How the Brain Solves the Cocktail Party Problem: Evidence from Human Auditory Neuroscience

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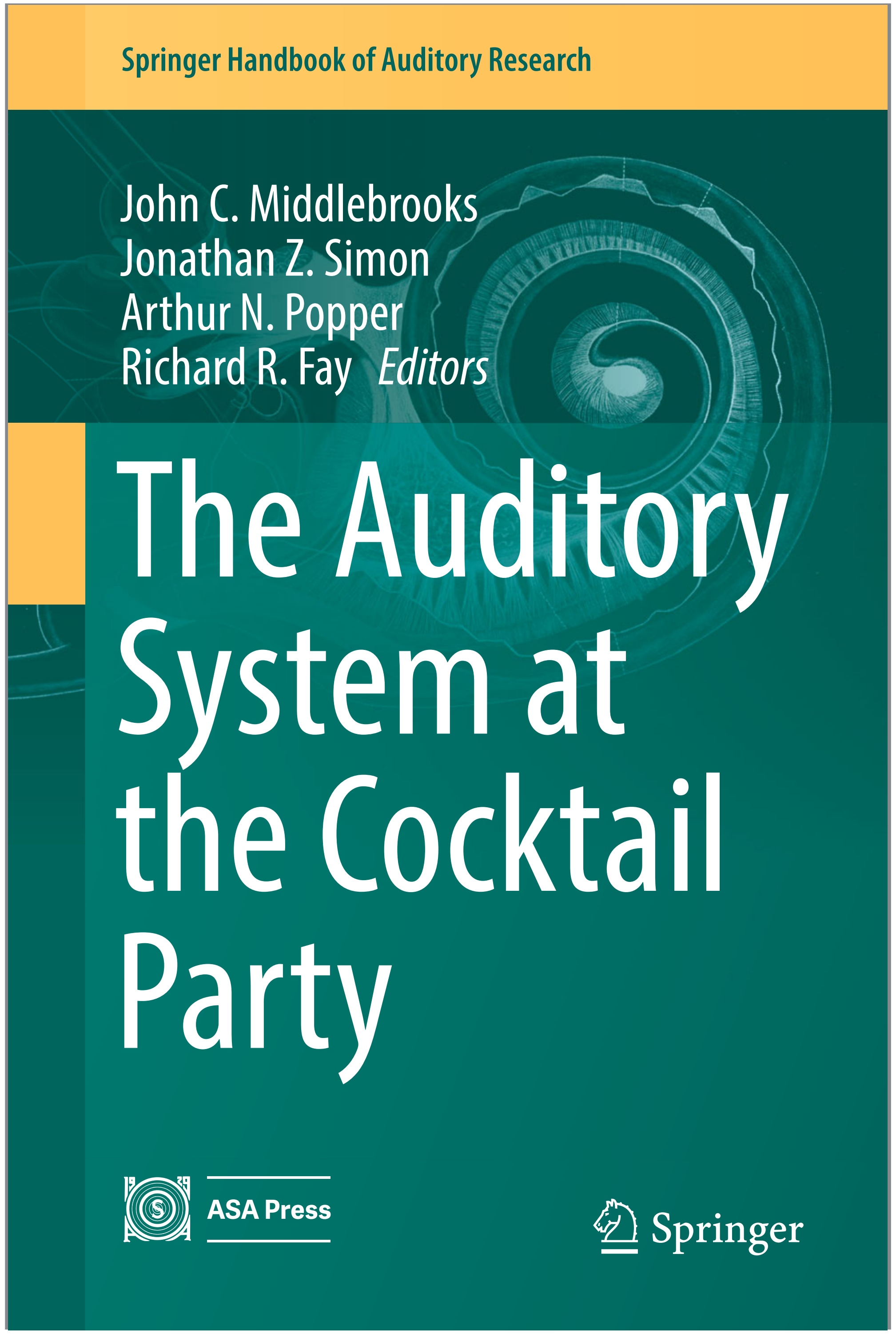
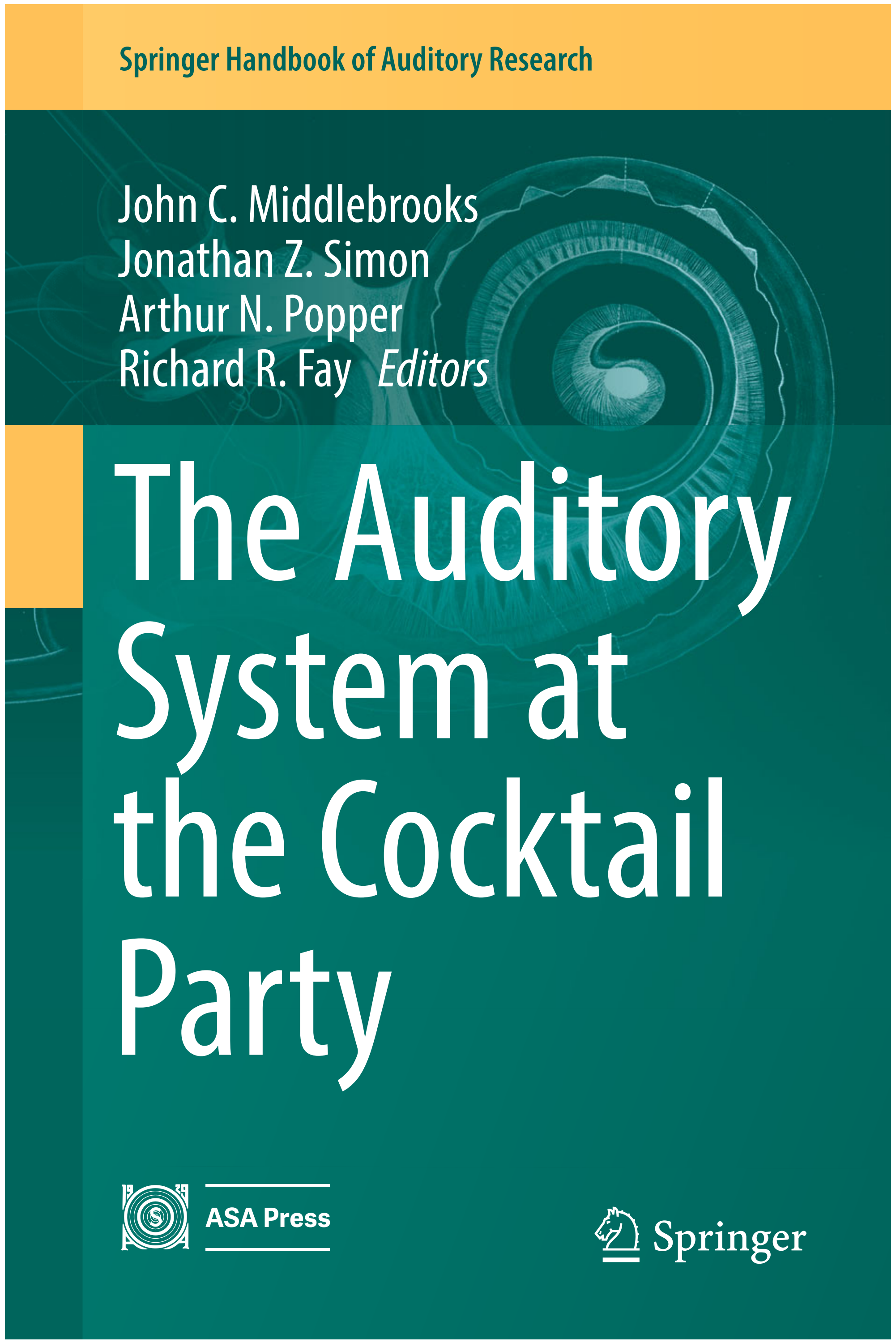
Shameless Plug



Valuable Resource



Chapter 7
Human Auditory Neuroscience and the Cocktail Party Problem

Jonathan Z. Simon

Abstract Experimental neuroscience using human subjects, to investigate how the auditory system solves the cocktail party problem, is a young and active field. The use of traditional neurophysiological methods is very tightly constrained in human subjects, but whole-brain monitoring techniques are considerably more advanced for humans than for animals. These latter methods in particular allow routine recording of neural activity from humans while they perform complex auditory tasks that would be very difficult for animals to learn. The findings reviewed in this chapter cover investigations obtained with a variety of experimental methodologies, including electroencephalography, magnetoencephalography, electrocorticography, and functional magnetic resonance imaging. Topics covered in detail include investigations in humans of the neural basis of spatial hearing, auditory stream segregation of simple sounds, auditory stream segregation of speech, and the neural role of attention. A key conceptual advance noted is a change of interpretational focus from the specific notion of attention-based neural gain, to the general role played by attention in neural auditory scene analysis and sound segregation. Similarly, investigations have gradually changed their emphasis from explanations of how auditory representations remain faithful to the acoustics of the stimulus, to how neural processing transforms them into new representations corresponding to the percept of an auditory scene. An additional important methodological advance has been the successful transfer of linear systems theory analysis techniques commonly used in single-unit recordings to whole-brain noninvasive recordings.

Keywords Attentional gain · Auditory scene analysis · Binaural integration · Electrocorticography · Electroencephalography · Functional magnetic resonance imaging · Heschl's gyrus · Human auditory system · Interaural level difference · Interaural time difference · Magnetoencephalography · Maskers · Planum temporale · Positron emission tomography · Selective attention · Speech · Superior temporal gyrus

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Outline

- What is the Cocktail Party Problem?
- What is Human Auditory Neuroscience?
- Cocktail Parties, Simplified:
  - Tones—with and without directed Attention
  - Speech
- Recent Results: Perceptual & Neural Filling-In

Outline

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The Cocktail Party (I)

Alex Katz,
The Cocktail Party

The Cocktail Party (I)

Alex Katz,
The Cocktail Party

The Cocktail Party (I)

Alex Katz,
The Cocktail Party

The Cocktail Party (I)

Alex Katz,
The Cocktail Party

The Cocktail Party (II)

Inter-related Processes

- The Cocktail Party Problem
  - Multiple ***speech*** streams (sources)
- Auditory Scene Analysis
  - Auditory objects
- Stream Segregation
  - Segregation / Identification / Formation
- Related Concepts, e.g., Filling-In

Cocktail Party Cues

- Sound source location
- Pitch (f0) [when it exists]
- Timbre (spectral envelope, vibrato, …)
- Speaker sex, age, accent, language, …
- Derived not Intrinsic
  - not clear **how** a cue is reconstructed when sounds linearly mixed in a complex scene
- Number of sources also must be derived
- Statistics of a speech stream (or other source)

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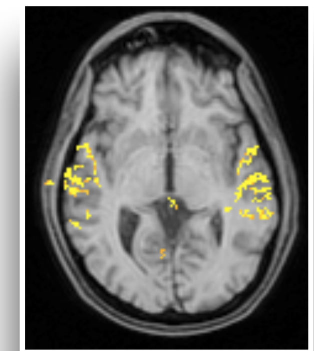
Functional Brain Imaging

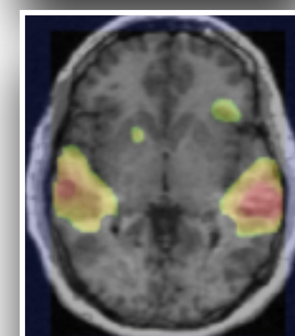
Functional Brain Imaging
= **Non-invasive recording from human brain**

Hemodynamic techniques

fMRI
functional magnetic resonance imaging



PET
positron emission tomography



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

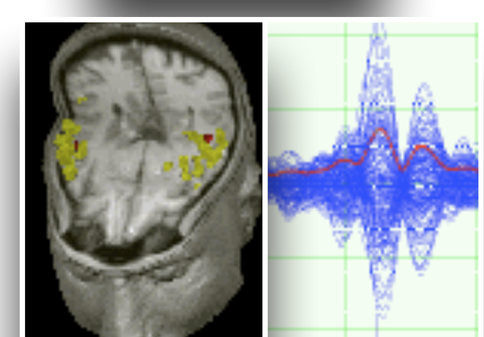
Poor Temporal Resolution **(~1 s)**

fMRI & MEG can capture effects in single subjects

Electromagnetic techniques

EEG
electroencephalography

MEG
magnetoencephalography

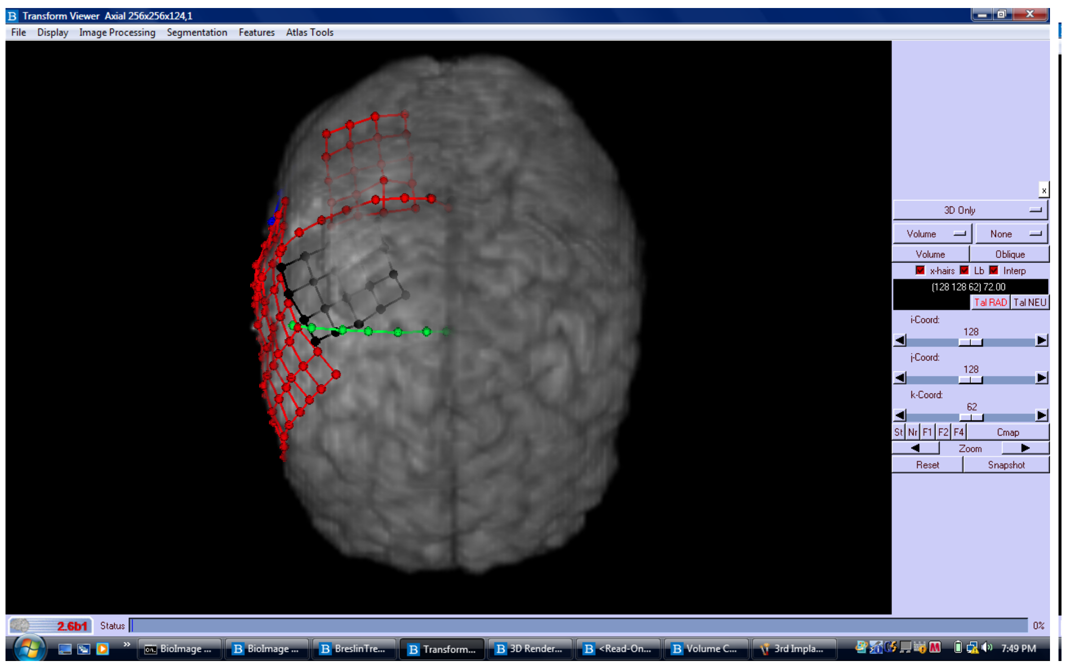


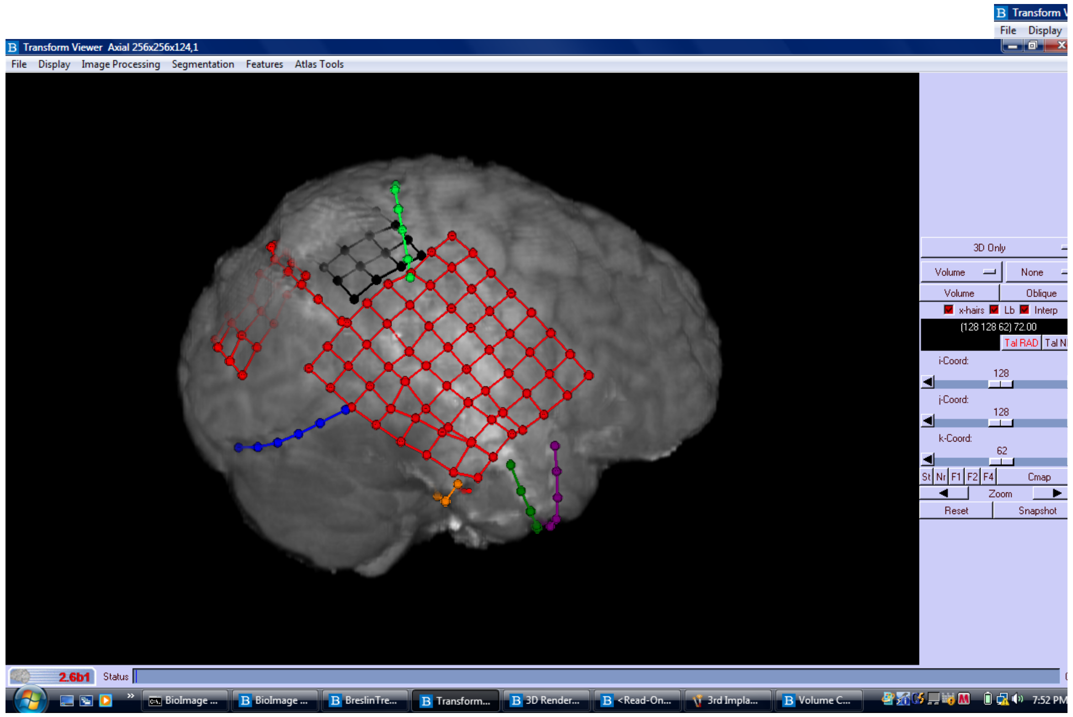
Poor Spatial Resolution **(~1 cm)**

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

Invasive Recording Methods

ECoG





Depth Electrodes

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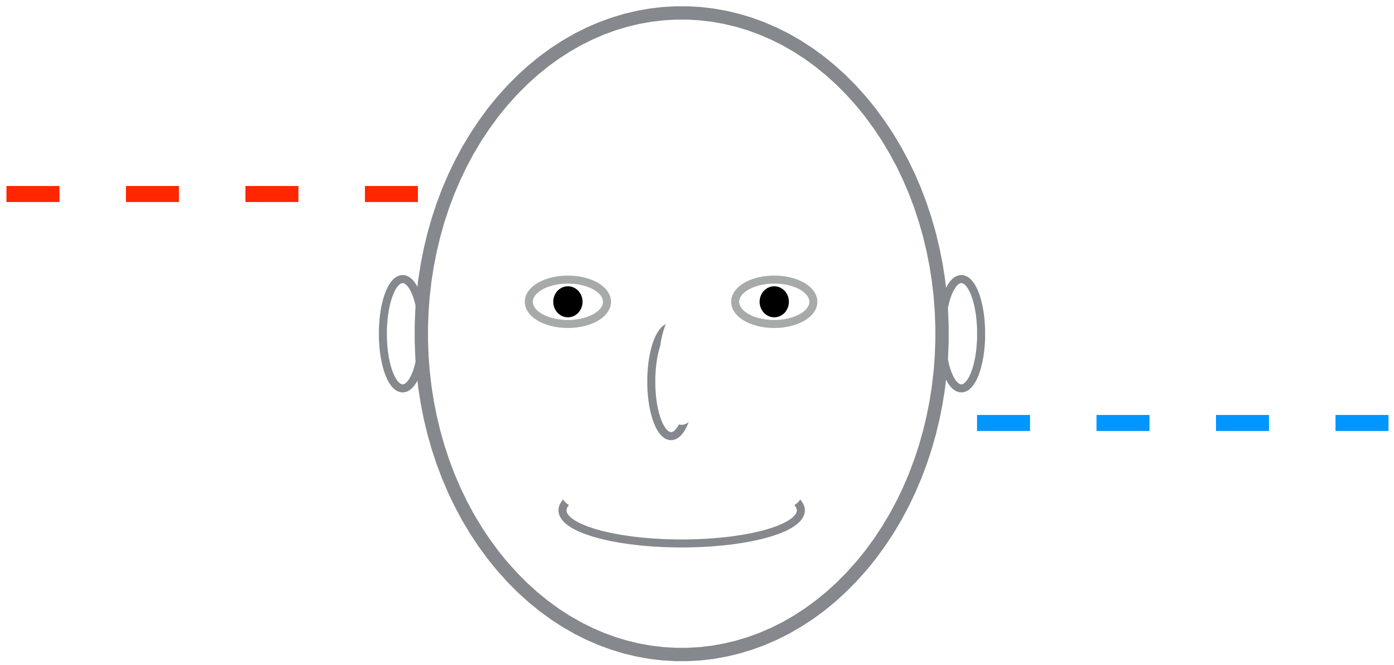
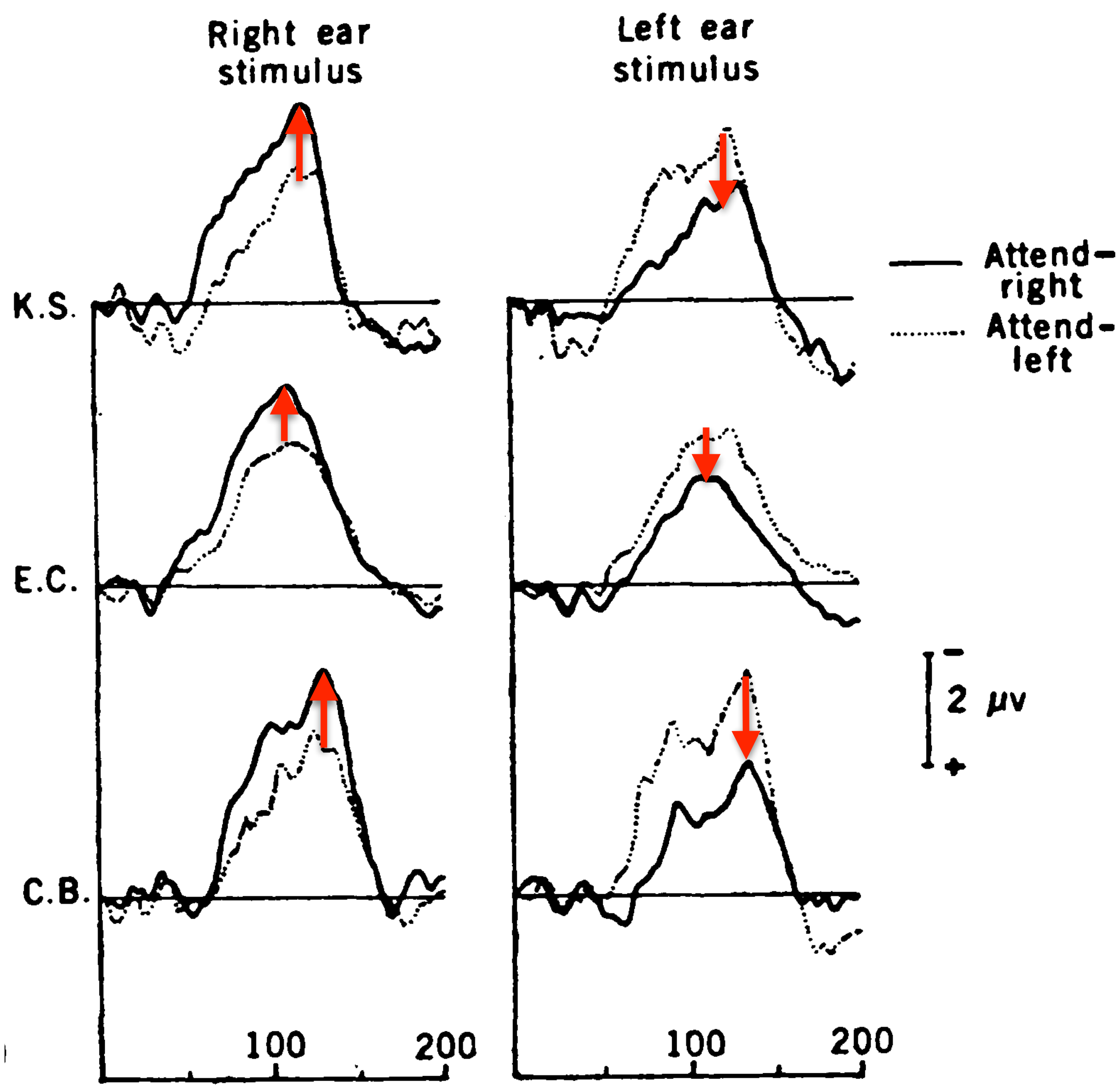
Foundational Evidence



- Simple Auditory Scene
  - Separate tone-pip streams in each ear (dichotic)
  - Attend to one stream only

Hillyard et al (1973)

Foundational Evidence



Hillyard et al (1973)

- Simple Auditory Scene
  - Separate tone-pip streams in each ear (dichotic)
  - Attend to one stream only
- Strong EEG N1 Responses
  - (Negative peak with ~100 ms latency)
- Enhanced N1 amplitudes for attended (foreground) stream
- *Historically*: Neural Correlate of ***Selective Attention***
- *Better(?)*: Neural Correlate of ***Successful Auditory Scene Segregation***

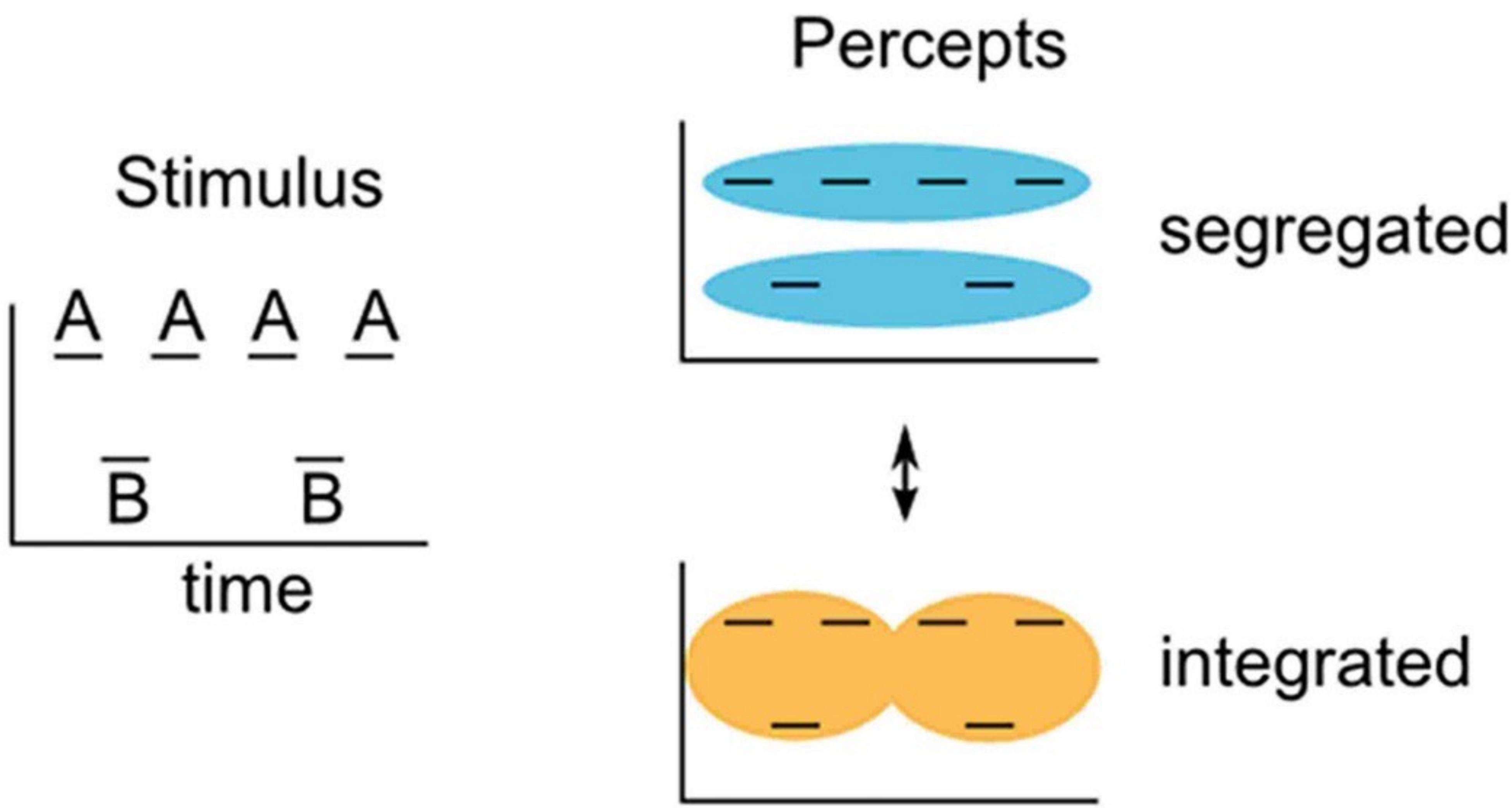
Simple Complex Scenes

- Remove spatial information (diotic only)
  - Spatial information Useful but not Necessary
  - not Fundamental
- Other cue(s) still needed

Simple Complex Scenes (I)

- No attentional manipulation
  - Tone-based (no speech)
  - Ambiguous auditory scene
    - Distinct percepts despite single stimulus
    - Avoid confound of stimulus-dependent percept

van Noorden streams

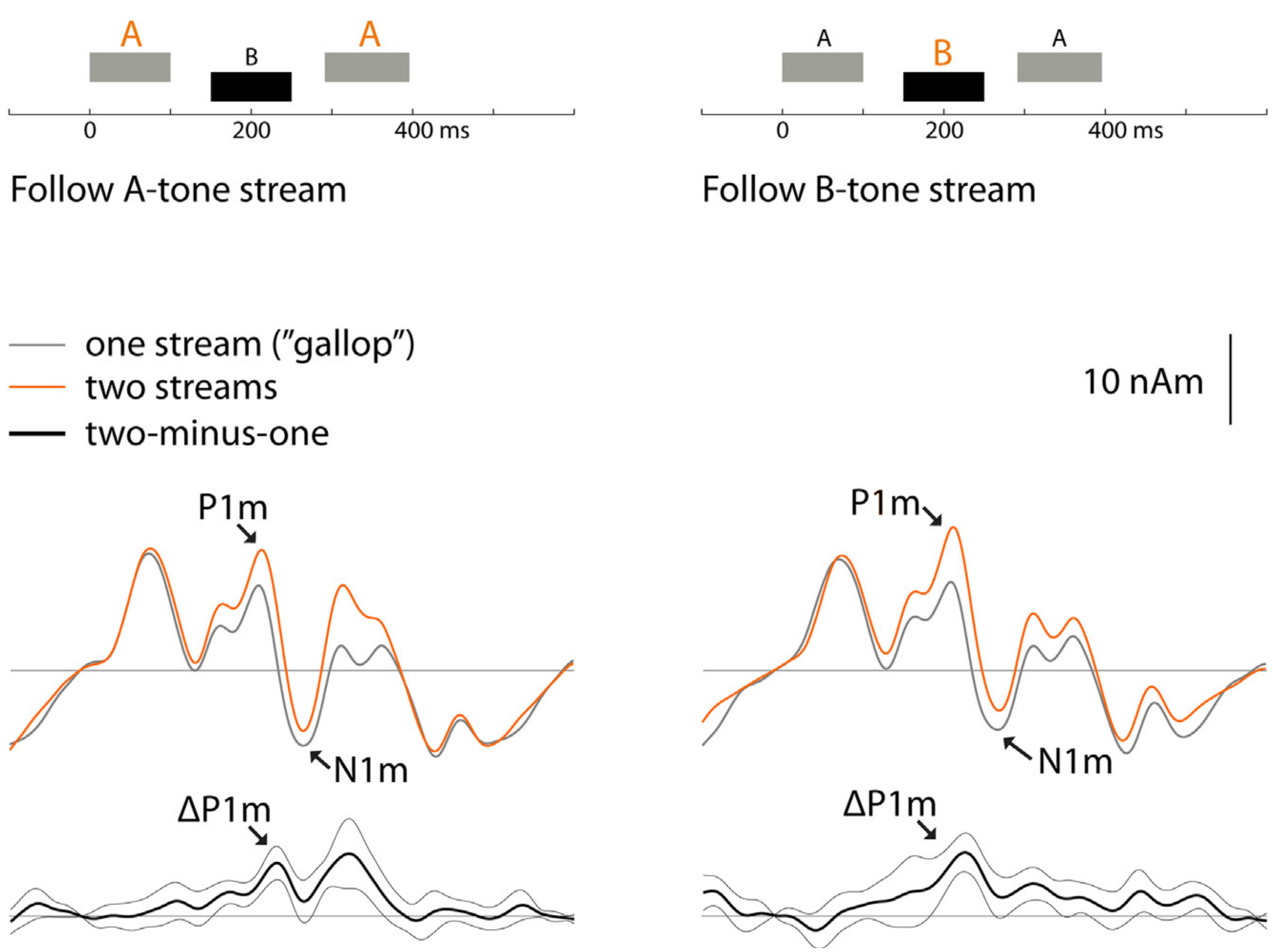


adapted from Steele et al (2015)

- One stimulus, Two percepts

van Noorden (1975)

Neural Measures of Perception



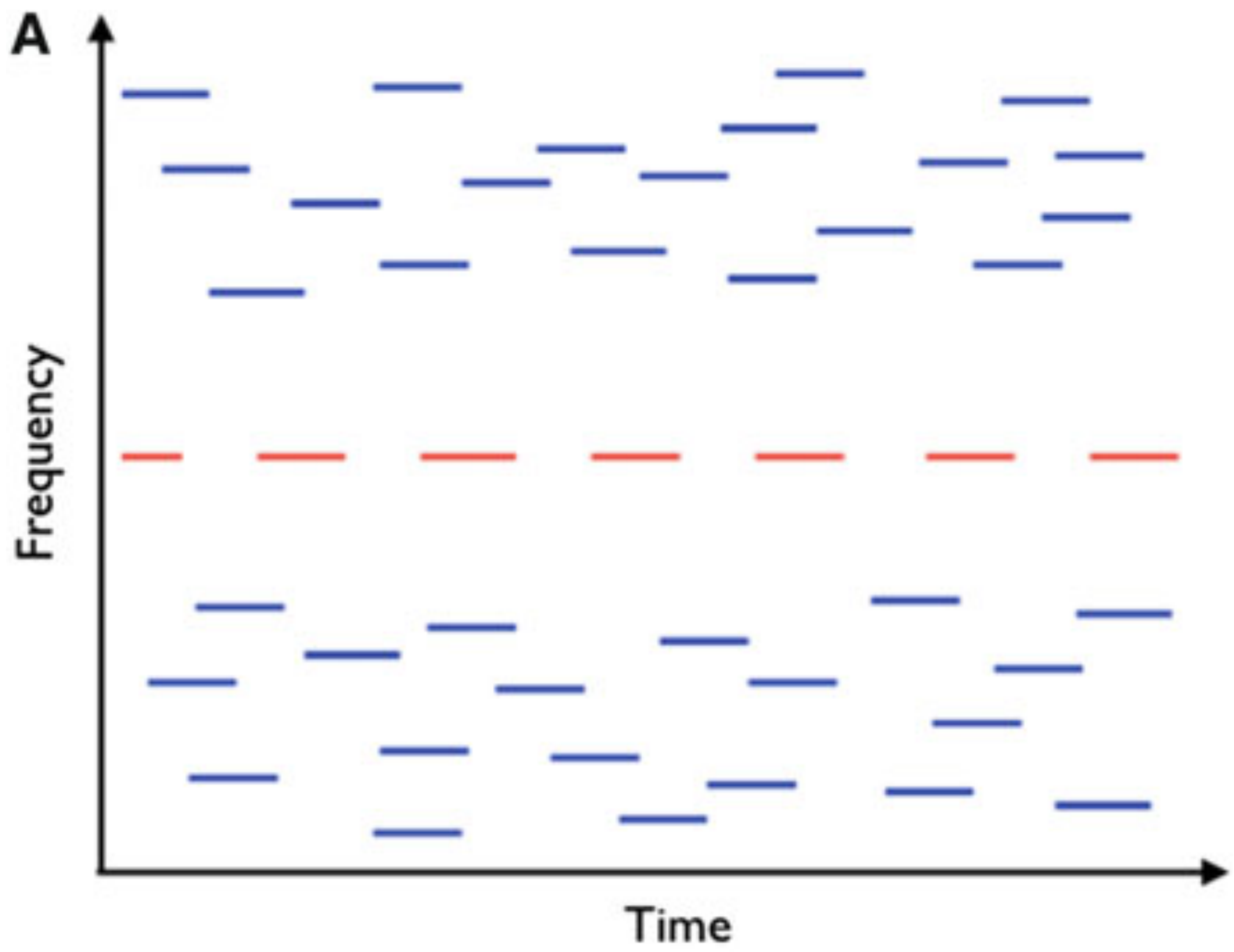
Gutschalk et al (2005)

- Segregation increases with frequency separation
- MEG P1m and N1m increase with frequency separation & segregation
- For ***constant frequency separation***, P1m and N1m increase if *perceptually* segregated
- Neural measure follows perception, not (just) physical acoustics
- Additional dissociation between neural measures and stimulus in EEG by Snyder et al (2006)
- ECoG also by Dykstra et al (2011)

Neural Measures of Perception: fMRI & PET

- Neural measures that track a percept are more difficult to see with fMRI & PET
  - Even when stimulus manipulated too
- Most effects seen only *outside* of auditory cortex
  - Only in intraparietal sulcus for Cusack (2005), varying the frequency separation
  - EEG & MEG results dominated by responses from auditory cortex
  - *ABAB* or *ABBB* patterns work better with fMRI, perhaps by avoiding habituation

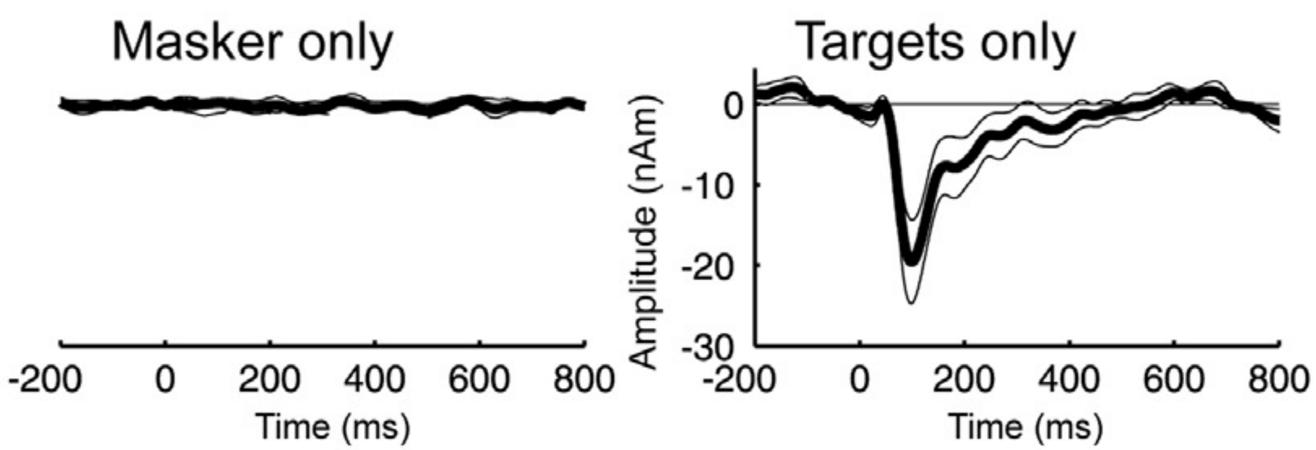
Informational Masking
Tone Clouds



modified from Kidd et al (2003)

