Cortical Encoding of Auditory Objects at the Cocktail Party

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Neural processing of speech and complex auditory streams

Magneoencephalography

Neural Modeling

Neural Signal Processing

Neurally Inspired Algorithms

Advanced Neuroimaging

Cocktail Party Problem

Figure 11: Schematics depicting models that are more complex. (a) Using the output of a temporally symmetric (TS) neuron as sole input to another neuron results in a temporally symmetric (TS) neuron (see equation 3.17). (b) Feedback from such a temporally symmetric neuron whose sole source is the first temporally symmetric neuron is still self-consistently temporally symmetric (see equation 3.19). (c) Multiple examples of feedback and feedforward: The initial neuron TS 1 provides temporal symmetry to all other neurons in the network due to its role as sole input for the network. All other neurons inherit the temporal symmetry, and the feedback is also self-consistently temporally symmetric.

Feedback:

$$h_{TS1}(t, x) = \left( \sum_{m=1}^{M} k_A m(t) g_{Cm}(x) \right) + \left( \sum_{n=1}^{N} k_\theta n(t) g_{Dn}(x) \right) * k_A(t) + h_{TS2}(t, x)$$

$$h_{TS2}(t, x) = h_{TS1}(t, x) * k_2(t).$$

(3.19)
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Introduction

- Magnetoencephalography (MEG)
- Auditory Objects
- Neural Representations of Auditory Objects in Cortex: Decoding
- Neural Representations of Auditory Objects in Cortex: Encoding
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
Functional Brain Imaging

- Non-invasive recording from human brain

**Hemodynamic techniques**

- **fMRI**
  functional magnetic resonance imaging

- **PET**
  positron emission tomography

**Electromagnetic techniques**

- **EEG**
  electroencephalography

- **MEG**
  magnetoencephalography

**Comparative Analysis**

- **fMRI & MEG** can capture effects in single subjects

  - Excellent Spatial Resolution (~1 mm)
  - Poor Temporal Resolution (~1 s)

  - Poor Spatial Resolution (~1 cm)
  - Excellent Temporal Resolution (~1 ms)
Functional Brain Imaging

Functional Brain Imaging
= Non-invasive recording from human brain

Hemodynamic techniques

fMRI
functional magnetic resonance imaging

PET
positron emission tomography

Electromagnetic techniques

EEG
electroencephalography

MEG
magnetoencephalography

Excellent Spatial Resolution (~1 mm)
Poor Temporal Resolution (~1 s)

Poor Spatial Resolution (~1 cm)
Excellent Temporal Resolution (~1 ms)

fMRI & MEG can capture effects in single subjects
Functional Brain Imaging

= Non-invasive recording from human brain

**Hemodynamic techniques**

- **fMRI**
  functional magnetic resonance imaging
- **PET**
  positron emission tomography

**Electromagnetic techniques**

- **EEG**
  electroencephalography
- **MEG**
  magnetoencephalography

**Excellent Spatial Resolution** (~1 mm)

**Poor Temporal Resolution** (~1 s)

**Poor Spatial Resolution** (~1 cm)

**Excellent Temporal Resolution** (~1 ms)

fMRI & MEG can capture effects in single subjects
Neural Signals & MEG

- 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)

Photo by Fritz Goro
MEG Auditory Field

Flattened Isofield Contour Map

Instantaneous Magnetic Field

Sink | Source
---|---
40 fT/step

$t = 98$ ms
MEG Auditory Field
3-D Isofield Contour Map

Sagittal View

Axial View

Chait, Poeppel and Simon, Cerebral Cortex (2006)
Magnetic Field Strengths

- Earth's field
- Urban noise
- Contamination at lung
- Heart QRS
- Fetal heart
- Muscle
- Spontaneous signal (α-wave)
- Signal from retina
- Evoked signal
- Intrinsic noise of SQUID

Biomagnetic Signals
MEG = “Squid head”
Time Course of MEG Responses

Auditory Evoked Responses

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

Pure Tone

Broadband Noise
Phase-Locking in MEG to Slow Acoustic Modulations

AM at 3 Hz

3 Hz phase-locked response

Ding & Simon, J Neurophysiol (2009)
Wang et al., J Neurophysiol (2012)
Phase-Locking in MEG to Slow 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 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

Speech Envelope

Decoder

MEG Responses

(up to ~ 10 Hz)
Neural Reconstruction of Speech Envelope

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

Speech Envelope

Decoder

MEG Responses

---

Stimulus speech envelope

Reconstructed stimulus speech envelope

Reconstruction accuracy comparable to single unit & ECoG recordings

2 s
Neural Reconstruction of Speech Envelope

Reconstruction accuracy comparable to single unit & ECoG recordings (up to ~ 10 Hz).

