{ fT} \ (10^{-13} \text{ Tesla})$
  low: $\sim 10^4 - \sim 10^6 \text{ neurons}$
• Temporal Resolution: $\sim 1 \text{ ms}$
• Spatial Resolution
  coarse: $\sim 1 \text{ cm}$
  ambiguous
Neural Activity = Neural Current

Photo by Fritz Goro
Direct electrophysiological measurement
- not hemodynamic
- real-time
- No unique solution for distributed source
Instantaneous Magnetic Field

MEG Response
Flattened Isofield Contour Map

Sink Source
40 fT/Step

$t = 98$ ms

Computational Sensorimotor Systems Laboratory
MEG Response
3-D Isofield Contour Map
About the Cover

Cover Picture: Axial view of the cortically-generated magnetic field of a human listener, measured using whole-head magnetoencephalography (MEG), at a single moment in time. Isofield contours in red (respectively, blue) indicate the strength of outward (inward) magnetic flux; the digitized scalp surface is in gray. For each hemisphere, a magnetic dipole-like pattern is centered over temporal cortex, and the neural generator itself, located in planum temporale, is an inferiorly flowing neuronal electric current. The MEG channels responding most strongly (in the center of each flux area) are designated by filled yellow circles. The acoustic stimulus is a 1 kHz pure tone; time is 100 ms post-onset. The data were acquired with the MEG160 system (Yokogawa electric corporation, KIT, Japan). See Chait, Poeppel, and Simon, p. 835-848.

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MEG Response
Spatial Map of Time Series
Time Course of MEG Responses

Evoked Responses
MEG Events Time-Locked to Stimulus Event

- Pure Tone
- Broadband Noise

![Graphs showing time course of MEG responses to pure tone and broadband noise](image-url)
MEG as Auditory Physiology Tool

- Advantages of humans over animals
  Subjects can be rented (by the hour)
  Subjects can be trained in minutes
  Better grasp of subjects perceptual space (?)
  Access to Speech & Language processing (?)

- Advantage of Whole Head Recording

- Disadvantage of Neural Source Localization
  Coarseness/Ambiguity in Source Location
  Blindness to Many Kinds of Coding

- Neutral Aspects
  Neural Source is Dendritic Current (not Spikes)
  Humans not typical mammals (?)
  New Technique/Immature Analysis Tools
Modulation Encoding

- Simple Modulations ➔ Simple Cortical Encoding
  - Amplitude Modulation coding for slower modulations
  - Rate coding (invisible to MEG) for faster modulations

- Applies to general modulations: AM, FM, other

- Amplitude Modulation coding is easily detectable in Fourier/Spectral domain
  - Spectral Peak at Modulation Frequency
Frequency Response

Stimulus Modulated at Single Frequency ➞ Steady State Response (SSR)

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

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

SSR Amplitude

SSR Phase

Ross et al. (2000)

SSR Phase Follows Carrier

Phase Modulation Encoding

Correlation = 0.72    DFT duration = 72 sec

0.08 Hz

Sample Dual Modulation Stimuli

\[ f_{FM} = 3.1 \text{ Hz} \]
\[ f_{AM} = 37 \text{ Hz} \]

\[ f_{FM} = 8 \text{ Hz} \]
\[ f_{AM} = 37 \text{ Hz} \]
Neural Modulation Models

- **Amplitude Modulation (AM) Coding**
  - Carrier Frequency
  - Envelope Amplitude
  - Neural Activity
  - Neural Power Spectral Density

- **Phase Modulation (PM) Coding**
  - Carrier Frequency
  - Envelope Amplitude
  - Neural Activity
  - Neural Power Spectral Density

- **Stimulus Carrier Frequency (FM)**

- **Neural Averaged Response**

- **Neural Response Spectrum**

- **Upper Sideband**

- **Lower Sideband**

- **SSR Frequency**

- **C.F. Patel & Balaban (2004)**

\[
\alpha_{AM} = 0 \text{ or } 2\pi
\]

\[
\alpha = (\varphi_{upper} - \varphi_{SSR}) - (\varphi_{SSR} - \varphi_{lower})
\]

\[
\alpha_{PM} = \pi
\]
Modulation Encoding, with coding transition at $f_{FM} \sim 5$ Hz
Phase Modulation Encoding below $f_{FM} \sim 5$ Hz
Conclusions

• MEG can address questions of Neural Coding
  • Coarseness of Localization not Intrinsic Obstacle
  • Modulation encoding gives family of response types

• Combined AM/FM modulations are encoded in Auditory Cortex
  • Phase Modulation seen at lowest FM rates
  • Modulation Encoding changes at higher rates

• Single Sideband Modulation unexpected
  • Speculate: Single Modulation Encoding type?
  • Or: Two populations of AM and PM encoding neurons whose phase happens to cancel in lower sideband?