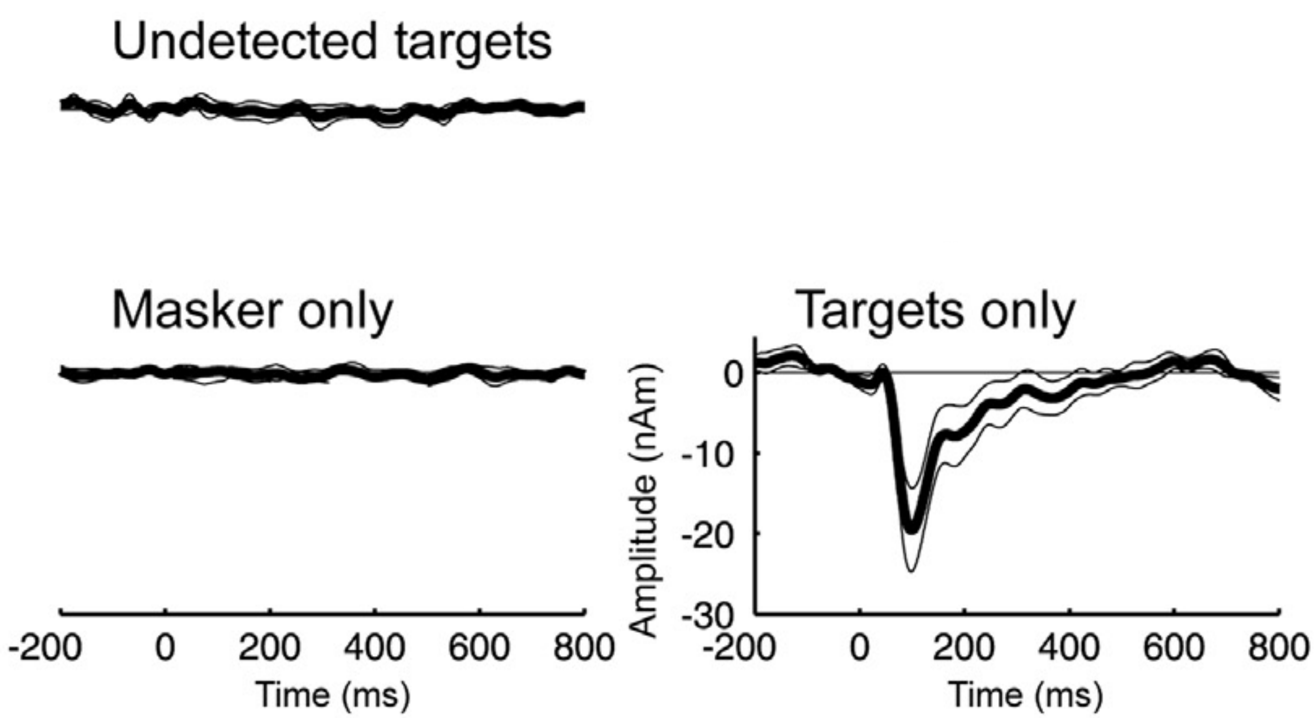
Detected vs Undetected Rhythmic Tone-Pips

- MEG respones to individual tones



Gutschalk et al (2008)

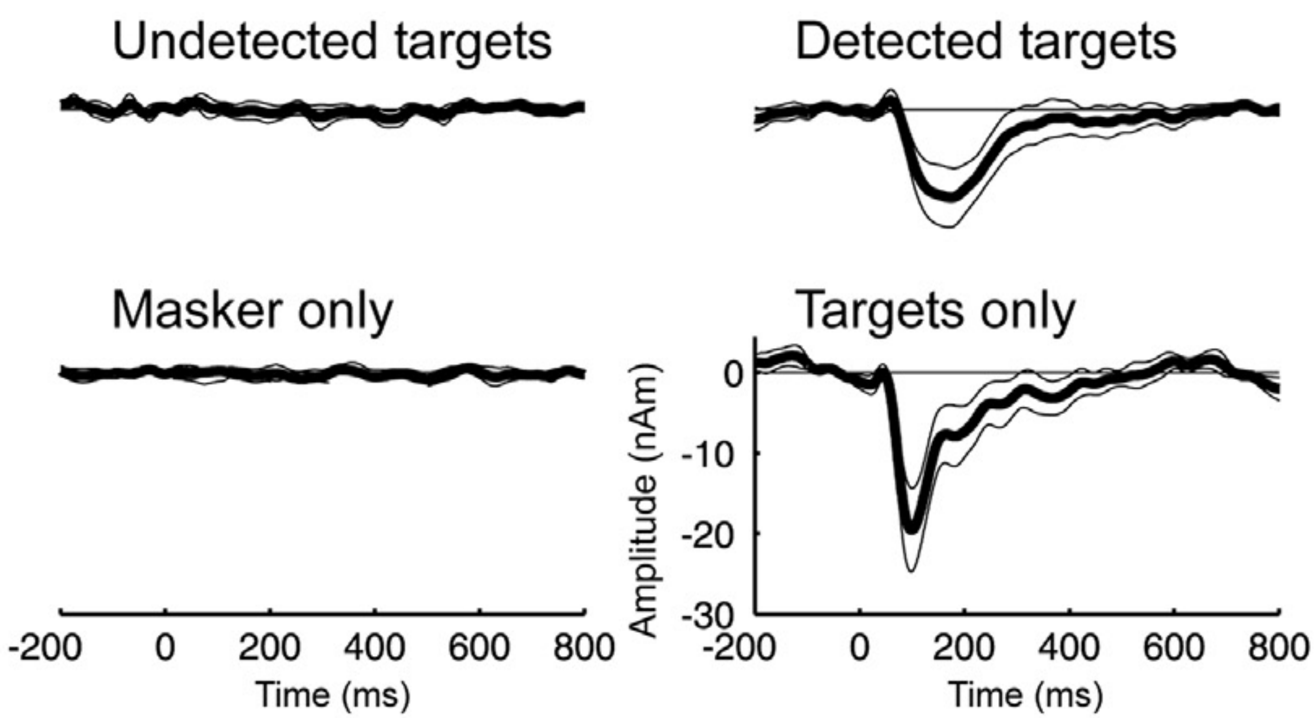
Detected vs Undetected Rhythmic Tone-Pips



- MEG respones to individual tones
  - Absent when not detected

Gutschalk et al (2008)

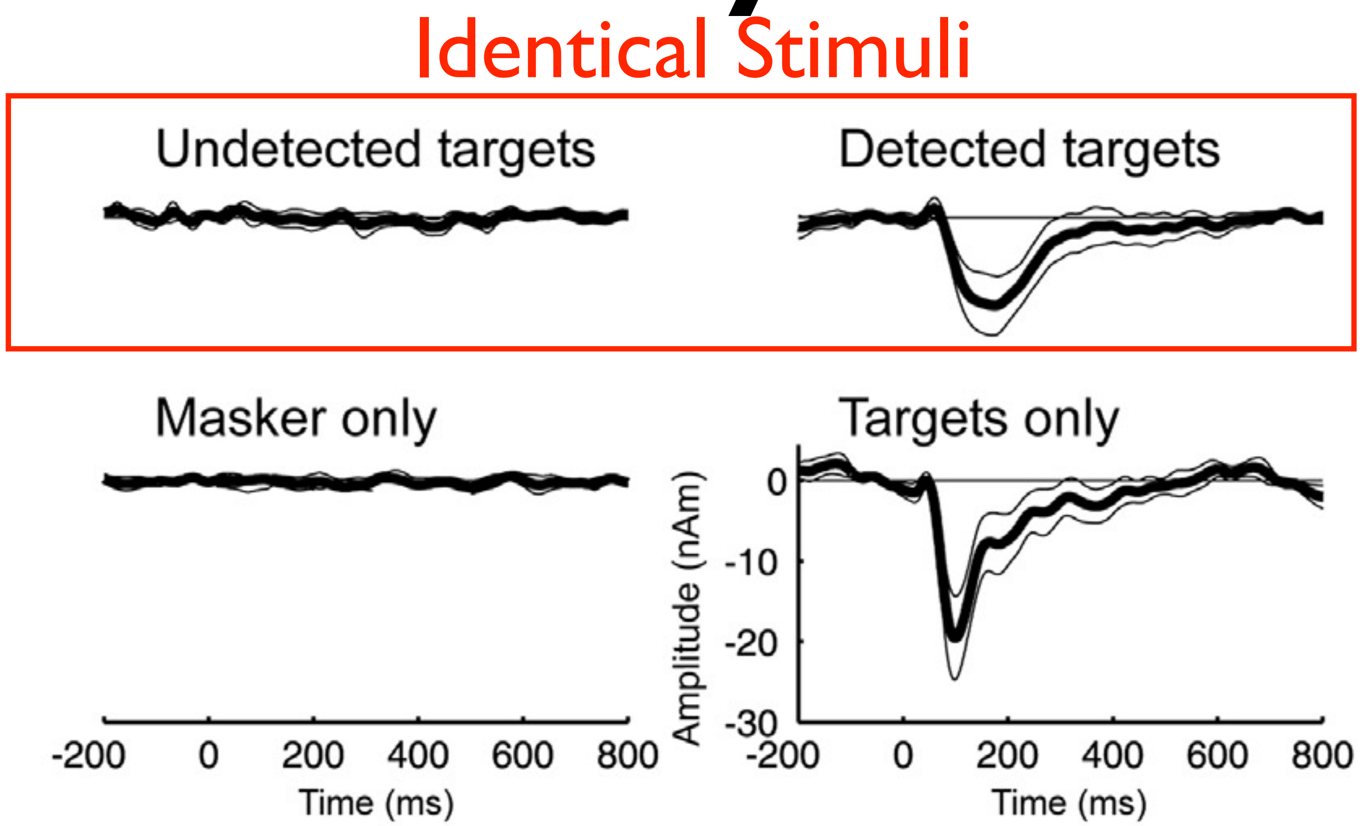
Detected vs Undetected Rhythmic Tone-Pips



- MEG respones to individual tones
  - Absent when not detected
  - Present when detected

Gutschalk et al (2008)

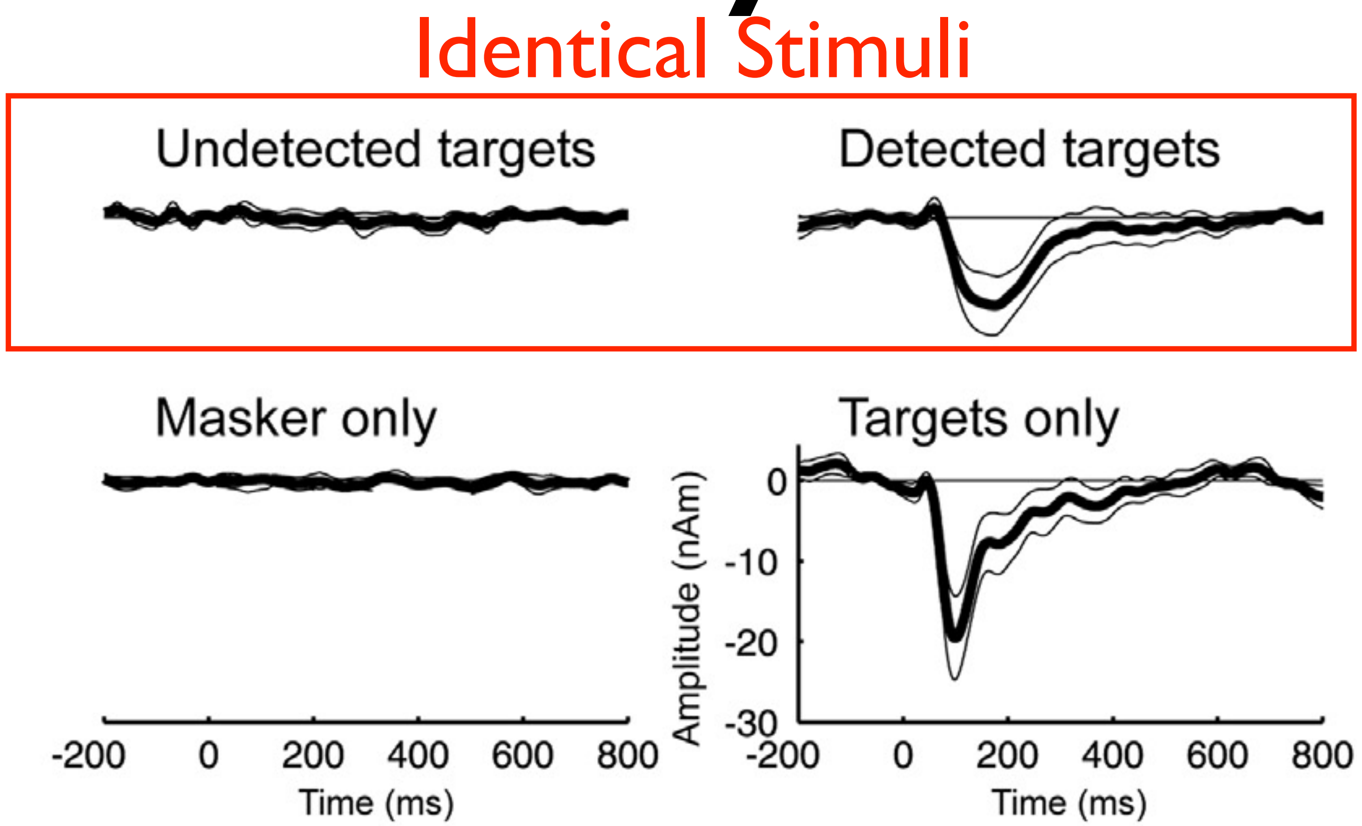
Detected vs Undetected Rhythmic Tone-Pips



- MEG respones to individual tones
  - Absent when not detected
  - Present when detected
- Origin in Auditory Cortex (Planum Temporale)
- Auditory Response linked to percept not acoustics

Gutschalk et al (2008)

Detected vs Undetected Rhythmic Tone-Pips



- MEG respones to individual tones
  - Absent when not detected
  - Present when detected
- Origin in Auditory Cortex (Planum Temporale)
- Auditory Response linked to percept not acoustics
- fMRI results do not completely agree: widespread activation across auditory cortex, with perceptual contrast only in Heschl's Gyrus [Wiegand and Gutschalk (2012)]

Gutschalk et al (2008)

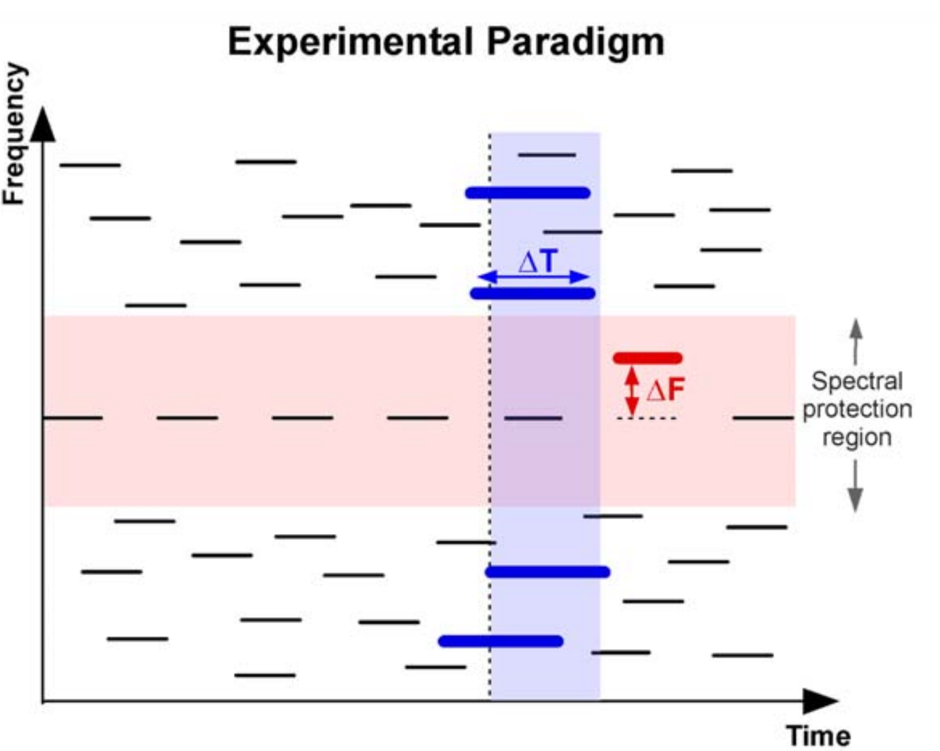
Neural Measures of Perception

- Multiple cortical representations of the sounds present in an acoustic scene.
- Some determined more by the percept of a sound than its acoustics (typically later representations in higher-order auditory cortex: Planum Temporale)
- Some neural measures track (or perhaps more likely, precede) the percept of the sound

Simple Complex Scenes (II)

- Now ***with*** attentional manipulation
  - Still tone-based (no speech)
  - Still ambiguous auditory scene
    - Distinct percepts despite single stimulus
    - Avoid confound of stimulus-dependent percept
  - *Directed* ***attention*** *determines percept* (mostly)

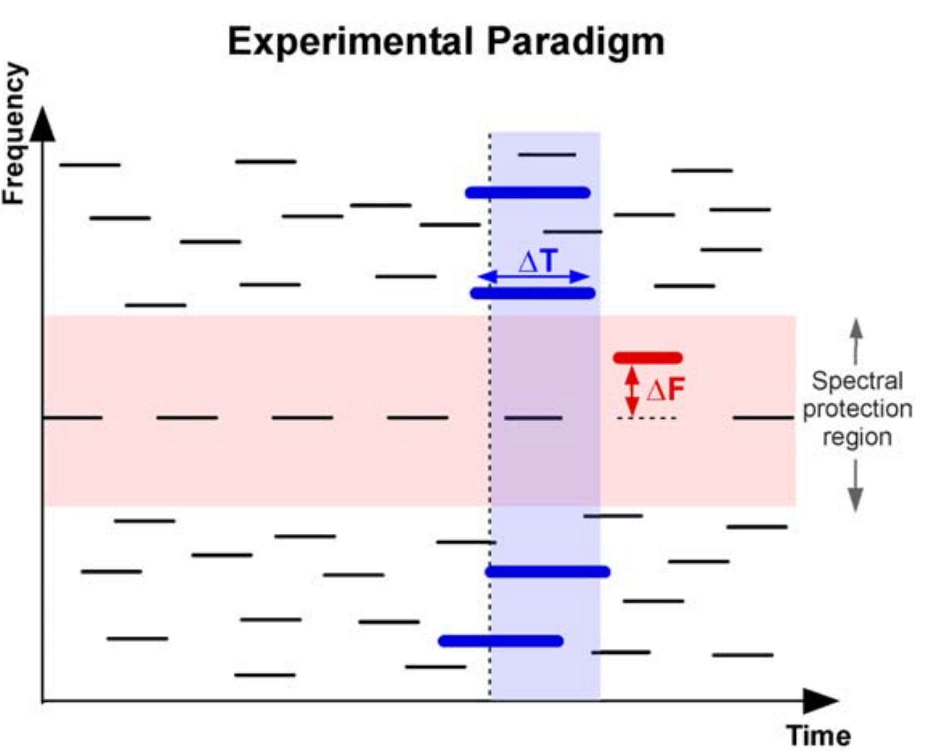
Neural Measures of Attentionally-Guided Perception

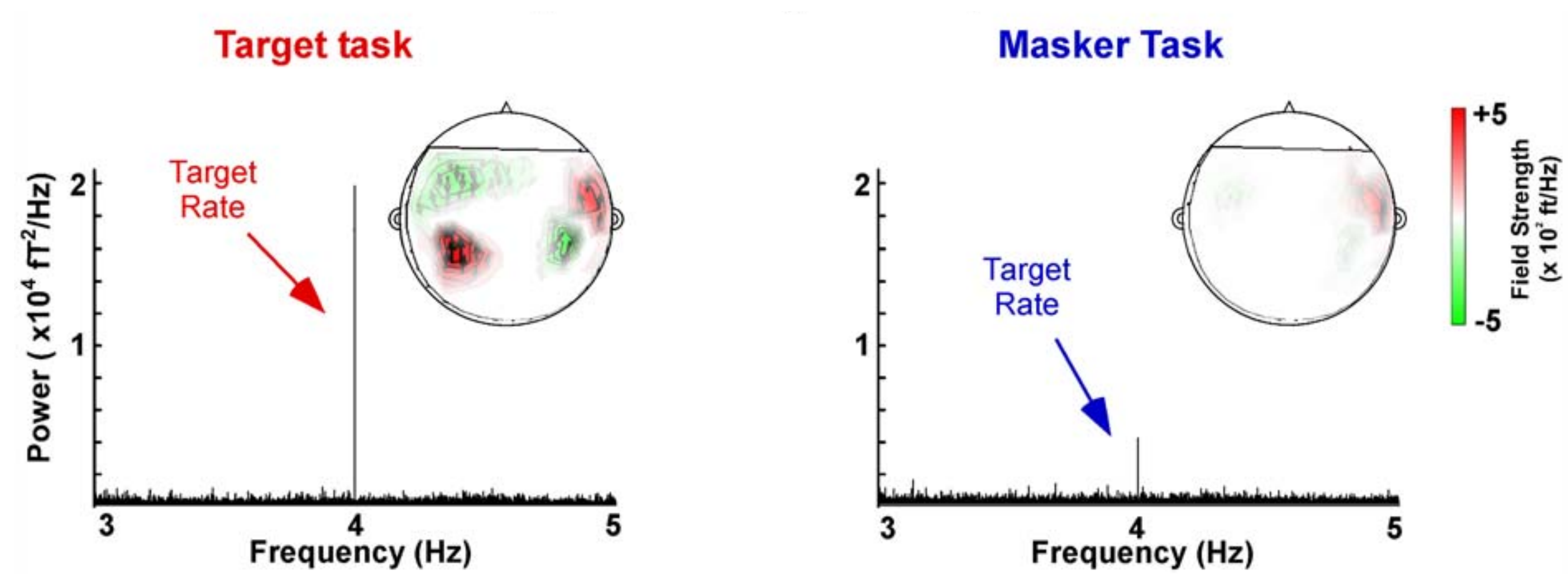


Attention **Always** On

Elhilali et al. PLoS (2009)

Neural Measures of Attentionally-Guided Perception





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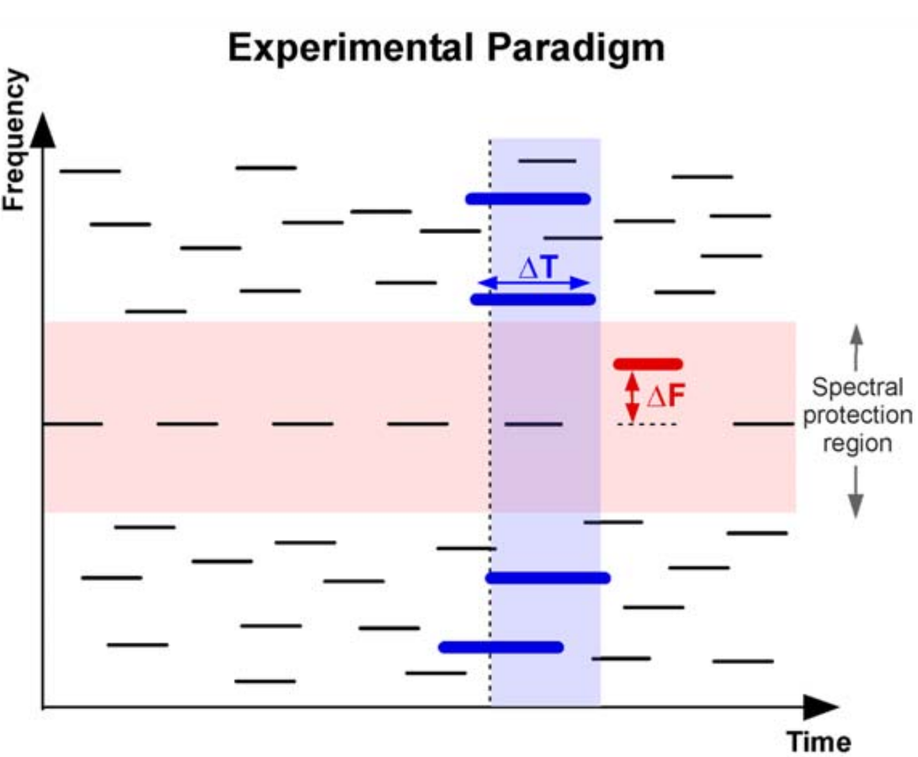

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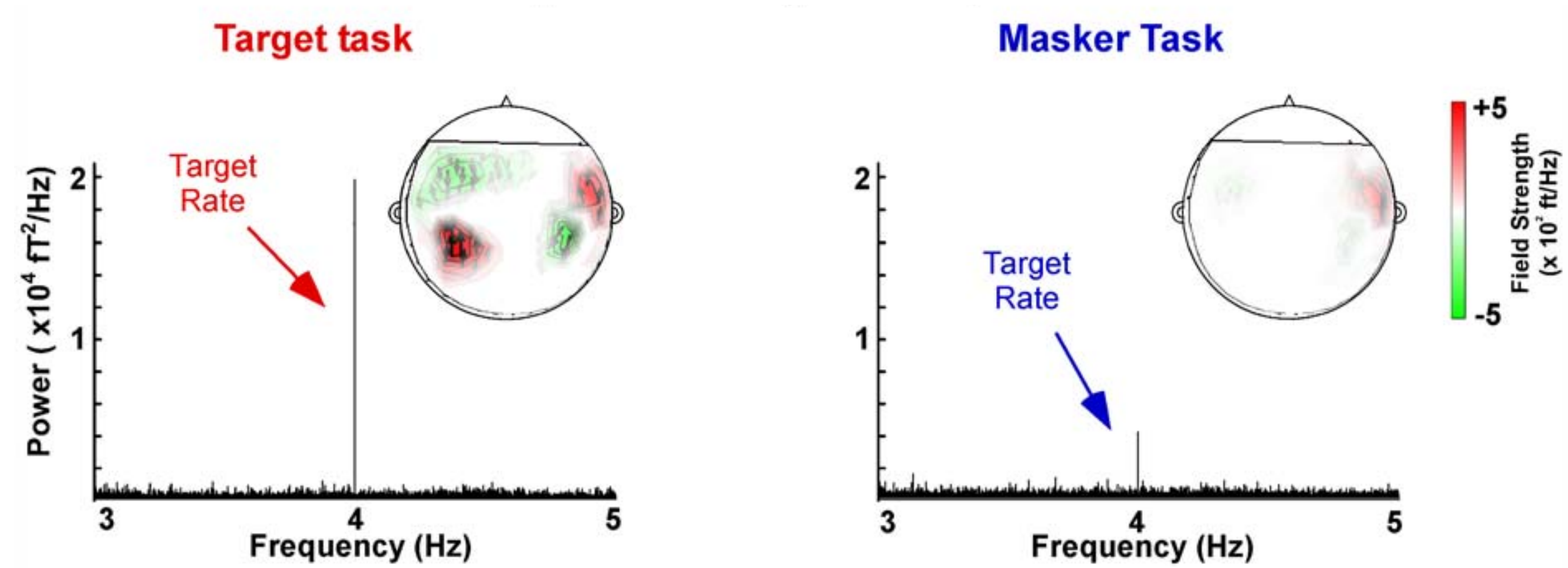

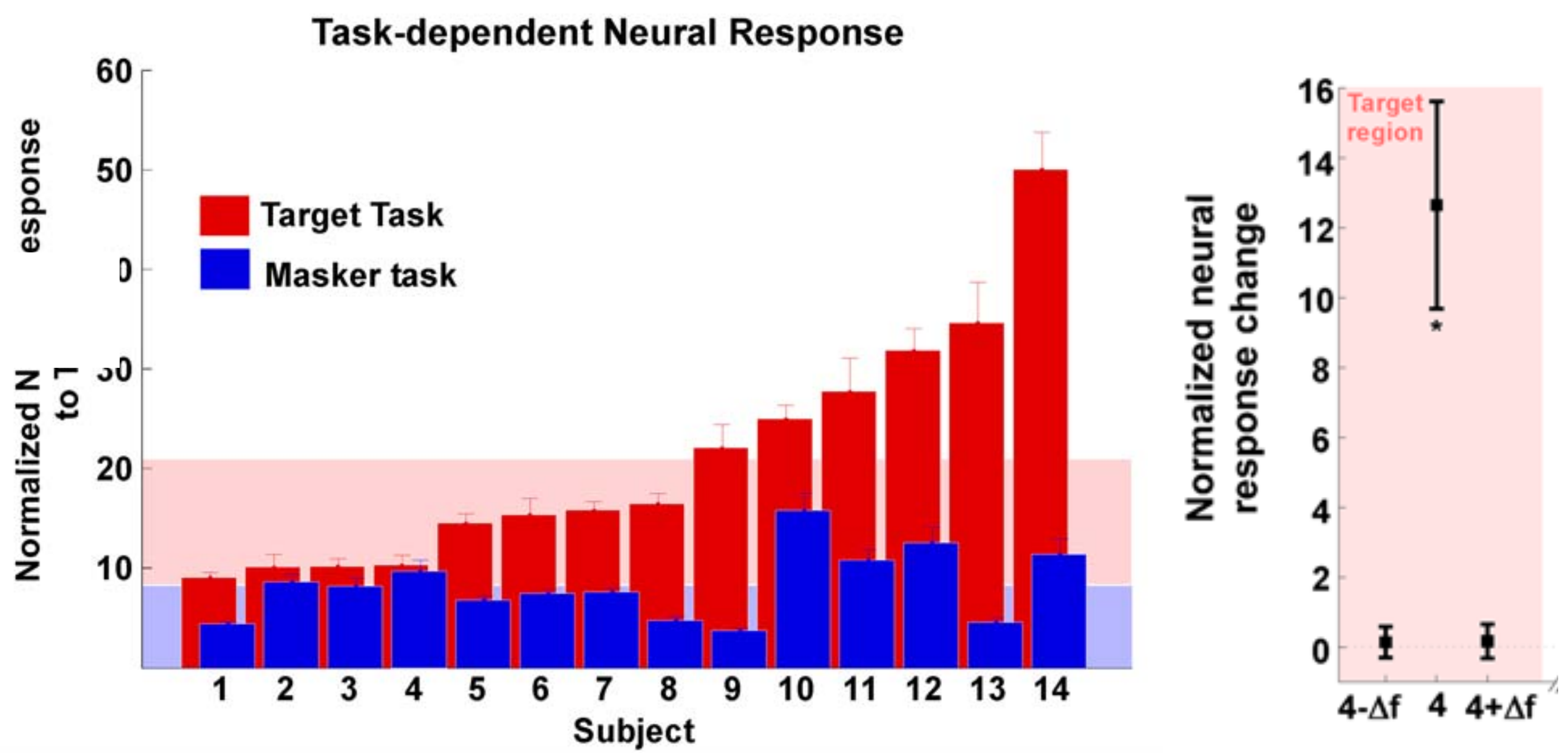

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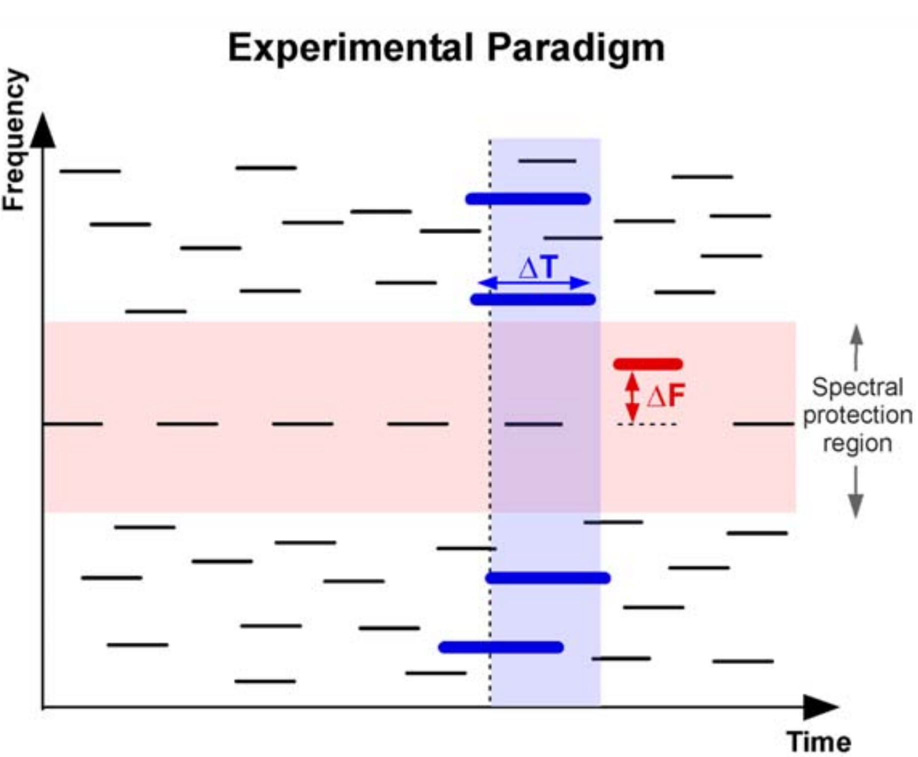

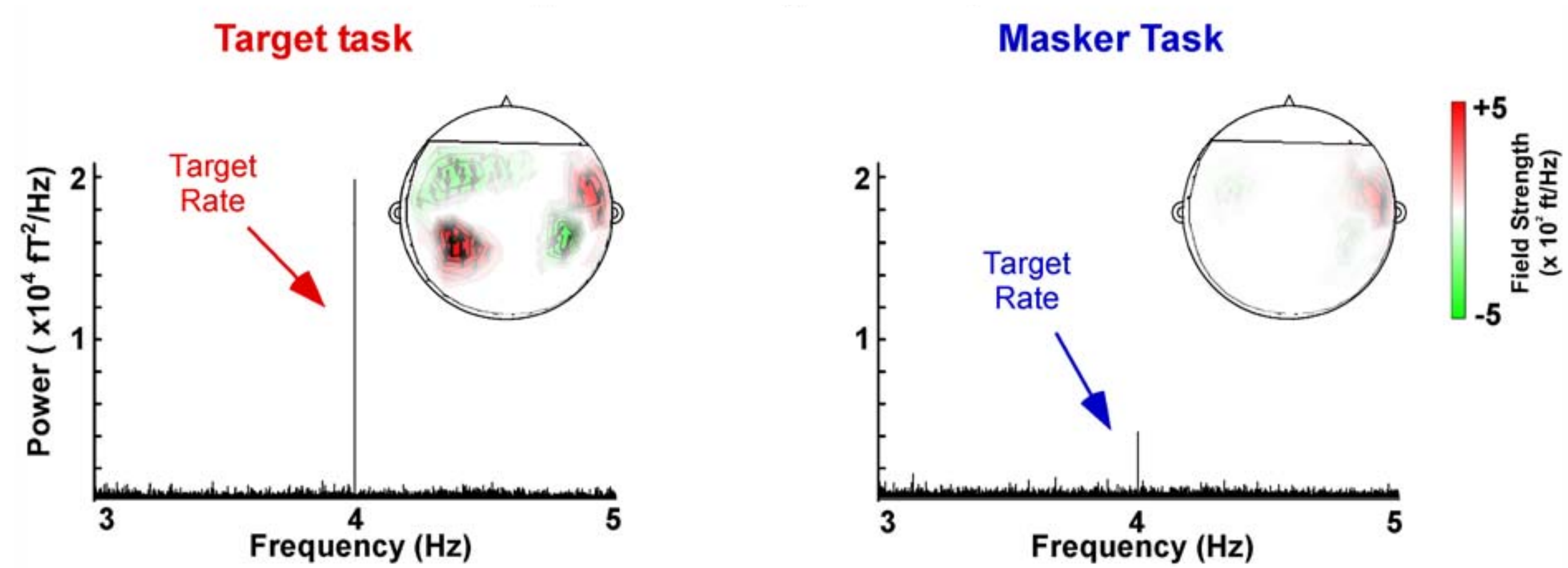

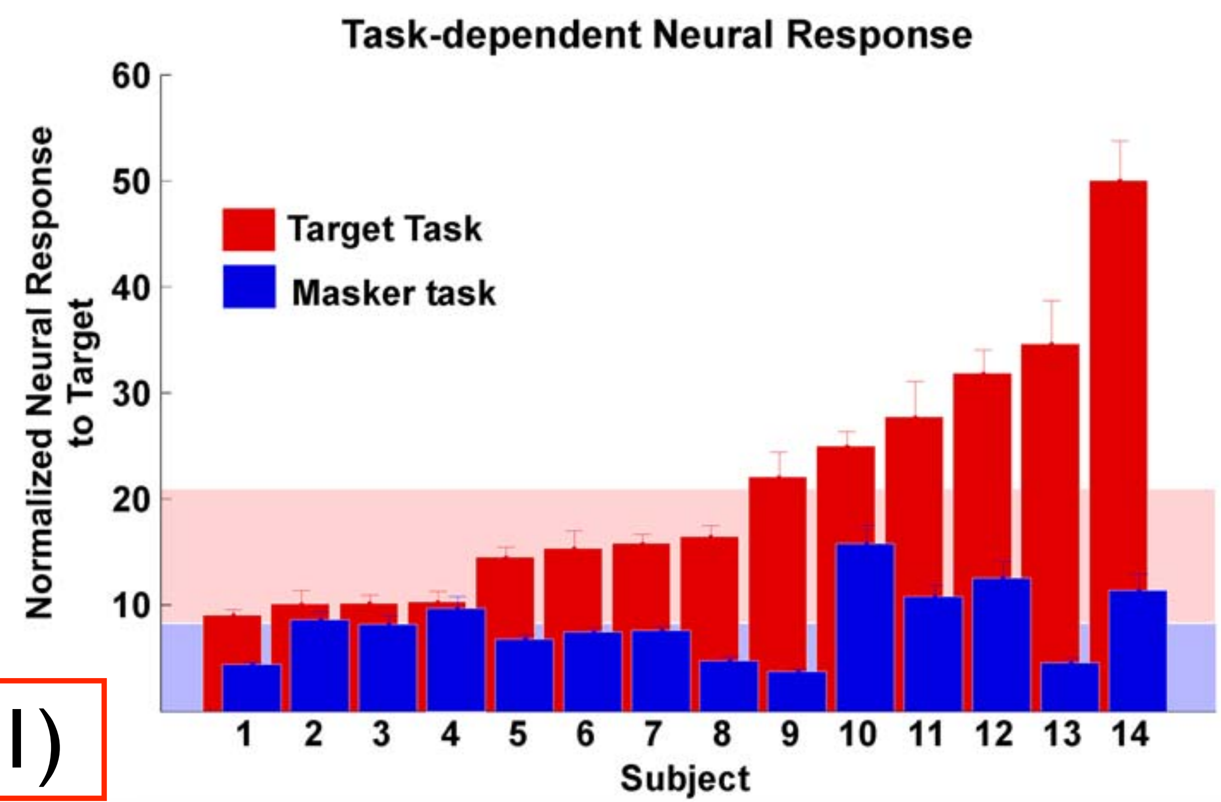

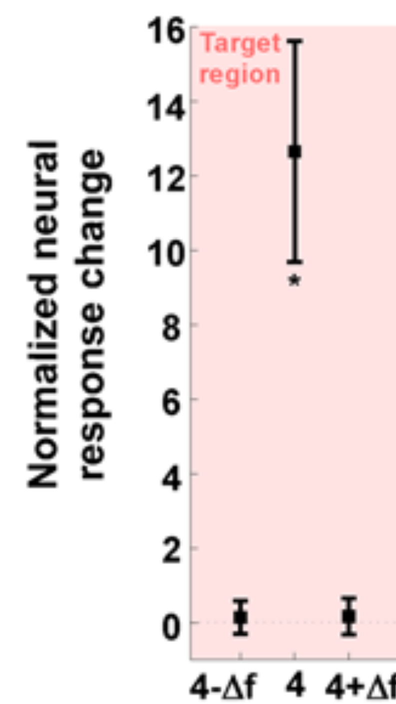

see also Ahveninen et al. (2011)