Decoder

Speech Envelope

MEG Responses
Auditory Objects

• What is an auditory object?
  • perceptual construct (not neural, not acoustic)
  • commonalities with visual objects
  • several potential formal definitions
Auditory Object Definition

- Griffiths & Warren definition:
  - corresponds with *something* in the sensory world
  - object information *separate from* information of rest of sensory world
  - abstracted: object information *generalized over particular* sensory experiences
Auditory Objects at the Cocktail Party
Auditory Objects at the Cocktail Party
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Alex Katz,
The Cocktail Party
Auditory Objects at the Cocktail Party
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Alex Katz,
The Cocktail Party
Experiments
Experiments

Ding & Simon, PNAS (2012)
Speech Stream as an Auditory Object

• corresponds with something in the sensory world

• information separate from information of rest of sensory world
  e.g. other speech streams or noise

• abstracted: object information generalized over particular sensory experiences
  e.g. different sound mixtures
Neural Representation of an Auditory Object

- neural representation is of something in sensory world
- when other sounds mixed in, neural representation is of auditory object, not entire acoustic scene
- neural representation invariant under broad changes in specific acoustics
Selective Neural Encoding
Selective Neural Encoding

[Diagram showing waveforms and brain images]
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!

reconstructed from MEG

attended speech envelopes

reconstructed from MEG
Stream-Specific Representation

Representative subject  Grand average over subjects

Attending to speaker 1

Attending to speaker 2

Identical Stimuli!
Single Trial Speech Reconstruction

**Attended Speech Reconstruction**

- *Attentional focus*
  - Speaker one: red dots
  - Speaker two: green stars

![Graph showing attended speech reconstruction with speaker one and speaker two data points.](image-url)
Single Trial Speech Reconstruction

Attended Speech Reconstruction

Background Speech Reconstruction

attentional focus
speaker one
speaker two
Invariance Under Acoustic Changes
Invariance Under Acoustic Changes
Invariance Under Acoustic Changes
Invariance Under Acoustic Changes
Invariance Under Acoustic Changes
Stream-Based Gain Control?

Gain-Control Models

Object-Based

Stimulus-Based

Speaker Relative Intensity (dB)

correlation

attended

background

Speaker Relative Intensity (dB)

 attends

background
Stream-Based Gain Control?

Gain-Control Models

Object-Based

Stimulus-Based

Neural Results

Speaker Relative Intensity (dB)
Stream-Based Gain Control?

Gain-Control Models

Object-Based

-8 -5 0 5 8

Speaker Relative Intensity (dB)

Stimulus-Based

-8 -5 0 5 8

Speaker Relative Intensity (dB)

Neural Results

-8 -5 0 5 8

Speaker Relative Intensity (dB)
Stream-Based Gain Control?

Gain-Control Models

Object-Based

Stimulus-Based

Neural Results

- Stream-based not stimulus-based
- Neural representation is invariant to acoustic changes.
Neural Representation of an Auditory Object

✓ neural representation is of something in sensory world

✓ when other sounds mixed in, neural representation is of auditory object, not entire acoustic scene

✓ neural representation invariant under broad changes in specific acoustics
Forward STRF Model

Spectro-Temporal Response Function (STRF)
Forward STRF Model

Spectro-Temporal Response Function (STRF)
STRF Results

- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M_{50}^{STRF}$ positive peak
- $M_{100}^{STRF}$ negative peak
STRF Results

- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M_{50}^{STRF}$ positive peak
- $M_{100}^{STRF}$ negative peak
STRF Results

- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M_{50_{\text{STRF}}}$ positive peak
- $M_{100_{\text{STRF}}}$ negative peak
- $M_{100_{\text{STRF}}}$ strongly modulated by attention, but not $M_{50_{\text{STRF}}}$
Neural Sources

- \( M_{100_{\text{STRF}}} \) source near (same as?) \( M_{100} \) source: Planum Temporale

- \( M_{50_{\text{STRF}}} \) source is anterior and medial to \( M_{100} \) (same as \( M_{50} \)?): Heschl’s Gyrus
• $M_{100}^{STRF}$ strongly modulated by attention, but not $M_{50}^{STRF}$.
• $M_{100}^{STRF}$ invariant against acoustic changes.
• Objects well-neurally represented at 100 ms, but not 50 ms.
Not Just Speech

Competing Tone Streams

Tone Stream in Masker Cloud

Xiang et al., J Neuroscience (2010)

Elhilali et al., PLoS Biology (2009)
Tone Stream in Masker Cloud
Tone Stream in Masker Cloud
Tone Stream in Masker Cloud

Neural Response to Target
Target Task

Neural Response to Target
Masker Task

Field Strength (x 10^1 MHz)

10^1 ft^2/Hz

Time

Frequency

Hz

3  4  5

3  4  5
Tone Stream in Masker Cloud

Neural Enhancement for Foreground/Background

Normalized neural response change

Normalized neural response change

Frequency (Hz)

Normalized neural response change

Normalized neural response change
Competing Tone Streams
Competing Tone Streams

Tracking 4 Hz task

Tracking 7 Hz task

Power (×10^2 \text{ Torr})

Field Strength (×10 \text{ Torr})

Frequency (Hz)

Time

Frequency

Power (×10^2 \text{ Torr})

Frequency (Hz)

Frequency (Hz)