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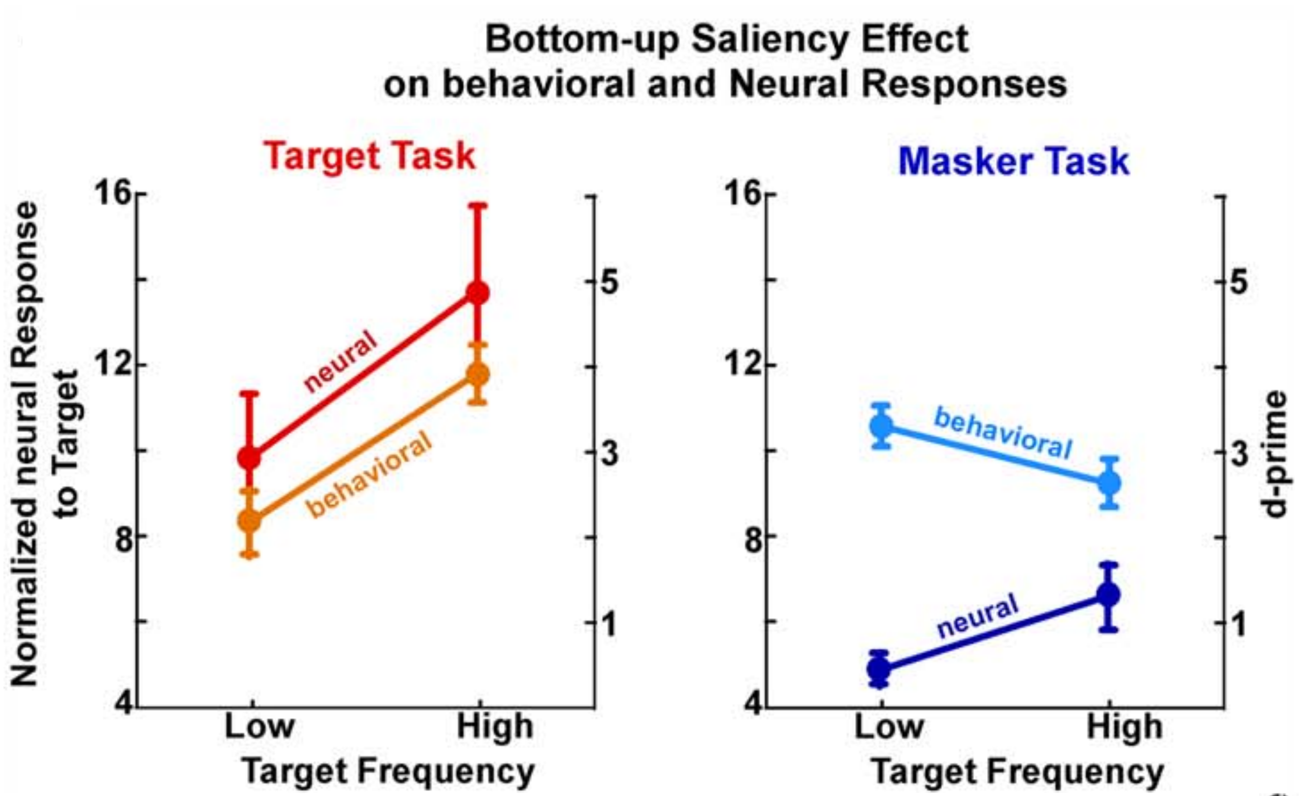
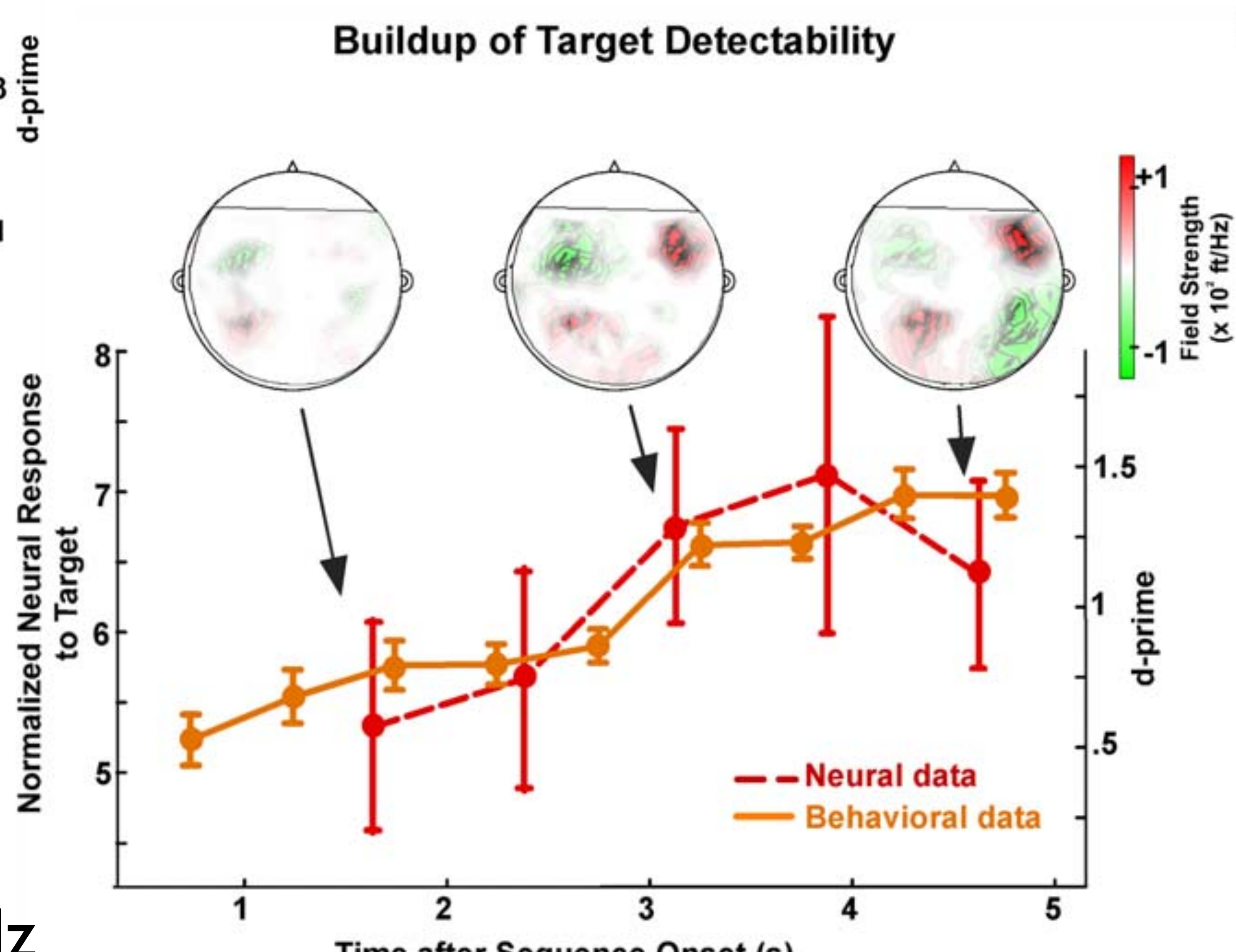




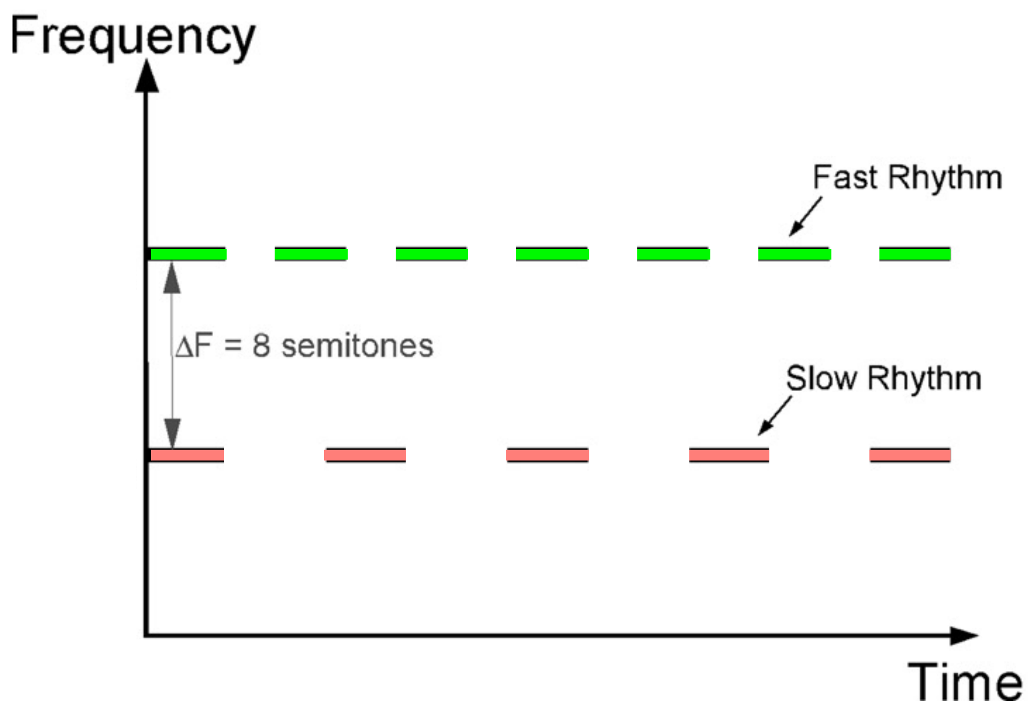
Elhilali et al. PLoS (2009)

see also Akram et al. (2014) for 7 Hz

Neural Measures of Perception

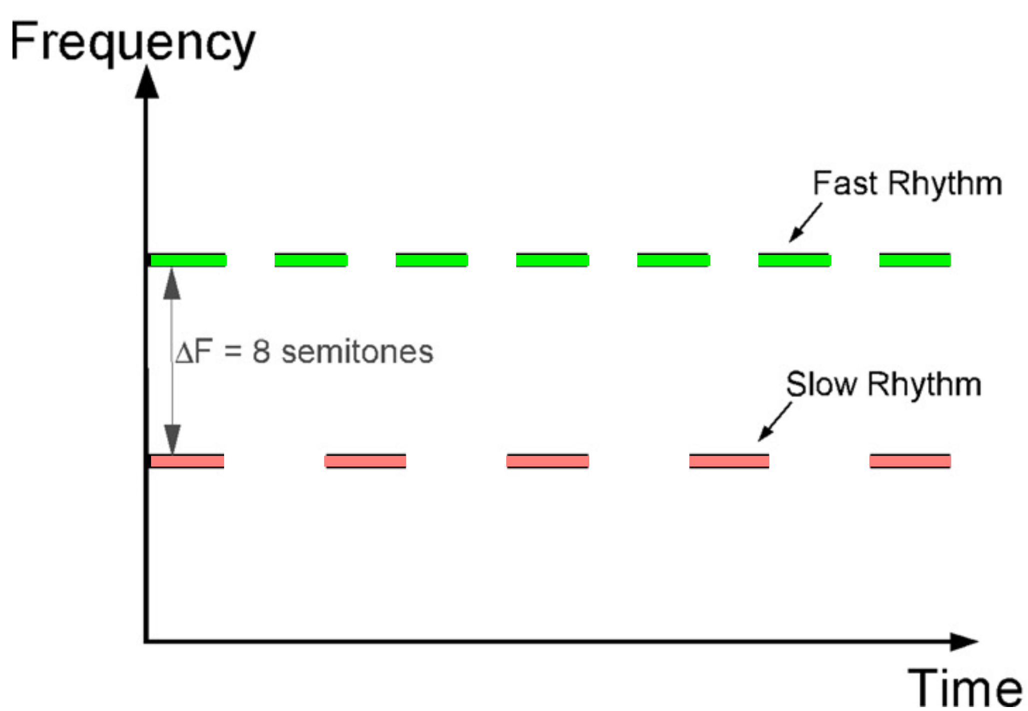
- Direction of auditory attention influences both *percept* and *neural response*
- Robust effect
- Both bottom-up and top-down
- Temporal build-up (over seconds) for both *percept* and *neural response*

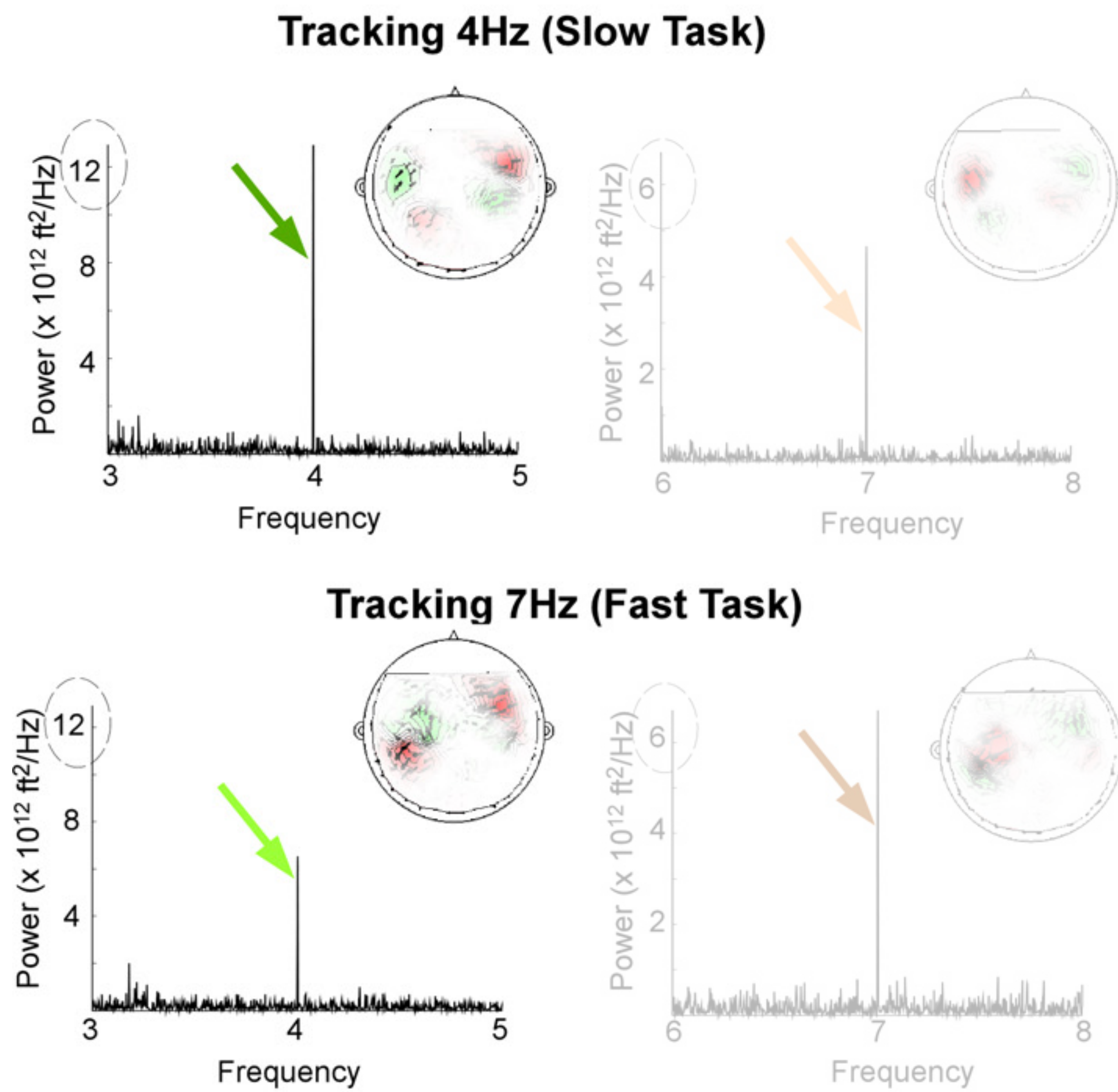
Neural Measures of Attentionally-Guided Perception



Xiang et al. (2010)

Neural Measures of Attentionally-Guided Perception





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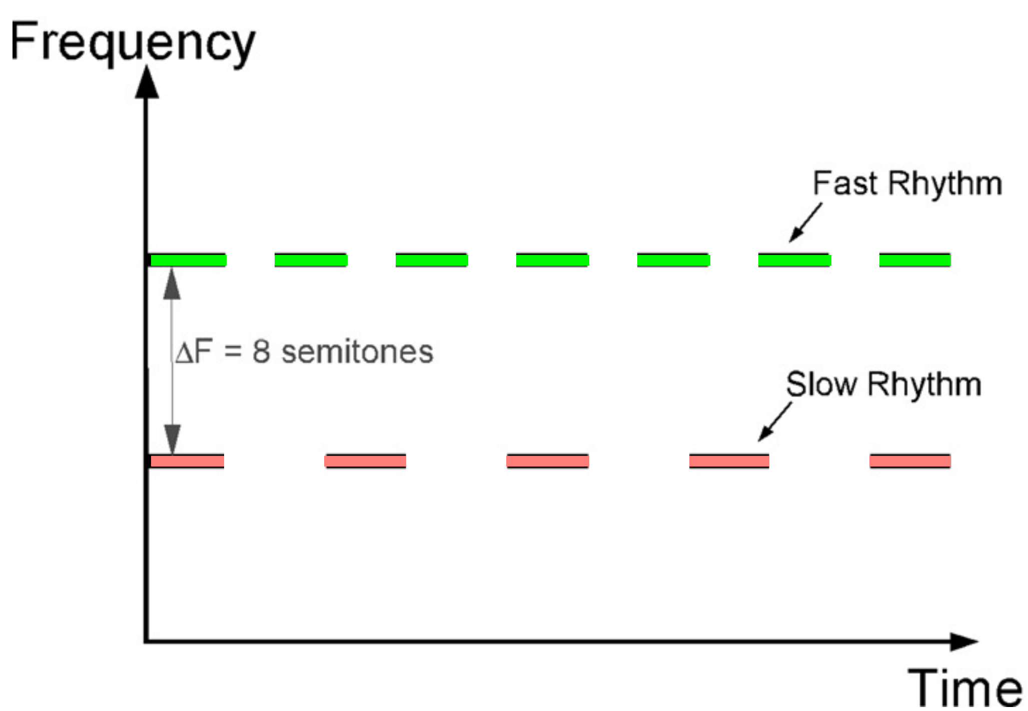

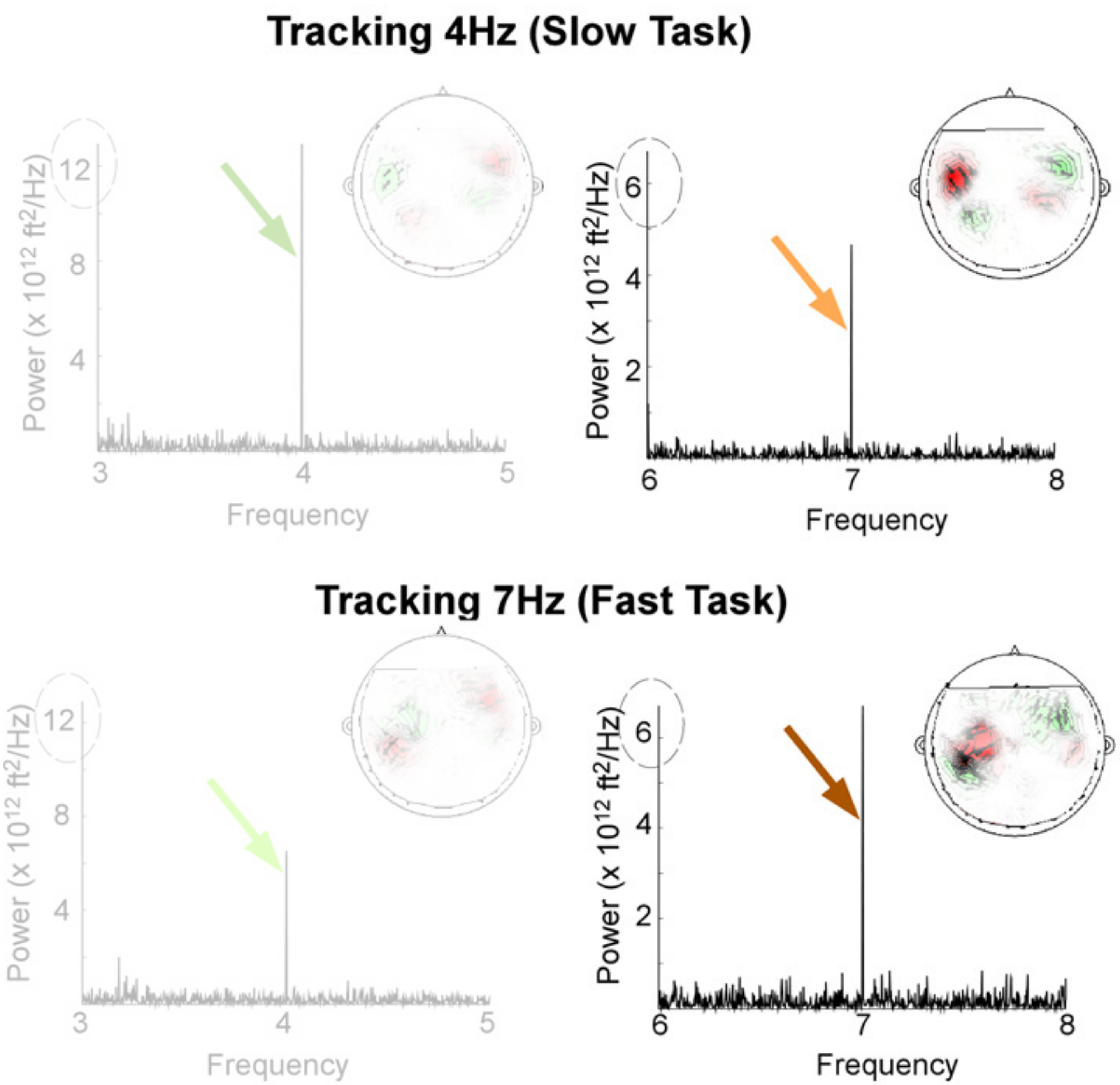

Xiang et al. (2010)

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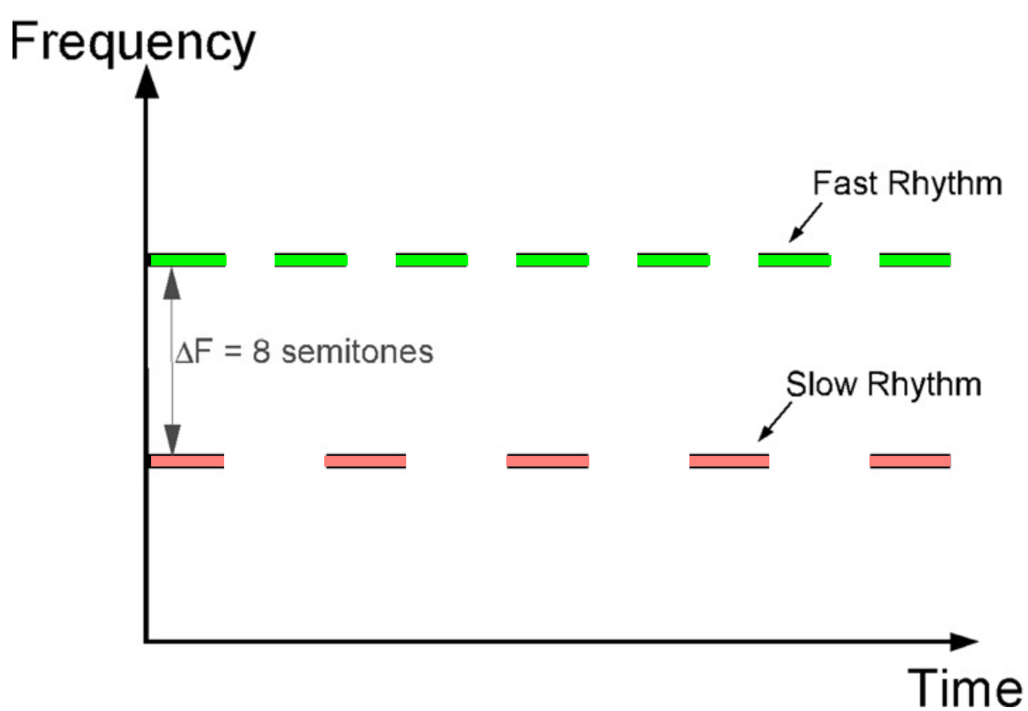

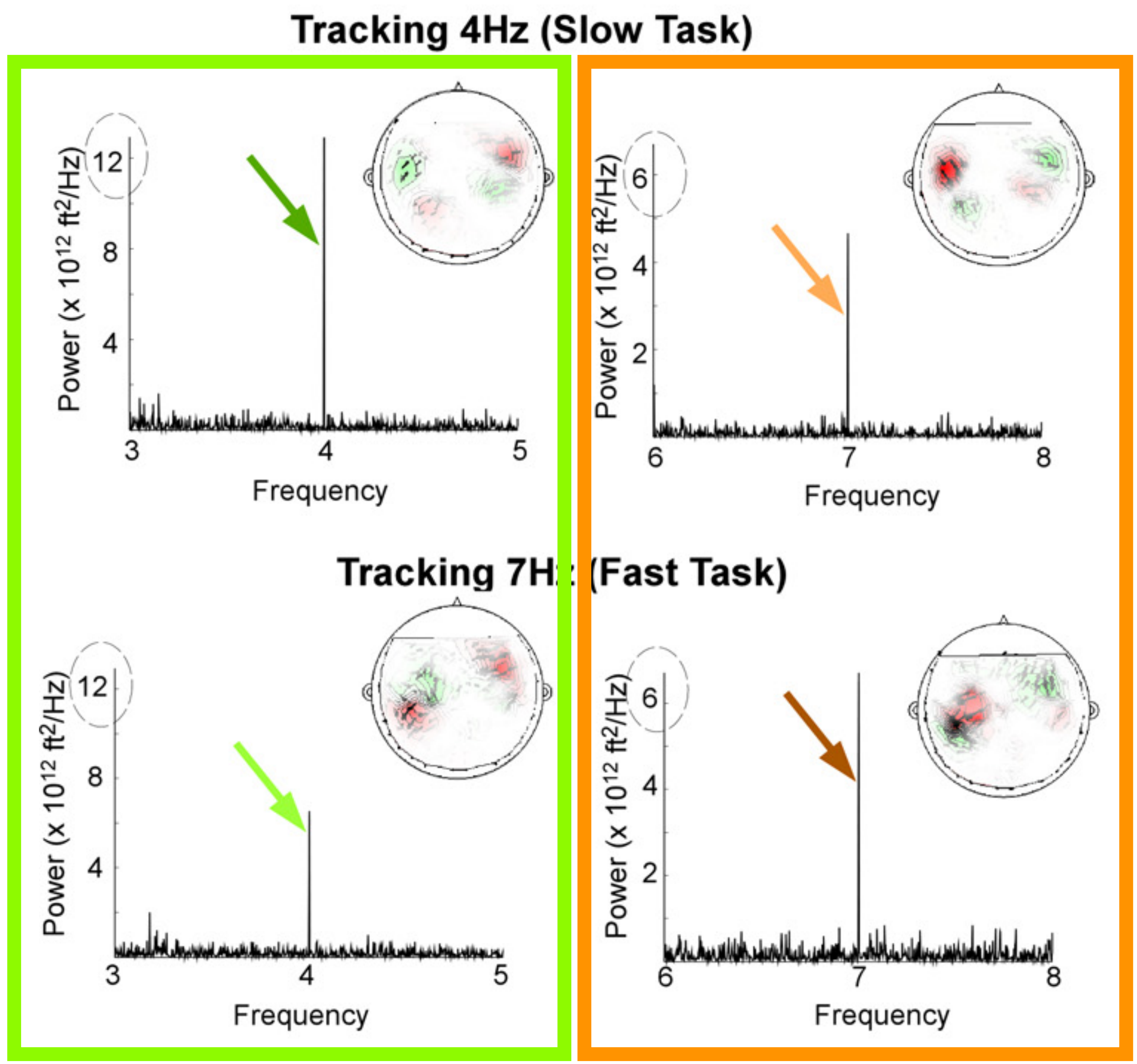

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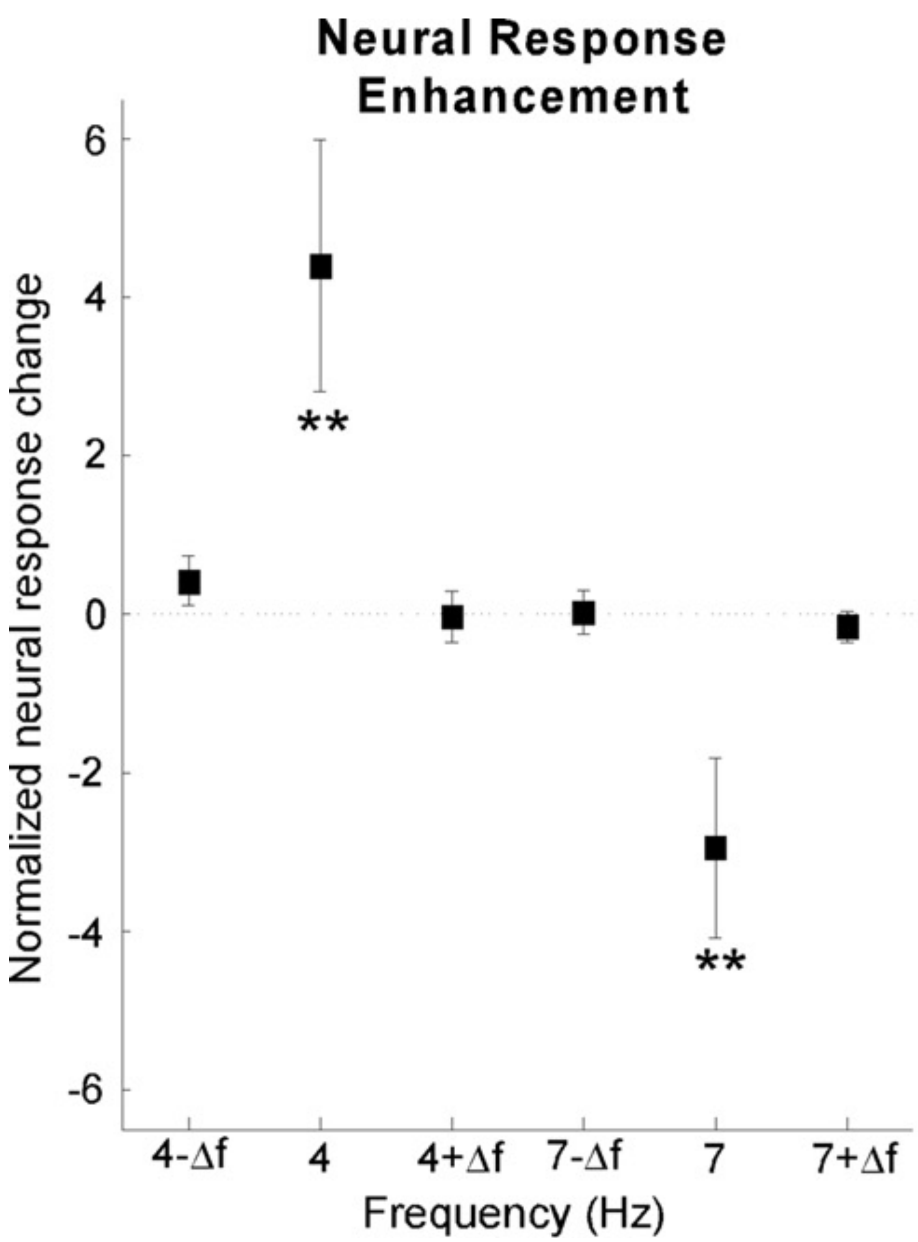

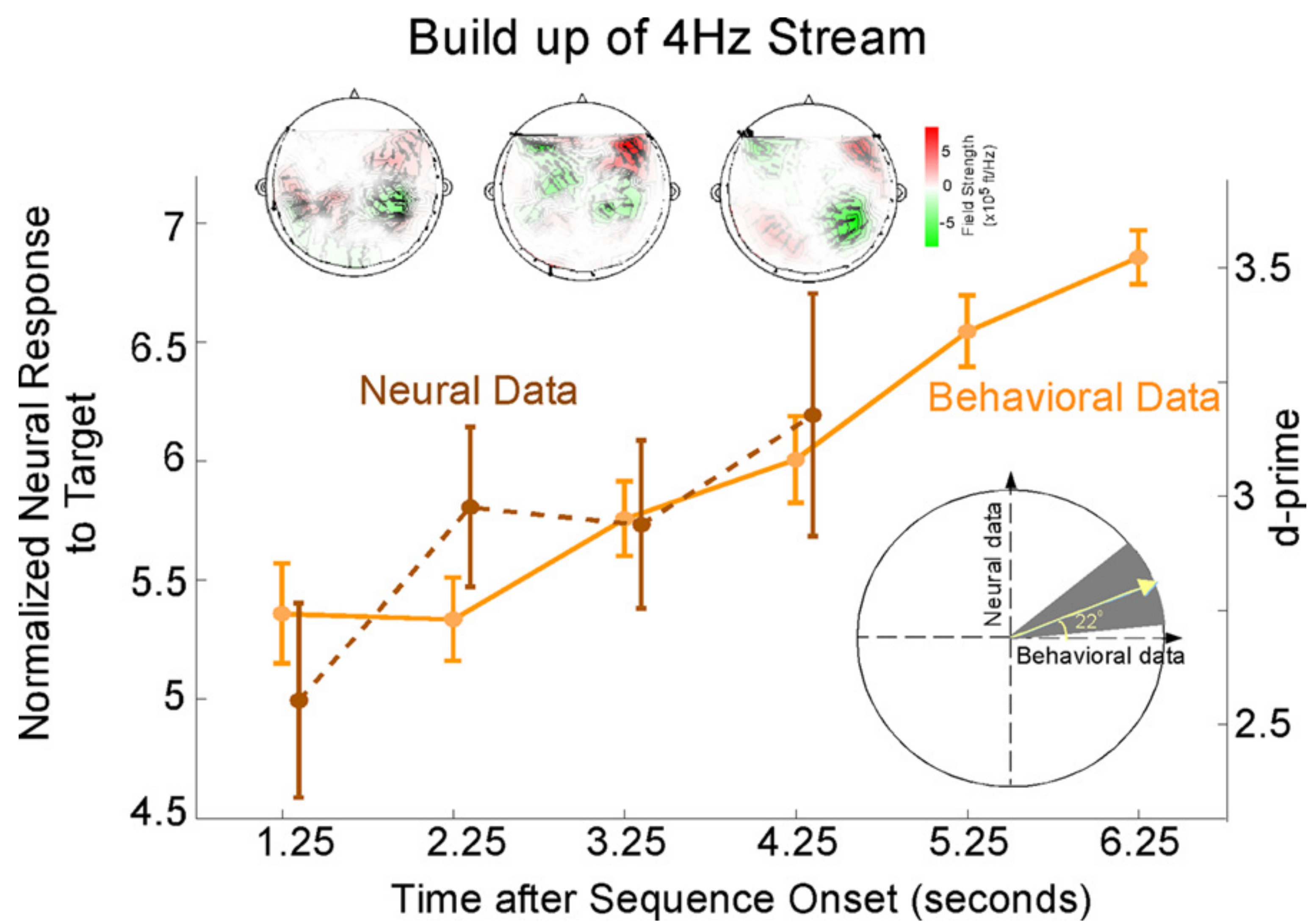

Xiang et al. (2010)

see also Bidet-Caulet et al. (2007) with depth electrodes at 21 and 29 Hz

Neural Measures of Perception

- Closer to Cocktail Party
- Direction of auditory attention still influences both *percept* and *neural response*
- Still temporal build-up (over seconds) for both *percept* and *neural response*

Suppressive Attention / Active Ignoring

Neural dynamics of attending and ignoring in human auditory cortex

Maria Chait[a,*], Alain de Cheveigné[b], David Poeppel[c], Jonathan Z. Simon[d,e]

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[b] *Equipe Audition, Laboratoire de Psychologie de la Perception, UMR 8158, CNRS and Université Paris Descartes and Département d'études cognitives, Ecole normale supérieure, Paris, France*
[c] *Psychology and Neural Science, New York University, New York, NY, USA*
[d] *Department of Electrical & Computer Engineering, University of Maryland, College Park, MD, USA*
[e] *Department of Biology, University of Maryland, College Park, MD, USA*

"[We] provide new, direct evidence that listeners ***actively ignoring a sound*** can ***reduce their stimulus related activity*** in auditory cortex by ***100 ms*** after onset when this is required to execute specific behavioral objectives."

Simple Complex Scenes Summary

- Experiments all tone-based (speech not needed)
- Neural responses can dissociate from physical acoustics, tracking perception instead
- Latency of responses tracking perception ~100 ms ➧ plausible neural substrate of perception
- Different roles available for Attention
    - directed vs. undirected
    - bottom-up vs. top-down

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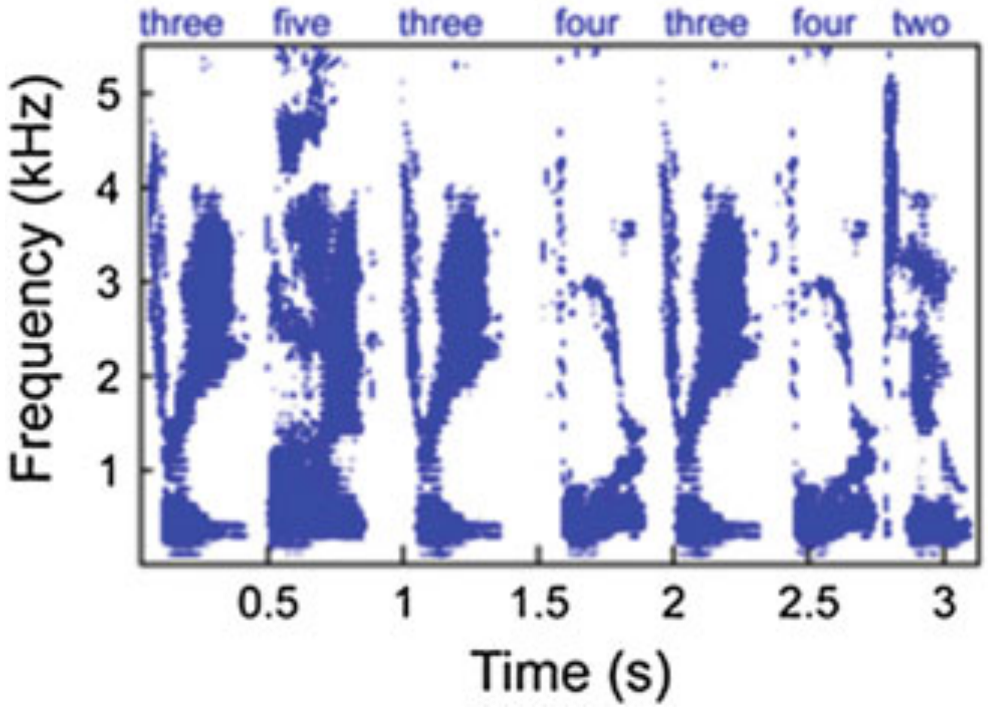
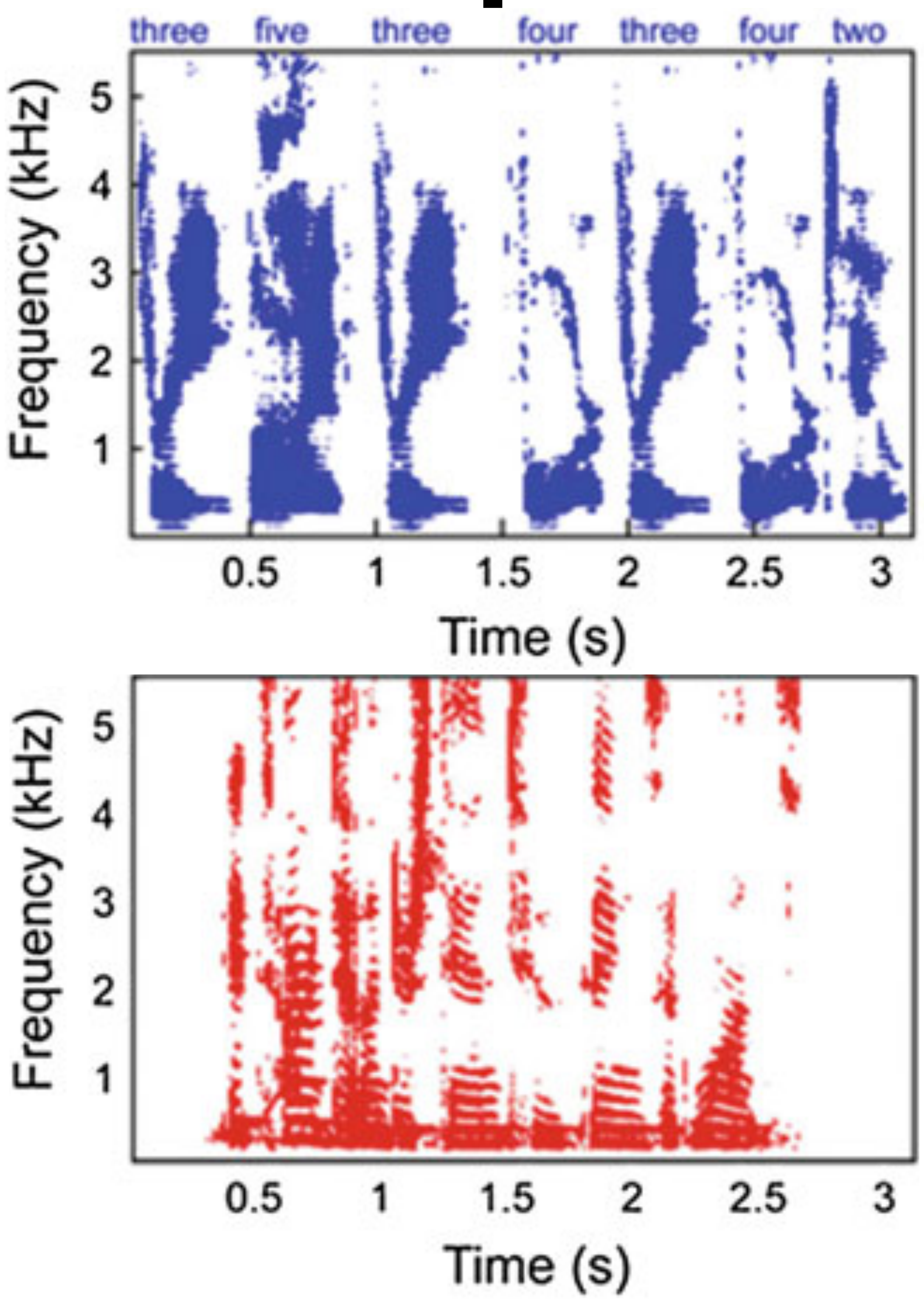
Complex Scenes: Speech



from Shinn-Cunningham et al. (2017), Chapter 2: "Auditory Object Formation and Selection"

Complex Scenes: Speech



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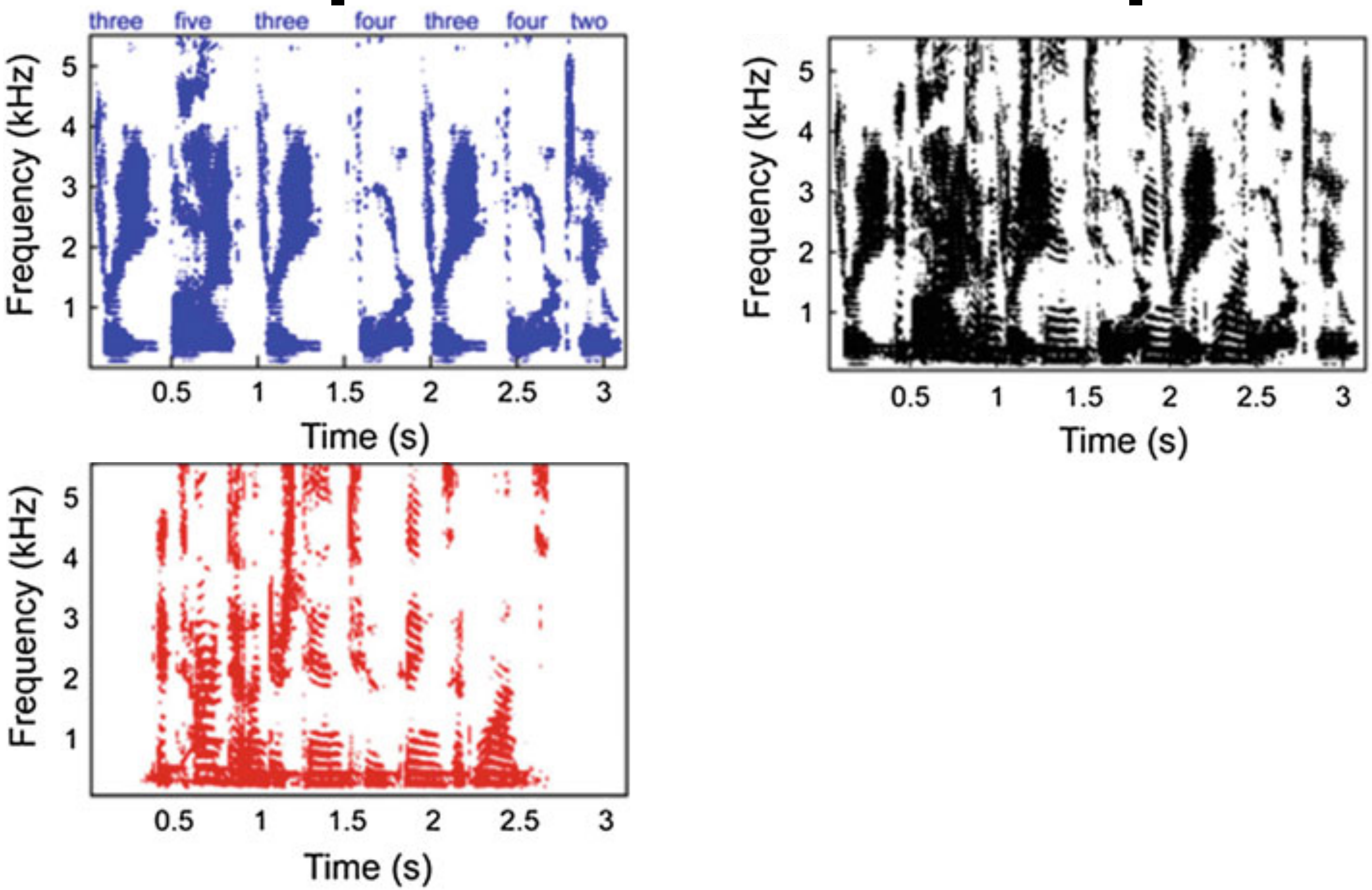

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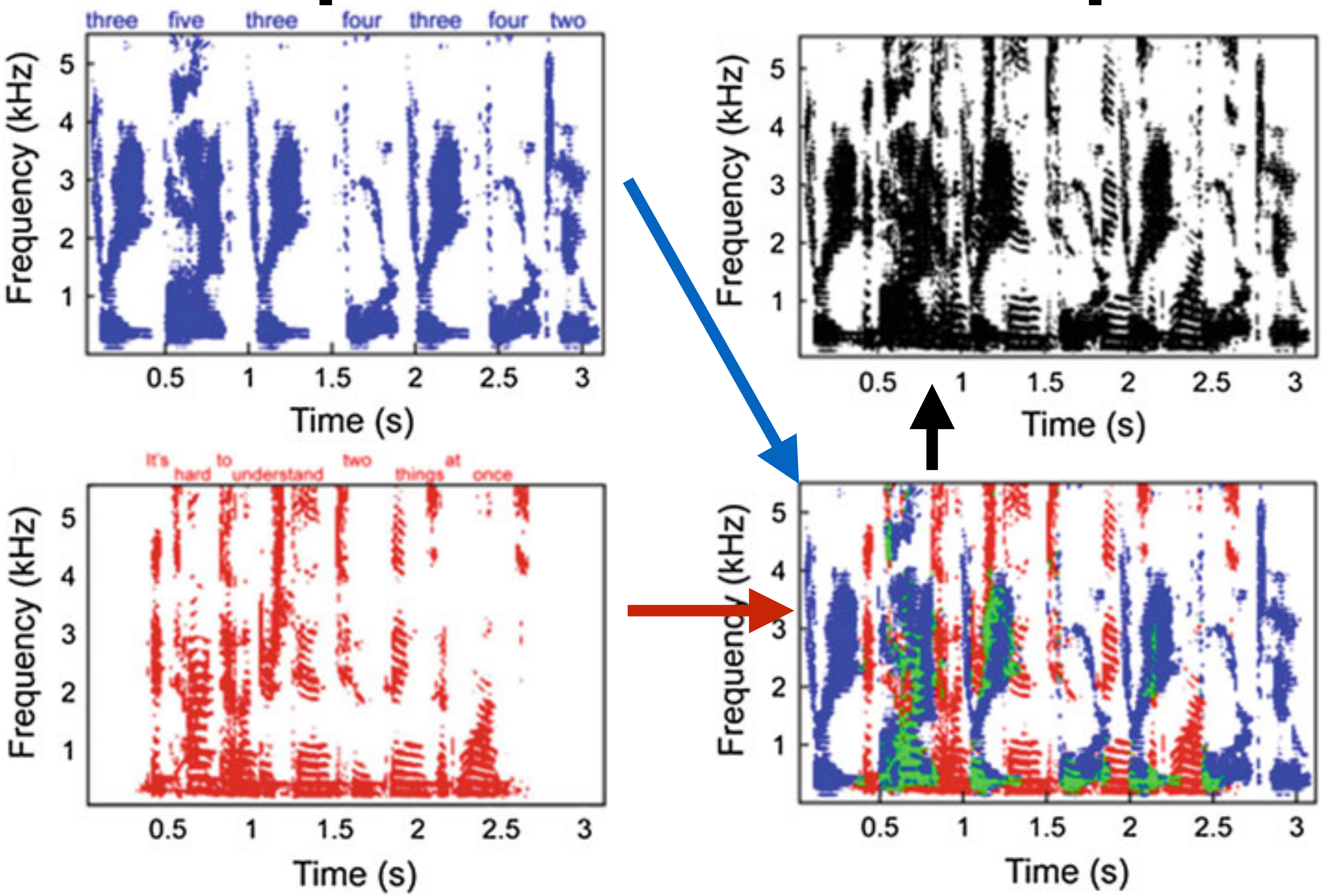
Complex Scenes: Speech



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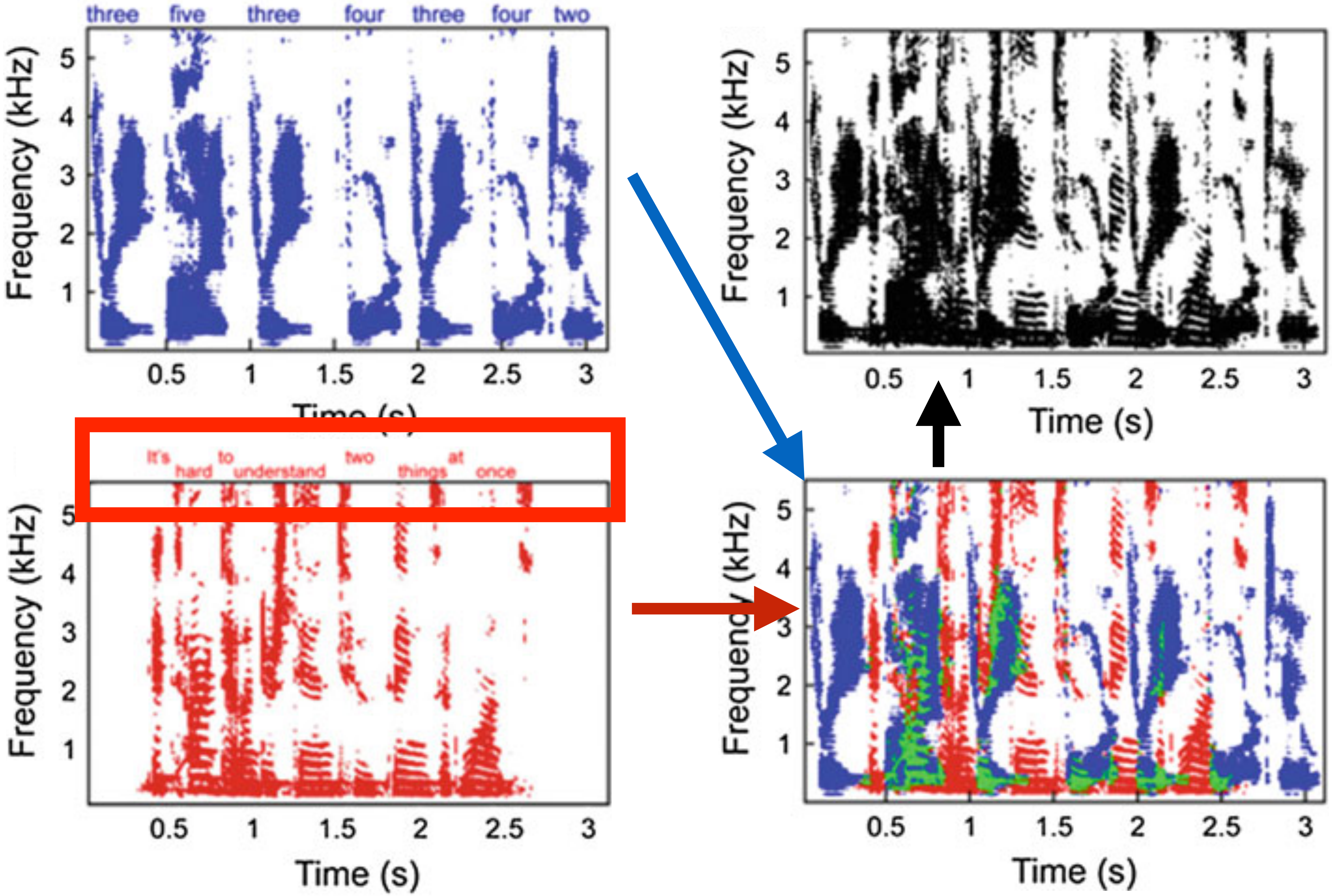
Complex Scenes: Speech



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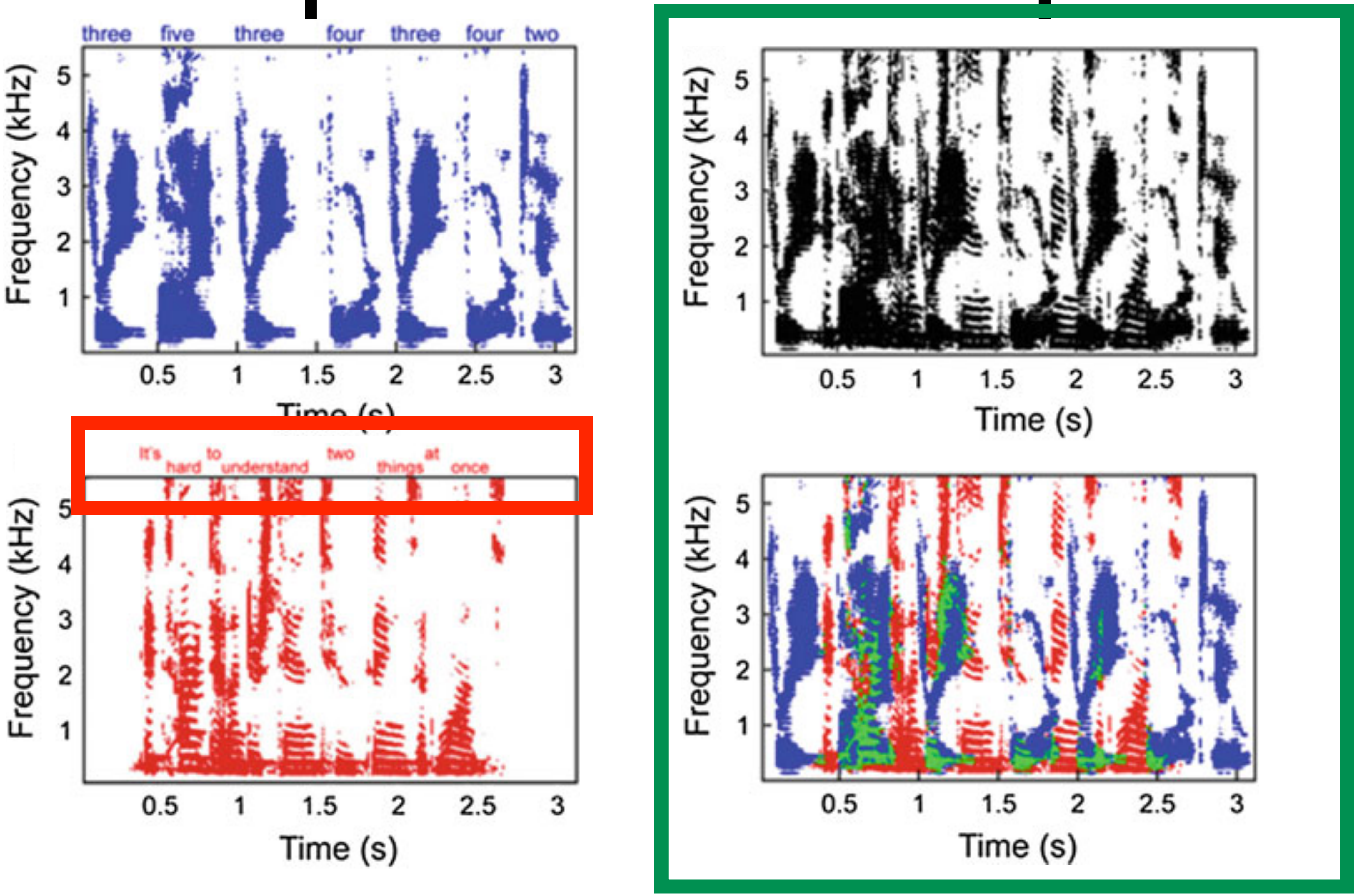
Complex Scenes: Speech



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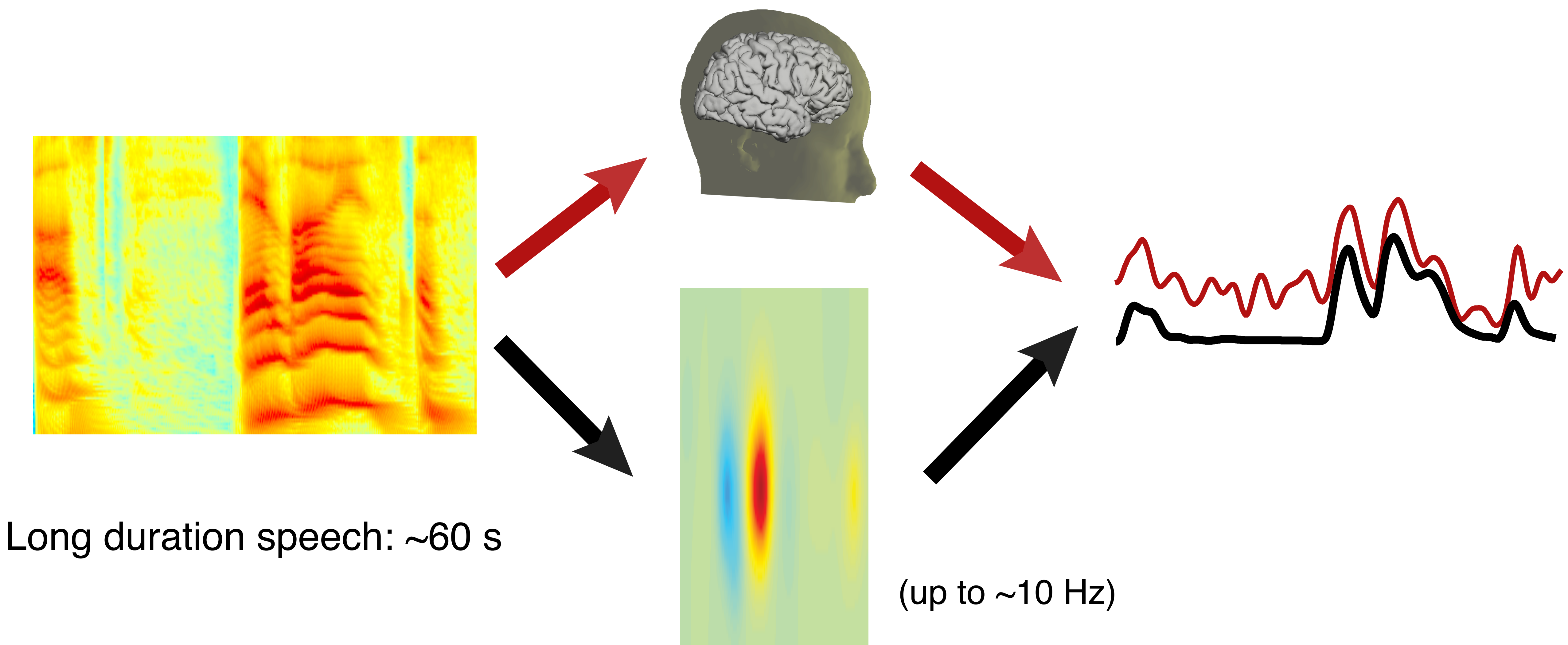
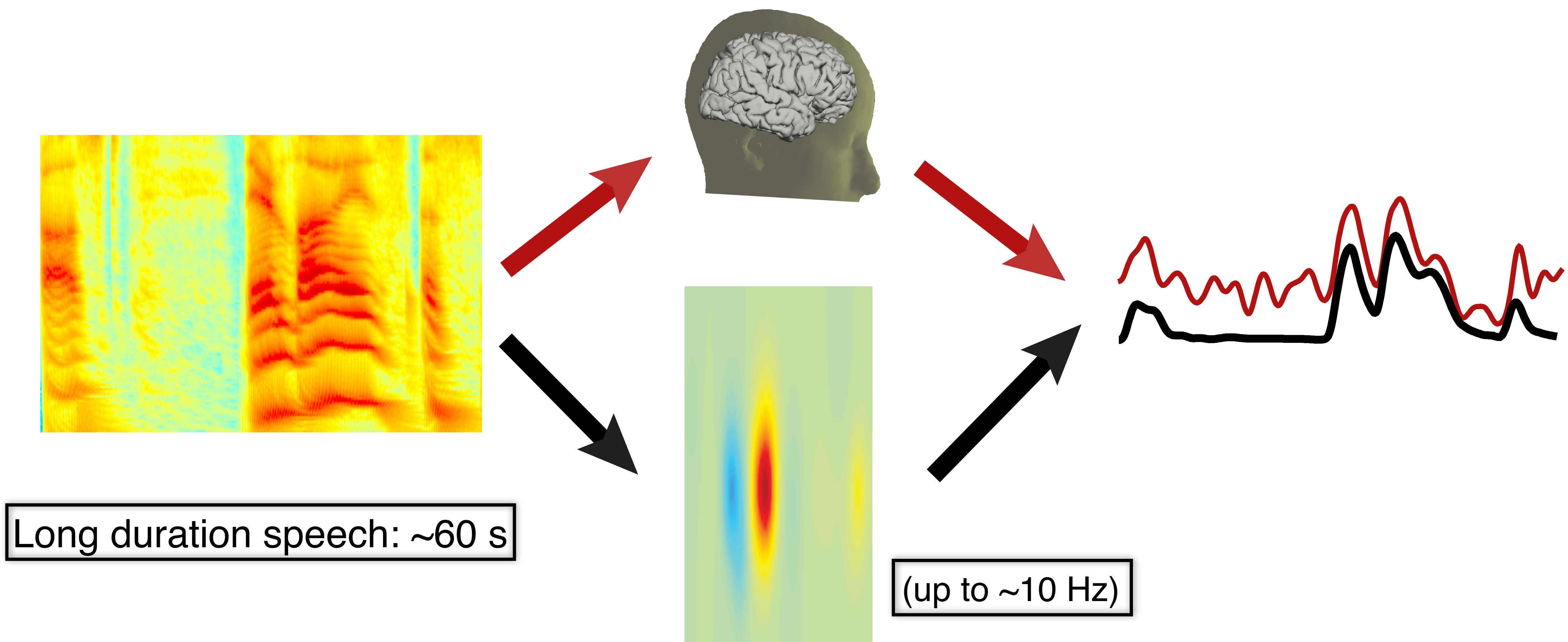
MEG Speech Responses Predicted by STRF



Linear Kernel = STRF
"Spectro-Temporal Response Function"

Ding & Simon, J Neurophys (2012)

MEG Speech Responses Predicted by STRF

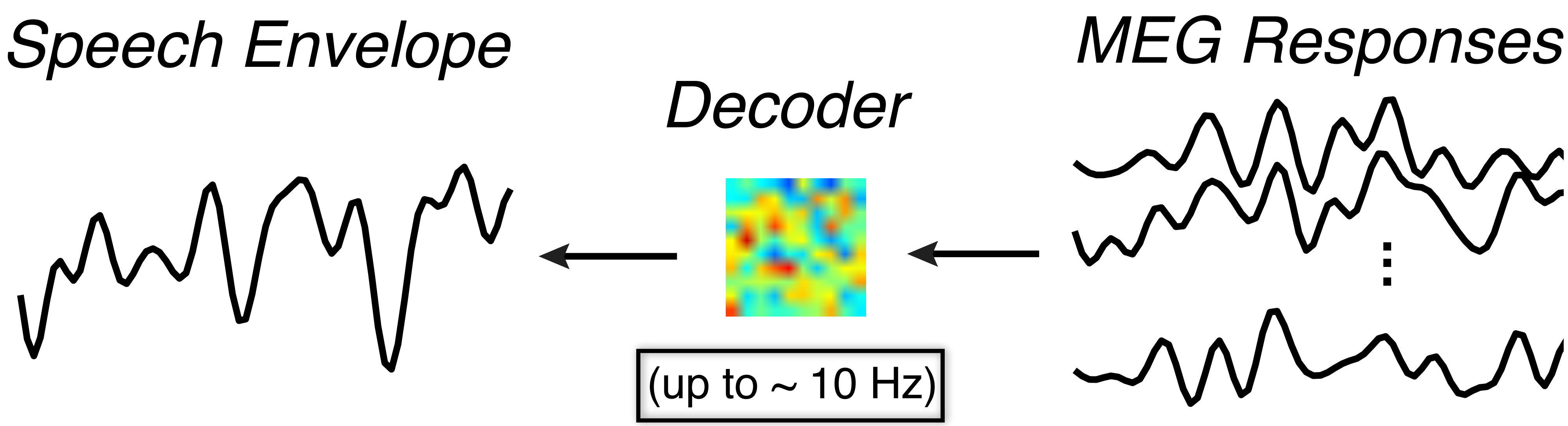


Linear Kernel = STRF

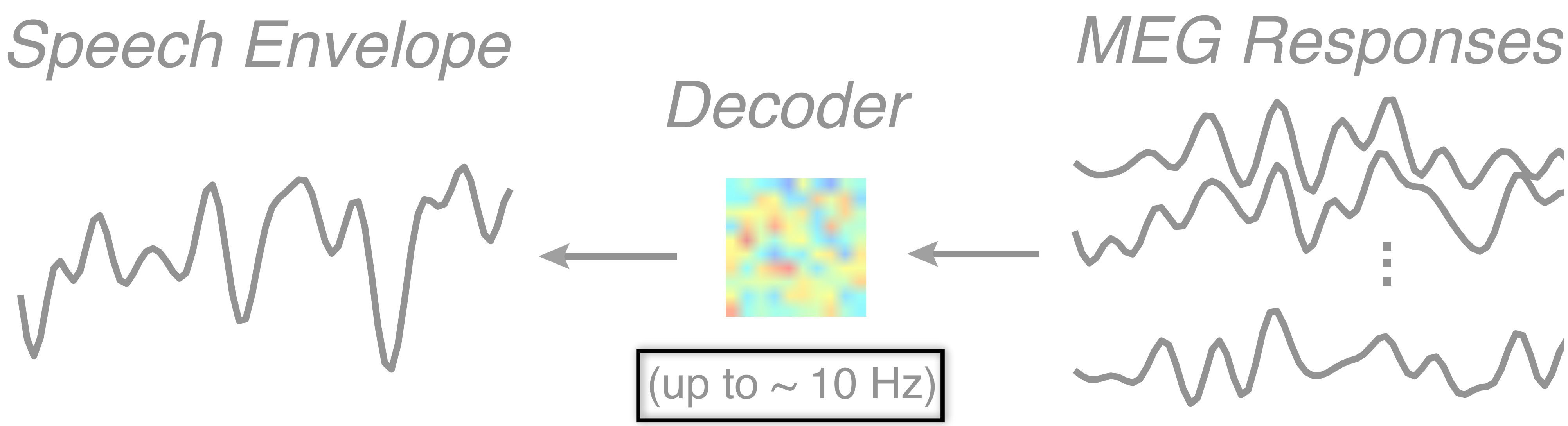
"Spectro-Temporal Response Function"

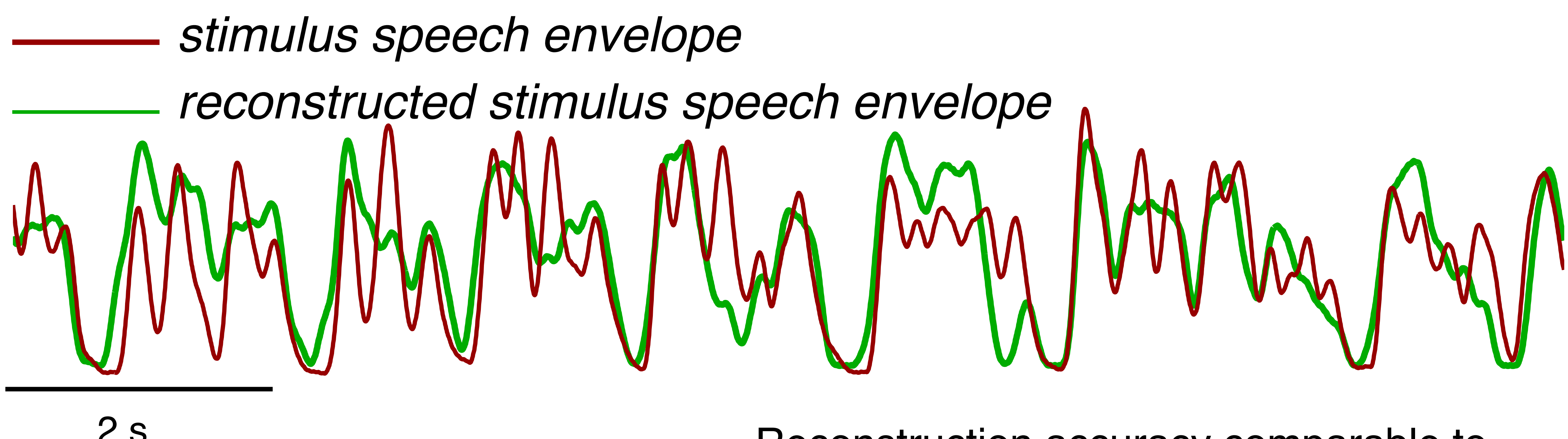
Ding & Simon, J Neurophys (2012)

Neural Reconstruction of Speech Envelope



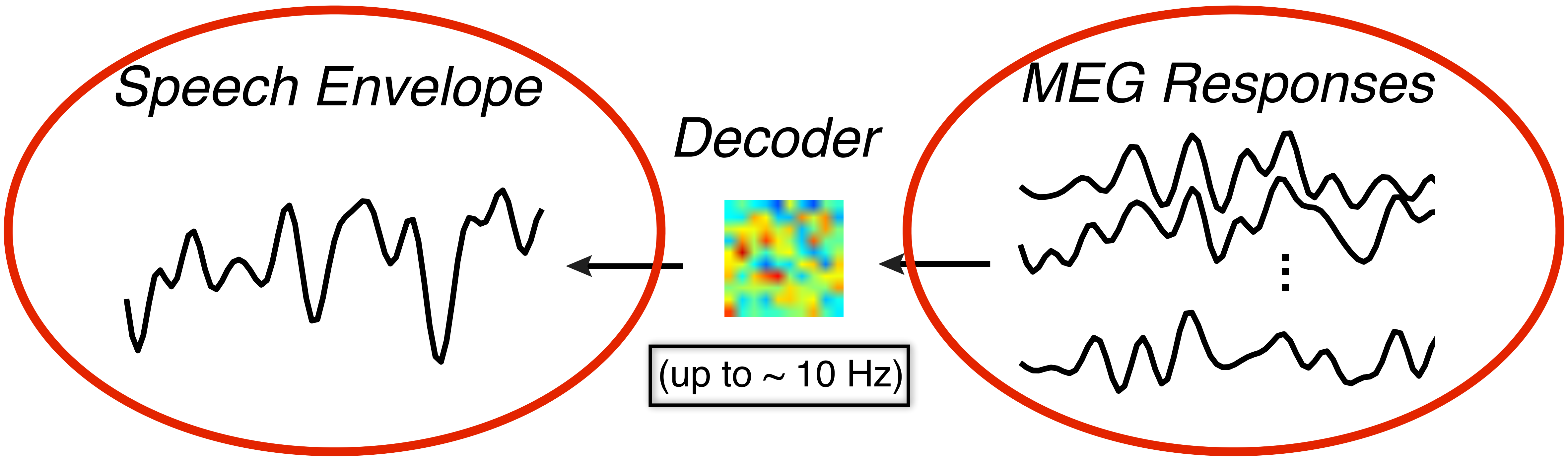
Neural Reconstruction of Speech Envelope



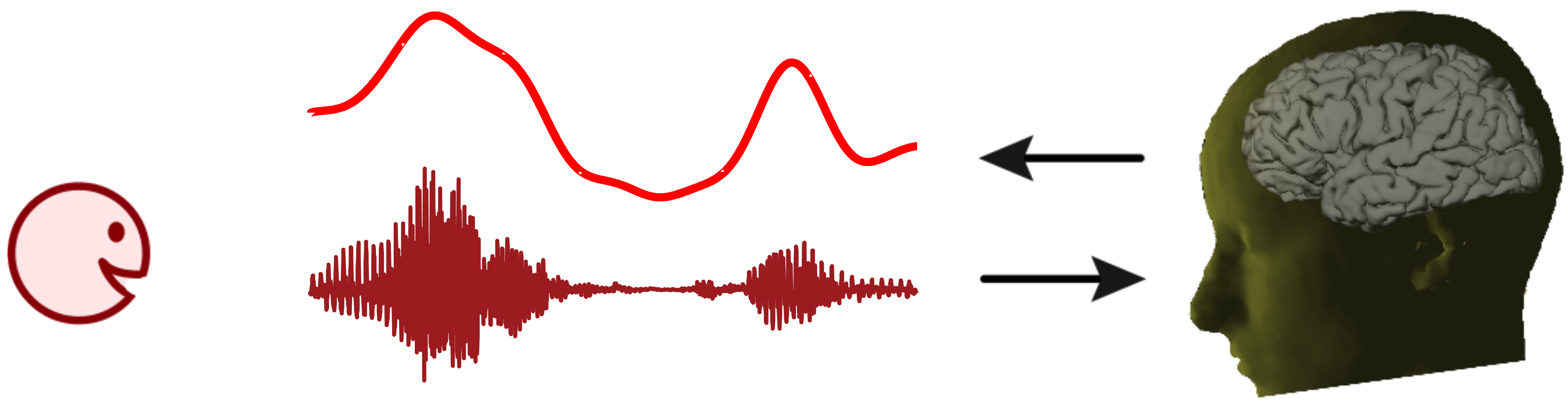


Ding & Simon, J Neurophysiol (2012)
Zion-Golumbic et al. (2013)