Frequency (Hz)
Competing Tone Streams
Summary

• Cortical representations of speech found here:
  ✓ consistent with being neural representations of auditory (perceptual) objects
  ✓ meet 3 formal criteria for auditory objects

• Object representation fully formed by 100 ms latency (PT), but not by 50 ms (HG)

• Not special to speech
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ILS courses are based on the national initiatives for reforming undergraduate biology education: BIO 2010, Scientific Foundations for Future Physicians, and Vision and Change. These initiatives provide explicit guidelines for designing multidisciplinary life sciences curricula necessary for preparing life science and pre-medical students for successful careers in the 21st century. The ILS academic program is composed of a core of four accelerated courses in integrated organismal biology, genetics and genomics, mathematical modeling in Biology, and scholarship-in-practice, plus the first-semester introduction course. These courses represent either honors versions of BSCI courses or unique new courses designed to satisfy the objectives of the national initiatives linked above. Furthermore, all ILS courses emphasize innovative pedagogy strategies intended to encourage student active engagement and small-group problem solving.

**Course Descriptions**

**HLSC 100: Developing Life Scientists for the Global Good** (1 credit) - This small group, service-learning course provides students with the information needed to develop into professionals in the Life Sciences. Class dialogue focuses on the resources available to students at UMD as well as three important facets of the life sciences: the social determinants of health, sustainability, and STEM education. Students also participate in an ongoing service experience where they work with an organization that focuses on addressing the needs of the local community. (Those students entering ILS as rising second-year students may substitute other UNIV 100 courses to satisfy this requirement.) This course satisfies the freshmen seminar requirement for most majors.

**HLSC 207 Principles of Biology III: Organismal Biology** (3 credits) - This course is recognized as a national model for teaching rigorous introductory organismal biology, since it utilizes mathematical, physical, chemical, genomic, and evolutionary principles to develop an integrated perspective toward the functioning and evolution of all organisms, including humans. This course is equivalent to BSCI 207 [Sample Syllabus](#).

**HLSC 322 Genetics and Genomics** (4 credits) - This course starts with an overview of basic Mendelian and molecular genetics, then focuses on the understanding and application of genomics to contemporary research in medicine, biotechnology, and societal issues. This course is equivalent to BSCI 222 [Sample Syllabus](#).

**HLSC 374 Mathematical Modeling in Biology** (4 credits) - This course is designed specifically to teach students how to apply advanced mathematics and modeling techniques in order to: 1) address important problems in human physiology, epidemiology, and complex biological systems, and 2) do research in emerging disciplines, such as molecular biophysics and bioinformatics. NOTE: The prerequisite for this course is two semesters of Calculus or the equivalent AP credits. This course is equivalent to BSCI474 [Sample Syllabus](#).

**HLSC 377 Research and Application in Life Sciences** (3 credits) - This scholarship in practice course integrates the academic and experiential aspects of ILS to help students approach complex real-world problems having a biological basis, such as genetic diseases, viral epidemics, ageing, global warming, green energy, and environmental sustainability. This course counts as a capstone course for CORE requirements and a scholarship in practice course for GEN ED requirements. [Sample Syllabus](#).

**HLSC 279R ILS Research Internship** (1 credit) - This course should be taken during the semester in which a student is completing their internship experience. While there are no formal class meetings students are required to document their research experience using the ILS electronic portfolio system. [Sample Syllabus](#).
Thank You
Reconstruction of Same-Sex Speech

**Attended Speech Reconstruction**

- Attended speech
- Background speech

**Single Trial Decoding Results**

- Attended Speaker
  - One
  - Two

Correlation

Speaker One

Speaker Two
Speech in Noise: Stimuli

A. Mixtures of Speech and Spectrally Matched Stationary Noise
   - quiet background
   - 6 dB
   - -3 dB
   - -9 dB

B. Contrast Index
   - SNR (dB): Q +6 +2 -3 -6 -9
   - 12 dB

C. Intelligibility (%)
   - SNR (dB): Q +6 +2 -3 -6 -9
   - 100
   - 50
   - 0
Speech in Noise: Results

A. Neural Reconstruction of Underlying Speech Envelope

B. Reconstruction Accuracy

C. Correlation with Intelligibility
Speech in Noise: Results

**Temporal Response Function in Each SNR Condition**

**A**
- Power over sensors
- SNR (dB) vs. time (ms)
- Color scale: min to max

**B**
- M50_{TRF}
- M100_{TRF}
- Color scale: + to -

**Onset Latency**
- Time (ms) vs. SNR (dB)

**M50_{TRF} Amplitude**
- SNR (dB) vs. amplitude
- Bar graph with error bars

**M100_{TRF} Amplitude**
- SNR (dB) vs. amplitude
- Bar graph with error bars
Speech in Noise: Results

A. Stimulus Spectrum
- quiet
- +6 dB
- +2 dB
- -3 dB
- -6 dB
- -9 dB
- 18 dB

B. Response Spectrum
- Inter-Trial Correlation

C. Response Cutoff Frequency
- Frequency (Hz)
- SNR (dB)