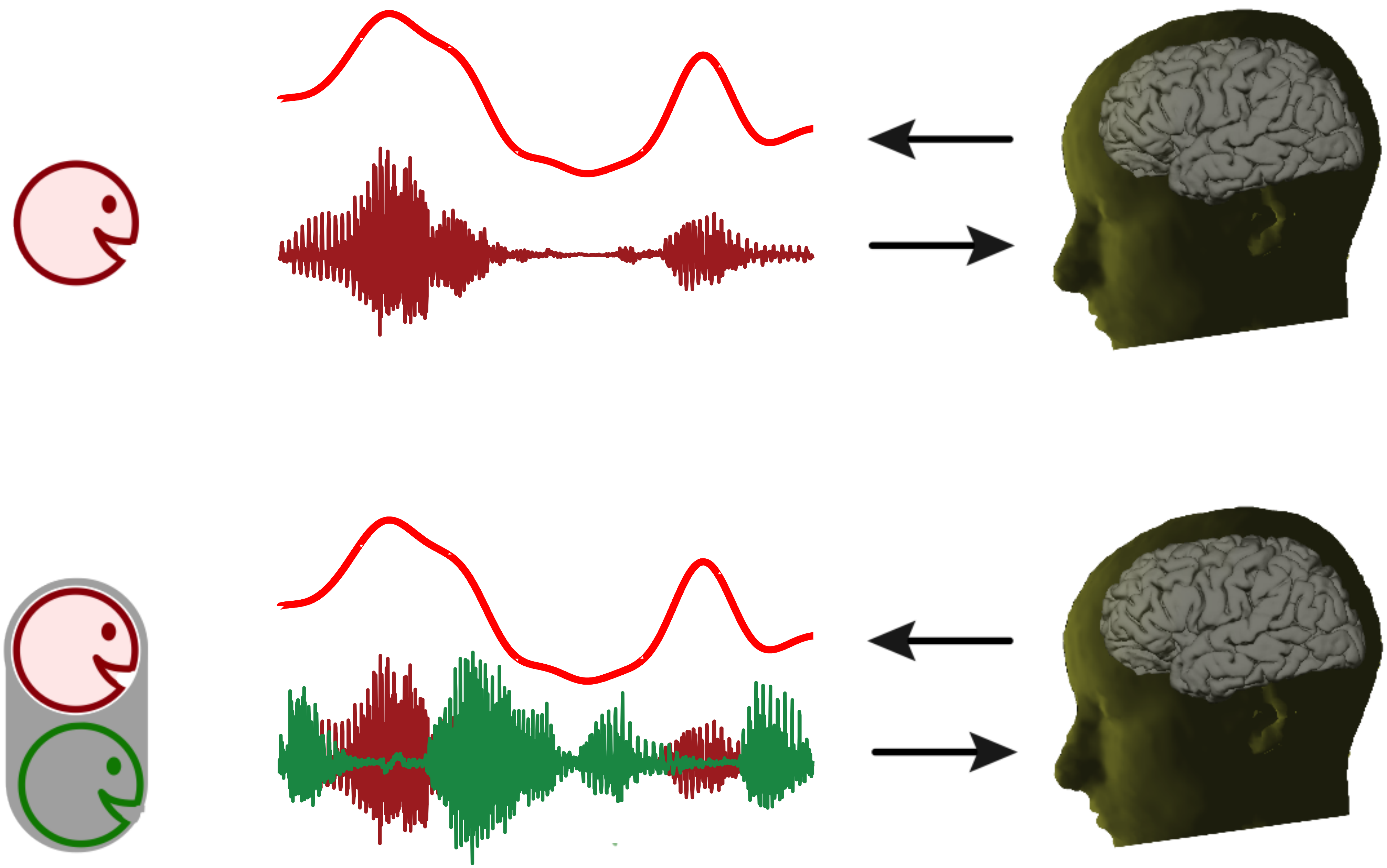
Reconstruction accuracy comparable to single unit & ECoG recordings


Speech Envelope
Decoder
(up to ~ 10 Hz)
MEG Responses

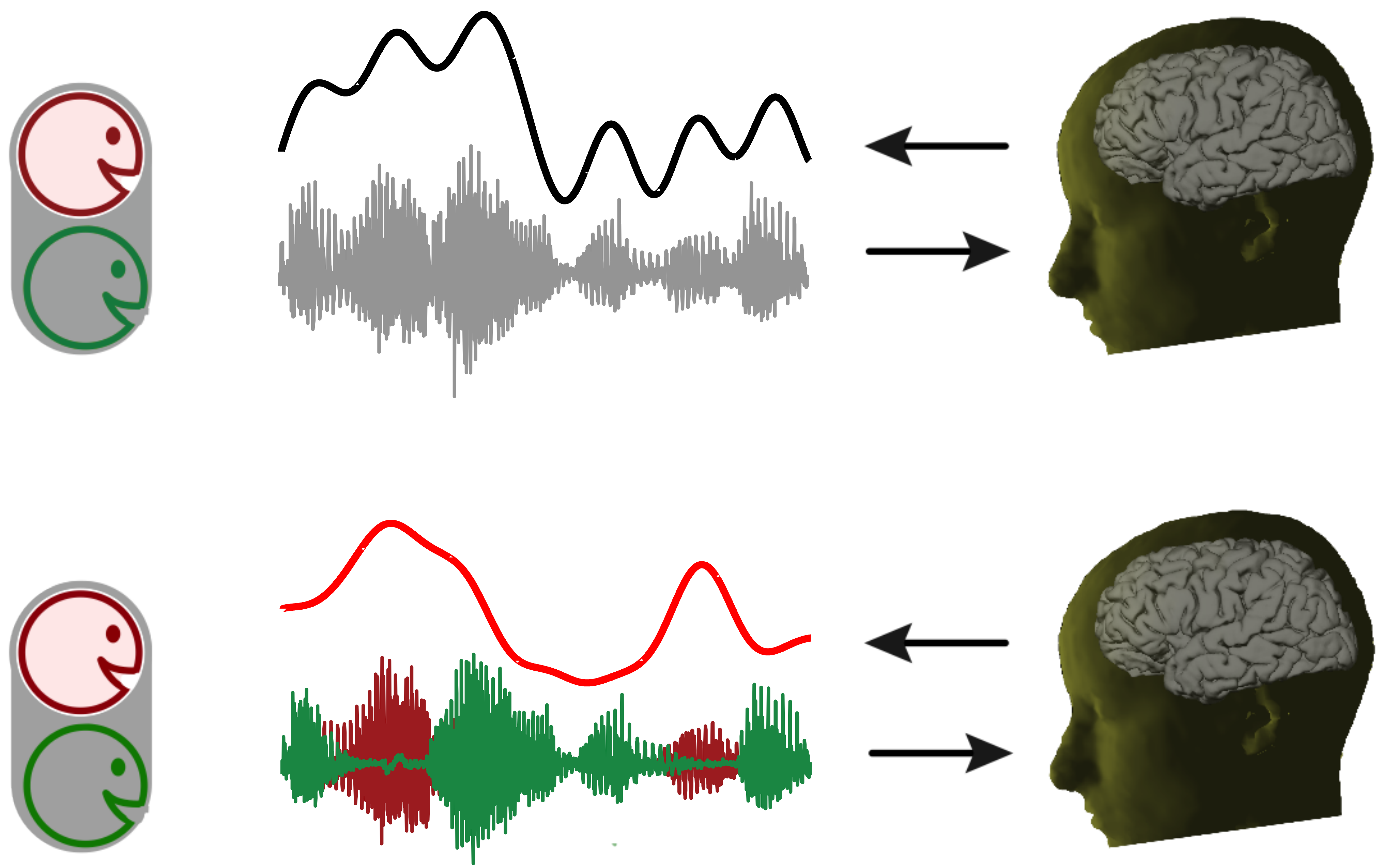
Neural Encoding of Speech



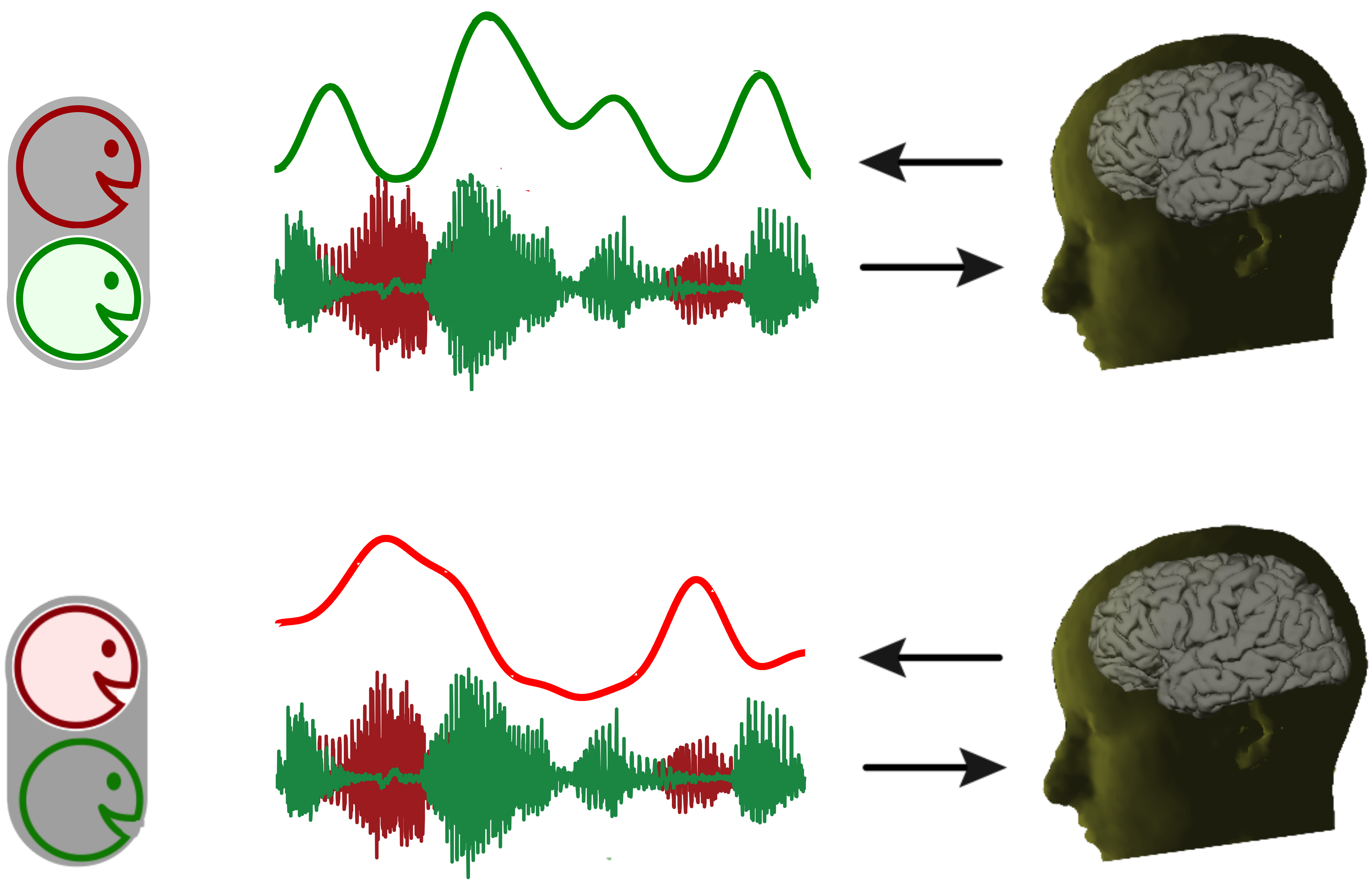
Selective Neural Encoding of Speech



Unselective vs. Selective Neural Encoding



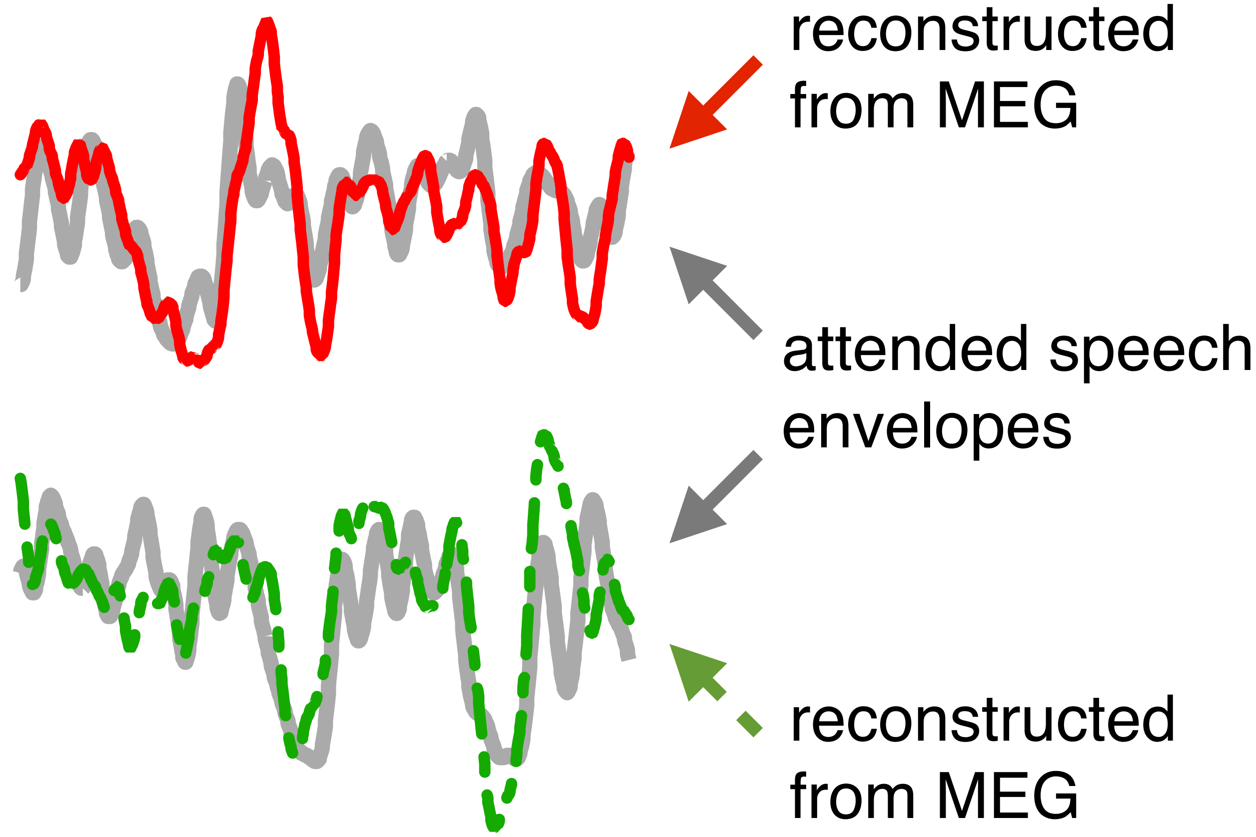
Selective Neural Encoding



Selective Encoding: Results

attending to speaker 1

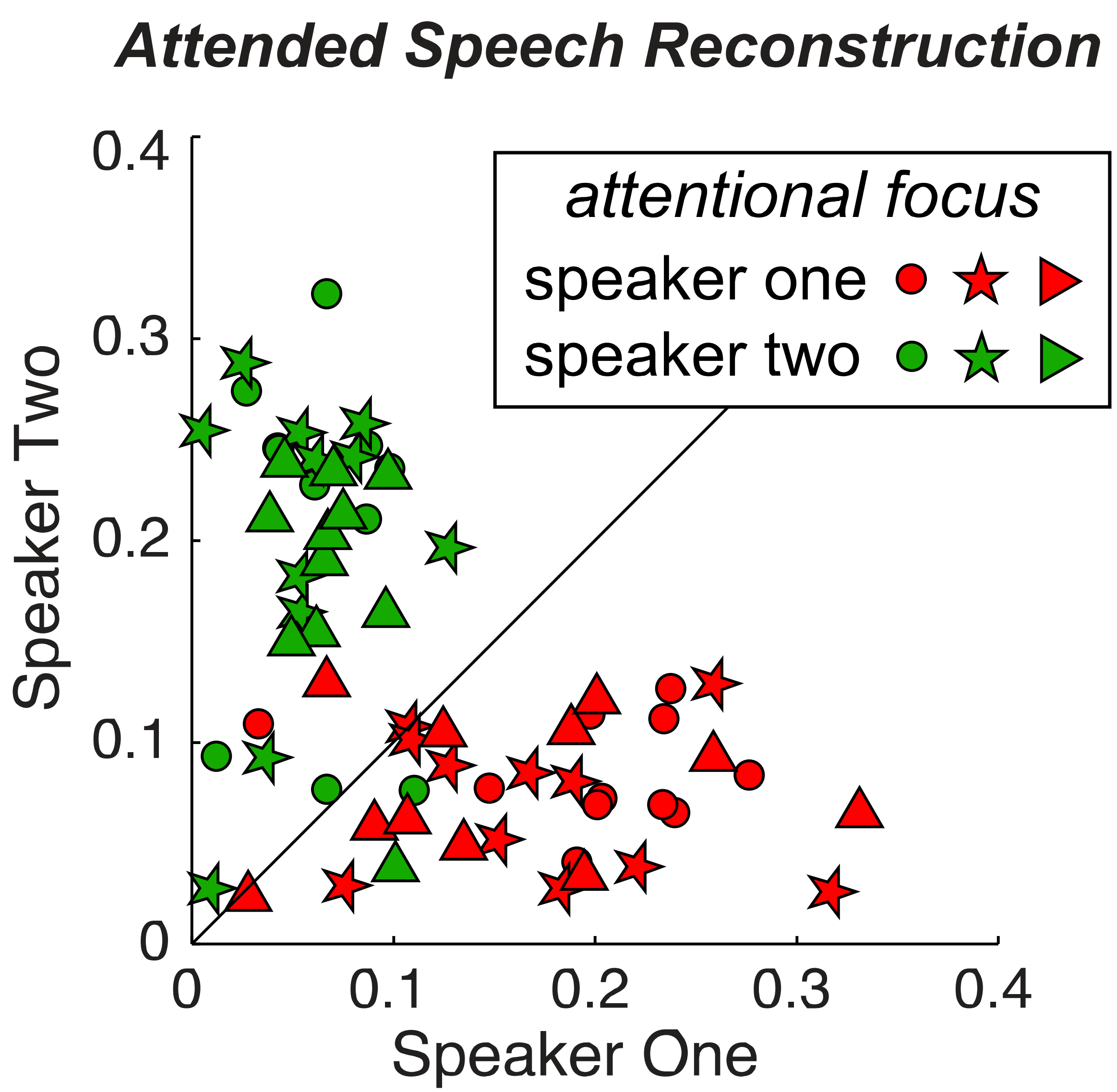
attending to speaker 2



Identical Stimuli!

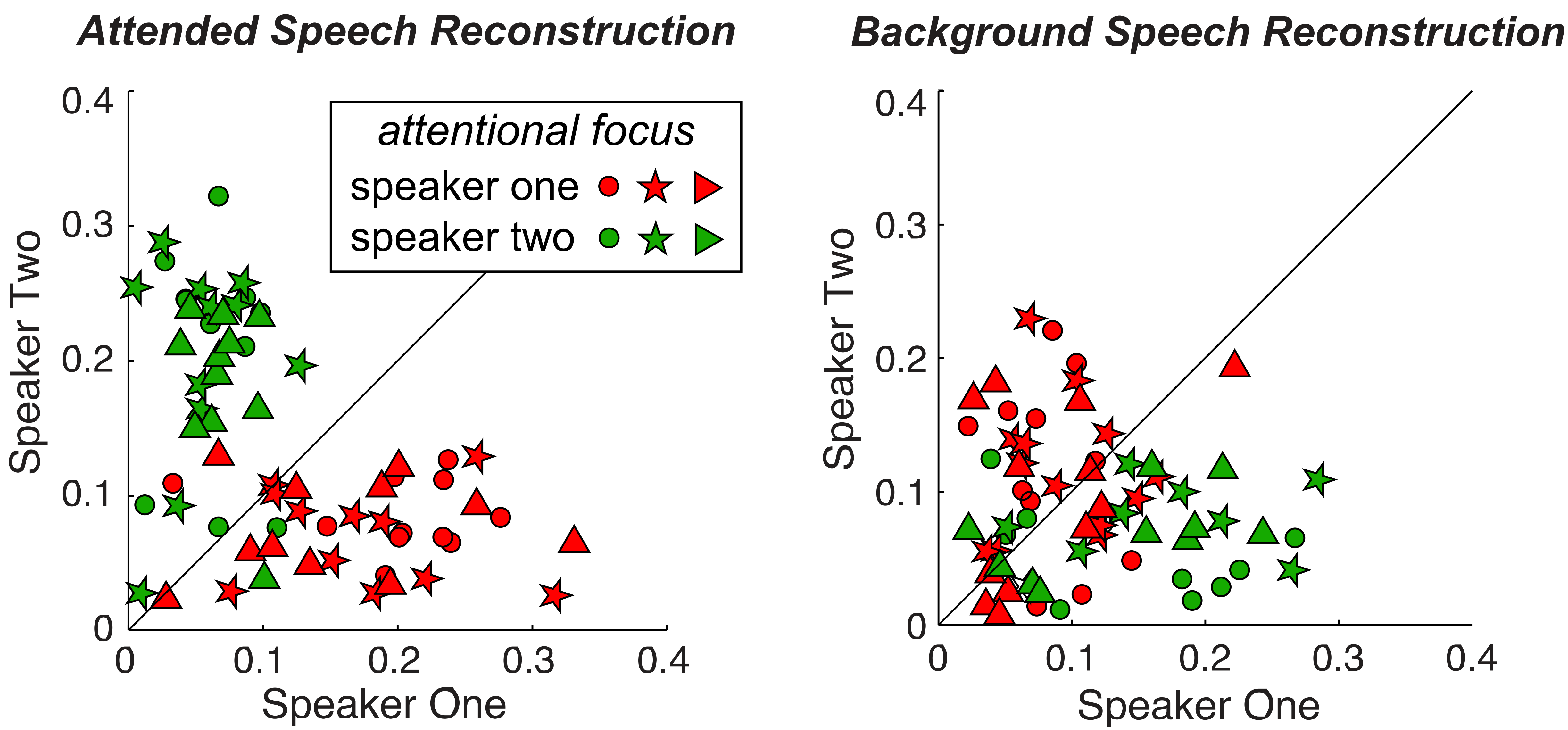
Ding & Simon, PNAS (2012)

Single Trial Speech Reconstruction



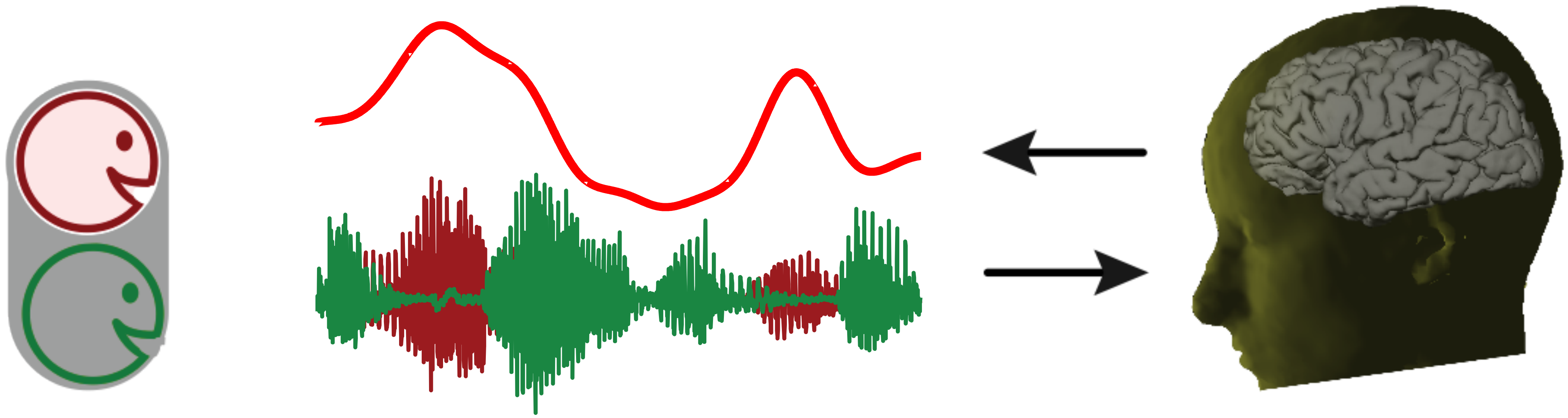
Ding & Simon, PNAS (2012)

Single Trial Speech Reconstruction

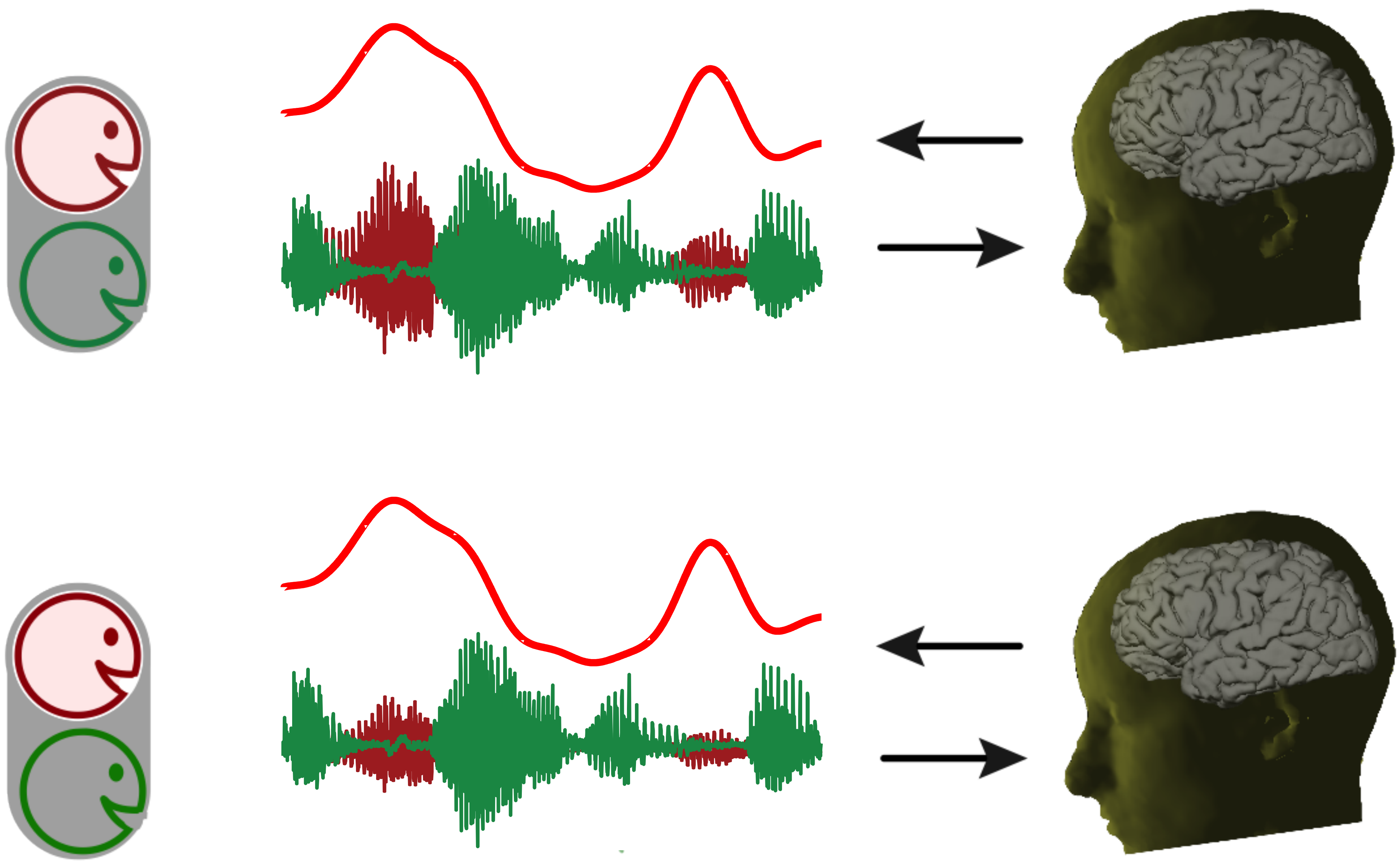


Ding & Simon, PNAS (2012)

Invariance Under Relative Loudness Change?



Invariance Under Relative Loudness Change?



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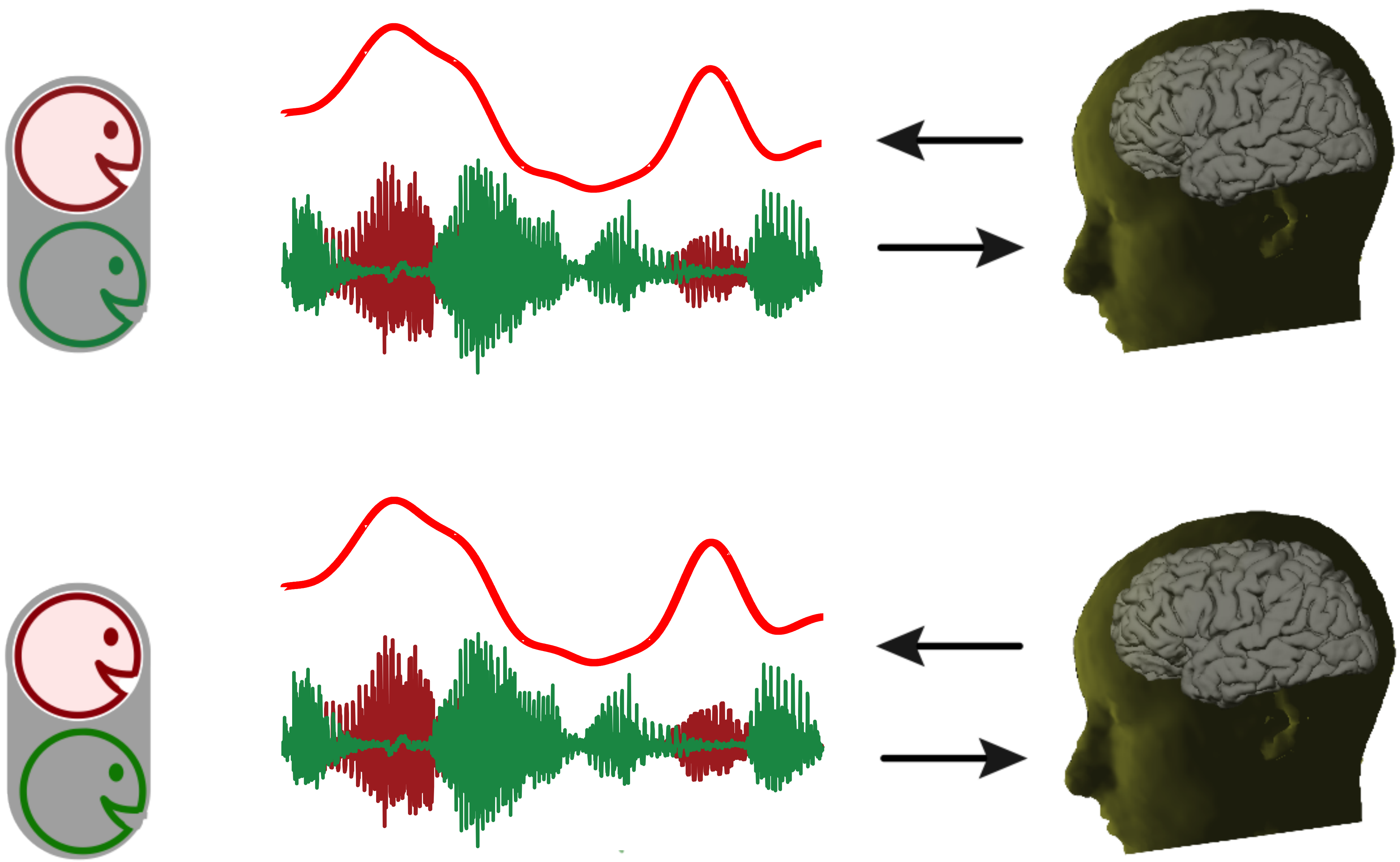

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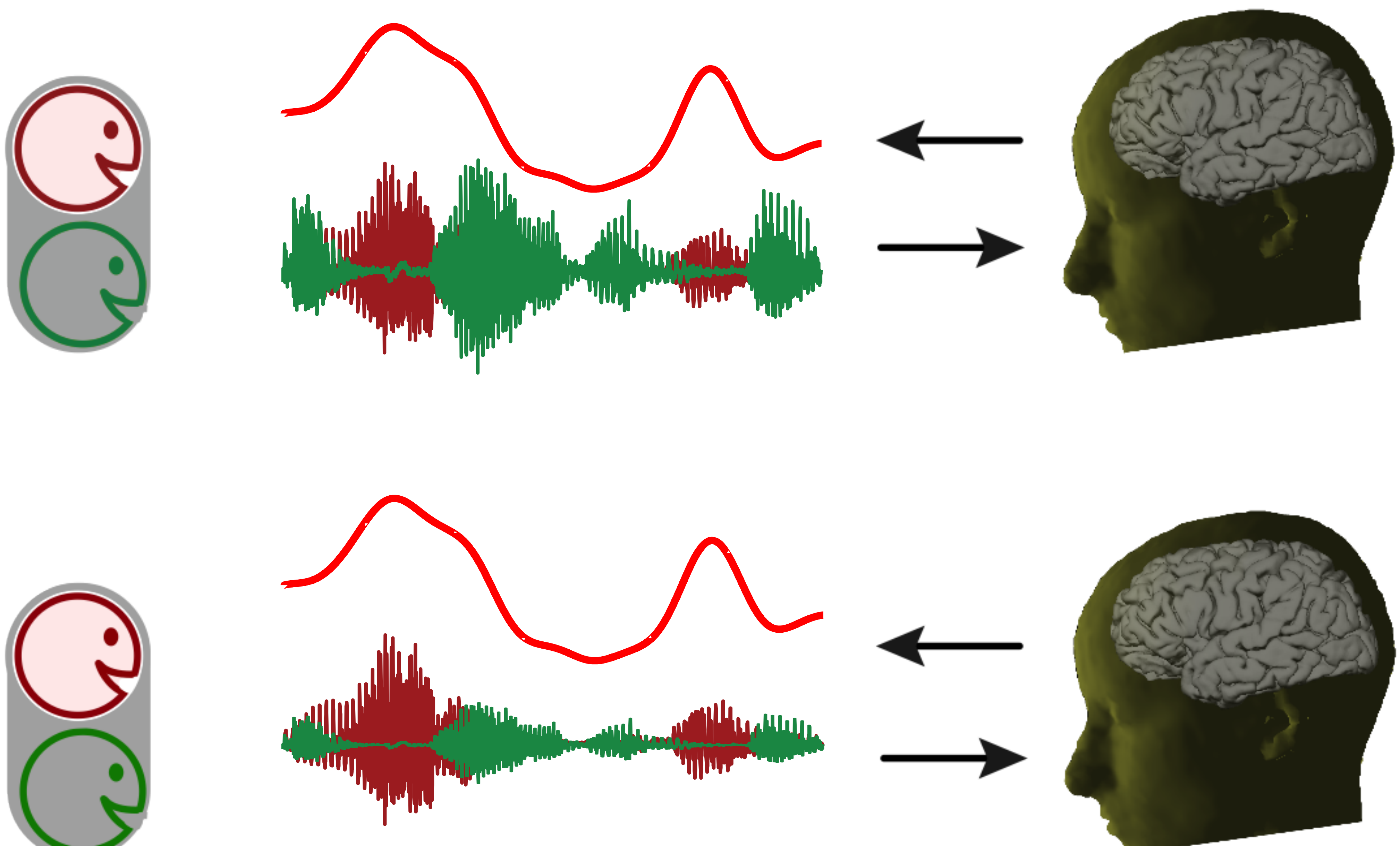
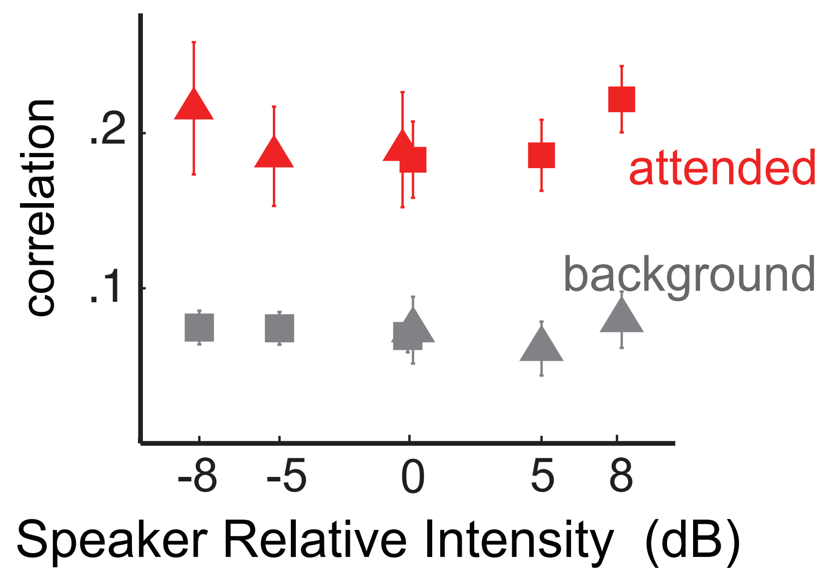


Invariance under Relative Loudness Change

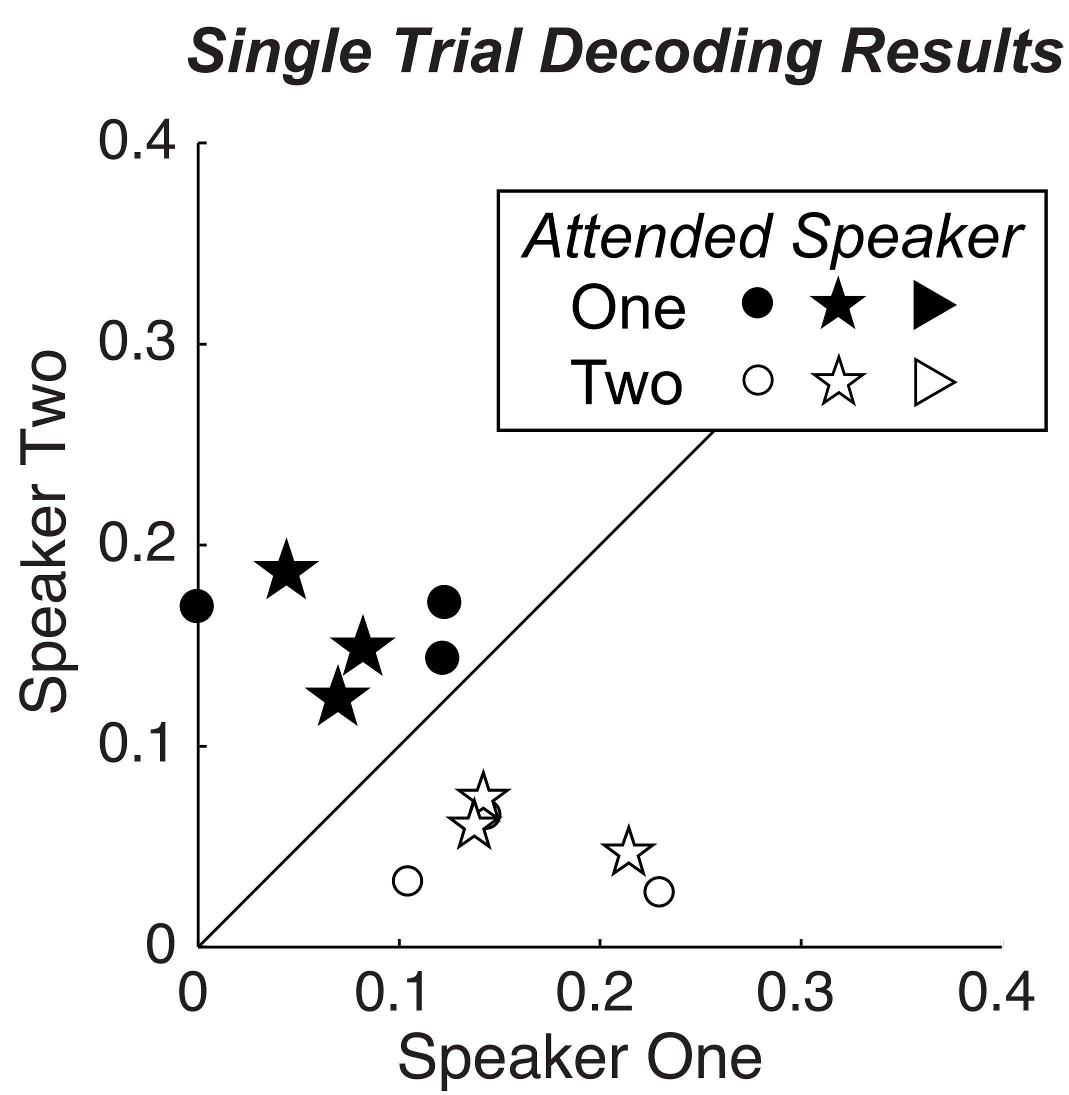
Neural Results



- Neural representation invariant to relative loudness change
- Stream-based Gain Control, not stimulus-based

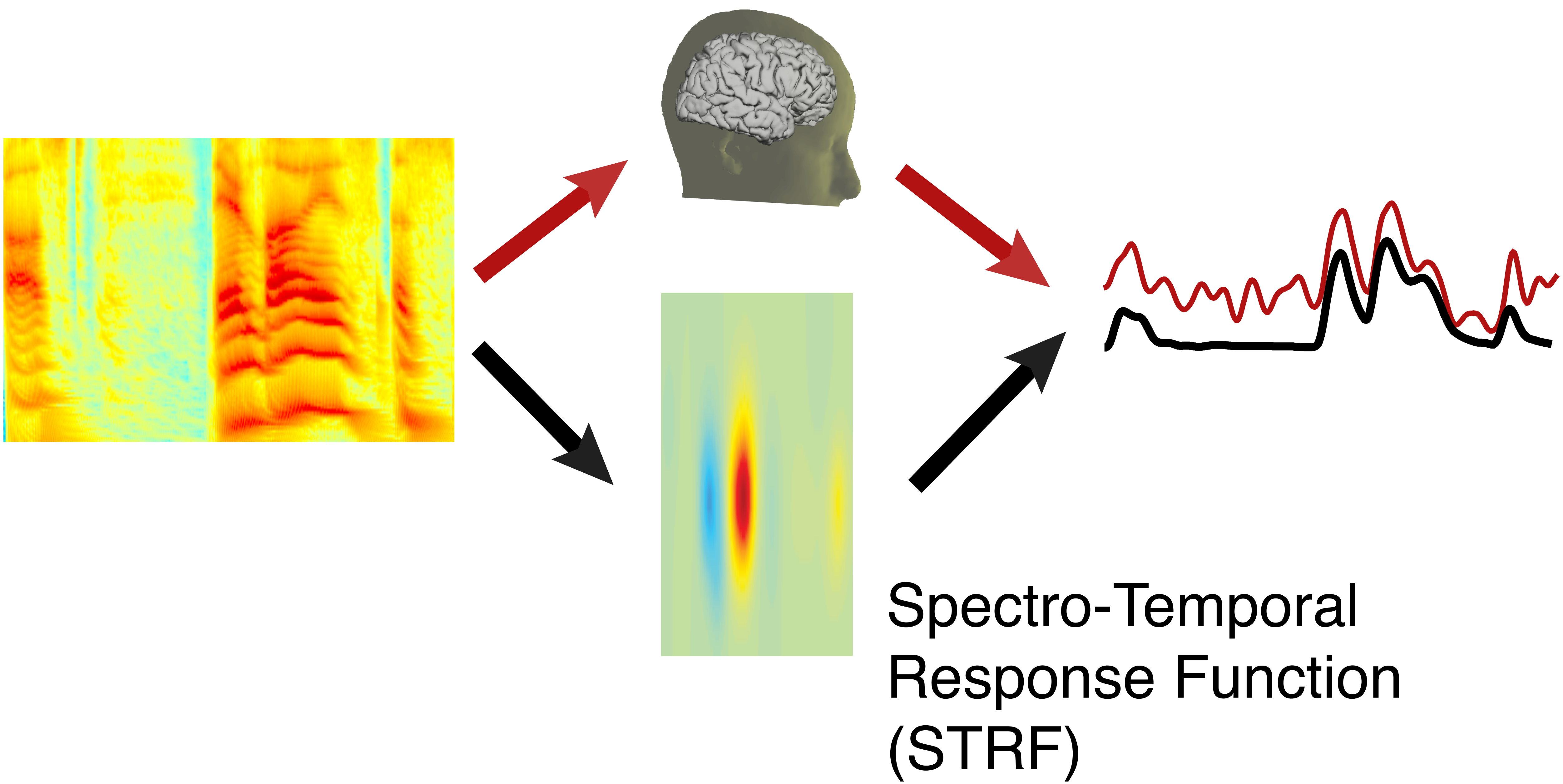
Ding & Simon, PNAS (2012)

Reconstruction of Same-Sex Speech

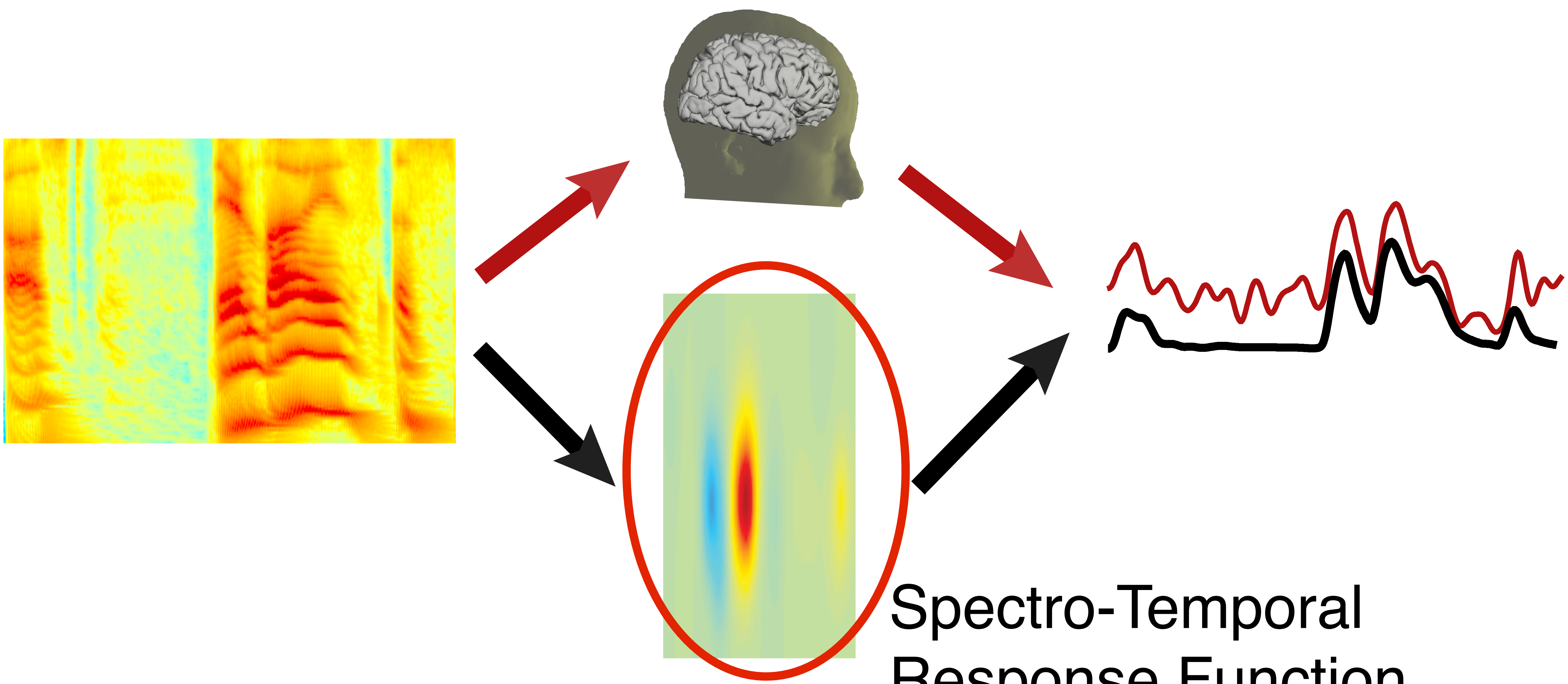


Ding & Simon, PNAS (2012)

Forward STRF Model

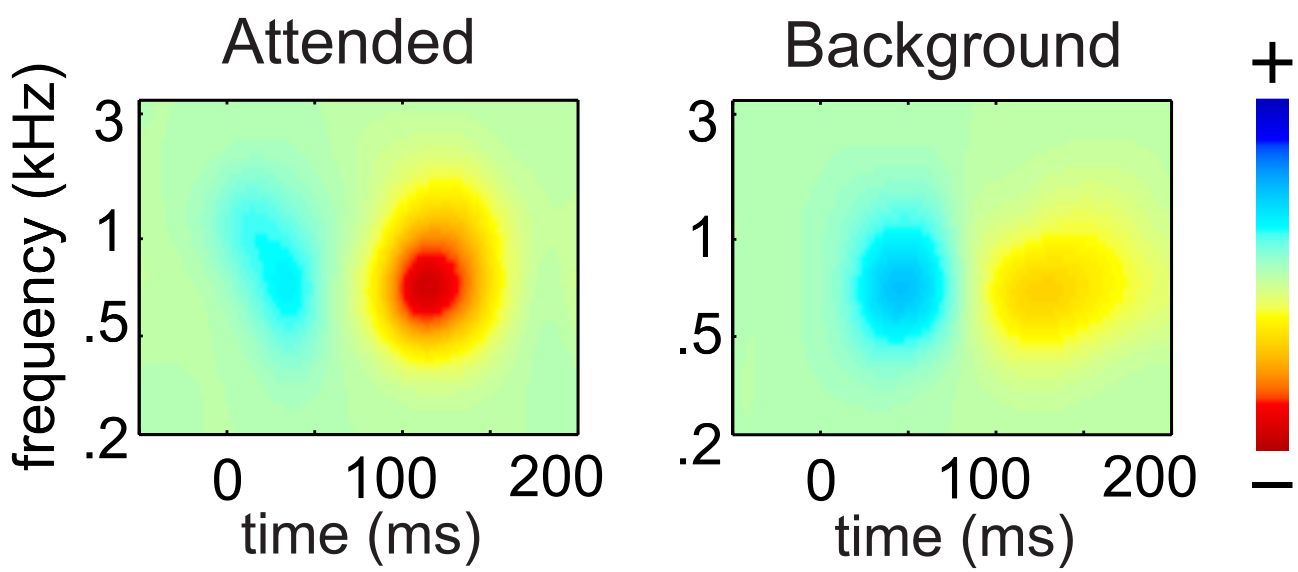


Forward STRF Model



Spectro-Temporal
Response Function
(STRF)

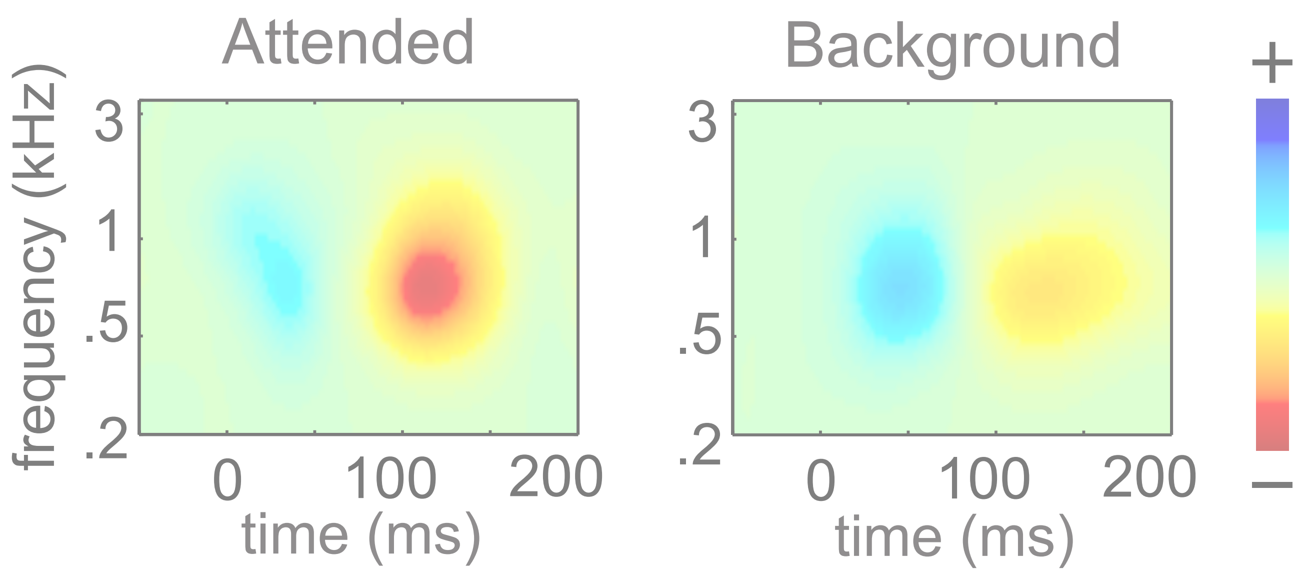
STRF Results

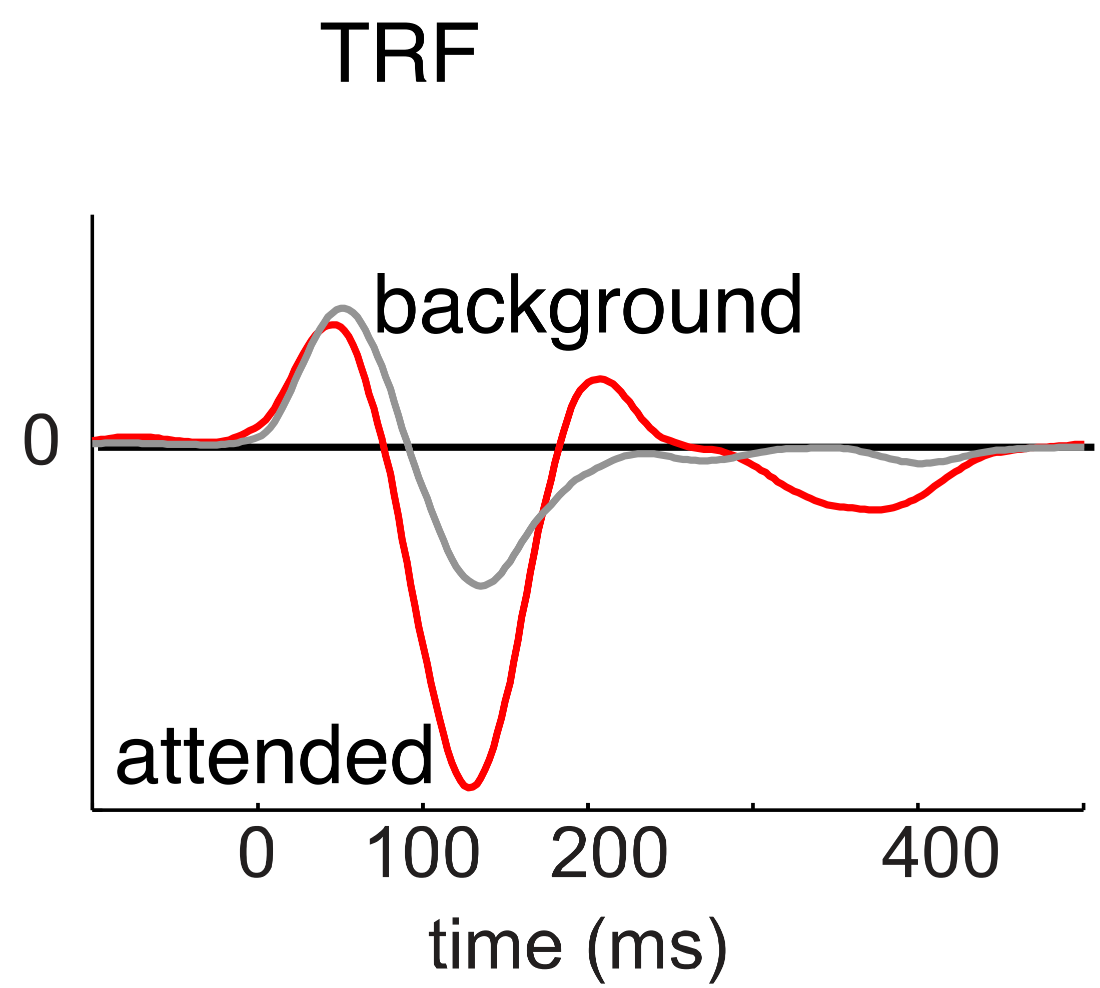


- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M50_{STRF}$ positive peak
- $M100_{STRF}$ negative peak

Ding & Simon, PNAS (2012)

STRF Results





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Ding & Simon, PNAS (2012)

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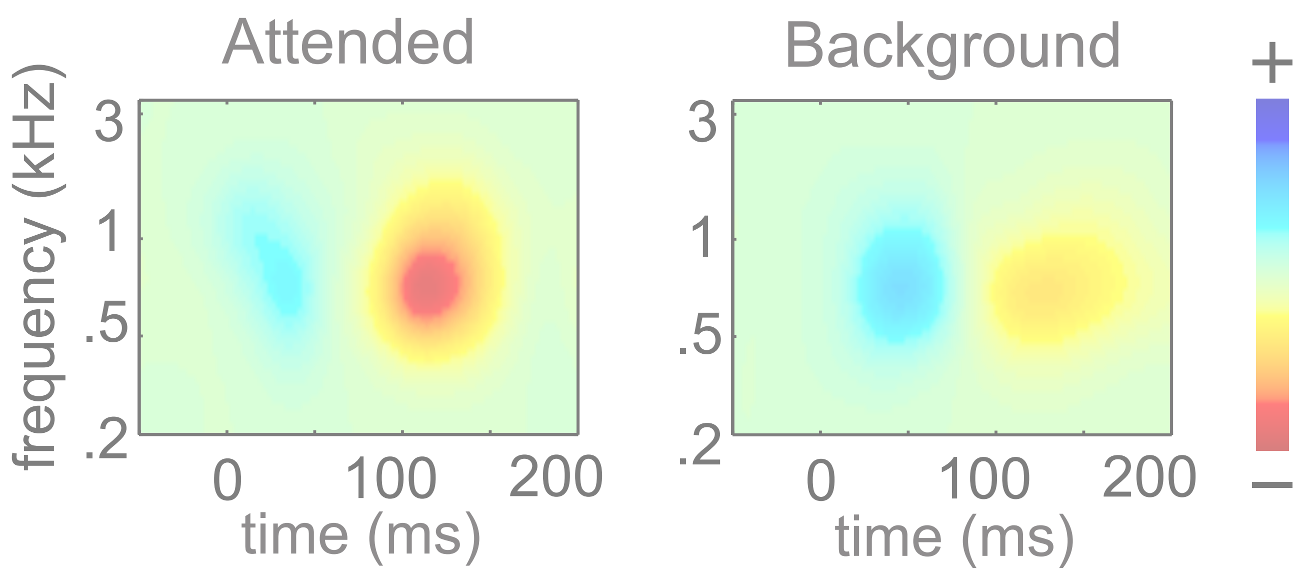

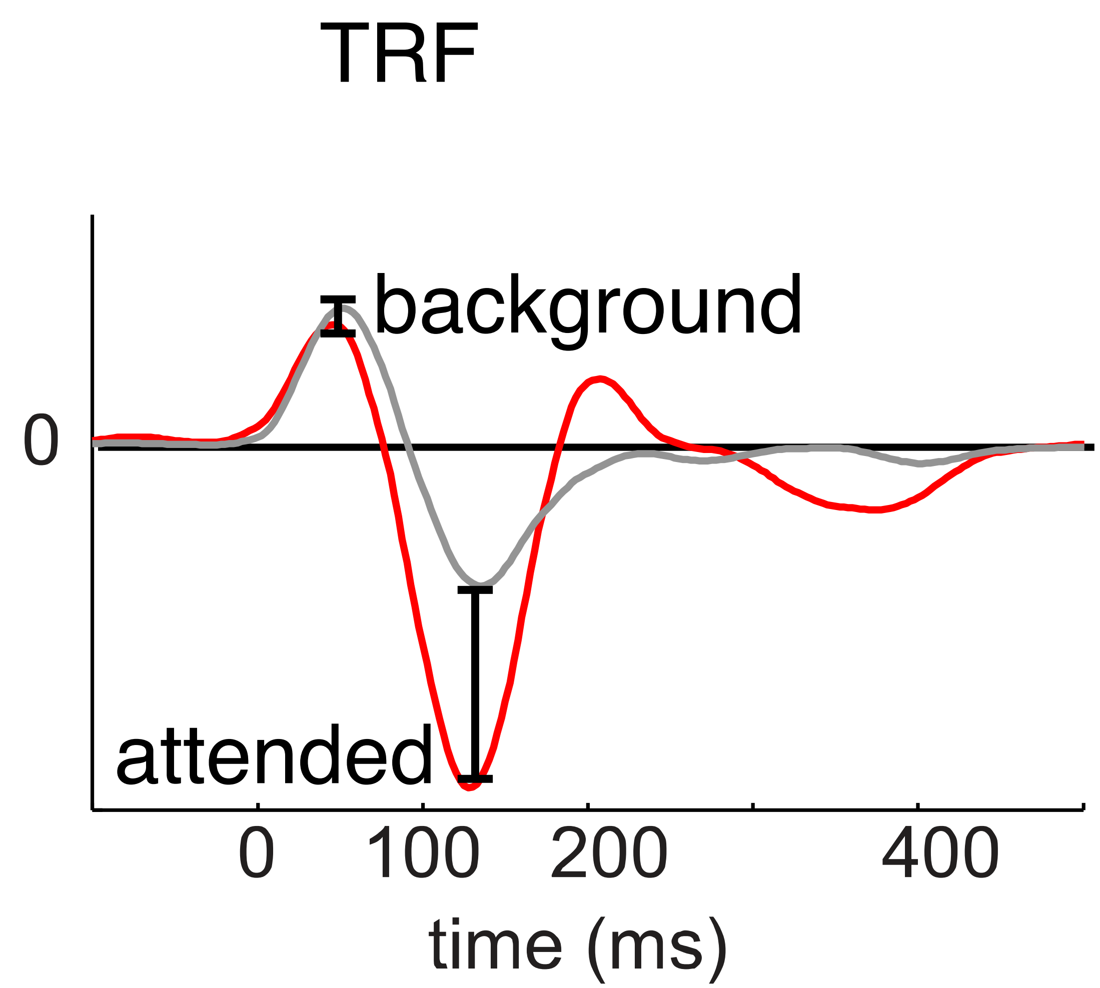

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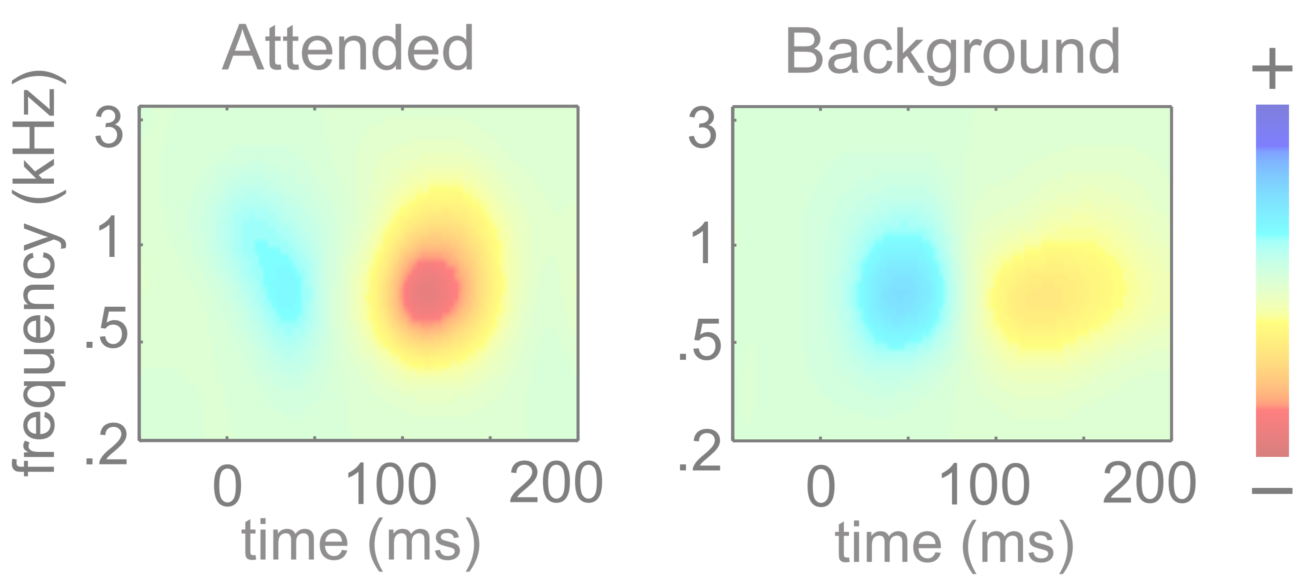
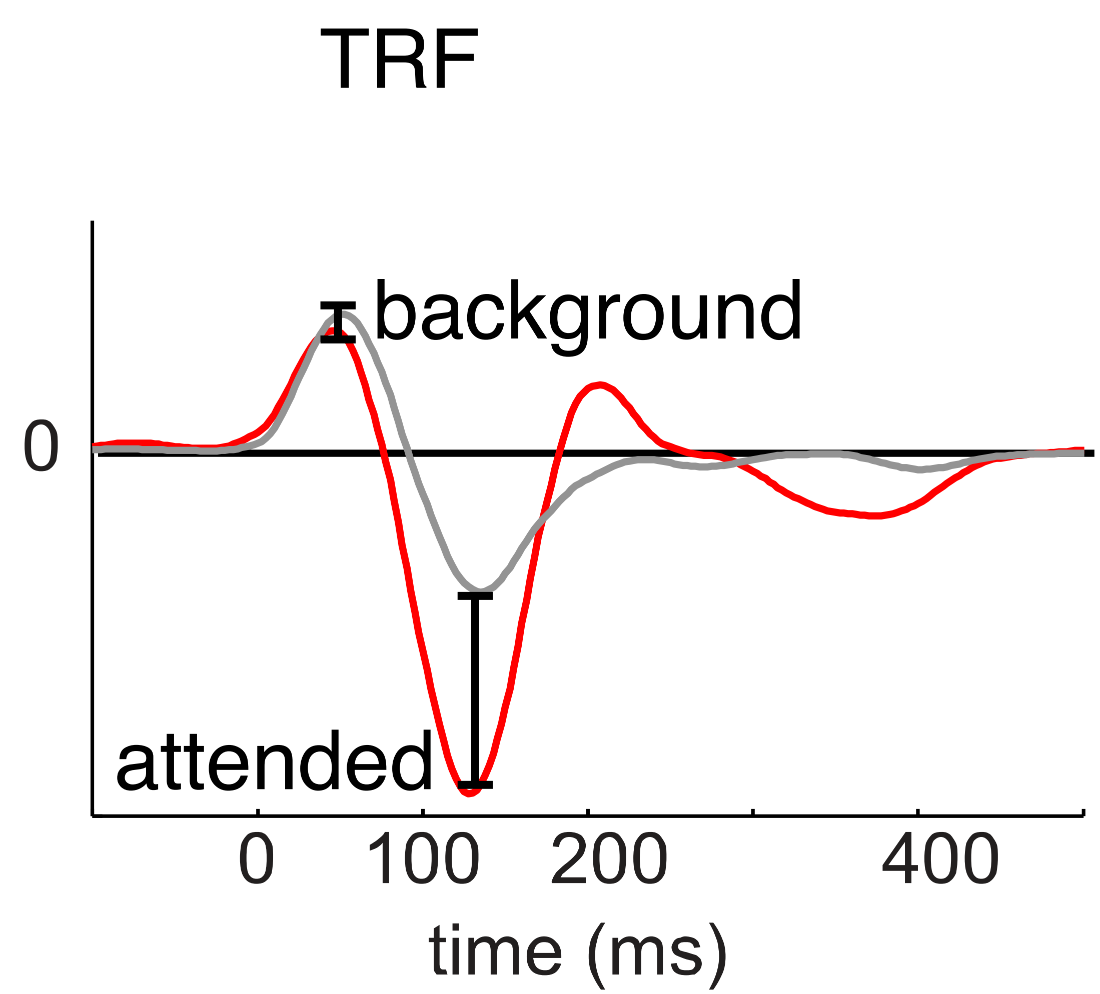
- **$M100_{STRF}$ strongly modulated by attention, *but not $M50_{STRF}$***

Ding & Simon, PNAS (2012)

STRF Results





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Ding & Simon, PNAS (2012)

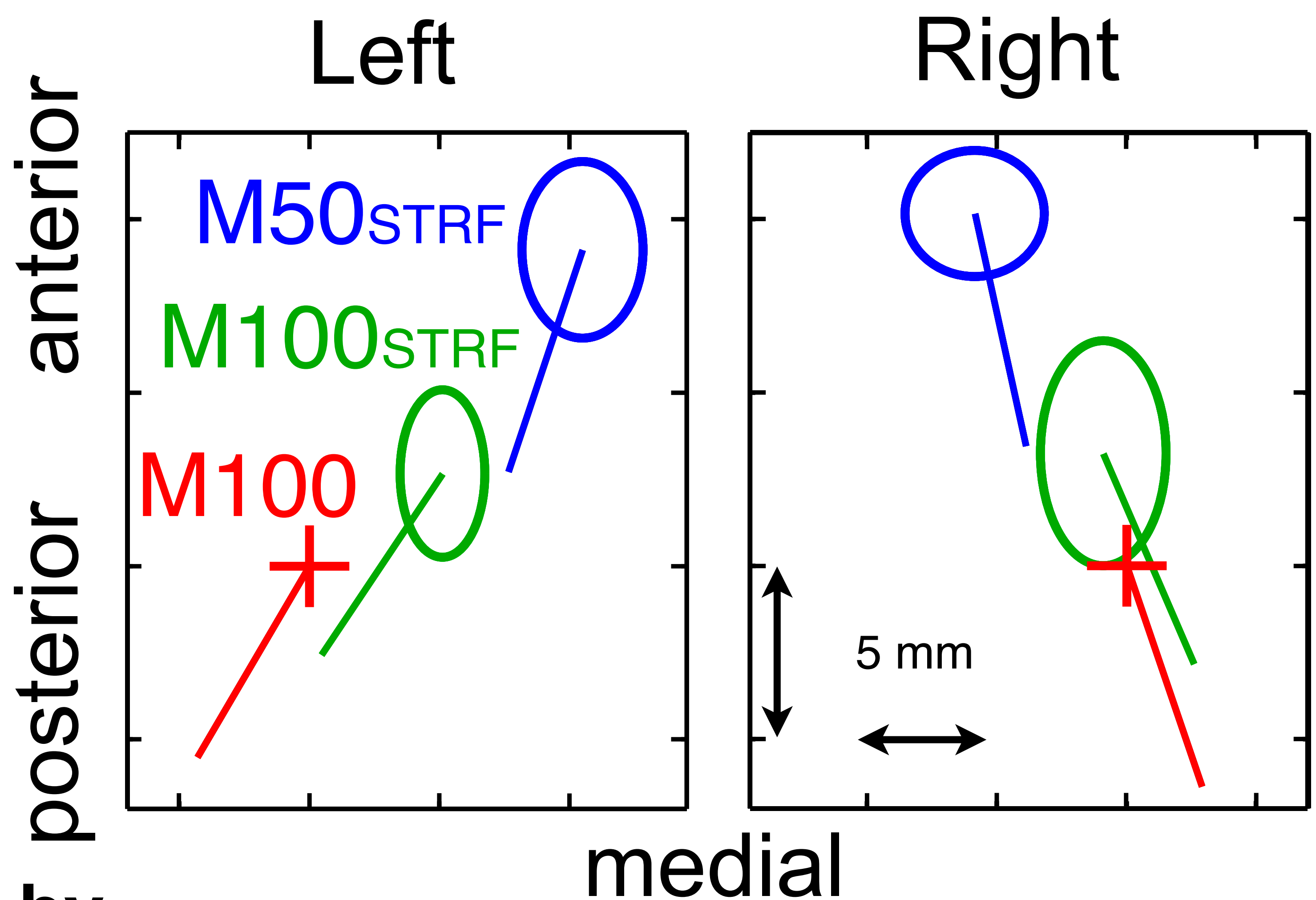
See also Power et al (2012) for EEG

Neural Sources

- **M100$_{STRF}$ source** indistinguishable from M100 source: ***Planum Temporale***

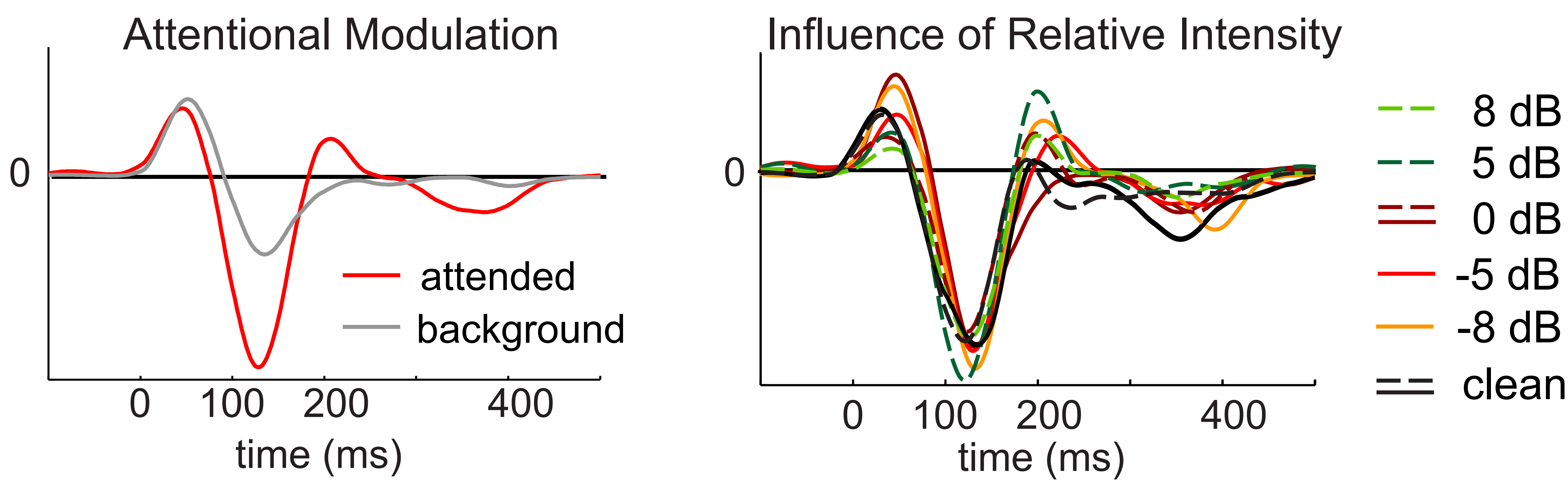
- **M50$_{STRF}$ source** is anterior and medial to M100: ***Heschl's Gyrus***

- **PT strongly modulated by attention, *but not HG***



Ding & Simon, PNAS (2012)

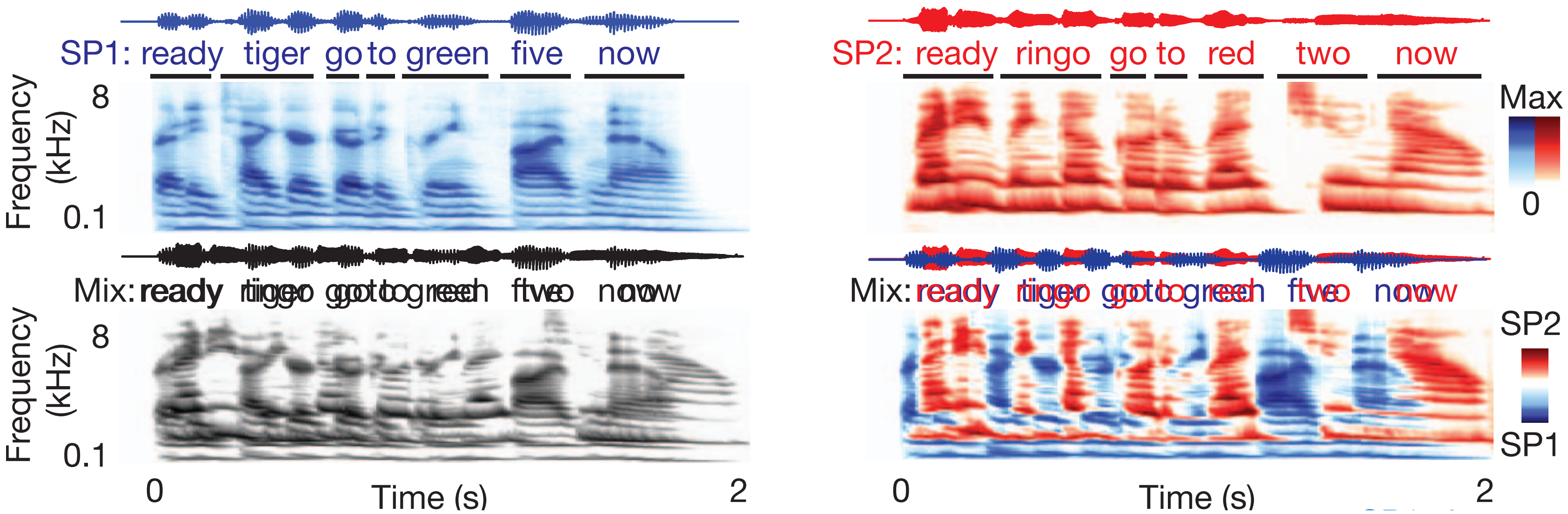
Cortical Processing of Auditory Objects



- $M100_{STRF}$ strongly modulated by attention, but not $M50_{STRF}$.
- $M100_{STRF}$ invariant against acoustic changes.
- Objects well-neurally represented at 100 ms, but not 50 ms.

Ding & Simon, PNAS (2012)

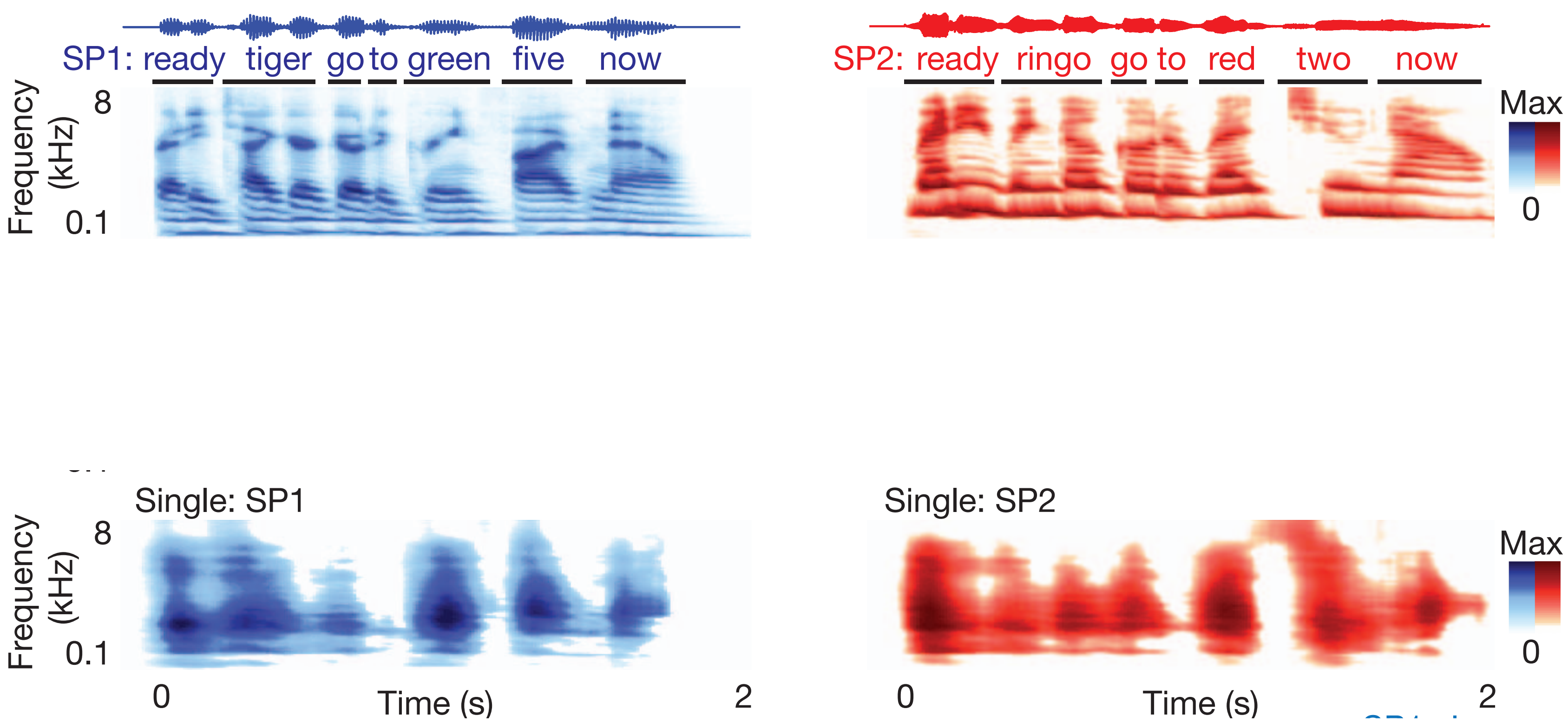
Selective Neural Encoding of Speech



- ECoG records from tens of independent sources
- Reconstruction possible for entire ***spectrogram*** (not just temporal envelope)

Mesgarani & Chang (2012)

Selective Neural Encoding of Speech



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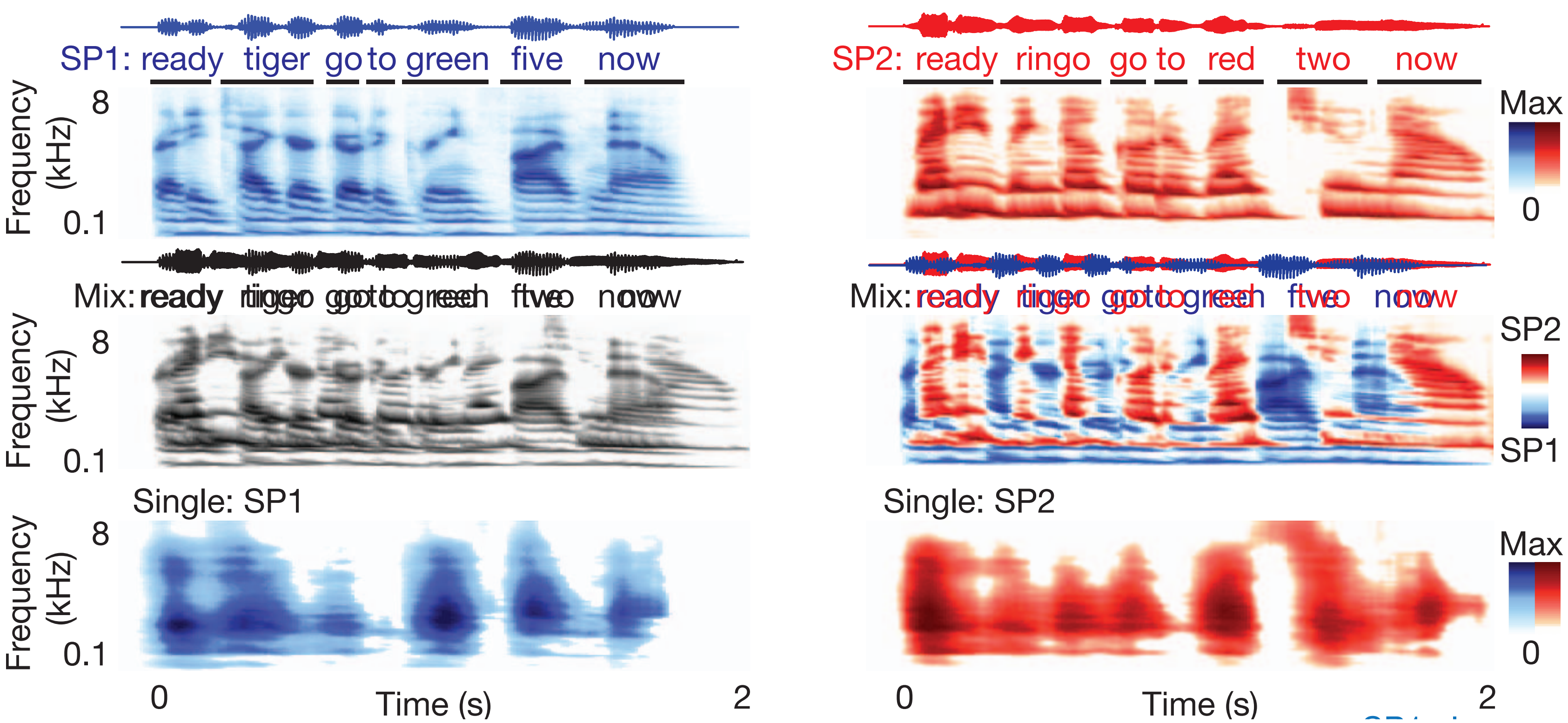

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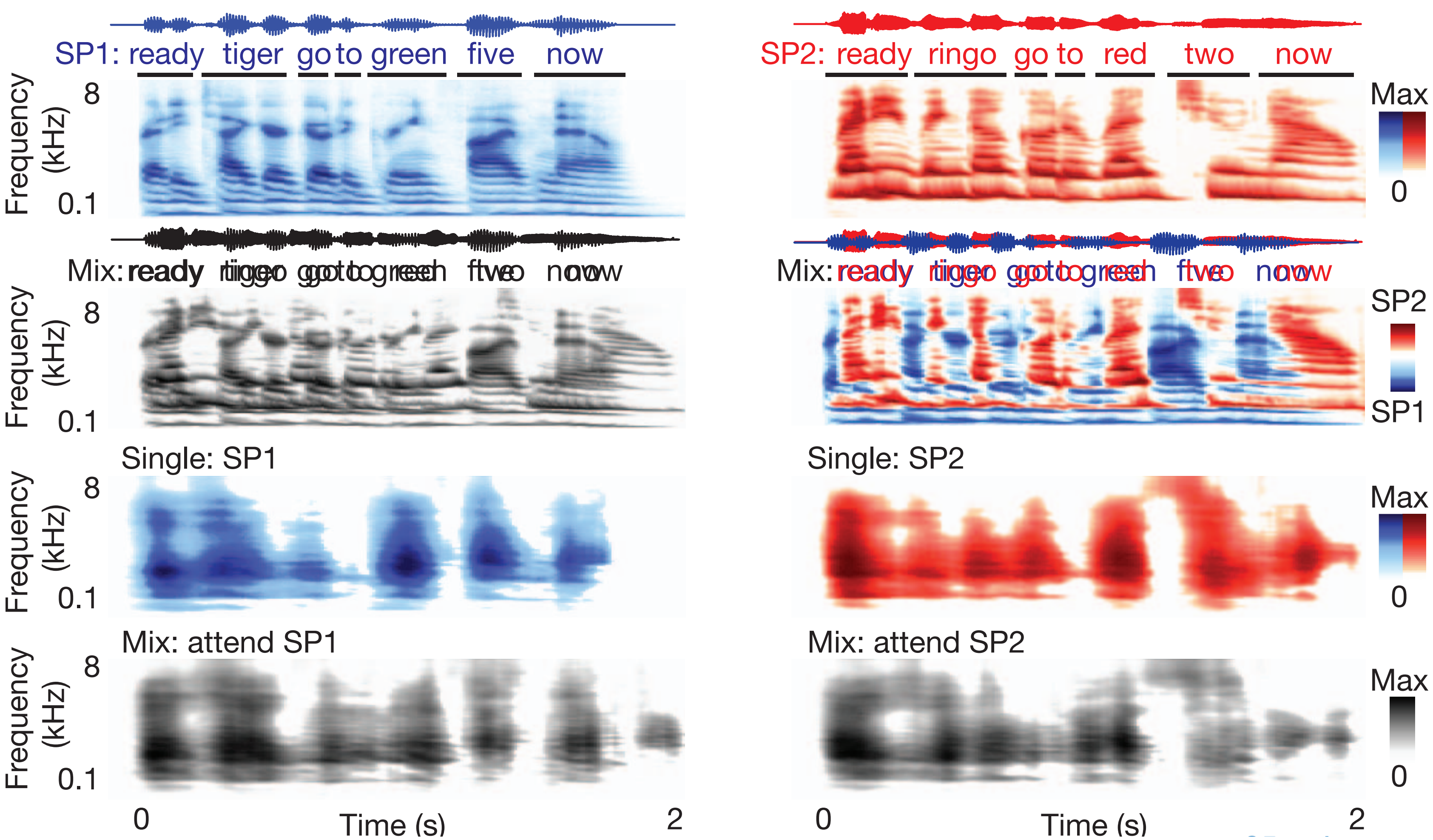
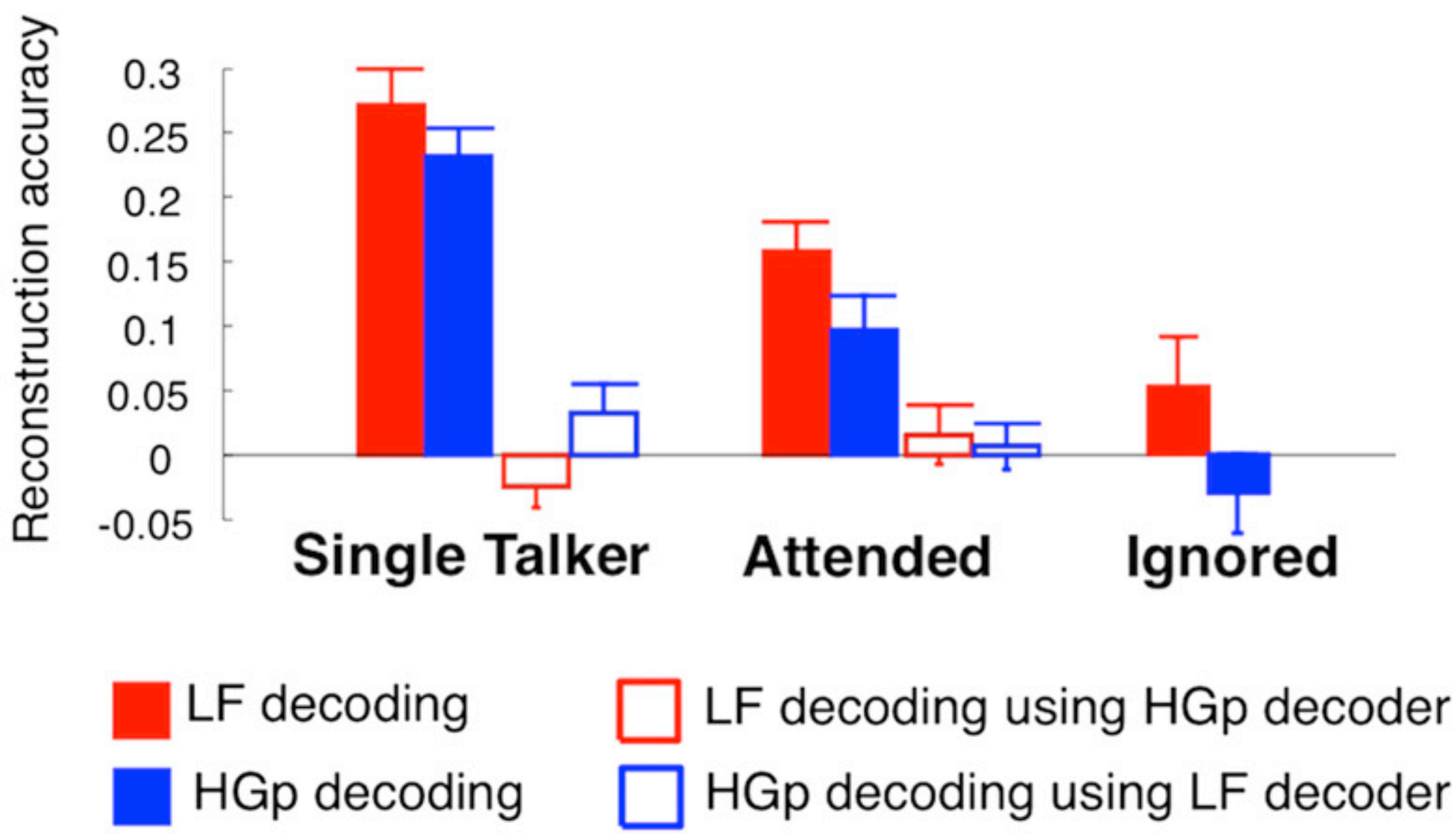


- ECoG records from tens of independent sources
- Reconstruction possible for entire ***spectrogram*** (not just temporal envelope)
- Neural measure follows perception, not (just) physical acoustics
- Reconstruction success only in successful trials
- No consistent spatial pattern observed over auditory cortex

Mesgarani & Chang (2012)

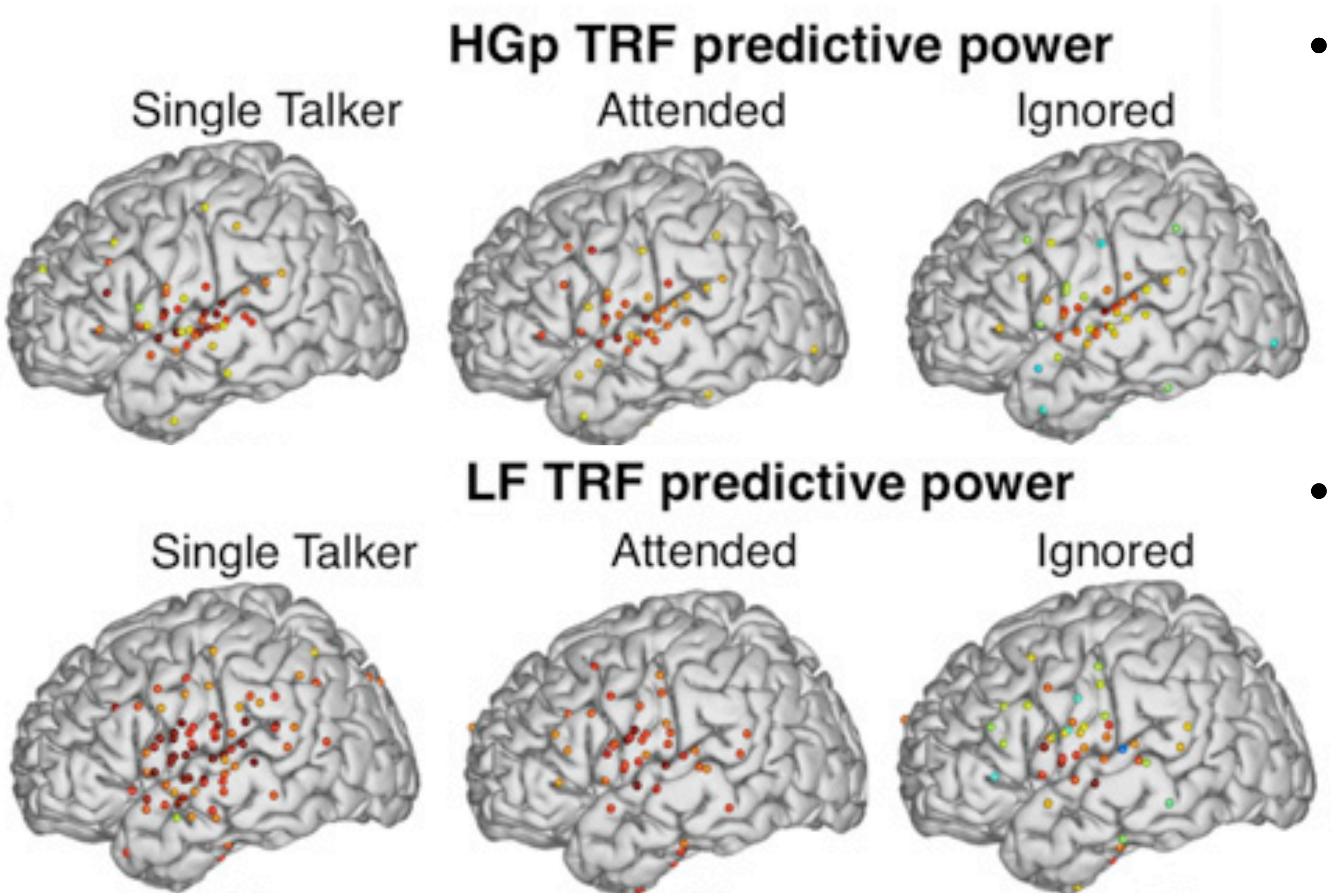
Selective Neural Encoding of Speech



- ECoG over auditory and non-auditory cortex (e.g., motor)
- Neural measures include High Gamma envelope (just seen) and Low Frequency (Delta and Theta band) responses
  - Low Frequency responses also used in MEG, EEG, and LFP
- Neural measure follows perception

Zion Golumbic et al. (2013)

Selective Neural Encoding of Speech



- Reconstruction success from auditory and non-auditory cortex (e.g., motor), for single, foreground, and background speech
- Low Frequency (c.f. LFP) representations more widespread than High Gamma, especially in non-auditory areas
  - Not due to "return" currents

Zion Golumbic et al. (2013)

Neuroanatomy of Speech in Noise

- ECoG studies show widespread representations of speech in a noisy background, across all of, and beyond, auditory cortex (but limited in anatomical scope)
- fMRI & PET show even greater diversity of (non-phase-locked) activity from processing of speech in a noisy background
  - Bilateral activation of auditory cortex
  - Throughout prefrontal and parietal cortex

Scott & McGettigan (2013)

Top-Down vs. Bottom Up Attention

Investigating bottom-up auditory attention

Emine Merve Kaya and Mounya Elhilali*

Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, MD, USA

"Predictions from the model corroborate the relationship between ***bottom-up auditory attention and statistical inference***, and argues for a potential ***role of predictive coding*** as mechanism for saliency detection in acoustic scenes."

Evidence for Models of Segregation

- Temporal Coherence
- See Shamma seminar

Elhilali et al. Nat Neurosci (2009) O'Sullivan et al. (2015)

Direction of Directed Attention?

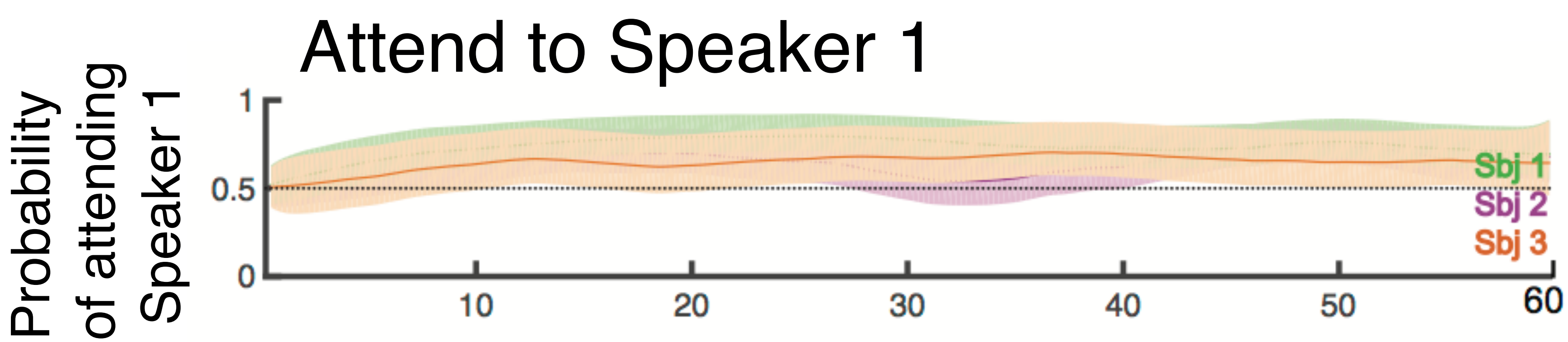
Attentional Selection in a Cocktail Party Environment Can Be Decoded from Single-Trial EEG

James A. O'Sullivan[1], Alan J. Power[1,2], Nima Mesgarani[3,4], Siddharth Rajaram[5], John J. Foxe[6], Barbara G. Shinn-Cunningham[5], Malcolm Slaney[7], Shihab A. Shamma[8] and Edmund C. Lalor[1]

[1]School of Engineering, Trinity Centre for Bioengineering and Trinity College Institute of Neuroscience, Trinity College Dublin, Dublin 2, Ireland, [2]Department of Psychology, Centre for Neuroscience in Education, University of Cambridge, Cambridge, UK, [3]Department of Neurological Surgery, [4]Department of Physiology, UCSF Center for Integrative Neuroscience, University of California, San Francisco, CA 94143, USA, [5]The Center for Computational Neuroscience and Neural Technology, Boston University, Boston, MA 02215, USA, [6]The Sheryl and Daniel R. Tishman Cognitive Neurophysiology Laboratory, Children's Evaluation and Rehabilitation Center, Departments of Pediatrics and Neuroscience, Albert Einstein College of Medicine, Bronx, NY 10461, USA, [7]Microsoft Research, Mountain View, CA 94043, USA and [8]Institute for Systems Research, University of Maryland, College Park, MD 20742, USA

"Despite the fact that we used unaveraged EEG, and did not correct for muscle or blink artifacts, we were able to ***classify attention*** accurately on a ***single-trial basis***. … [with] decoding accuracy of 82%–89%."

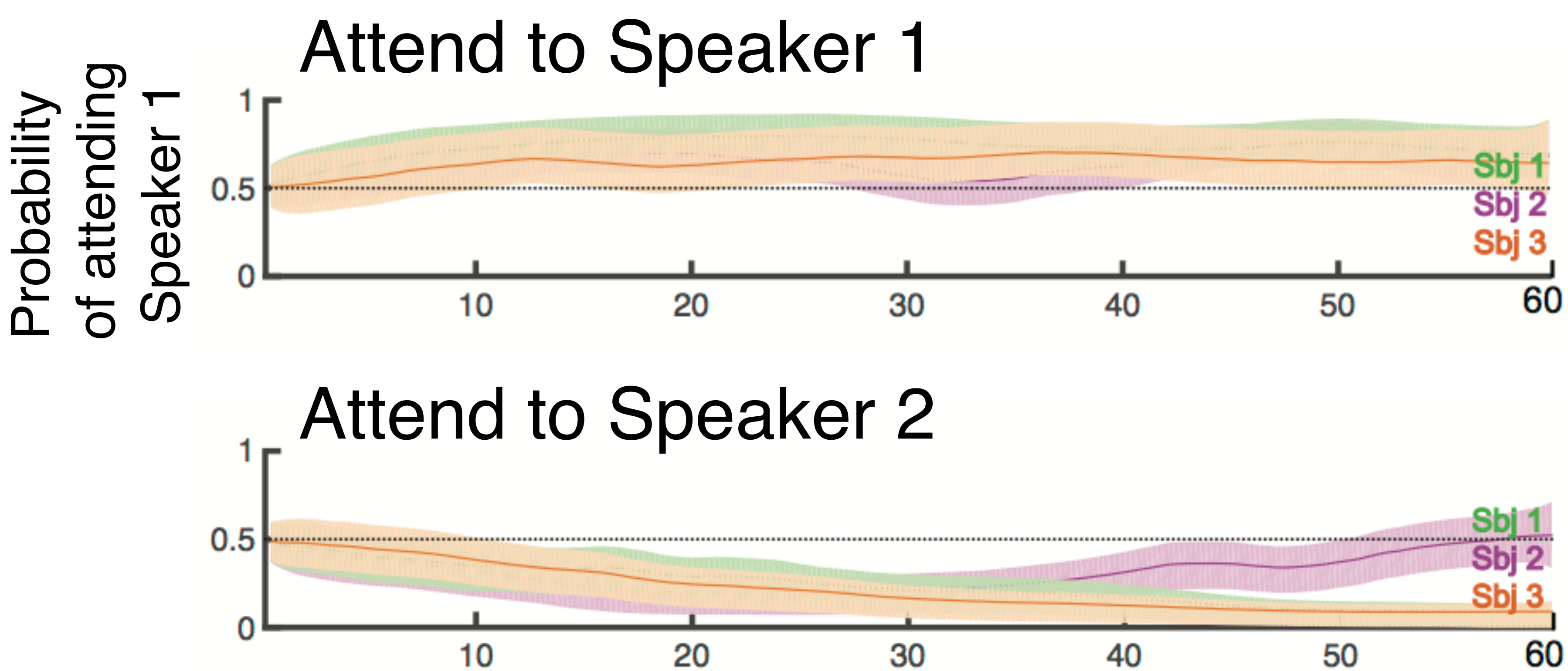
Attentional Dynamics



- Simple *dynamical* model of neural correlate of attentional direction
- Time resolution ~5 s (not, e.g., 60 s)

Akram et al. NeuroImage (2016)

Attentional Dynamics



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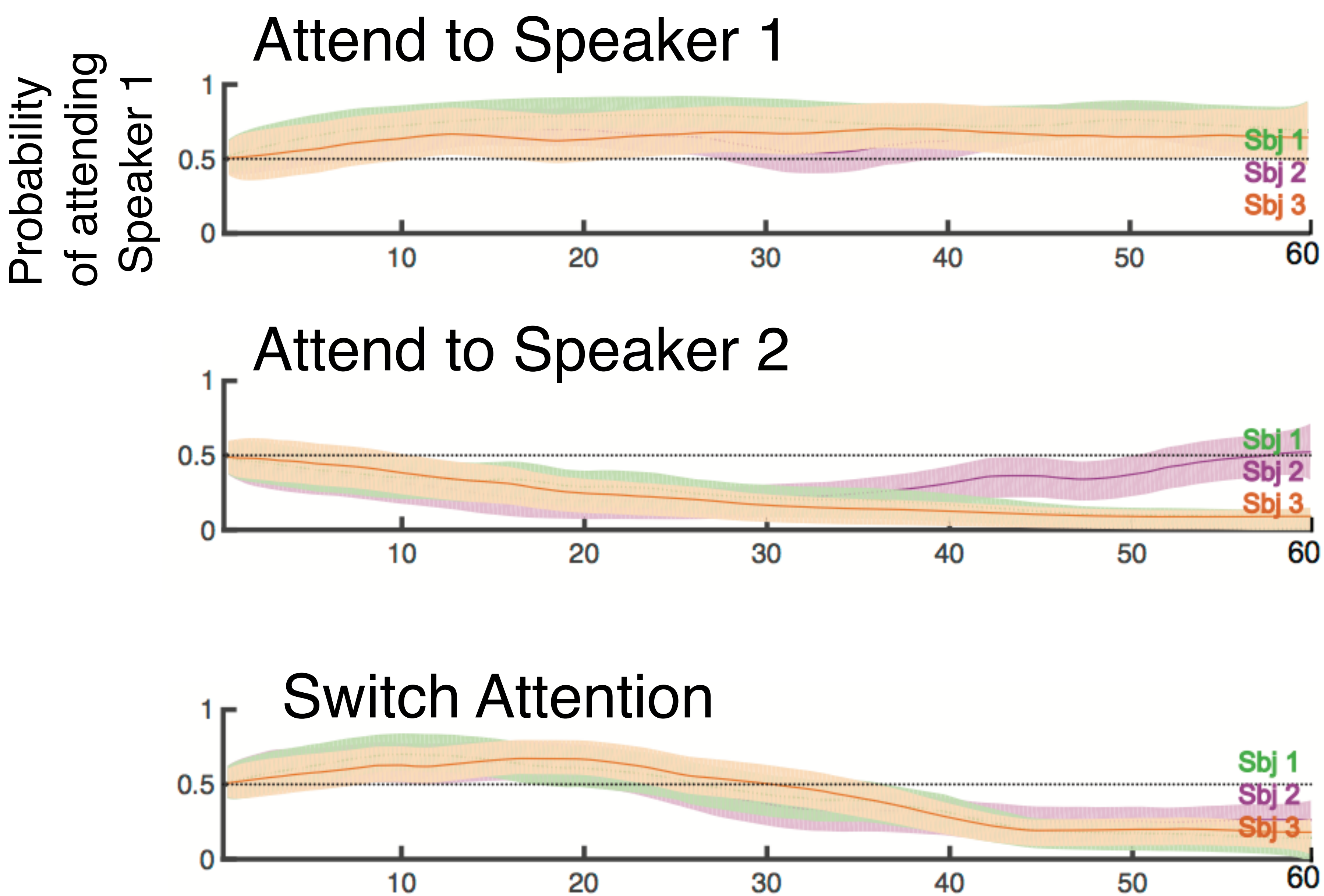
- Less conservative in assumptions regarding actual subject behavior

Akram et al. NeuroImage (2016)

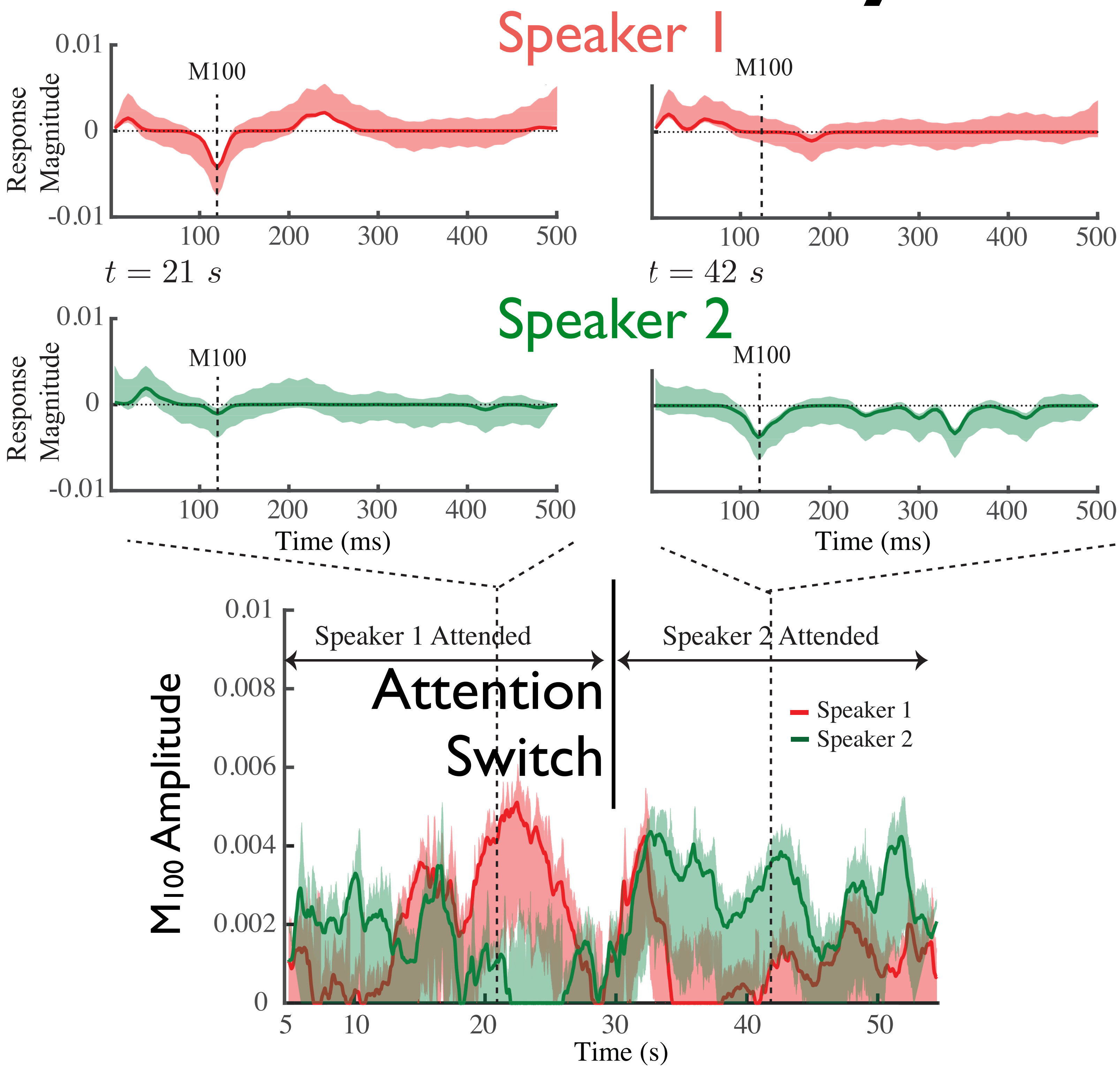
Attentional Dynamics



- Simple *dynamical* model of neural correlate of attentional direction
- Time resolution ~5 s (not, e.g., 60 s)
- Less conservative in assumptions regarding actual subject behavior
- Observable attentional (neural) dynamics

Akram et al. NeuroImage (2016)

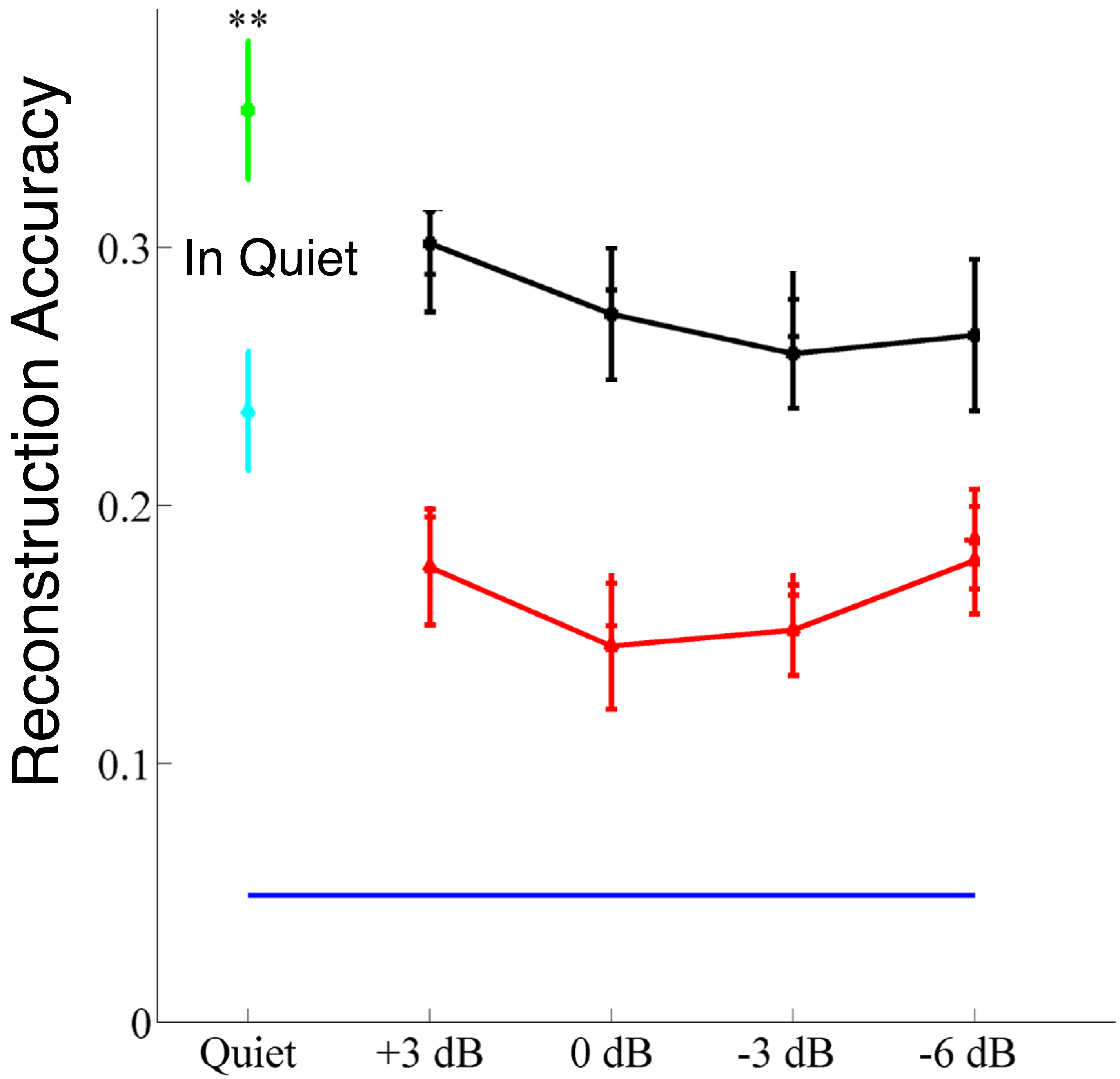
TRF Dynamics



- Dynamical model entire TRF, including attentional modulation
- Time resolution still ~5 s

Akram et al. IEEE Tr Biomed Eng (2016)

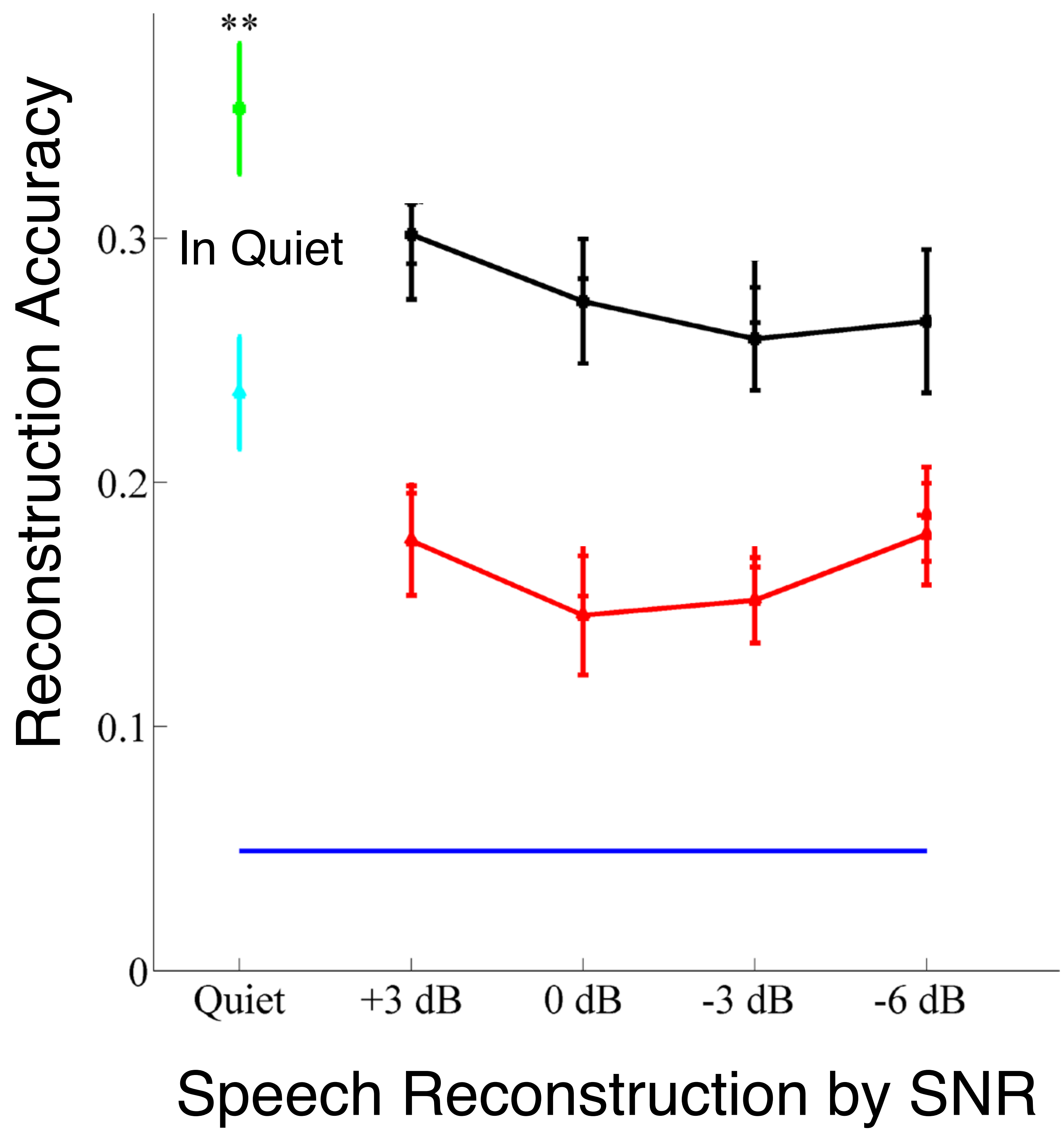
High Level Interference Effects



Speech Reconstruction by SNR

Presacco et al. (2016b)

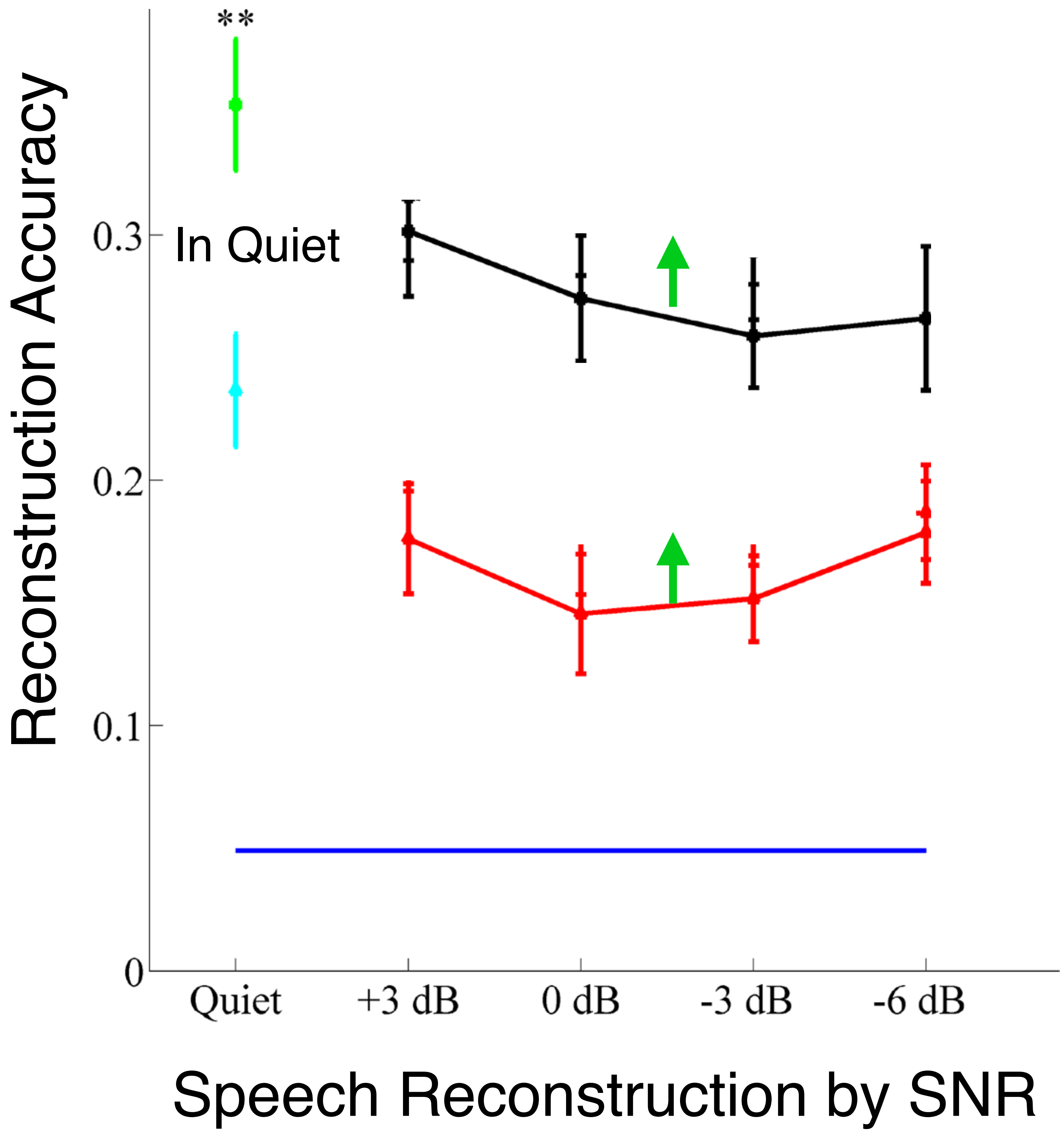
High Level Interference Effects



- **Unfamiliarity of Background**
  - Boosts Intelligibility of Attended Speech

Presacco et al. (2016b)

High Level Interference Effects



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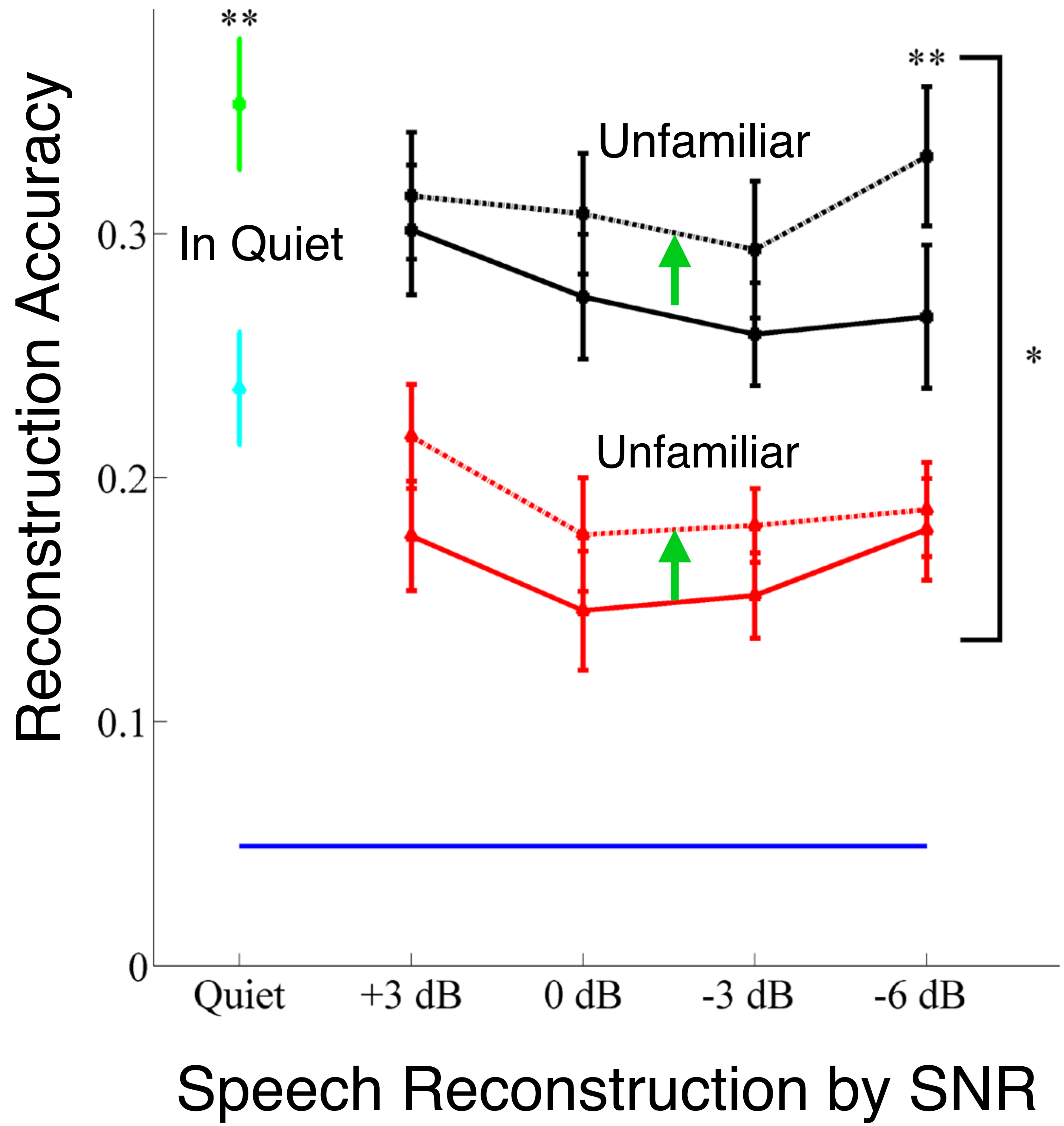
Presacco et al. (2016b)

High Level Interference Effects



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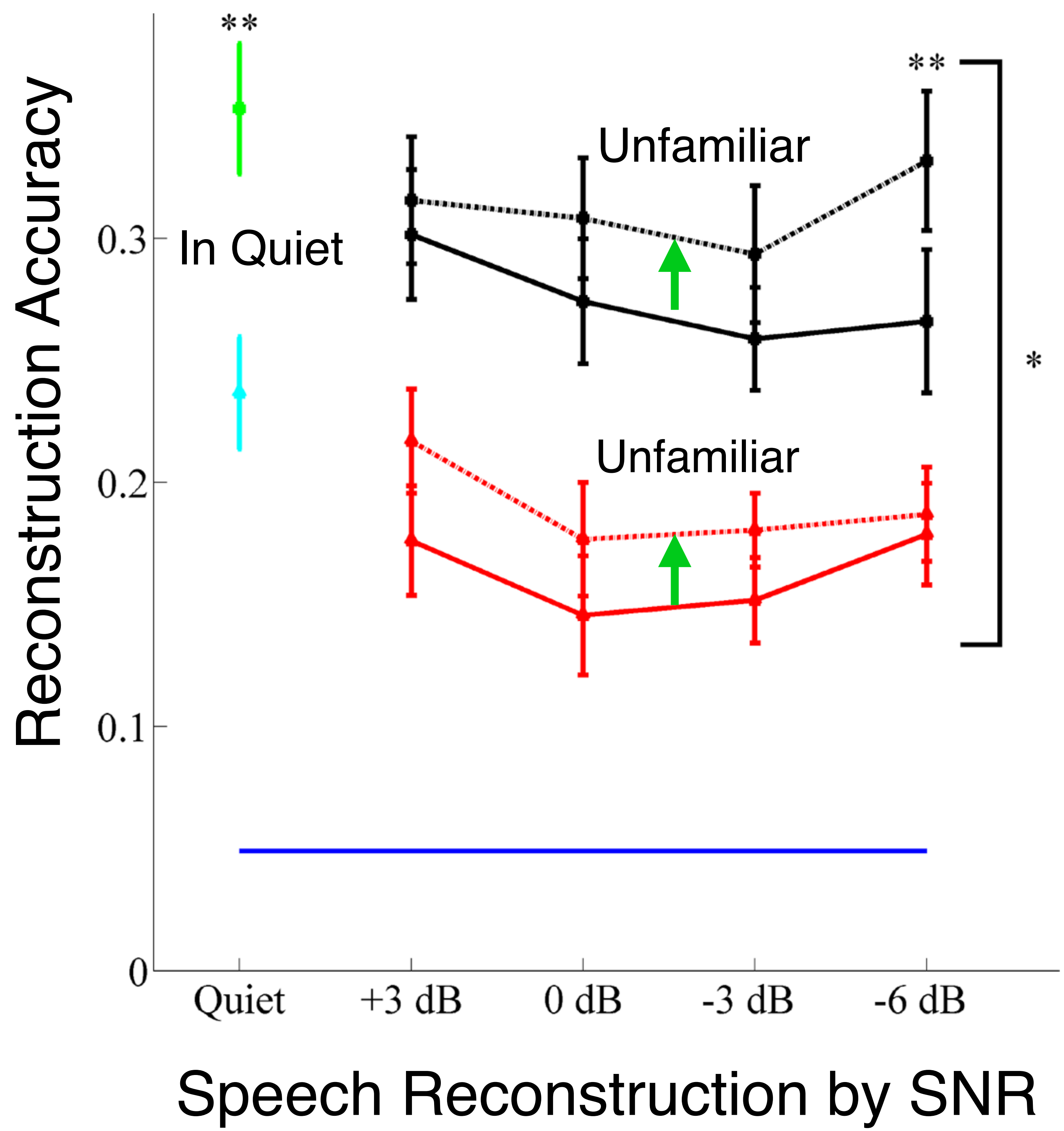
Presacco et al. (2016b)

High Level Interference Effects



- **Unfamiliarity of Background**
  - Boosts Intelligibility of Attended Speech
  - *Also Boosts Cortical Reconstruction of Attended Speech*

Presacco et al. (2016b)

Simple Speech Mixtures Summary

- Speech separation works too (not just tones)
  - strict frequency segregation not necessary
- Neural responses can dissociate from physical acoustics, tracking perception instead
- Strong preference for foreground speech at ~100 ms (in Planum Temporale), so plausibly a neural substrate of perception
- Processing hierarchy: no attentional preference at ~50 ms (in Heschl's Gyrus)

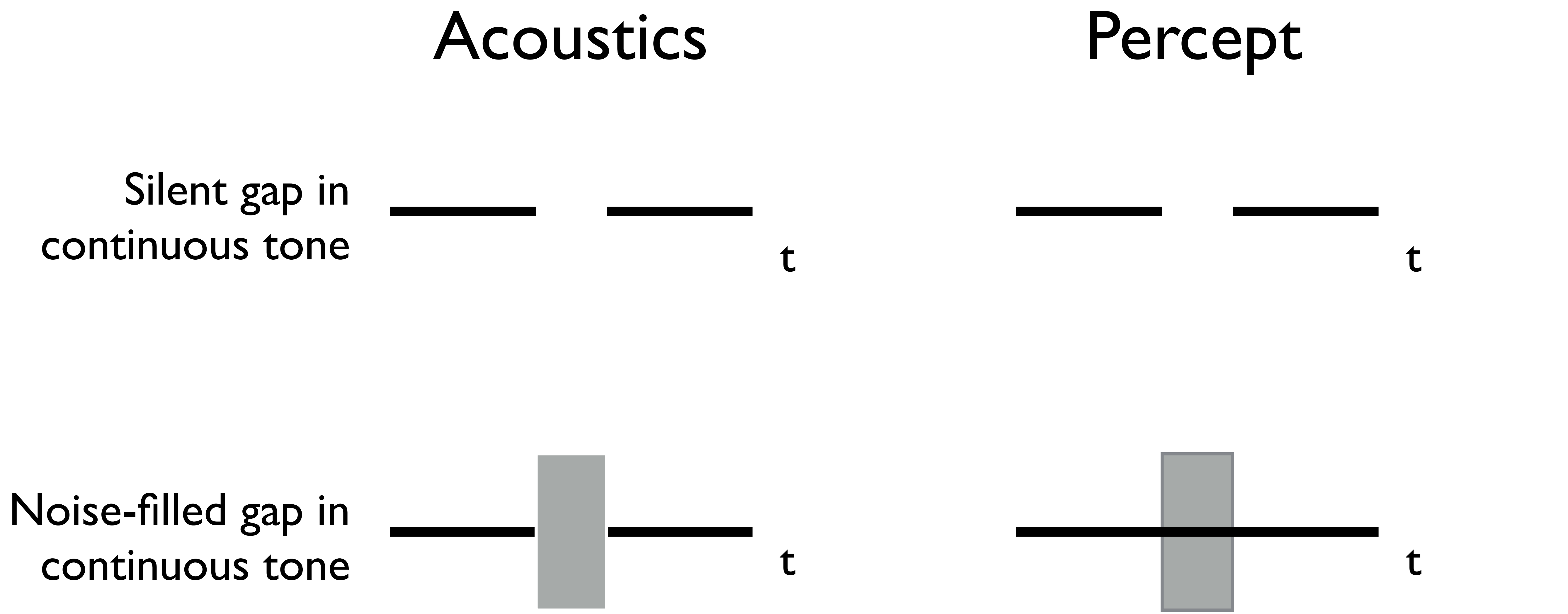
Outline

- What is the Cocktail Party Problem?
- What is Human Auditory Neuroscience?
- Cocktail Parties, Simplified:
  - Tones—with and without directed Attention
  - Speech
- Recent Results: Perceptual & Neural Filling-In

Perceptual Filling-In / Restoration

- Perceptual Phenomenon
- Acoustically absent but plausibly masked stimulus can nonetheless be heard
- Strong percept for constant frequency tones
- Also occurs at phonemic level

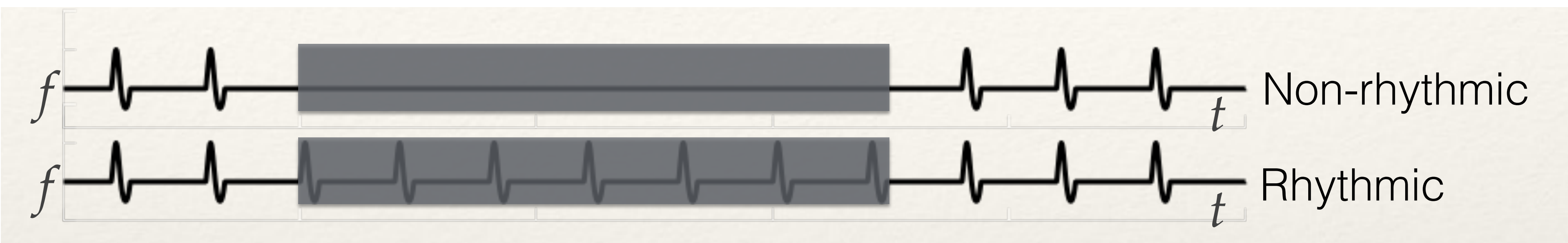
Perceptual Filling-In / Restoration



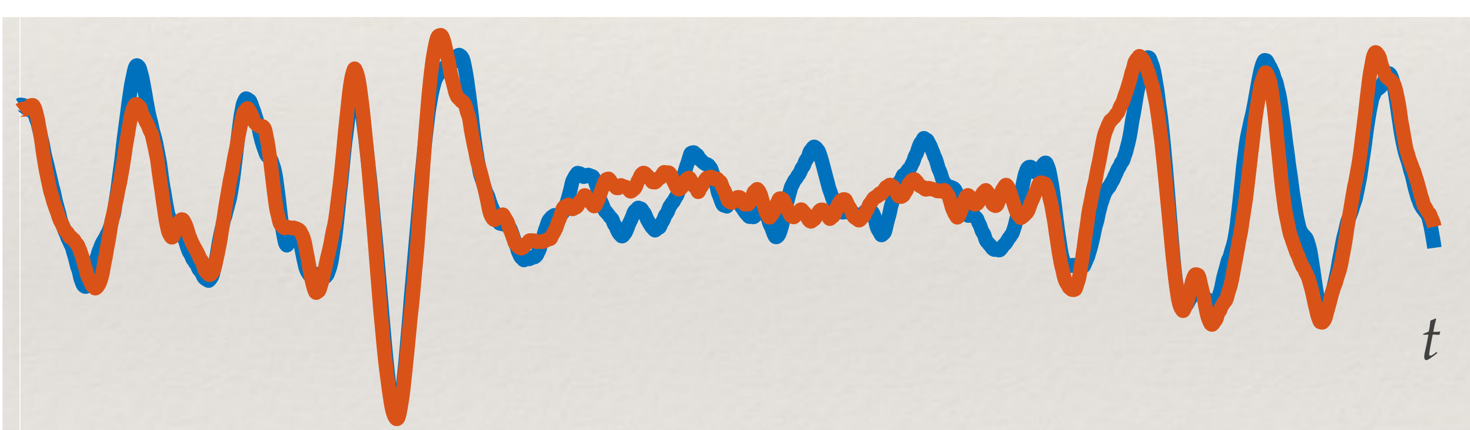
based on Bregman (1990)

Dynamic Filling-In / Restoration

Stimuli



Typical Responses



But perception does not always follow from acoustics

Cervantes Constantino & Simon (unpublished)

Dynamic Filling-In / Restoration

Stimulus / Response	Rhythmic	Non-rhythmic
Rhythmic	Driven	Filling-in
Non-rhythmic	Missed	Absent

Cervantes Constantino & Simon (unpublished)

Dynamic Filling-In / Restoration

Stimulus / Response	Rhythmic	Non-rhythmic
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Dynamic Filling-In / Restoration

Response \ Stimulus	Rhythmic	Non-rhythmic
Rhythmic	Driven	Filling-in
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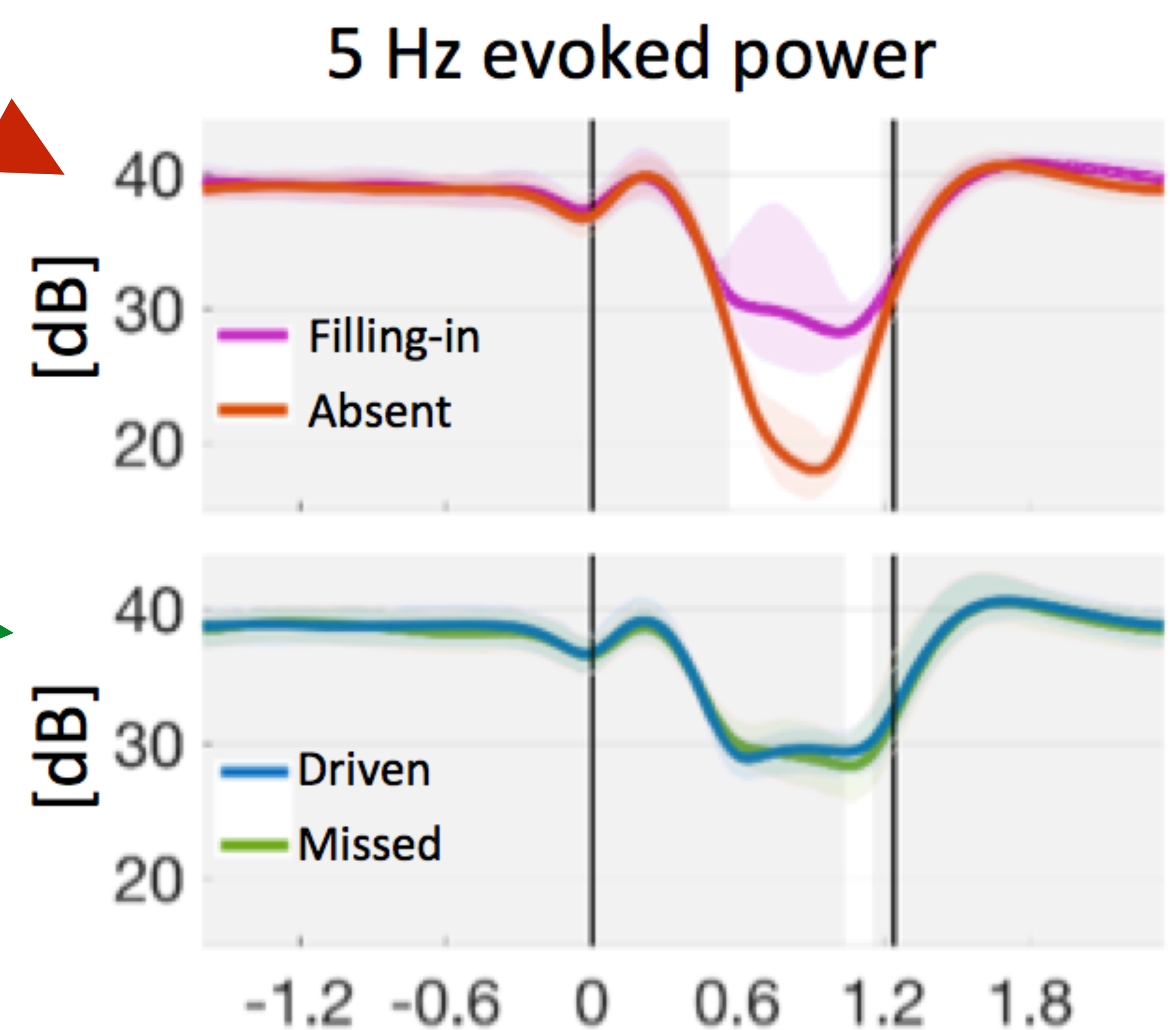

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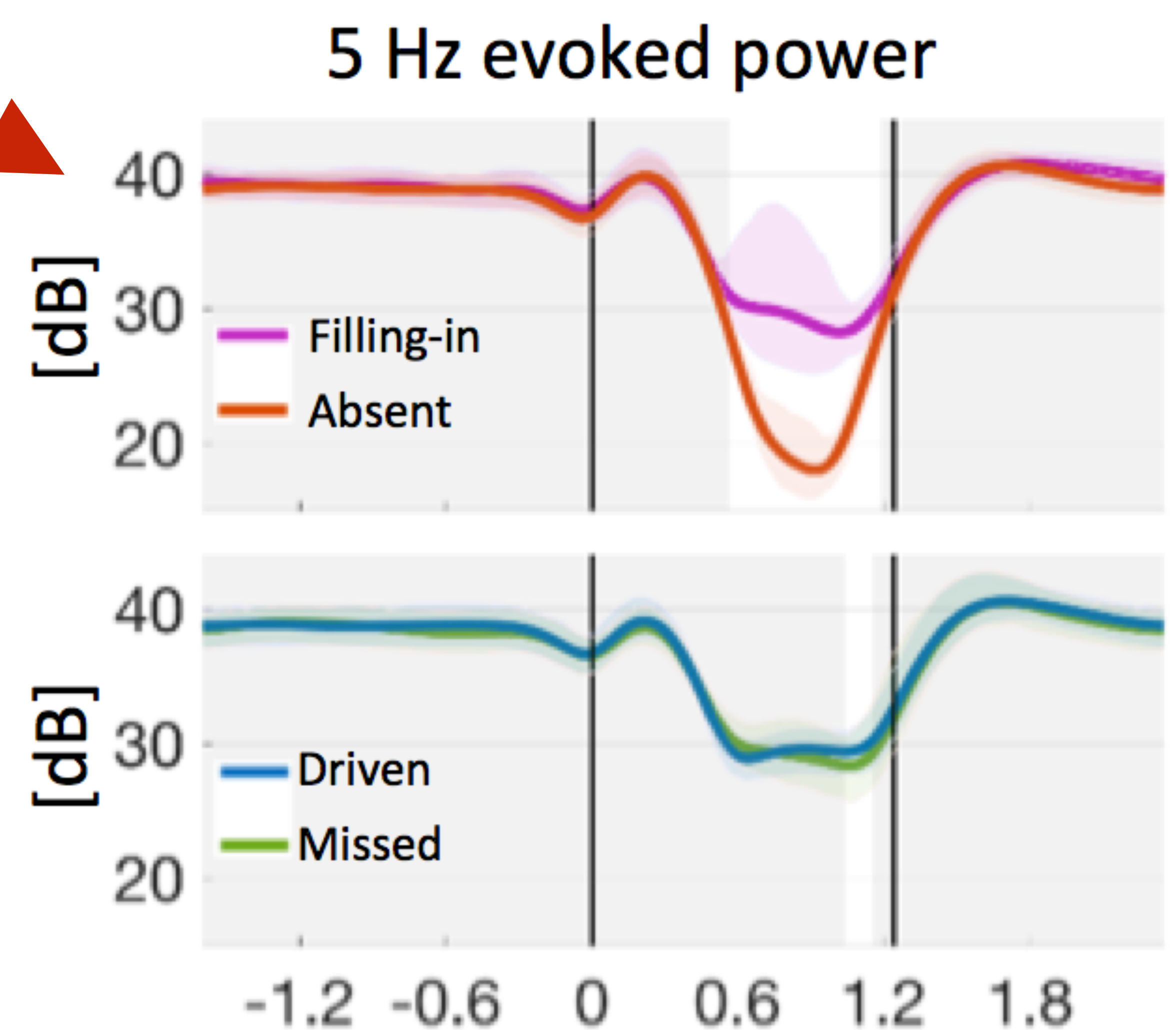

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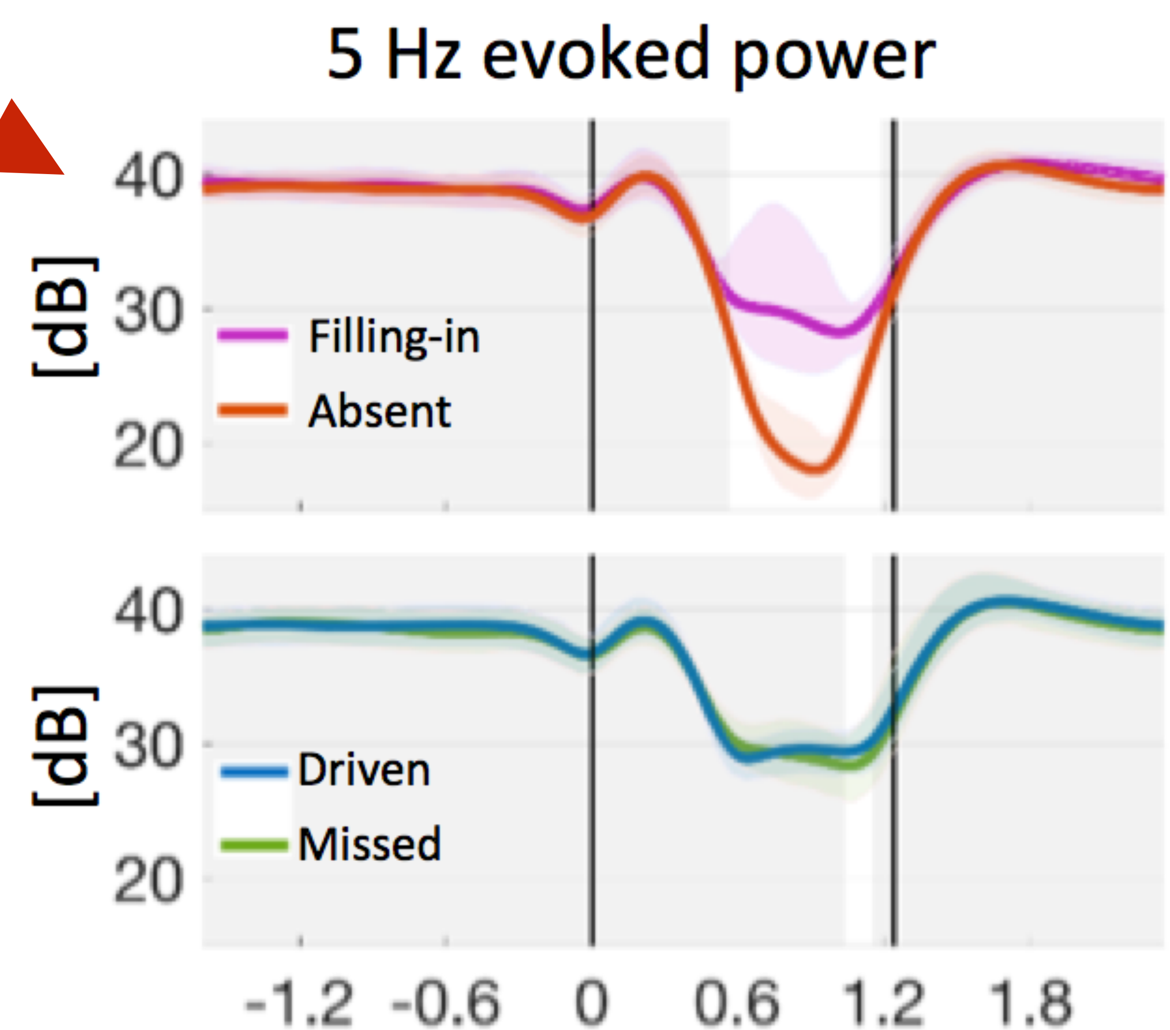
Non-rhythmic	Missed	Absent



Stimulus absent **+** *neural rhythm present* predicts ***percept of rhythmic filling-in***

Cervantes Constantino & Simon (unpublished)

Summary

- Auditory (neural) representations of *acoustic* stimuli and of *perceived* stimuli are related but separable
  - There seem to exist neural representations of perceptual objects, especially auditory foreground (e.g., in Planum Temporale, ~100 ms)
- Robust Dynamical Foreground Monitoring
- The concept of "attentional modulation" of neuronal responses is *misleading* and *likely counter-productive*

References & Resources

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Thank You